Marine Bioresources

Prospects and Obstacles

EDITED BY
Sesan Abiodun Aransiola, Suhasini Bhatnagar, Naga Raju Maddela



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Dr Suhasini Bhatnagar(she/her) is a Ph.D. in medical genetics from Sanjay Gandhi Postgraduate Institute of Medical Sciences, Lucknow, India. She started her career post Ph.D. by teaching biotechnology at various colleges all over India. At last retired from education to open up her own company and ran it with partners initially and now on her own. The company works on project basis, and the work includes projects around sustainable development goals, mainly water and food. Have a few patents in the area, too. Active researcher in the areas of heavy metals and basically recycling. Interested to do projects that help people live better and more scientifically. Shall be writing based on my experiences and literature reviews. Basically, sensitivities to problems around including the environment. The problems are not just restricted to these but love challenges in all fields with an ultimate aim to make living better for all.



Naga Raju Maddela received his M.Sc (1996–98) and PhD (2012) in microbiology from Sri Krishnadevaraya University, Anantapuramu, India. During his doctoral program in the area of environmental microbiology, he investigated the effects of industrial effluents/insecticides on soil microorganisms and their biological activities, and he is working as faculty in microbiology since 1998, teaching undergraduate and postgraduate students. He worked on Prometeo Investigator (fellowship received from SENESCYT) at Universidad Estatal Amazónica, Ecuador, during 2013–15, received "Postdoctoral Fellowship" (2016–18) from Sun Yat-sen University, China. He also received external funding from "China Postdoctoral Science Foundation" in 2017, internal funding from "Universidad Técnica de Manabí" in 2020. He participated in national/international conferences and presented research data in China, Cuba, Ecuador, India, and Singapore. Currently, he is working as a full professor at the Facultad de Ciencias de la Salud, Universidad Técnica de Manabí, Portoviejo, Ecuador. He has been actively publishing scientific articles, books (authored and edited), and chapters since 2007. As of now, he published 110 articles, 25 books, and 50 book chapters.

Foreword



In 2015, the United Nations adopted 17 Sustainable Development Goals not only to prevent further harm to the planet but also to improve the quality of life for everyone globally. According to the 2024 data from the Food and Agriculture Organization (FAO), the world's total land area is 13 billion hectares. Of this, 4.8 billion hectares, or 37%, are classified by the FAO as agricultural land. As of November 2022, the global population stands at approximately eight billion. The population growth is currently the highest in the world's least developed, low-income countries. The UN projects that the global population will reach 9.15 billion by 2050, representing a 32.7% increase from 6.89 billion in 2010. While many books have examined land use and resources, the authors of this book have succinctly explored the vast potential of the ocean as an ideal resource center for sustaining the planet. This book seeks to provide scientific backing for the National Geophysical Data Center's estimates that the ocean holds 1,335,000,000 cubic kilometers (321,003,271 cubic miles) of water—enough to fill approximately 352.67 quintillion gallon-sized milk containers.

Thus, this book, titled *Marine Bioresources: Prospects and Obstacles*, delves into the oceans as a promising source not only for food but also for pharmaceuticals and cosmetics. This book explores innovative sources of clean energy, food preservation through marine microbial products, green hydrogen derived from the ocean, and various biotechnological applications, such as enzymes, bioactive molecules, pharmaceuticals, neuroprotective agents, and other advancements from the marine environment. This book enables readers to explore the vast potential of water-based resources, organized into sections for clarity and ease of understanding. Each section covers a distinct topic, ranging from the exploration of ocean resources to various technological solutions addressing modern challenges, such as antibiotic resistance and the development of new drugs. This book is unique in its comprehensive coverage of various ocean-related aspects, addressing contemporary challenges in both food and health.

This book is intended for students, researchers, and professionals interested in exploring and harnessing marine resources. It will also benefit marine scientists and engineers.

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Preface

Marine environments are aquatic ecosystems with high dissolved salt. This ecosystem includes the deep-sea ocean, open-ocean, and coastal marine ecosystems with different resource potentials, including marine greens, biological diversity, oil and gas, sand and gravel, fish and seafoods supply, tourism potential, renewable energy resources, and many important ecosystems like coral reefs. The world has a large population that needs constant feeding and current disturbances around the world make it a challenge to feed all, at least full stomach. Several methods for land and agriculture are being evolved continuously, yet for various reasons, we are still unable to reach our purpose, hence the need to discuss the marine potential in helping humanity.

The book titled *Marine Bioresources: Prospects and Obstacles* consists of three sections. The first section explores the possibilities to use the sea and explains various basics policies and values required to establish its usage. Simultaneously, the chapters in this section discuss the possibility of using remote sensing and the geographic information system (GIS) in monitoring marine bioresources. Other chapters discuss how to explore the role of marine greens in climate change mitigation and the management of marine microplastics pollution using marine bioresources. The second section is titled Cosmos Preservative Power of Marine Lives. In this section, authors reviewed critically on marine bioresources for sustainable energy production, antimicrobial agents in food preservation, and food from marine to feed humans and animals. The third section discusses various biotechnological applications in the environmental, agricultural, pharmaceutical, and biomedical sector. This section also discusses the applications of marine biotoxins, the use of marine microbial products, and various industrial applications with the possibility of developing or searching for model organisms to study human diseases.

The entire book is to add values to how sea and its resources can be harness to solve human problems. The chapters were contributed by 121 academicians, scientists, and researchers from 19 different countries, namely, Brazil, Canada, China, the Czech Republic, Denmark, Ecuador, Germany, India, Iran, Nigeria, Qatar, Rwanda, South Africa, Sweden, Taiwan, Thailand, the UAE, the UK, and the US, across the world.

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Section 1

Policies and environmental issues

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Chapter 1

Marine bioresources: An overview

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1. Introduction

Preceding this shift that took hold over the last several years, as terrestrial resources continued to diminish, human resource development and utilization started shifting toward the ocean (Aransiola, Oyewole, et al., 2024, p. 1–257; Aransiola, Bamisaye, et al., 2024; Taelman et al., 2014). Marine resources contain precious life support assets, social sustainable development resource reserves, and future high-quality economic development advantage spaces. Nevertheless, human activities have increasingly threatened marine resources through interactions that have incurred many challenges to the relation between marine resources and economic development (Barange et al., 2014). As man continues to exploit marine resources and develop marine industry in large scale, the natural self-purification ability and self-balancing ability of the ocean are reducing the cases of marine water pollution, devastation of habitat, and destruction of resources. Marine biological resources are the marine organisms, and their activities in a given ecosystem for which marine flora and fauna are involved more often in a direct or indirect manner system likely to be effected by the proposed action within the declared marine region of influence. According to context deployed the ROI means, the nearshore waters are reaching up to the 164 ft (50 m) isobaths. This ROI boundary was set up because of the type of action proposed in the nearshore zone and the absence of the uncertainty in the species of marine mammals at this depth. In environmental impact, the analysis is made on species or areas relevant to the functionality of the system, social relevance or restriction under federal, state common wealth, or territory law or statutes. For the purpose of this Environmental Impact Statement/Overseas Environmental Impact Statement, marine biological resources have been divided into four major categories: marine plants and invertebrates, fish and EFH, stressed species, and aquatics invasive species. Moreover, the inefficiency in managing marine resource systems is enhancing (Aransiola, Oyewole, et al., 2024, p. 1–257; Aransiola, Bamisaye, et al., 2024; Halpern et al., 2008; Visbeck et al., 2014). Because the tension between economic development and marine resources is very sharp, since the late 1990s and especially since the beginning of the 21st century, there were signs of increased concern for marine resources and economic development. In the Our Oceans, Our Future initiative launched in June 2017, the United Nations invited all partners to work together for the stewardship and responsible use of ocean and marine resources for the sustainable development. Furthermore, the various nations and international organization are indeed working on formulation of "Blue Economy" to enhance the production and export of existing consumables related to marine ecosystems (Fenichel et al., 2020; Okewu et al., 2024, p. 205–225) to achieve the goal of a positive interaction between marine resources and economic development.

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2. Marine bioresources

The relationship between the sea resources and economic development can therefore be more or less strong. Studying these relationships and the role and influence of all these linkages and embeddings is a central task of marine resource economics (Fath, 2015). In the body of work already available on Marine Resources and Economic Development, the research objects incorporate different forms of marine resources, which include biodiversity, community management, environmental concerns economic progress, and accounting. Huminiecki described how private and foreign influxes of investors would benefit from rich marine resources (Aleksynska & Havrylchyk, 2013) to strengthen the basis for economic development. Wang et al. (2021) identified that industrial marine resource extraction and consumption structures in China: The most vital industrial marine resource supply chain routes ultimately originate from the marine resource extraction industry and extend to the marine construction industry. With the exception of the case of the UK, a wide range of endowment forms result from marine resources; thus, they are able to have some important impacts on the manufacturing structure of the country. At the same time, the promotion of the exploitation and use of marine resources is yet another driver of technological advancement (Tsuboi, 2019). Thus, according to Ahmadov and van der Borg, due to the richness of the marine resources of the country, the use of renewable energy sources and, in particular, wind energy is possible. Marine ecosystem includes vast numbers of biological resources; some of these resources contain compounds with possibilities for development of commercial goods and services (Arrieta et al., 2010). The ability to create and invent commercial products originating from marine bioresources may be regarded as a factor that supports the notion of blue bioeconomy growth. Blue bioeconomy refers to an emerging and innovative sector under blue economy that deals with biotechnology and bio fuels in many market segments. Employment of marine bioresources as source of biotechnological intervention is recognized as blue biotechnology and has been mentioned as one of the main components of blue bioeconomy (OECD, 2013).

Marine bioresources have a broad definition where it includes bacteria, fungi and other microorganisms, cyanobacteria, micro and macro algae, sponges, mollusks and other invertebrates, fish and fish co-products, plants, and compounds derived from marine organisms of the described types (Vasconcelos et al., 2019).

3. Marine ecosystems

As a cumulative set of habitats, the marine environment is a complex system of individual components that are different in terms of biological and ecological properties and that are home to numerous species and offer various kinds of valuable services to people and Earth. These ecosystems, ranging from tidal flats and coral reefs to the open ocean and the floor of the ocean, support a wide spectrum of species, including coral polyps and mangrove trees, algae and other such microscopic organisms, and marine mammals and many other forms of animals. For example, coral reefs are frequently likened to a rainforest because of high density of species and interdependence such as coral polyps dependent on zooxanthellae, which increase the reef's ability to adapt (Souter, Wilkinson, & Schutte, 2021; Souter, Linden, & Cooper, 2021). Mangrove forests and seagrass meadows support fish and invertebrate production for enhancement of ecological sustainability and provision of food. The exercising pelagic zone in the open sea includes this species from the smallest protistan plankton to marine mammals and particularly the large elasmobranchs and seabirds in those regions of the oceans The confined kelp forest areas that are widely distributed along the coastal lines also support life forms such as sea urchins, sea otters among others, which are critical in restoring order in ecosystems (Estes, Tinker, & Bodkin, 2022; Estes, Tinker, Williams, et al., 2022). All of these ecosystems are involved in global processes such as carbon storage, nutrients cycling, and climate modification, and mangrove and seagrass beds are both important carbon stocks to tackle climate change (Feller, Friess, & Krauss, 2021; Feller, Lovelock, & McKee, 2021; Gimba et al., 2024, p. 35–44). Coral reef ecosystems benefit coastal communities by preventing shore line erosion, supporting economies by favoring tourism and fishing industries and other resources (Dove, Gutiérrez-Isaza, & Hoegh-Guldberg, 2022; Dove, Foster, & Falter, 2022). But these valuable ecosystems are at a higher risk of pollution, overfishing, habitat loss, and worsening effects of climate change including heat and ocean acidification that pose danger to coral reefs and other fragile habitats (Friess, Richards, & Sidik, 2020). People are of course able to view and appreciate these ecosystems and the multiple uses that come along with them, and thus, it becomes important that they are properly managed and conserved for local and global biodiversity.

4. Types of marine ecosystems

Marine environment is a complex environment that is available in different forms including shallow water habitats, deep sea habitats, and mid-water habitats. Here is an elaborate classification of the major marine ecosystems together with the usual inhabitants of each.

4.1 Coral reefs

Coral reefs are complex and colorful formations that can be compared to tropical forest as far as the abundance of the life they support is a concern. Existing in the shoal areas, tropical climate zones, these structures are the product of coral polyps that have secrets of hard texture covering beneath the sea. About one quarter of all marine organisms can be found in coral reefs; primary producers in this ecosystem are Acropora and Porites corals and zooxanthellae algae. This association is vital for the welfare of corals because zooxanthellae are involved in photosynthesis to generate energy for the corals and assist in the creation of reefs (Souter, Wilkinson, & Schutte, 2021; Souter, Linden, & Cooper, 2021). Small fish including parrotfishes, butterflyfishes and clownfish, and other inhabitants like turtles, crustaceans and mollusk, depend on the corals for shelter and food most of which are interrelated in a complex manner. The role of coral reefs is immense, in addition to acting as barriers to wave energy that would otherwise cause shore erosion they contribute to tourism, fish stocks, and nutrient recycling. Besides, the Sumatran coral reefs support biomedical studies as diverse species possess bioactive compounds with potential for use in medicine (Dove, Gutiérrez-Isaza, & Hoegh-Guldberg, 2022; Dove, Foster, & Falter, 2022). However, reefs are fragile structures that depend on its environment; this makes conservation extremely important due to factors such as; heating seas, acidification, and man's interference.

4.2 Mangrove forests

Mangrove forests are located along the tropical and subtropical coasts where the vegetation found is adapted to saline water environments. These are known to have a built-up structure of their roots that anchor underlying sediments and diverse organisms. Special organisms found in mangrove forests include the different mangrove species like *Rhizophora* and *Avicennia*, fish like snapper and mullet as well as shrimps and crabs as crustaceans. These areas also support a lot of birds such as the herons and egrets and serve as nurseries for fish and shellfish, which then migrate to open waters. Mangrove forests are of a special importance as they absorb a significant amount of carbon dioxide and thus reduce the unique issue of climate change. Used also to safeguard shoreline from storm surges and flooding issues and also to help act as buffer to pollution, maintaining water quality and supporting fish stocks (Feller, Friess, & Krauss, 2021; Feller, Lovelock, & McKee, 2021; Friess, Rogers, et al., 2020). Mangroves, the coastal ecosystems, are richest and most productive among all ecosystems, but vulnerable for coastal development and changes in land use patterns, therefore, the importance of their conservation.

4.3 Seagrass meadows

Seagrass meadows are mostly distributed in the low-light penetration areas, sandy, or muddy substrates, usually associated with coastal lagoons and estuaries. These meadows will include flowers such as *Zostera* and *Posidonia* that are underwater grasslands that are primary producers in their respective ecological systems. Seagrasses also provide support for herbivores such as dugongs, manatees and green sea turtles, and many fish and invertebrates. These primary organisms are a key part of the meadow's productivity and species richness, fish, and other invertebrates depend on the seagrass beds both as feeding and breeding grounds. One cannot overemphasize the value of seagrass meadows, which anchor sediments, store carbon, feed diverse fish stocks that are economically valued. Seagrass meadows are remarkable in terms of carbon storage, a factor that plays a role of mitigating climate change impacts, but the habitats suffer from water pollution, mechanical damage, and oceanization (Nordlund et al., 2023).

4.4 Kelp forests

This biome consists of cool, nutrient wealthy ocean coastal waters, and is populated through giant brown algae varieties such as *Macrocystis* and *Laminaria*. They allow the growth of thick underwater canopies that support other marine life making it one of the most productiveness systems in the ocean. The basic organisms are kelp itself, which forms a top layer that offers protection and food to sea urchins starfish, rock fish, and sea mammals such as the sea otters. Sea otters contribute by feeding on sea urchins, which in turn helps maintain the balance of the kelp ecosystem (Estes, Tinker, & Bodkin, 2022; Estes, Tinker, Williams, et al., 2022). Kelp forests are important in acting as a barrier to waves and hence reduce the occurrence of shoreline erosion. They are also vitally important to commercial fisheries and are significant for nutrient recycling, carbon storage, and marine species support. Challenges affecting kelp forests are changes in water temperature, water pollution, and excessive grazing by herbivores making the conservation of kelp forests crucial (Smale et al., 2021).

4.5 Open ocean (pelagic zone)

The open ocean region also known as the pelagic zone is a large area of the ocean that is divided by the levels of light penetration and can be categorized mainly into the Epipelagic zone, which is the sunlit zone of the ocean and the others such as the mesopelagic, the bathypelagic, the Roxas zone, the abyssopelagic, and the hadopelagic all of which exist in the dark parts. The primary organisms differ by the zones and in the epipelagic zone, phytoplankton and zooplankton are dominant and fundamental entities in marine trophic pyramid. Tuna, mackerel, and shark are found in the upper levels, while the mesopelagic and bathypelagic levels are host to lanternfish and deep-sea squid, respectively. Some of the biota of the ocean's abyssal zone include the giant squid and angler fish that exist in pitch darkness, while extremophiles in hydrothermal vent regions depend on chemosynthesis rather than photons (Kahru et al., 2023). The vast deep sea is of uttermost importance for feeding people through fisheries, for transportation of nutrients and global carbon cycling. Its size is of great importance in climate control by acting as a carbon sink and source of oxygen (Jönsson et al., 2023). Some disturbances are caused by human activities like fishing and pollution affecting the balance hence the need to management open ocean habitats.

4.6 Deep-sea vents and cold seeps

Hydrothermal venting and cold seep ecosystems are among the most specialized habitats known to occur within the global ocean, situated in the deepest abyssal trenches of the sea floor. Some of the primary organisms here are sulfate- or methane-substituting bacteria which differ from photo organisms that use light to produce food. These bacteria are grouped on the base of the food chain feeding complex life forms like tube worm (*Riftia pachyptila*), deep sea clams, fish, and crustaceans. The significance of deep-sea vents and cold seeps is in the cycling of nutrients and nutrients such as sulfur and methane and in the extensive habitat that permits the assessing of evolutionary adaptations and older life forms (Dove, Gutiérrez-Isaza, & Hoegh-Guldberg, 2022; Dove, Foster, & Falter, 2022; Levin & Van Dover, 2022). They may also have biotechnological implication further. Some applications of these ecosystems may include: But they are still threatened with deep sea mining and climatic change, hence the need for protection and study.

4.7 Salt marshes

Salt marshes constitute coastal wetland which are common in temperate climates and which are subjected to tidal inundation with saline waters. Principal vegetation within these ecosystems include cordgrass (*Spartina*), pickleweed (*Salicornia*), and other salt-tolerant plants which offer not only feeding and nesting ground for the ranging fish, crustaceans, and avian such as egrets and herons. Apart from acting as natural barriers against storm surges, accretion contains pollutants, enhances water quality, and supports fish and birds' reproduction (Ouyang & Lee, 2023). They also support carbon storage activities and function as barrier islands mask the effects of climate change by trapping carbon in their sediment layers. These ecosystems are at high risk of habitat loss due to coastal development and sea-level rise and more as such the importance of insider protection of these areas for the sustenance of their services (Törnqvist & Hijma, 2021).

4.8 Estuaries

Estuaries are special water habitats characterized by the interaction of fresh water from a river with sea water thus making it a food supporting zone. They are breeding and hatchery grounds for many marine organisms, with Walling's primary organisms as fish; salmon and eels, Crustaceans; crabs, mollusks; oysters, and clams and plankton for the chain Franklin 719. There are many herons and egrets who visit the area because of the vast availability of food (Kennish et al., 2023). Estuaries are thus important for several reasons since they promote biodiversity, help in cleansing the water and are nurseries, which mean that most species are born and grow here that later migrate to the open ocean (Cloern et al., 2022). However, estuaries face challenges from pollution, habitat destruction, and climate change, underscoring the need for protective measures to safeguard their ecological and economic value.

5. Classification of marine ecosystems

5.1 Classification of biological groups

The marine industry is made up of numerous organisms, which exist in symbiotic and interactional relations with several other factors in the system. These ecosystems can be described on the basis of biological groups and the ecological roles

of these groups, which make up the organizational structure of the ecosystems. The primary classifications based on biological groups include:

- **Marine planktonic ecosystem**: This ecosystem consists of an extensive list of organisms which move with water currents and commonly referred to as plankton. They belong to phytoplankton which includes plant like organisms that can hardly be seen with a naked eye, zooplankton which consists of animals that are also too small to be seen without a lens and bacterioplankton which are bacteria. Phytoplankton forms the foundation of production, where they fix nutrients in the sea mostly carbon dioxide and sunlight to produce organic compounds. Phytoplanktons are fed on by zooplankton, which are in turn food for fish and whales and several other species. Variation of bacterioplankton at the gene level plays an important role in the cycling of nutrients and decomposition in the ocean. These organisms are mostly distributed in the epipelagic region of the marine environment since light is available to support photosynthesis and production (Wang et al., 2021; Kumar et al., 2023).
- **Marine benthic ecosystem**: The benthic ecosystem refers to the bottom of the sea that is occupied by organisms that live here with various types of organisms collectively called benthos. This group comprises of zoobenthos, which includes animals such as crustaceans, mollusks, and echinoderms, phytobenthos in which participants are algae and seagrass and bacteriobenthos comprising of bacteria which enhances decomposition of materials. Meiofauna in the benthic region of the aquatic system serves an important function in nutrient cycling and mobility of sediments and also in the support of overall health of coastal/ocean waters. It inhabits various areas, which range from between the surface of sea water and coastal zone, and the ocean depths and their number and variety can determine the state of the marine life two (Levin, 2022).
- **Deep-sea ecosystem**: The deep-sea ecosystem is one of the most extreme environments on Earth, characterized by high pressure, low temperatures, and complete darkness. Organisms in this ecosystem, including deep-sea fish, invertebrates, and microorganisms, have adapted unique physiological and behavioral traits to survive. For example, some species rely on chemosynthesis, a process where bacteria convert chemical energy from hydrothermal vents into organic matter, rather than relying on sunlight. This ecosystem is crucial for global biodiversity and plays an important role in carbon cycling and climate regulation (Shank & Figueiredo, 2022).

5.2 Ecological function division

The classification of marine ecosystems based on ecological functions reveals several essential components that contribute to their overall health and sustainability:

Marine productivity ecosystem: This classification looks at the efficiency at which the marine species obtain their food through "fixed energy loss system," which in organism organization type include photosynthetic and chemosynthetic organisms. The marine productivity ecosystem is crucial for preserving the base for food chains and feeding the higher trophic levels. For example, regions of high productivity such as upwelling zones are full with the food items that increases the stock of diverse species of fishes and hence biases the carrying capacity high (Duarte, 2022).

Marine food chain ecosystem: The marine food chain shows feeding dependencies and energy flow among the marine species. The food chain interconnecting is very close where both energy and nutrients move from the phytoplankton to zooplankton and from the zooplankton to the fishes and marine mammals. They determine the mode of functioning and organization of gregarious populations of sea organisms and play an essential role in terms of balancing ecosystems. That shifts in one species can affect an entire level of the food chain, only highlights the intricate web of marine life (Graham, 2022).

Mineral cycle of marine ecosystems: Mineral cycle is defined as the processes of cycling and changing of relevant mineral elements in the functioning of marine environment. Key cycles include:

- **Carbon Cycle**: The carbon cycle plays important role to expect climate and support lives of sea creatures. It dissolves in the water and reacts with phytoplankton by diffusing in the ocean atmosphere interface, to produce organic carbon compounds. This organic carbon finds its way into the base of the marine food chain and is recycled through decomposer organisms releasing CO_2 through respiration back into the atmosphere (Fig. 1.1). Carbon stocks, within and among our oceans, are thus critical for supporting the continued, natural regulation of ocean pH and, therefore, the health of marine ecosystems (Duarte, 2022; Thompson, 2023).
- **Nitrogen cycle**: Nitrogen plays an important role in the aquatic life and the processes, which occur within the marine environment include nitrogen fixation, nitrification, and denitrification (Fig. 1.2). Ecological communities in marine environments depend on these processes especially in replenishment of nutrient stocks for the primary producers and thus productivity and species diversity in the system. Pollutant disturbances of the nitrogen cycle can result in problems such as algal bloom or hypoxic conditions (Klein, 2022).

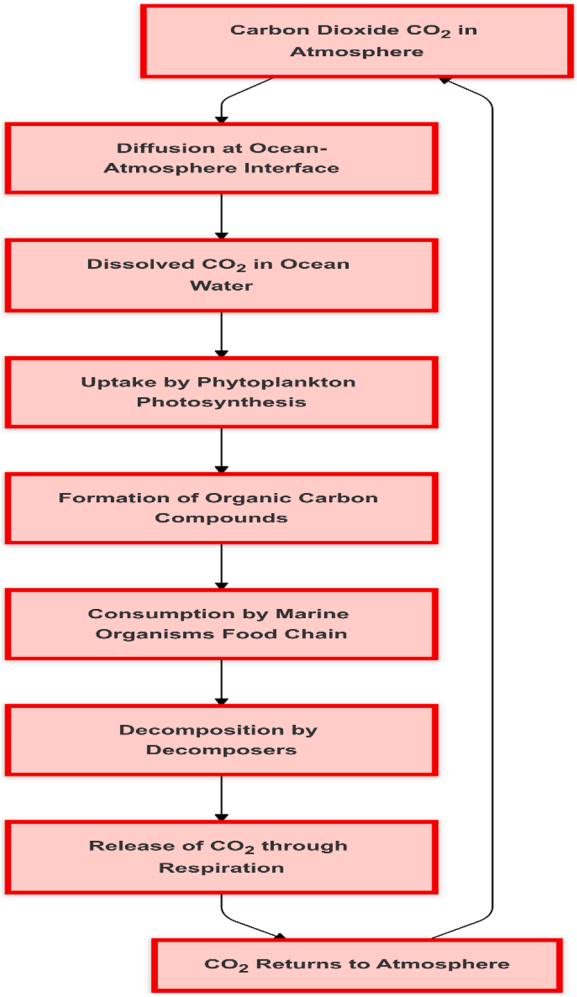

FIGURE 1.1 An illustration of the carbon cycle processes.

- **Phosphorus cycle**: The phosphorus cycle is similarly critical, as phosphorus is a key nutrient that supports the growth of phytoplankton and other primary producers (Fig. 1.3). The cycling of phosphorus involves biological uptake and recycling, which are essential for maintaining nutrient balance and promoting productivity in marine environments. Human activities, such as agriculture and wastewater discharge, can significantly impact the phosphorus cycle, leading to nutrient pollution and ecosystem degradation (Kumar, 2023).

6. Impacts of marine bio resources

Aquatic bioresources therefore needs to be efficiently and sustainably managed when the imperative is for the intertwinement of the economy and ecology. On one side, these resources provide remarkable advantages, such as employment generation, improved food security, and potentiality for development of new pharmaceuticals (Kumar, 2023; Udeme et al., 2023). Marine also delivers valuable biophysical and regulation goods like carbon storage and shoreline defense to enhance the quality of life of peoples (Duarte, 2022). On the other hand, the unsustainable practices, including over exploration of fish stocks and destruction of their natural habitats, pose potential risks to the stability of these ecosystems as well as contributing to depletion of resources, pollution, and unfair share (Graham, 2022; Thompson, 2023). Management of these challenges through appropriate management strategies is crucial to support optimum utilization of marine bio resources and at the same time ensure conservation of the environment for future generations. Sustainable use of marine bioresources is important for the improvement of the general standard of the people of Nigeria and the globe at large. The following sections present a discussion of the beneficial and costly effects of marine bioresources in detailing the need to adopt sustainable exploitation for the greatest gains with minimal environmental loss.

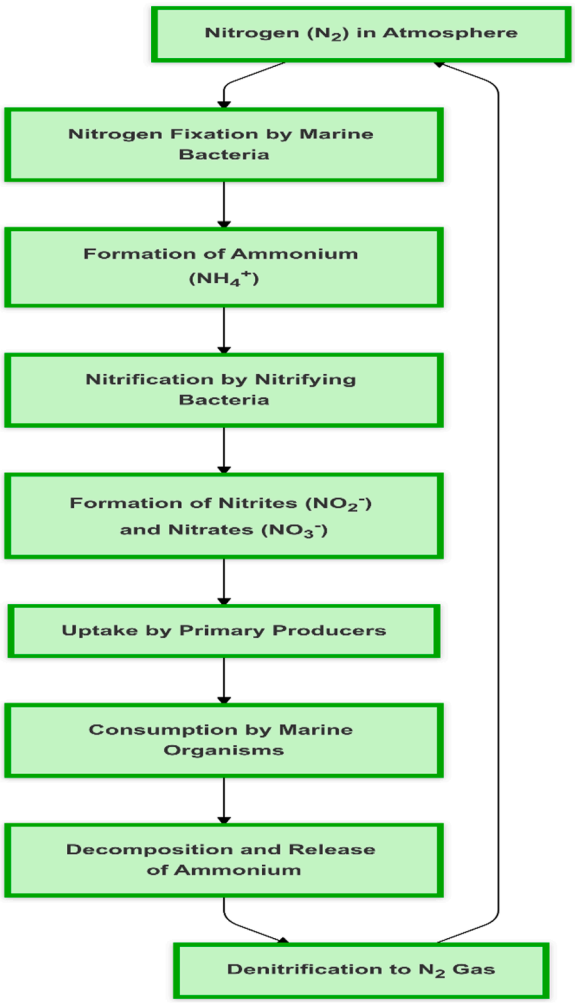

FIGURE 1.2 An illustration of the nitrogen cycle processes.

7. Positive impacts

7.1 Economic growth and job creation

Marine products are one of the most crucial sources in boosting economic returns and employment throughout many industries. Fishing, aquaculture, and marine biotechnology are essential industries in most coastal areas contributing to the food demands of over 100 million people. People from these communities who participate in sustainable management of these products can not only become economically stable but also benefit their respective countries. It will provide revenues that will further develop the local infrastructures, school systems, and hospitals which in return positively impact the inhabitants of the country. Furthermore, marine biotechnology is still in its early phases and offers significant prospects for growth, and new job openings in research, production, and product promotion for marine-related products (Abioye et al., 2021).

7.2 Food security and nutrition

They are an important supply for high protein and essential nutrients and important food security commodity. Fish and other seafood products are foods that are consumed globally everywhere but especially by the coastal people since they get to enjoy fresh water products from the sea easily. It is well explained that marine foods have so many nutritional positives that nourish the body with omega-3 fatty acids vitamin and mineral products that are helpful in the body. The concept of sustainable fish production and fishing involves utilization of techniques of fishing so as to provide sustained

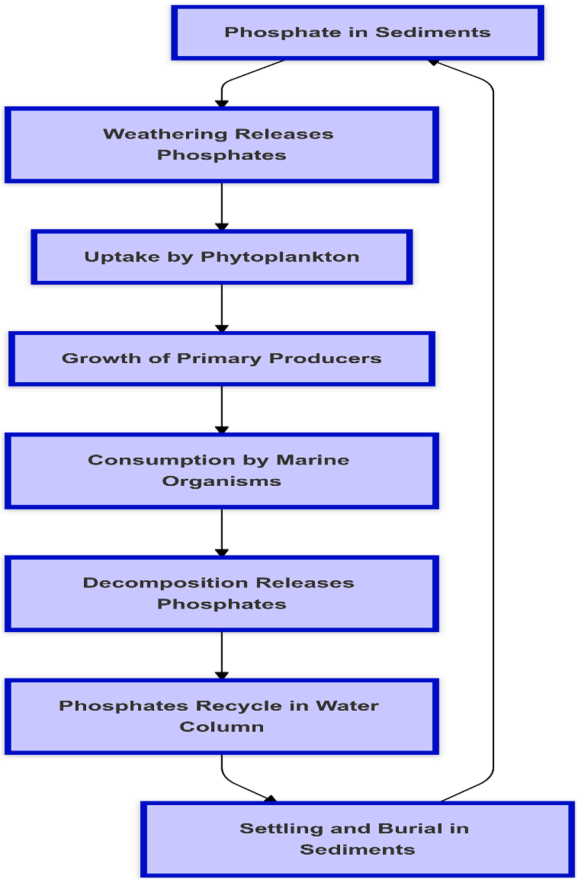

FIGURE 1.3 An illustration of the phosphorus cycle processes.

food for ever growing population. As the demand for food continues to rise, the sustainable management of marine resources becomes increasingly crucial to ensure that future generations have access to these important food sources (Fisheries and aquaculture, 2023).

7.3 Pharmaceutical and biotechnological advancements

Marine organisms have been identified as a source of new and diverse compounds with biopharmaceutical and biotechnological potential. Many drugs have been obtained from marine organisms hence illustrating the exclusive biochemical reactivity that can be exploited to design new drugs to treat different health conditions such as cancer, inflammations, and bacterial infections. Marine ecosystem exploration of the various forms of life has given scientists new drugs, which are effective than the known drugs and at the same time have minimum side effects. Thus, while undertaking research in marine biotechnology persists, there are broader opportunities in terms of creating new treatments for diseases and other health related products for global health care (Kumar, 2023).

7.4 Ecosystem services

These ecosystems are able to offer a broad variety of valuable products which can significantly improve the conditions not only in the local environment but also in the world as a whole. They include carbon storage which reduces climate change by removing the carbon dioxide from air and coastal warding which prevents disasters such as storm surge or coastal erosion from affecting communities. Moreover, any ecosystems contribute to the existing biodiverse species, which facilitate the marine stability and enhance marine environment. These ecosystems enable ecological equilibrium besides implementing plans that protect the inhabitants and creatures in ocean areas from catastrophes resulting from climatic change (Duarte, 2022).

8. Negative impacts

8.1 Overfishing and resource depletion

Over exploitation of marine bioresources, particularly through fishing activities, is one of most complex threats with roots in unsustainable fishing practices. It is a fact that over fishing acts as a major menace in the extinction of different species and disrupting the delicate balance of marine ecosystems. If fish stock is depleted then the means of living of peoples, in relation to the fishing industries, faces higher risks which result in economic imbalance and food shortage. There are devastating effects of overfishing such as depletion of an important fish species stocks, crippling the biological structure of the ocean and degrading the general health of the seas. This situation calls for the need to implement efficient management of the fishery resources and emphasize on the responsible fishing for the future supply (Graham, 2022).

8.2 Habitat destruction

Such activities as bottom trawling, coastal development, as well as polluting marine environment have negatively affected marine environment, which include corals reef, mangroves, and seagrasses. Loss of these key habitats does not only mean leading to the reduction of species numbers but also impacts on the capacity of the marine systems to deliver human benefits such as grow-out grounds for young fishes and seaward barriers to storm surges. Information on habitat loss shows that its impacts are felt in many ways along the how species prepares for breeding, feeding, or even seeking protection. The degradation of these habitats causes decreases in fish stocks and other marine animals that living in the sea, which worsens the problems affecting fisheries and marine environments. Conservation of habitat must be employed as a way of supporting the increased rate of species diversity as well as the overall average health of marine ecosystems (Klein, 2022).

8.3 Pollution and environmental degradation

Marine bioresources are day by day being threatened by different types of pollution such as plastic pollution, heavy metals pollution, and nutrient pollution from agricultural practices. Some of these pollutants can be very destructive to marine life, thus meddling with food chain systems and bringing strikes to fish and other sea creatures. Thirdly, pollution of the sea has negative impacts on people who consume seafood because toxins affect the subject and other organisms. Global warming compounds these challenges, through influencing ocean acidity and temperature that is dangerous to the marine ecosystem. The indirect consequences of pollution and environmental degradation require that this situation needs to be addressed in the long-run so as to protect marine resources (Thompson, 2023).

8.4 Inequitable resource distribution

The value chains arising from the utilization of marine bioresources are normally inclined toward certain groups of people and nations, hence causing extreme polarization. For example, vulnerable groups of patients including those in the developing countries may find it extremely hard to gain access to these vital inputs owing to economic, social, and political reasons. Such imbalance may pose conflict within peoples and hampers conservation of the seas and oceans products. Nonetheless, equal and reasonable utilization of the marine bioresources can be posited as a boon for creating harmonious society and operationalizing sustainable development. Only by addressing these issues and engaging all the relevant actors in the governance of the country's marine resources, it is possible to create equities that can benefit all communities and stakeholders (Daw, 2022).

8.5 Marine resources management

To understanding and managing coastal and marine resources, geography is rather essential. While many may consider that marine resource management as a discipline, which stems from the biophysical sciences, it is critical to appreciate that the management of marine resources is inherently a politically and culturally constituted process, constructed out of human practices and representations of space and place where politics enter policies and decisions in ways that are most profound. The management of marine resources currently incorporates a diverse of strategies. These are: top-down strategies like zonation of the ocean, restricted access either through licensing or creation of no take zones, regulation of tackle usage, or species targeted or imposition of quotas on fish catches. This also includes community-based

approaches and other types of management regimes including informal as well as traditional management regimes, a combination of a variety of management techniques based on the social-ecological context of the area.

Increasingly, managers of marine resources are beginning to adopt spatial methods. Currently, many management agencies are turning their attention to ocean zoning and marine spatial planning (Agardy, 2010); the major difference of which from traditional rights and management systems is that it deals with regulation of space (and more specifically protected space) rather than use (and more specifically catch and gear). It also possible to identify growing efforts to designate areas in the oceans for energy generation whether in wind, wave, or offshore oil drilling without interference with other uses of the ocean space (Abioye et al., 2021).

9. Uses of marine resources

Marine resources are some of the most vital for the sustenance of economic, ecological, and human services as pertaining human society. Marine resources are most extensively used in the fisheries sector where ocean resources constitute the major part of food supply in the form of large fish stocks required by humans. Besides fisheries, oceans contain oil and gas deposits; these, as much as they are problematic, supply about 80 percent of global energy; the transportation sector is the largest consumer of this energy at 58 percent (IEA, 2022). Yet, the availability of fossil fuels, pollution costs such as climate altercations, loss of species, and rising sea levels have been a cause for development of other sources such as the bio fuel. Biofuels, derived from renewable biomass, are classified into three generations based on biomass type: The first-generation comes from crops, second-generation from agricultural residues and energy crops, and third-generation from marine such as seaweeds and cyanobacteria (Patel et al., 2022). These are cleaner assaying bio-fuels which the world has been working on to blend with fossil fuels to decrease the carbon dioxide impact on energy production because they work on a carbon dioxide cycle absorbing carbon dioxide from the atmosphere as they grow (IEA Bioenergy, 2023).

Besides energy, oceans also contain mineral assets; gold, cobalt, and manganese ore, among others, are believed to be available in future deep seas exploitation as terrestrial locations are depleted. Small marine aggregates like sand and gravel are importantly used for construction especially in supporting structures, hence infrastructural matters. For instance, the UK utilizes approximately 13 mt annually for construction. Eco-tourism is also now mainstream, with marine tourism which includes diving, whales, and dolphins watching, big game fishing, and boosting the economy while making people conscious of protecting endangered marine animals. Further, reefs containing corals as the biodiversity hotspots contribute to tourism and serve as habitats for potential medicinal uses of substances in treatment of ailments including pain and cancer. Marine nutrient cycling is crucial to the life cycle support and plant growth as well as native ecosystem maintenance. More so, the oceans remain a viable source of clean energy as wind, wave, and tidal energy surface as moderate renewable energy resources. Scientists are also evaluating the role of the ocean in climate change because of its capability in carbon capture and storage (Chin et al., 2023). Exploration of marine resources supports economic growth, environmental conservation, and humans' welfare in diverse applications.

9.1 Importance of marine ecosystems

Marine ecosystems support a vast array of beneficial services for both the biophysical world and man/society in ways that do not end with their fundamental roles as life support systems in the biosphere. Their contributions can be categorized into several key areas, each highlighting unique benefits and essential services:

- **Biodiversity conservation**: Marine habitats are one of the richest found in the world, supporting an incredibly diverse range of life from the smallest organisms, such as marine protists like plankton, to the largest including, marine mammals. Basic to species survival and well-being, this biological diversity is important in the ability of marine systems to adjust and rehabilitate itself following instances of stress, including storms, pollution, and commercial over exploitation. Preservation of species diversity especially in marine environment is crucial for the preservation of genetic pool that is crucial for survival of species, contributing to the stability of food webs and ecosystem functions. Measures aimed at preserving marine biodiversity are necessary to uphold sustainability of essential ecosystem services, which include food security, regulation of climate, cultural, and recreational value to the societies (Udeme et al., 2023).
- **Climate regulation**: Marine systems are central to global climatic control especially through carbon cycling. More than a third of manmade CO_2 ends up dissolving in the oceans, and phytoplankton and seagrasses play the role of natural carbon sequestration systems. Photosynthesizing phytoplankton sequesters atmospheric CO_2 into organic matter and thus is thought to play a role of a biological pump that takes carbon to the deep. This process is also beneficial in cutting down strides that provoke climate change such as the emission of greenhouse gases into the atmosphere.

Furthermore, they pointed out that through their calcium carbonate structures, marine organisms like corals and mollusks can store carbon for thousands of years. Therefore, the status of marine ecosystems, particularly coastal habitats such as mangroves, salt marshes, and seagrass meadows, will determine the stability of climate globally as well as the sustainability of ecosystems (Graham, 2022; Duarte, 2022).

- **Economic value**: Nevertheless, the economic being of the marine organisms is privileged as they offer employment and food resources to millions of people. This paper will examine the relevance of fisheries and aquaculture industries especially in food security and primary income. Marine ecosystems also support functioning tourism industries in recreational fishing, diving, and coastal tourism and are a key source of income in the tourism business around the world. That is why proper management of the marine resources is needed to preserve these economic values; overfishing and polluting of Seas affect negatively on new and old economics base on fishery and tourism on the shores. Sustainable measures that are adopted to continue the sustainability of these ecosystems also contribute to the economic stability and social welfare of human being (Fisheries and aquaculture, 2023).
- **Nutrient cycling and water quality**: Marine ecosystems are the cyclers of nitrogen, phosphorus, and sulfur that are these peculiar elements beneficial for the persistence of marine and terrestrial life. Coastal and open ocean environments assist to regulate water quality by regulating and purging pollutants, recycling nutrients, as well as controlling sediments. Thus, mangrove forests and seagrass beds are better known to integrate sediments and enhance water penetration, developing better living conditions for fish and other sea dwellers. Preserving and sustaining the water quality in such ecosystems not only improves marine life but sustains resources, which are of importance to mankind for instance, fishing and water bodies (Aransiola, Zobeashia et al., 2024; Klein, 2022).

9.2 Threats to marine ecosystems

While marine ecosystems provide invaluable benefits, they face a myriad of threats from human activities and environmental changes, endangering their health and functionality:

Pollution: Water pollution can be categorized as one of the greatest threats affecting marine life, with problems ranging from plastics and chemicals in the water to excessive nutrients causing numerous ecological problems. The plastics degrade into microplastics, which the sea life consumes, which results in physical injury, disorders of the reproductive system, and sometimes death. These chemical pollutants include pesticides and heavy metals, and they bioaccumulate mainly in the food chain for marine organisms, which consequently affect the top consumers of these pollutants including man. The forms of pollution notably are the nutrient pollution emanating from the agricultural runoff, which triggers eutrophication—instances and formation of algal bloom and hypoxic zones that dramatically reduces the concentration of oxygen, triggering a massive loss of marine life. Combating pollution is a global phenomenon that also needs global solutions to implement sound waste management systems and prevent emissions of chemicals into oceanic systems (Auta et al., 2025; Thompson, 2023).

Overfishing and resource exploitation: Excessive exploitation of fish resources has rendered several fish species vulnerable to extinction and threatens food security too. This implies that conventional fishing techniques such as trawling and bycatching, among other dangerous practices, depress not only the target species but also the other species and marine environment as a whole. The local extirpation of species furthermore deliberately triggers trophic cascades, which extend across the food chain and influence the structure and function of marine benthic communities. Effective fisheries management, including catch limits, marine protected areas, and sustainable fishing practices, is essential for preserving fish populations, protecting marine biodiversity, and supporting coastal economies (Duarte, 2022; Job et al., 2024).

Climate change and ocean acidification: Climate change is one of the most important and complex pressures affecting marine habitats and species, since sea warming, ocean acidification, and sea-level changes alter marine biodiversity and ecosystem function. Higher water temperatures change locations and spatial densities of the organisms and change the pattern of reproduction and feeding. Coral bleaching stress responses to warmer waters have caused the depletion of coral reefs, which visible supports multispecies marine life. Increased CO_2 absorption leads to ocean acidification making it difficult for marine organisms, including corals and shellfish, to obtain the carbonate ions with which to form their calcium carbonate structures. To address these impacts, further efforts are required in the form of reducing greenhouse gases emissions and implementing policies that protect the ocean and that promote practices that can increase the capability of marine ecosystems to adapt to climate change (Job et al., 2024; Klein, 2022).

Habitat loss and coastal development: Feelings of coastal development through constructions, expansion of infrastructure, reclamation of additional land, and dredging brings about loss of marine features that are important for habitat including mangroves, seagrass beds, and corals. Such habitats provide nursery grounds to many of the marine living organisms, with shelters important to enhancing the stocks of living resources for human consumptions. Loss of coastal

habitats decreases the ability of the ecosystem to support necessary functions like acting as a buffer against storms and acting as a carbon sink. Many coastal development activities require the conservation of ecosystems for possible future uses in sustainably supporting the marine ecosystems (Udeme et al., 2023; Ugoma et al., 2023).

10. Conclusion

Marine bioresources are meant to reveal the function of ecological processes and ecosystem goods and services, food supplies, and potentials for sustainable bioenergy sources. Marine habitats including coral reefs, mangrove forests, seagrass beds, and the deep sea support species and link global biogeochemical processes. However, all these ecosystems are in danger now due to overfishing pollution and climate change. Overfishing affects the structures of the ecosystems, pollution affects the quality of water and affects the organisms living within them, and climate change exacerbates all these challenges and leads to corals being bleached, loss of habitats for species and shift in species location. These impacts eventually undermine the occurrence of species and ecosystem conditions that are required to sustain life in the world. Conservation of our marine resources is important for the health efficiency of our oceans. Measures such as proper fishing techniques, curtailing pollution, and rehabilitating marine habitats and species' populations are critical measures that may be used to safeguard the oceans and seas, and MPAs offer species a secure environment in which to grow and rebuild. Another factor necessary for promoting conservation of the marine bioresources is increasing public awareness of the ecological and economic benefits of the bioresources. Integrating science, policy, and community support can facilitate scientific breakthroughs to sustain the economic, ecological, and social capital of coastal and marine systems through the management and mitigation of climate change impacts for present and future generations.

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Chapter 2

Application of marine greens in climate change mitigation

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1. Introduction

The phenomenon of environmental change, marked by a dramatic shift in climate patterns largely driven by the release of greenhouse gases (GHGs), stands as one of the most pressing crises facing the globe today. Central to this shift is the greenhouse effect, a process whereby gases such as carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) trap heat within Earth's atmosphere, thereby fueling the ongoing escalation of global temperatures. While these gases are emitted through both natural mechanisms such as volcanic activity, forest fires, and the release of gases from oceans and thawing permafrost (Aransiola, Oyewole, et al., 2024, p. 1–257), the overwhelming contribution comes from human activities, notably energy production, industrial operations, and significant alterations in land use.

To fully grasp the scope of the current climate crisis, it is essential to recognize the profound and different impacts environmental change has on both natural ecosystems and human societies. Recent findings from the United Nations Climate Change Secretariat (UNCCS) highlight several key climate indicators affected by these changes, such as increasing global temperatures, shifting precipitation patterns, rising sea levels, ocean acidification, and a marked increase in the frequency of extreme weather events. Particularly alarming are the climate-related hazards droughts, hurricanes, heatwaves, floods, and wildfires that have surged in recent years. For instance, the UNCCS reported a significant uptick in such disasters, and the Center for Research on the Epidemiology of Disasters (CRED) recorded 315 climate-related catastrophic events in 2018 alone, underscoring the pervasive threat environmental change poses to global ecosystems and human populations.

The global consciousness surrounding climate change began gaining serious traction in 1979, following the inaugural World Climate Conference held in Geneva. Organized by the World Meteorological Organization (WMO), this conference was a pivotal event that reviewed the scientific understanding of climate change and laid the groundwork for future global actions. This momentum continued with the creation of the Intergovernmental Panel on Climate Change (IPCC) in 1988, established by the WMO and the United Nations Environment Program (UNEP), to provide governments with critical scientific insights necessary for shaping climate policy. The adoption of the United Nations Framework Convention on Climate Change (UNFCCC) in 1992, which became legally binding in 1994, solidified the international community's commitment to combating climate change through coordinated efforts.

Nevertheless, despite significant strides, there remain concerns regarding the adequacy of current climate policies. A comprehensive analysis by Nieto et al. of the Paris Agreement's Intended Nationally Determined Contributions (INDCs) from 188 countries paints a rather disconcerting picture if additional measures are not adopted, global emissions could rise by 31.5% by 2030. Moreover, projections suggest that the current trajectory of emissions would likely lead to a global temperature rise of at least 3°C by 2050, with the possibility of a 4°C increase if emissions continue to grow unchecked.

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To meet the ambitious goals set forth by the Paris Agreement, a 45% reduction in anthropogenic GHG emissions by 2030 relative to 2010 levels is required to limit global warming to 1.5°C. For a 2°C cap, emissions must fall by approximately 25% by 2030, with the goal of reaching net-zero by 2070. However, current and projected mitigation efforts appear insufficient, necessitating further innovation and stringent policy actions (Gimba et al., 2024).

Mitigation strategies, which are indispensable in curbing climate change, center on reducing GHG emissions or enhancing carbon sinks. Schmitz defines mitigation as any human intervention aimed at diminishing the atmospheric concentration of GHGs. Given the global nature of the issue, international cooperation is often paramount for effective mitigation. Common strategies include decarbonization technologies such as renewable energy adoption, improvements in energy efficiency, and the deployment of carbon capture and storage (CCS) systems. Additionally, negative emissions techniques, such as bioenergy coupled with CCS, afforestation, and soil carbon sequestration, offer promising pathways to reduce atmospheric CO_2 levels.

Among these strategies, marine greens—particularly macroalgae and microalgae play a crucial role in climate mitigation by sequestering carbon. These organisms absorb carbon from their environment, which can then be utilized in energy production or converted into chemicals, thus serving as a natural counterbalance to rising CO_2 levels (Gimba et al., 2024). Incorporating marine-based carbon capture solutions into broader mitigation strategies may significantly bolster global efforts to mitigate climate change. The all-encompassing nature of climate change impacts ranging from the collapse of ecosystems and biodiversity loss to significant socio-economic disruptions demands urgent, comprehensive action. Reducing emissions while simultaneously enhancing resilience against climate shocks requires a multipronged approach that engages every sector of society. Only through concerted global efforts can we secure a sustainable future for humanity and the planet.

2. Marine greens

Marine greens, a diverse group of photosynthetic organisms thriving in marine ecosystems, either anchor themselves to substrates in benthic zones or float freely in the water column. These organisms, integral to the food web of tropical benthic ecosystems, include various algae species along with other marine photosynthesizers (Acosta-Calderón et al., 2016; Aransiola, Babaniyi, et al., 2024). Uniquely adapted to saltwater environments, marine green algae play an essential role in marine ecology, serving as a primary food source for numerous aquatic species and supplying critical nutrients to the broader oceanic food chain (Cardol et al., 2008). Often referred to as sea greens, these marine plants and algae are found in or near oceanic environments (Leslie, 2022), with their biochemical makeup typically consisting of lipids, proteins, nucleic acids, carbohydrates, and pigments like astaxanthin, fucoxanthin, and lutein (Chen & Xu, 2020). Notably, the specific composition of marine greens varies depending on the algae strain and cultivation practices.

Marine greens employ a relatively simple reproductive strategy and harness sunlight through photosynthesis, forming the foundation of their role as primary producers (Shanab et al., 2012). Their biomass exhibits remarkable structural and functional diversity, allowing them to thrive amid various environmental stressors such as salinity fluctuations, osmotic pressure, temperature extremes, nutrient shortages, and photo-oxidative stress (Shanab et al., 2012). As some of the oldest known photosynthetic organisms, with a lineage stretching back roughly 3.8 billion years (Stolz & Obermayer, 2005), marine greens encompass an estimated 280,000 species.

These organisms can be classified by their pigmentation and structure into different types. Brown algae, or Phaeophytes, are defined by their filamentous or thalloid forms and their characteristic brown hue, driven by the pigment fucoxanthin, which conceals other pigments (Ellamie et al., 2020). Species like *Laminaria, Saccharina,* and *Sargassum muticum* are examples of brown algae commonly found in temperate and arctic marine zones (Ko et al., 2014). Although these algae have holdfasts that resemble roots, they function merely to anchor the algae to surfaces in rocky coastal waters, as brown algae are strictly confined to saltwater habitats.

Another vital subgroup within marine greens is cyanobacteria, also known as blue–green algae. These prokaryotic organisms, capable of oxygenic photosynthesis, occupy various extreme habitats (Kauff & Budel, 2011; Dvorak et al., 2015). Cyanobacteria such as *Chroococcus subnudus* and *Planktothrix agardhii* have played a crucial role in the evolution of oxygenic photosynthesizers, significantly contributing to the development of Earth's oxygen-rich atmosphere (Bekker et al., 2004). Cyanobacteria are highly adaptable, engaging in nitrogen fixation and displaying cellular differentiation, with some genera even exhibiting eukaryotic-like characteristics (Nurnberg et al., 2014).

Marine greens are found across a broad spectrum of habitats, from coastal areas to the expansive open ocean. Coastal ecosystems, which account for just 7% of the world's oceanic area, nevertheless support high biodiversity, while open ocean environments span vast distances beyond the continental shelf (Charette & Smith, 2010a, 2010b). Phytoplankton, including marine greens, occupy the euphotic zone ranging from the ocean surface down to depths of 250 m where they

contribute substantially to global primary production, generating over 5 × 10̈13 kg of biomass annually (Kumar & Singh, 2021). Their distribution and metabolic functions are influenced by key environmental factors such as nutrient availability, temperature, and light conditions (Upadhyay et al., 2019).

Marine macroalgae, often referred to as seaweeds, are macroscopic, multicellular photosynthetic organisms that are classified into three major groups based on pigmentation: green (Chlorophyta), red (Rhodophyta), and brown (Phaeophyta) (Gupta et al., 2017). Seaweeds are critical components of marine macrophyte ecosystems, coexisting alongside seagrasses and mangroves, and serve as essential links in the aquatic food web. Globally, approximately 20,000 species of seaweed have been identified, with 221 species being used commercially for diverse applications. Of these, 110 species are harvested for phycocolloid extraction, while 145 species are used as food sources. The burgeoning fields of biotechnology, genetic engineering, and omics technologies hold great promise for optimizing the utilization of marine greens, positioning them as pivotal tools in addressing various global challenges.

3. Contribution of marine greens to climate change mitigation

Since the advent of industrialization, human activity has dramatically escalated the atmospheric concentration of GHGs, with carbon dioxide (CO_2) making up an overwhelming 68% of these emissions (Even et al., 2022; Farghali et al., 2022; Zobeashia et al., 2018). The primary culprits fueling this surge are the combustion of fossil fuels, factory farming, industrial operations, mining, and waste production. This rampant release of CO_2 has significantly accelerated global warming, triggering profound and widespread effects on human health, ecosystems, soils, and aquatic systems. In response, the 2015 Paris Agreement underscored the urgent necessity for the development of eco-friendly, cost-efficient, and scalable solutions to curb CO_2 emissions and combat climate change (Troell et al., 2022). However, despite the multitude of strategies put forth to reverse these dangerous emission trends, tangible progress has been frustratingly elusive, underscoring the need for innovative approaches.

In this quest for novel solutions, ocean-based strategies have emerged as a particularly promising avenue, rivaling traditional land-based efforts. The ocean, a massive natural regulator of CO_2, plays a pivotal role in controlling atmospheric carbon levels through its vast carbon sequestration and storage capabilities . Since the dawn of industrialization, marine ecosystems have absorbed over 560 Pg (Pg) of CO_2, an astonishing figure that translates to the daily uptake of roughly 25 million tons of human-made CO_2 (Gao & Hader, 2020; Wu et al., 2022). In fact, the ocean is responsible for capturing about 30% of global CO_2 emissions, solidifying its status as the second-largest reservoir of organic carbon on the planet. This immense capacity for carbon storage highlights the ocean's indispensable role in climate change mitigation.

Complementing the ocean's natural carbon sequestration, biological solutions that leverage marine greens have emerged as a significant frontier in the battle against climate change. Marine greens comprising both macroalgae (such as kelp, wakame, and nori) and microalgae are proving to be powerful carbon sinks with unique advantages (Mehrotra & Pathak, 2020). Through photosynthesis, these organisms draw CO_2 from their surroundings, transforming it into organic carbon and thereby reducing atmospheric CO_2 levels. On a global scale, the cultivation of marine greens has demonstrated the potential to sequester considerable quantities of carbon, making a substantial contribution to climate mitigation efforts. This carbon-capturing process not only helps slow climate change but also provides an ecologically sustainable pathway to reduce GHG concentrations.

In essence, the integration of marine greens into climate change mitigation strategies presents a highly promising area for both research and practical application. By capitalizing on the natural carbon sequestration potential of marine ecosystems and scaling the use of algae biomass, substantial headway can be made in the global fight against climate change. Incorporating these ocean-based approaches into larger climate action frameworks could significantly enhance efforts to reduce CO_2 emissions, steering humanity toward a more sustainable future.

3.1 Carbon sequestration

Carbon sequestration, as outlined by the Intergovernmental Panel on Climate Change (IPCC), refers to the process by which the carbon content of a pool other than the atmosphere is increased. This mechanism is critical to the broader effort of mitigating climate change, a process the IPCC defines as "a human intervention aimed at reducing greenhouse gas emissions or enhancing their sinks." Of particular importance is carbon sequestration within soils, where atmospheric carbon is transferred into soil reservoirs, effectively converting them into carbon sinks. To properly evaluate the impact of environmental mitigation efforts, it is vital to measure the flux of GHGs before and after such interventions, particularly in relation to carbon sinks. However, it is essential to recognize that merely reducing emissions does not equate to achieving

negative emissions; rather, it influences the behavior of carbon sinks. Furthermore, soil carbon sequestration might not always contribute to climate change mitigation, as the process can be impacted by historical sink capacities or past GHG emissions.

Beyond terrestrial ecosystems, carbon sequestration extends to the capture and long-term storage of carbon dioxide (CO_2) and other carbon forms, a critical strategy for mitigating the harmful effects of CO_2, a potent GHG responsible for exacerbating global warming. Within this framework, the cultivation of marine greens such as kelp, wakame, and nori has emerged as a highly effective strategy for reducing CO_2 levels. Studies reveal that marine greens can sequester up to 700 million tons of carbon annually across the global continental shelf (Mehrotra & Pathak, 2020). Among these, kelp stands out as a key player, responsible for more than 70% of the total carbon fixed by cultivated marine greens. Other species, including nori, wakame, and Gracilaria, also contribute significantly to the process, converting dissolved inorganic carbon and CO_2 into organic carbon.

In addition to their inherent carbon sequestration capacity, marine greens offer a broader range of environmental benefits. Banerjee et al. demonstrate that these organisms can effectively reduce CO_2 emissions by capturing carbon from stationary sources. This captured carbon can then be repurposed for the production of valuable chemicals or used to generate energy, thereby amplifying the ecological and economic benefits of marine greens. Furthermore, research conducted by Mashoreng et al. has highlighted the potential of various seaweed species including maricultured varieties like *Kappaphycus alvarezii* and strains of *Eucheuma spinosum*, as well as pond-cultured seaweeds such as *Gracilaria verrucosa* and *Caulerpa* racemose to act as effective carbon sequestrants. These findings underscore the significant role marine greens play in capturing atmospheric CO_2 and advancing global climate mitigation strategies.

3.2 Albedo effect

Albedo, defined as the fraction of solar radiation reflected from the land surface back to the atmosphere, plays a critical role in controlling the Earth's energy balance. It is essentially a measure of the planet's reflectance and determines how much sunlight the Earth absorbs. The concept of albedo is pivotal in understanding how various methods aimed at mitigating climate change, collectively referred to as climate intervention strategies, impact the environment. These approaches involve boosting the reflection or scattering of sunlight back into space, effectively cooling the Earth by manipulating its energy balance. Techniques to achieve this range from stratospheric aerosol injection, which disperses reflective particles high in the atmosphere, to marine cloud brightening, aimed at increasing cloud reflectivity, and enhancing surface albedo through reflective surfaces or materials. By artificially amplifying the planet's natural reflectivity, these interventions seek to offset the warming caused by rising GHG concentrations.

However, the application of albedo enhancement strategies is fraught with potential risks and challenges, particularly when considering large-scale deployments. For instance, the application of biochar to soil surfaces a method proposed for carbon sequestration raises significant concerns regarding its impact on albedo. Biochar, when applied at high rates (e.g., 30–60 tons per hectare), can lead to a decrease in surface reflectivity. This reduction in albedo can subsequently increase soil temperature, thereby potentially undermining the carbon sequestration benefits of biochar. This highlights a crucial balance that must be maintained: while biochar may offer benefits in terms of carbon storage, its effects on surface reflectivity and soil temperature must be carefully evaluated.

Additionally, there are broader risks associated with albedo enhancement techniques. One such risk is the issue of reversibility. Once certain albedo interventions are implemented, they may not be easily reversible, leading to potential long-term consequences that could be challenging to mitigate. Furthermore, effective monitoring, reporting, and verification of albedo interventions pose significant challenges. Accurate assessment of the impacts of these interventions is essential for ensuring that they achieve the intended effects without unintended side consequences.

3.3 Oxygen production

Marine green algae are vital pillars of marine ecosystems, playing an intricate and indispensable role in sustaining ecological balance while simultaneously aiding in the fight against climate change. These algae serve as the backbone of oceanic environments, providing critical nutrients, producing oxygen, and fostering biodiversity across a wide array of marine habitats. As foundational components of the aquatic food web, they support a diverse range of life, from fish, crustaceans, and invertebrates to larger marine mammals like manatees and sea otters (Edison et al., 2016). Through photosynthesis, marine algae not only generate substantial oxygen, maintaining the delicate oxygen balance in underwater ecosystems but also contribute to the overall vitality of marine habitats (Ghoneim et al., 2014). This oxygen production supports the respiration of marine organisms, making it essential for the health and functionality of these ecosystems. In

addition to their oxygen-producing capabilities, marine algae are formidable players in carbon sequestration. By absorbing carbon dioxide during photosynthesis and storing it within their biomass, they effectively reduce atmospheric CO_2 levels, making them key agents in mitigating the impacts of climate change (Edison et al., 2016). Their role in reducing the greenhouse effect is pivotal, helping to curb the rising concentrations of CO_2 in the atmosphere and slow global warming.

Beyond carbon capture, marine greens like seagrasses and certain seaweed species are essential to nutrient cycling in marine environments. Seagrass roots release oxygen into the sediment, creating aerobic zones that facilitate nutrient uptake and enhance water quality. Similarly, the thallus of certain seaweeds can absorb nutrients directly from the water, thereby mitigating issues such as eutrophication and preventing harmful algal blooms from proliferating (Mantri et al., 2020). This nutrient absorption helps maintain ecological balance, preventing nutrient overload that could otherwise trigger detrimental algal blooms. Marine algae also play a crucial role in bioremediation, contributing to environmental cleanup efforts. By fixing carbon dioxide, releasing oxygen, and increasing biological oxygen demand, they help purify contaminated water (Babaniyi et al., 2023; Singhal et al., 2021). Their incredible adaptability allows them to thrive under varying conditions—whether autotrophic, heterotrophic, or mixotrophic—depending on the availability of light and substrates. Microalgae, in particular, are highly efficient at absorbing pollutants during photosynthesis, improving water quality and reducing the need for external aeration in biodegradation processes (Nithin et al., 2020). Moreover, when paired with heterotrophic microorganisms, microalgae can break down complex pesticides, demonstrating their versatility and effectiveness in environmental restoration (Chen & Wang, 2020).

3.4 Habitat preservation: Marine greens for habitat preservation

Marine algae hold a pivotal role in safeguarding marine ecosystems, significantly impacting both ecological stability and overall marine health. Their growth and metabolic processes are highly influenced by environmental variables such as pH, salinity, temperature, light, aeration, and water mixing. Among these, temperature plays a particularly crucial role in driving the biochemical mechanisms of marine algae. Typically, optimal growth conditions are achieved within the 20–35°C range, where photosynthesis and other metabolic functions operate most efficiently (Chowdhury et al., 2020; Okewu et al., 2024). Salinity, another key factor, affects species differently; while most marine algae thrive at salinity levels between 20 and 24 g/L, this is often lower than the salinity of their natural oceanic habitats (Perumal et al., 2012). Light, too, is fundamental, providing the energy required for photosynthesis a process by which marine algae convert light energy into chemical energy, using it to fix carbon dioxide and synthesize essential carbohydrates and proteins (Nigam et al., 2020; Ozkurt, 2009). Remarkably, certain marine greens like *Spirulina* demonstrate a remarkable ability to survive in highly alkaline environments, with pH ranges from 8.5 to 11.0. Despite this resilience, their optimal growth tends to occur within a narrower pH range of 8.2–8.7 (Blinová et al., 2015; Vo et al., 2015).

Marine habitats are classified into two main categories: coastal and open ocean environments, each supporting a distinct array of ecosystems. Coastal regions, which span from the shoreline to the edge of the continental shelf, are exceptionally biodiverse, despite comprising just 7% of the ocean's surface area. These nutrient-rich areas are hotspots for biological activity and sustain a wide range of species (Charette & Smith, 2010a, 2010b). In contrast, open ocean environments beyond the continental shelf tend to be less nutrient-dense, harboring species adapted to the deeper, more expansive areas of the ocean. Within the open ocean, the pelagic zone is further segmented by depth, light availability, and nutrient concentration. These subdivisions include the epipelagic, mesopelagic, bathypelagic, and abyssopelagic zones. Of these, the epipelagic zone also referred to as the photic or euphotic zone occupies the uppermost layer of the ocean, where sunlight penetrates sufficiently to sustain photosynthesis in phytoplankton. This zone is vital for primary production and supports the vast majority of marine life due to its high biological productivity. A comprehensive understanding of these habitat dynamics is essential for protecting marine algae and ensuring the long-term sustainability of marine ecosystems.

4. Technological applications

4.1 Biofuel production

Marine green microalgae are rapidly gaining recognition as a potent resource for biofuel production, thanks to their remarkable growth rates, rich lipid profiles, and carbon-capturing capabilities. Their unique attributes position them as an innovative solution for tackling rising CO_2 emissions, directly addressing the global climate crisis. Microalgal biomass, in its versatility, serves as an ideal feedstock for a range of bioproducts, particularly biofuels. These microorganisms thrive by absorbing key nutrients carbon, phosphates, and even heavy metals from wastewater, transforming pollutants into valuable biomass. This process not only supports bioenergy production but also contributes to CO_2 mitigation efforts.

Beyond their role in carbon sequestration, microalgae stand at the forefront of future energy strategies, playing a critical part in absorbing significant quantities of harmful emissions, including CO_2, nitrous oxide, and sulfur dioxide, especially from industrial sites like power plants (Aransiola et al., 2023). When it comes to biofuel generation, marine microalgae open up diverse possibilities, ranging from bioethanol and biodiesel to biogas. Their biomass, rich in sugars and capable of rapid multiplication, makes them especially attractive for bioethanol production. The high sugar content of marine green microalgae has sparked intense interest in their potential as a sustainable and renewable bioethanol feedstock. Similarly, their high oil content and environmental adaptability make them highly efficient for biodiesel production (Fig. 2.1). These algae offer a unique advantage in biofuel creation: their capacity to absorb CO_2 during growth renders the fuel carbon-neutral, as the CO_2 emitted upon biodiesel combustion is balanced by the CO_2 captured in the algae's life cycle.

In the framework of biogas production, marine green microalgae offer significant benefits due to their high concentrations of carbohydrates, proteins, and lipids key organic compounds that are readily converted by microorganisms during anaerobic digestion. This bioconversion process produces biogas, a renewable energy source that reduces dependence on fossil fuels while simultaneously addressing the environmental impact of excess algae biomass from aquaculture or industrial operations. The integration of microalgae into waste management systems for biogas production further enhances process efficiency and sustainability. Thus, marine microalgae not only represent a clean energy source but also provide a different approach to climate change mitigation and resource management.

4.2 Carbon capture and storage

Carbon capture and storage represents a cutting-edge technological approach aimed at dramatically curbing CO_2 emissions from industrial processes, particularly those associated with coal-fired electricity generation and various manufacturing sectors. This technology is capable of capturing an impressive 90% of CO_2 emissions, effectively preventing these GHGs from permeating the atmosphere and intensifying climate change (Fig. 2.1). The CCS framework consists of three essential phases: the initial capture of CO_2 from industrial operations, followed by the transportation of this gas to designated storage sites, and finally, its secure confinement within geological formations such as depleted oil and gas reservoirs or deep saline aquifers. Such a methodology is vital for diminishing the carbon footprint of high-emission industries and fits within a broader array of carbon abatement strategies that encompass nuclear power and renewable energy sources.

The underlying technology of CCS employs advanced processes engineered to ensnare carbon dioxide produced through the combustion of fossil fuels or other chemical and biological reactions, subsequently storing it in a manner that

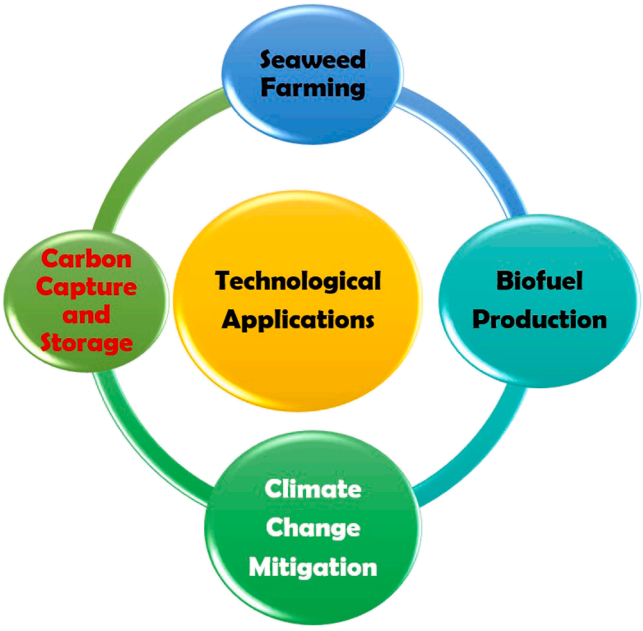

FIGURE 2.1 Technological applications of marine greens.

prevents its release into the atmosphere. The advancement and widespread application of CCS technologies are paramount for reaching global net-zero emissions targets, particularly as the pivotal year of 2050 draws near. Current forecasts indicate that achieving net-zero emissions is implausible without the effective and widespread adoption of CCS technologies. This assertion is bolstered by ongoing developments in related fields, including hydrogen, ammonia, and methanol emerging as promising contenders for zero-carbon emissions. The transition toward these alternative fuels is being propelled by collaboration among equipment manufacturers, engine builders, and energy companies, all striving to enhance technology, improve fuel flexibility, and develop the necessary infrastructure for renewable and sustainable hydrocarbon fuels.

A noteworthy instance of innovation within the carbon capture landscape is ARAMCO's introduction of mobile carbon capture units tailored for automobiles, trucks, and marine vessels. This initiative exemplifies a broader trend in the industry, emphasizing the reduction of GHG emissions and the integration of sustainable technologies across various sectors. In the maritime realm, the International Maritime Organization (IMO) has made substantial strides in enhancing fuel efficiency and curtailing marine exhaust emissions through the implementation of the Energy Efficiency Design Index (EEDI) and the Ship Energy Efficiency Management Plan (SEEMP). These initiatives have already yielded significant reductions in both fuel consumption and emissions. Moreover, the establishment of Emission Control Areas (ECAs) has further catalyzed modifications in operational strategies and equipment, compelling the industry to pursue new technologies and alternative fuels.

The shift toward alternative fuels like hydrogen, ammonia, and methanol signifies a profound transformation in maritime fuel strategies. Hydrogen and ammonia are deemed zero-carbon fuels, emitting no CO_2 when combusted. However, their current production predominantly hinges on natural gas reforming, a process that generates GHGs unless paired with CCS technologies. To achieve genuinely green fuel production, it is essential to harness renewable energy sources such as hydropower, wind, or solar power to supplant traditional methods. This transition is crucial to ensuring that the entire lifecycle of fuel production minimizes GHG emissions. Methanol also stands as a viable alternative fuel, with potential production from renewable sources utilizing captured CO_2 and hydrogen generated via electrolysis, resulting in what is termed green methanol. Despite these encouraging developments, the large-scale production and GHG-friendly utilization of these fuels remain in the nascent stages of implementation.

In summary, CCS technology emerges as a cornerstone in the global effort to mitigate CO_2 emissions and realize climate objectives. Its integration with burgeoning alternative fuels and renewable energy sources will be instrumental in steering us toward a low-carbon future. Terminology such as carbon neutral, zero GHG emissions, net-zero emissions, and negative emissions technologies is becoming increasingly pivotal as industries, regulators, and governments collaborate to combat climate change and cultivate sustainable energy solutions.

4.3 Seaweed farming

Seaweed, a broad term encompassing a variety of marine algae, plays an indispensable role within marine ecosystems. Although these fascinating organisms can mimic the appearance of aquatic plants some reaching lengths of over 150 feet they do not belong to the plant kingdom; instead, they are classified within the Protista kingdom. This diverse assemblage includes brown algae (Phaeophyta), green algae (Chlorophyta), and red algae (Rhodophyta). Unlike true plants, seaweeds lack root systems, internal circulatory mechanisms, and the capability to produce seeds and flowers. Nevertheless, these remarkable organisms are crucial allies in the fight against climate change and global warming. They act as natural buffers for coastlines, dissipating wave energy in marine environments, thereby playing a vital role in curbing coastal erosion. For example, the kelp forests found in Norway, predominantly composed of *Laminaria hyperborea*, have been documented to reduce wave heights by approximately 60%. Moreover, macroalgae and various seaweeds are significant players in mitigating ocean acidification, a key contributor to climate change.

The potential of seaweeds for climate change mitigation can be distilled into four pivotal strategies. First, protecting and restoring wild seaweed forests can yield significant co-benefits for climate mitigation efforts. Second, the expansion of sustainable nearshore seaweed aquaculture offers promising avenues for enhancing climate resilience. Third, seaweed-derived products can be strategically employed to offset industrial CO_2 emissions, bolstering emission reduction initiatives. Finally, a method involving the sinking of seaweed into the deep sea serves as an innovative approach to carbon sequestration. Each of these strategies highlights the different contributions of seaweeds to tackling environmental challenges.

Effective management at the local level is paramount in minimizing the adverse effects of climate change on seaweed ecosystems. Coastal managers play a critical role in safeguarding seaweed forests against threats like overharvesting, pollution, and bottom trawling activities that can severely compromise these essential habitats. By addressing these

stressors, it becomes feasible to bolster the resilience of seaweed forests in the face of climate change. Restoration initiatives can be further supported by various strategies. For instance, restoring artificial reefs can create new substrates for algal growth, while selectively harvesting grazers like sea urchins can alleviate pressures on vulnerable seaweed populations. Genetic modifications aimed at enhancing resilience to stressors, such as heat waves, also represent a promising avenue of research. However, one innovative management strategy for restoring kelp forests involves the application of "green gravel." In this method, small kelp are cultivated on gravel substrates and then released into the environment, a technique that has shown promise in promoting kelp forest restoration while enhancing the overall resilience of these vital ecosystems. Such forward-thinking techniques underscore the continuous research and development within the realm of seaweed farming and restoration, with the goal of unlocking the full potential of seaweeds in mitigating climate change.

5. Conclusion

As specter of climate change looms ever larger on the horizon, the role of marine ecosystems, particularly marine green technology, cannot be overstated. The root of this discourse lies in the relationship between marine environments and their potential to serve as formidable tools in the global resource against climate disruption. Marine green, encapsulated by entities such as seagrasses, algae, and mangroves, offers a panacea of sorts, embedding itself as a critical component in the broader narrative of ecological restoration and climate resilience. More so, at the heart of marine green's efficacy is its ability to act as a carbon sink. The ocean's vast expanse, coupled with its biological richness, makes it an unparalleled repository of carbon dioxide.

Through the processes of photosynthesis and carbon sequestration, marine plants not only absorb atmospheric CO_2 but also facilitate its storage in sediments, a function that terrestrial counterparts struggle to match in scale and efficiency. The sheer volume of carbon sequestered by marine flora stresses their indispensability in mitigating the anthropogenic footprint. However, this process is not devoid of complexities; the dynamics of oceanic carbon sequestration are influenced by many factors ranging from temperature fluctuations to ocean acidification each adding a layer of unpredictability to an already complicated system. Yet, marine green's contribution transcends mere carbon capture. The preservation and restoration of these marine ecosystems offer co-benefits that ripple through the broader environmental matrix. For instance, seagrass beds not only sequester carbon but also provide critical habitats for marine biodiversity, stabilize coastlines, and purify water bodies. Mangroves, with their dense root networks, serve as organic barriers against coastal erosion and storm surges, providing both ecological and socio-economic benefits to coastal communities. These different roles highlight the importance of an integrated approach to marine conservation, one that recognizes and leverages the interconnectedness of ecosystem services.

Nonetheless, the potential of marine green is not without its challenges. The degradation of marine ecosystems, driven influenced by elements like pollution, overfishing, and the climate change, poses a significant threat to their carbon sequestration capabilities. Ocean acidification, a byproduct of increased CO_2 levels, further complicates the picture by altering the chemistry of seawater, thereby impacting the growth and survival of marine plants. Moreover, the spatial variability of these ecosystems dictated by geographical, climatic, and anthropogenic factors necessitates tailored conservation strategies that are responsive to local environments. A one-size-fits-all approach is unlikely to yield the desired outcomes; instead, adaptive management practices that are informed by continuous monitoring and research are essential.

In light of these challenges, the integration of marine green technologies into climate policy frameworks emerges as a critical priority. Governments, international bodies, and environmental organizations must collaborate to foster the development and deployment of marine-based solutions. This includes not only the protection and restoration of existing marine ecosystems but also the exploration of innovative approaches such as ocean fertilization and the cultivation of seaweed farms, which hold promise for enhancing the ocean's capacity to serve as carbon sink. Furthermore, inclusion of marine green strategies in the Nationally Determined Contributions (NDCs) under the Paris Agreement could serve as a catalyst for their broader adoption, aligning global climate goals with the imperatives of marine conservation.

Yet, the efficacy of these measures hinges on a robust framework of governance and financing. The mobilization of financial resources both public and private is imperative to support large-scale marine restoration projects. Equally important is the establishment of regulatory mechanisms that ensure the sustainable use of marine resources, preventing exploitation that could undermine conservation efforts. International cooperation will be key in this regard, particularly in addressing transboundary issues such as marine pollution and the management of shared water bodies. In summary, leveraging marine greens in the battle against climate change marks a transformative shift in our approach to environmental stewardship. This strategy demands a comprehensive and integrated framework that marries ecological wisdom with socio-economic foresight and cutting-edge technological innovation. The vast potential of marine ecosystems to bolster climate resilience is undeniable, yet unlocking this potential hinges on collaborative action, bold creativity, and a

steadfast commitment to sustainability's core values. As we navigate toward a more climate-resilient future, it is crucial to place the oceans the blue lungs of our planet at the heart of our fight against global warming. The moment to act is upon us, and the path ahead is unmistakable: embrace the power of marine greens and harness the ocean's immense capacity to pave the way for a sustainable tomorrow for all.

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Chapter 3

Marine bioresources in managing ocean microplastics pollution

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1. Introduction

The marine environment is an aquatic environment with high salinity, viable temperate, a zone that can be penetrated by light, and a deeper zone that sunlight cannot be reached, including subsystems like coral reefs and sea grasses, serving as a highly productive zone for numerous diversity of species and habitats (Aransiola, Oyewole, et al., 2024). This environment, comprising 71% of the Earth's surface, is an intricate and vital component of the planet's ecosystem that provides us with invaluable resources and services (Aransiola, Babaniyi, et al., 2024; Costanza et al., 1997). This complex and dynamic environment provides habitat for a wide variety of biodiversity ranging from primitive species like horseshoe to more complex organisms like whales and dolphins contributing to a stable and productive ocean ecosystem. These resources include marine biodiversity and natural compounds with pharmaceutical potential (Amobonye et al., 2023; Leal et al., 2016) that can be used for biotechnological applications and research. Marine resources include living organisms that live in or on the ocean such as, fish, seabirds, marine mammals, sponges, and seaweeds as well as nonliving resources like dissolved organic and inorganic materials, minerals, and oil reserves (Auta et al., 2022; Rogers et al., 2014). The marine environment provides critical services like carbon sequestration, nutrient cycling, and coastal protection and is also of great importance to humans in terms of climate regulation, food security, transportation, and other economic activity. However, this environment is increasingly threatened by anthropogenic activities leading to the pollution of microplastics creating a growing global concern (Thompson et al., 2004).

Large plastic debris breakdown either by biotic or abiotic means to form smaller fragments of plastic referred to as microplastics with size ranging from 1 to 5 mm and are widely distributed in aquatic and terrestrial environments (Musa et al., 2024). Due to their tiny size, they are easily and widely distributed, becoming more prevalent, particularly in the ocean, and have raised significant concerns in recent years. These significant threats not only affect marine life and environment but also human health having a significant ecological impact (Aransiola et al., 2023; Suzuki et al., 2024). Microplastics take various forms such as, fragments, pellets, fibers, foams, and microbeads. These tiny particles can be ingested by different marine organisms like fishes, low-nutrient organisms (Zooplankton e.g., Artemia), larvae of shellfish, and sea squirt (Yang et al., 2021) due to the fact that these microplastics are similar in size and density to planktonic organisms. Bioaccumulation of microplastics have been observed in suspensions and deposit-feeding organisms at the base of the food web with evidence showing that these ingested microplastics can be transported to higher trophic levels, that is, from planktons to whales (Harrison et al., 2011), thereby leading to accumulation of toxic substances within the food web, physical harm, and even death affecting species of different trophic levels (Wright et al., 2013). This by extension poses risk to other seafood consumers including humans. According to Yang et al. (2021), this has been demonstrated in an experimental exposure test that showed how persistent organic pollutants (POPs) could be accumulated in food webs from the ingestion of microplastics. The impact of toxic substances on marine fish that ingests

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TABLE 3.1 Ingestion of microplastics by various marine organisms.

Marine organism	Type of microplastic	Size range (mm)	Effect	References
Fish of various species	Fragments, fibers	<5	Gastrointestinal blockages, Liver inflammation, Oxidative stress	Rochman et al. (2013)
Seabirds	Pellets	1–10	Reduced feeding and digestive issues	Lavers and Bond (2016)
Zooplankton	Fragments, fibers	<1	Reduced feeding and impaired reproduction	Cole et al. (2013)
Oysters	Microbeads and fibers	<1	Damage tissue and oxidative stress	Sussarellu et al. (2016)
Crabs	Fragments, fibers	>5	Redarded growth and change in feeding behavior	Watts et al. (2014)

microplastics has been observed to develop liver inflammation, pathological effects, and oxidative stress (Rochman et al., 2013) (Table 3.1).

The physical properties of microplastics such as its size and density make it easier to be distributed and transported over long distances in both aquatic and terrestrial environments, making it more challenging to remediate and control. The use of traditional cleanup methods could be less effective, necessitating the integration of innovative techniques that could be more sustainable in addressing this environmental issue. This chapter helps provide a comprehensive overview of how this microplastics pollution can be managed and mitigated in marine environments by the use of marine bioresources. Through this exploration, this chapter highlights the use of marine bioresources as a more sustainable, effective, and environmentally friendly method of combating the pollution of microplastics in marine ecosystems and the world at large.

2. Microplastics pollution of the marine

2.1 Sources and types of microplastics

The significant primary sources of synthetic plastic wastes in marine environments includes coastal tourism, fishing activities, marine industries, and plastic product manufacturing of which directly impacts seas and oceans (Urbanek et al., 2018). These synthetic plastic fragments to smaller fragments of less than 5 mm in size are referred to as microplastics. These microplastics are classified into primary and secondary microplastics. Primary microplastics comprise synthetic materials directly manufactured into small size such as microbeads and microfibers used to manufacture personal care products and are usually found in municipal and domestic wastewater sludge (Sooriyakumar et al., 2022; Zhang et al., 2020). Instead of the traditional exfoliants (ground almonds and oatmeal), microplastics are utilized in the form of microbeads varying in shape, size, and composition depending on the product to be produced. This type of microplastics is used in the production of cosmetics products like shower gel, eye shadow, and facial cleanser and other products like toothpastes, sanitary products, and pharmaceuticals (Thushari & Senevirathna, 2020). This use of microbeads has subsequently resulted in the increase in demand for microplastics, which are utilized in large amounts for the manufacturing of cosmetic products, which eventually makes their way to the ocean through waste streams, rivers, and drainage systems by bypassing wastewater treatment procedures (Auta et al., 2017). Secondary microplastics, on the other hand, result from the fragmentation of larger plastics through processes like mechanical abrasion, photodegradation, and biological activities (biodegradation). Common sources are the breakdown of plastic bags, bottles, fishing gears due to wave action, UV radiation, and so on (Fig. 3.1), which subsequently degrade into microplastics. Synthetic textiles shed microfibers during washing and make their way to the ocean when discharged into waterways (Napper & Thompson, 2016).

A way to categorize ways microplastics make their way to the ocean is by classifying them into land-based and marine-based activities. Land-based activities like tourism and recreational activities are significant contributors to the accumulation of plastics in coastal areas and marine ecosystems (Thushari & Senevirathna, 2020). Other activities include residential and domestic activities, agriculture activities (microplastics from fertilizers), and various economic activities, which are important sources of microplastics that can be carried into the ocean through runoffs. Another significant contributor to microplastic pollution, that is, land-based sources, is textile fibers. Plastic fibers, like polyester, acrylic, and nylon, shed from clothing during washing and are tiny enough to bypass water treatment systems and enter water bodies,

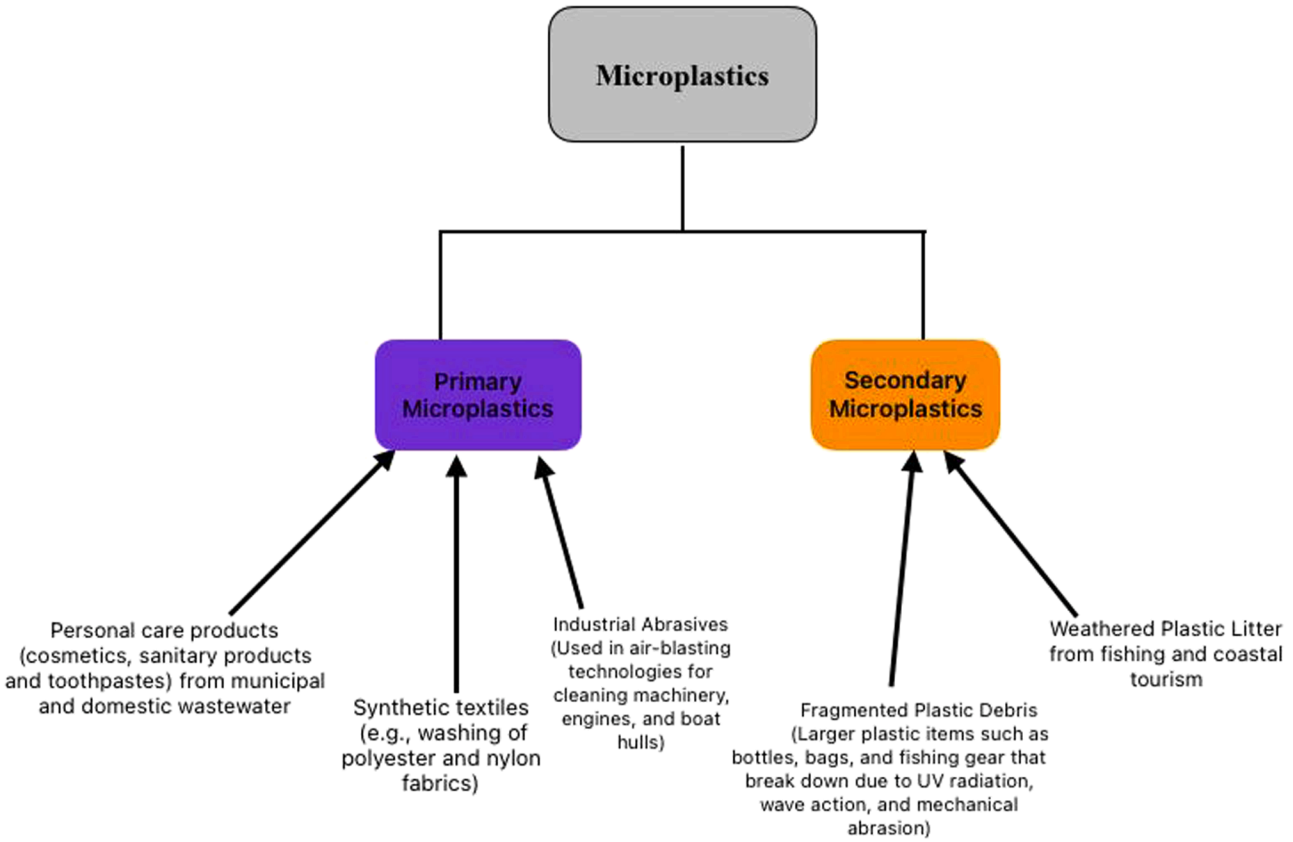

FIGURE 3.1 Source of microplastics in the ocean.

which eventually make their way into the ocean. The increased demand of synthetic textiles globally, the release of microfibers into the ocean, has increased drastically losing a threat to the marine ecosystem. Marine-based activities as a source of microplastics pollution in oceans on the other hand include commercial fishing, shipping, and other economic activities. The loss equipment like fishing gears, ropes, and so on degrade with time breaking down into smaller particles resulting in the release of microplastic in oceans.

2.2 Distribution and prevalence of microplastics in marine environments

Microplastics are widely distributed throughout marine environments, from surface water to the deep sea, and from coastal zones to remote oceanic regions. Their size and buoyancy make it easier for them to be transported over long distances by ocean current (Doughty & Eriksen, 2014). Microplastics have been found in various marine zones including seawater, biota, and sediments. Atmospheric deposition is also a pathway for microplastics to enter the ocean. Microplastics can be carried by the wind and deposited in the ocean by rain. This pathway shows how microplastics can be dispersed globally as airborne particles over long distances before settling in marine environments (Bergmann et al., 2017). Surface water has high concentrations of microplastics due to their buoyancy while coastal areas, especially those near urban centers and river entrances, also show increased levels of microplastics usually from offshore pollution sources (Jambeck et al., 2015).

A quite less obvious yet significant pathway for microplastics to enter the ocean is through the feces of zooplankton. In a study by Cole et al. (2016), zooplankton, particularly *Calanus helgolandicus* and *C. typicus*, were exposed to polystyrene microplastics. These organisms ingested the microplastics, which passed through their digestive system as they were not able to digest them and were then encapsulated in their feces. The fecal pellet with the microplastics could sink to the bottom of the exposure vessel and could be ingested by larger copepods. This study shows how fecal pellets could be a vector for microplastics dispersal and how these microplastics make their way to higher trophic organisms in the marine ecosystem.

The prevalence of microplastics in marine has grown significantly over the years. Tons of plastics are subsequently found in oceans all over the world and are estimated to increase in the future. Microplastics have been found in marine species such as plankton, fish, seabirds, and marine mammals indicating this nature of ubiquity (Cole et al., 2013). The density of plastics influences its accumulation in marine environments. It can gather within the water column, float on surface water, or sink to the ocean floor after being colonized by biotic and abiotic components. The way they spread in ocean environments is influenced by their density, where they originate from, and their movement through waves and currents of the ocean. The physical and chemical properties of microplastics contribute to their endurance and prevalence causing widespread pollution in the ecosystem facilitated by processes of water movement and forces of ocean current (Auta et al., 2017).

3. Mechanisms of plastisphere in the ocean environment in solving microplastics pollution

3.1 Plastic and microplastic pollution in aquatic environments

Plastics, being polymers, coupled with their ability to adsorb various substances (metals, POP's and additives) make a distinctive medium for microbial adhesion (Du et al., 2022). Owing to their relative novelty and being artificial media in marine systems, plastics may cause disruptions in the balance of the ecosystem and sever natural boundaries (Zhai et al., 2023), and because of their durability, plastics are not completely broken down in the environment; instead, they form smaller-sized particles, and when these particles become less than 5 mm in size, they are called microplastics (An et al., 2022). Microplastics are synthetic solid particles or polymeric matrix, that regular or amorphous in shape, ranging from 1 μm to 5 mm, of either primary or secondary manufacturing origin, which are insoluble in water (Frias & Nash, 2019). In the marine ecosystem, microplastics are found in shelf, beaches, deep water sediments, subsurface, and surface waters (Hossain et al., 2023), and of all the various anthropogenic wastes in aquatic environments, plastics are becoming the material of most concern to environmentalists (Ding et al., 2022).

3.2 The plastisphere

The plastisphere is a term first coined and characterized by Zettler et al. (2013), and it describes the new community of microorganisms attached to plastic surfaces and distinct from the environment (aquatic or terrestrial) where the plastics are found. The attachment and colonization of a community of microorganisms on free-floating plastic surfaces are referred to as the plastisphere (Mishra et al., 2024). Biofilm-forming microorganisms colonize microplastics creating the plastisphere. This unique environment aids dispersion of microbes as well as affects the development, transportation, persistence, and ecology of microorganisms (Barros & Seena, 2021). Like other biofilms, the plastisphere is built by attachment of microbes, secretion of extracellular polymeric substances, and exponential growth of microbes (Zettler et al., 2013). Plastisphere formation is influenced by a complex interaction of various factors, primarily spatial and seasonal. Polymeric characteristics (type, shape, and surface features), however, also play a role (Singh et al., 2022). Environmental factors, water current, availability of nutrients, and type of microplastic surface control the relationships between microorganisms on the plastic surface, ultimately controlling biofilm (plastisphere) formation (Ghosh & Das, 2018).

3.3 Plastisphere-mediated microplastic degradation

Physical plastic degradation processes (e.g., waves breaking them down against ricks and sand) and chemical degradation processes (e.g., photo-oxidation) happening in the aquatic environment lead to the breakdown of aquatic plastic waste to microplastics, ultimately leading to the formation of the plastisphere (Tang, 2024). These processes convert plastics to microplastics, making them more susceptible to further degradation. Microbial (plastisphere) regulated degradation of microplastics enhances microplastic catabolism without causing any negative effects to the environment and the ease of adaptability by microbes to various environments ensures microplastic degradation (Du et al., 2022). The microbial biodegradation process involves carbon (from plastics) metabolism into biogas and biomass by the action of microbial communities (bacteria, actinomycetes, and fungi) that use plastics as a carbon source (Alshehrei, 2017).

Microplastic degradation carried out by microorganisms is simply the catabolism of plastic macromolecules into smaller, environmentally friendly metabolites like water (H_2O), carbon(iv)oxide (CO_2), and methane (CH_4) by the action of various enzymes secreted in biofilms (Yuan et al., 2020).

Plastic fragments and microplastics have the ability to serve as a source of carbon, supporting growth and colonization by microbes (Alshehrei, 2017). In the environment, microplastics are found in association with microorganisms, organic matter, and inorganic particles. These associations enhance the formation of biofilms (plastisphere) by various microorganisms on the surface of the plastics by aiding the adsorption of microbes to the surface of microplastics, which act as a substrate (Mishra et al., 2024).

The cleavage and breakdown of microplastic particles by microorganisms are heavily dependent on the growth of the mycelium, as physio-chemical structure of the plastic is disrupted by mycelium growth (Mishra et al., 2024). Enzymatic reactions by microorganisms cause structural damage to microplastics, which causes a loss of properties. However, before degradation by microorganisms, these plastics waste particles must first be broken down by physical processes; abrasion, hydrolysis, and UV light (Alshehrei, 2017). After this, enzymatic secretion by microorganisms mediates the hydrolysis or oxidative breakdown of plastic macromolecules, releasing molecules of lower molar masses. Simple compounds like water (H_2O) and carbon(iv)oxide (CO_2) are produced when the micro molecules released are used up by microorganisms (Dussud et al., 2018; Mohanan et al., 2020).

Biodeterioration involves the changing of the physical and chemical properties of a polymer by microorganisms. After this, the polymers are broken down to simpler ones by **bio-fragmentation**. This is followed by the "taking up" of these simple compounds by microorganisms by **assimilation** and the products of the organisms' metabolism (like CO_2, CH_4, and H_2O) undergo **mineralization** (Fig. 3.2) (Rashed et al., 2023; Sanniyasi et al., 2021).

Higher molecular weight polymers, however, are more difficult for microorganisms to assimilate due to their large fragments and resulting difficulty to break down. Intracellular and extracellular degradation are used by microorganisms to overcome this molecular weight barrier (Rashed et al., 2023). Intracellular degradation involves the aggregation on and colonization of the microplastic surface by microbes and the hydrolysis of the polymer into shorter chains. Extracellular degradation involves the use of hydrolase enzymes secreted by bacteria to degrade complex polymeric units to simpler ones, which can be more easily metabolized prompting the start of the mineralization process (Rashed et al., 2023).

The part played by the fungi *Fusarium oxysporum* and *F. solani* in breaking down plastic polymers (PET) has been shown by previous studies (Mayali, 2018) and Zhai et al. (2023) reported the successful degradation of polystyrene by *Exiguobacterium*, *Bacillus anthracis*, *Enterobacter* sp., and *Aspergillus* sp. Bacillus sp., *Rhodococcus* sp., *Pseudomonas aeruginosa*, and *Aspergillus clavatus* have been successfully investigated for their biodegradation potential (Amobonye et al., 2021; Tareen et al., 2022). Microplastic degradation is the result of the joint metabolism of multiple microorganisms in the plastisphere, which have the ability to turn complex plastic polymers into simpler products of metabolism like CO_2 and H_2O.

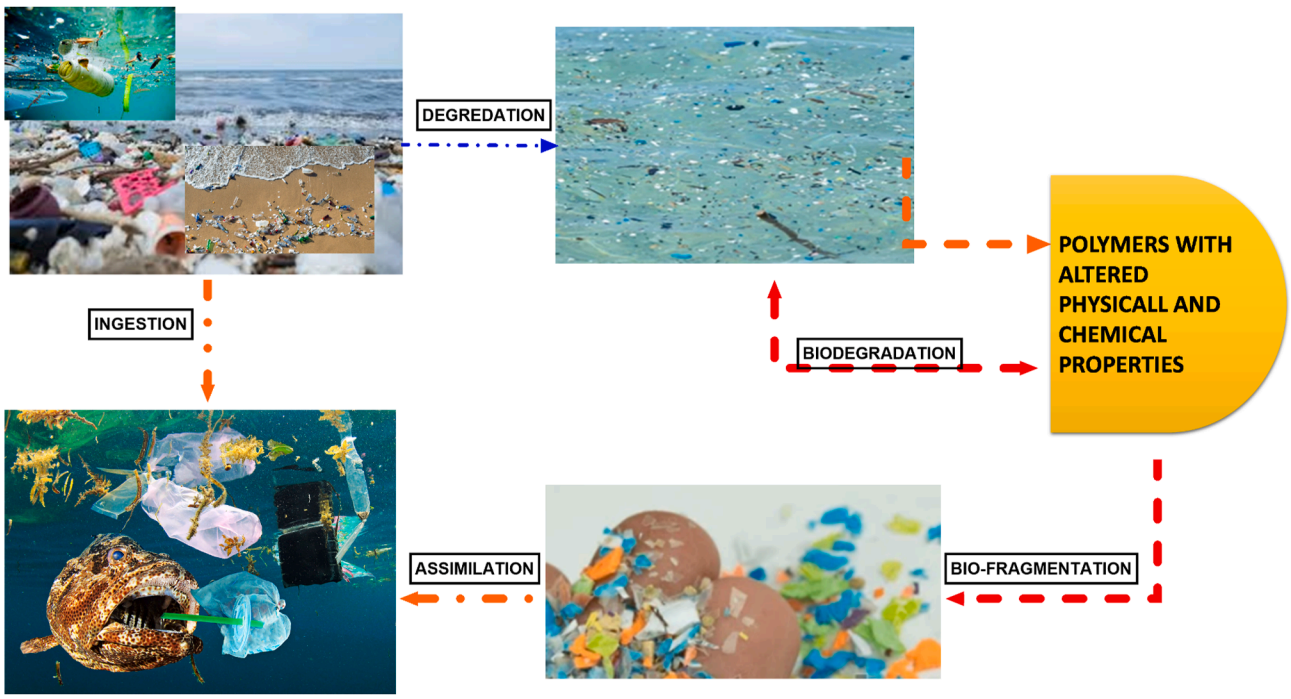

FIGURE 3.2 Consecutive steps in microplastics degradation.

4. Future guidelines in using marine bioresources to manage marine microplastics

4.1 AI in focus

New technologies are launching, often daily. These advancements are becoming popularly used in many different domain names as a way to handle problems worldwide. There are technologies that are used for manipulation of genes, and quantum mechanics, which are changing the way we work or think. Artificial intelligence along with machine learning (ML) is one of the most promising solutions to combat microplastic pollution among these emerging technologies. Machines can be created with the help of AI, and for analyzing data from the past, ML provides a method to predict or come up with consequences based on which they might work (Agarwala, 2021). With the help of ML and AI, ocean cleaning can play a vital role in protecting these ecosystems against pollution/degradation, as well as developing sustainable microplastic methods.

Recently, AI has been applied to the management of microplastics. Autonomous robots with AI are detecting and identifying microplastics (Koski, 2022; Taddia et al., 2021) as well as machine learning models that were used to analyze data providing meaningful information on the composition of microplastics (Michel et al., 2020; Zhu et al., 2020). Such developments have broadened the scope of research, utilization, and administration concerning microplastics. Some robots such as robotic fish, drones, and smart cars have been invented in order to take out microplastics from water bodies (Zhang et al., 2023; Zolich et al., 2022). It is highly resilient to environments and thus can be used a long time before replacement. Another is the creation of Gillbert, a peer-into-detail 3D-printed robotic fish, which was built with intentions of gathering microplastics from environments (Designboom, 2022). First up is Gillbert, an aquarium-roaming fish bot with a remote-control module and filtration. The robot's gills filters can block up to 2 mm wide microplastics from the water. The collected MP's are stored inside the cleaning robot in a container and can be disposed of safely or recycled. Gillbert, in its current form, is still too small to handle anything other than microplastic sampling. Future exploration efforts should focus on scaling up the machine so that it can rid waters of microplastics and plastics on a large scale (Guo et al., 2024).

Robotic systems serve for the digitalization of waste object sorting. The digital camera of the robots makes it possible to automate these sorting tasks by using an ML algorithm. These plastic weighs are photographed by the robot's digital camera and then examined using deep studying fashions. These models can be used to find, locate, and classify the plastic waste which in turn would help robots easily sort plastics using intelligent control (Guo et al., 2024). These robots and their cameras with machine learning algorithms can automate sorting tasks. Another study (Liu et al., 2021) constructed a robot equipped with an RGB-D camera and tasked this machine to search for and grasp plastic objects. The YOLACT model was trained with a dataset of 1500 images of plastic items dispersed against complex backgrounds (e.g., bottle caps drinking bottles; foam food containers) on tiles, sidewalks, and/or grassy roads. This instructed the model to be able to know object detection properly in practical use cases. The trained model was used to detect and locate plastic items present in the scenes of RGB images from depth cameras, thereby achieving real-time detection scenarios since it can perform target localization on video feeds. Point clouds were created using the depth data from the cameras and used for a simulation of plastic object surfaces to create an effective grasping strategy. The success rate of grasps was more than 90% (Liu et al., 2021).

Automatic identification, classification, and quantification of microplastics (MPs) using ML methods have been tasked with identifying MPs from images taken by digital cameras (Sundar, 2022) and microscopes (Wang et al., 2023). These models are trained using MPs annotated images, the "knowledge source" of these models to identify features like shape, size, color, or texture related to factorial cells (Guo et al., 2022). Trained models contain the identification (Guo et al., 2021) and inserting of bounding boxes around detected MPs in new, previously not-observed images which might either be photos or frames from video recordings (Liu et al., 2022).

5. Conclusion

The study of marine bioresources as a means to reduce microplastics pollution in the marine environment provides a promising solution through natural biodegradation processes. These bioresources include marine organisms associated with plastics known as plastisphere with plastic-degrading enzymes, capable of degrading microplastic. Understanding the plastisphere reveals that communities of microorganisms are able to degrade plastics through biochemical means. The microbial biodegradation process involves carbon from plastics metabolizing into biogas and biomass by the action of these microbial communities, plastisphere. They break down plastic macromolecules into smaller, environmentally friendly metabolites like water (H_2O), carbon(iv)oxide (CO_2), and methane (CH_4) by the action of various enzymes that

they secrete. With the influence and use of AI, the identification and utilization of these agents of biodegradation increase the development of efficient and scalable bioremediation strategies. An integrative approach, involving partnership of marine biologists, environmental scientists, chemists, and AI specialists to maximize the potential of marine bioresources, is quite essential in other to provide an innovative and viable solution to mitigate microplastics pollution, thus addressing this environmental challenge and contributing to the long-term environmental-friendly marine environment.

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Chapter 4

Food for all: Exploring fulfilling SDG2 by sea

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1. Introduction

Let us start by defining hunger in simple terms: it occurs when a person cannot manage even half a stomach of food once a day, and this state continues for more than three consecutive days. While this definition may seem straightforward, a staggering number of people experience this daily. According to the 2023 edition of the "State of Food Security and Nutrition in the World" report, between 691 and 783 million people faced hunger in 2022, marking an increase of 122 million compared to 2019 (Sreehari et al., 2023). The rising cost of food compounds the problem. As reported by OECD (2021), the FAO Food Price Index—which tracks global price changes in a basket of food items like sugar, meat, cereals, dairy, and vegetable oil—rose from 95.1 points in 2019 to 143.7 points in 2022.

Rather than delving into the well-documented challenges of land-based agriculture—such as climate change, fertilizer shortages, limited space, and adverse geographical features like rivers and mountains—this discussion will focus on the potential of the sea to address hunger. Achieving zero hunger requires localized, adaptive, and participatory solutions that account for institutional capacities, agroecosystem diversification, ecological management, and improving local diets. Conceptual frameworks such as socio-ecological systems and sustainable diets provide integrated approaches to agricultural and food security challenges, informing policies that are more effective and holistic (Papargyropoulou et al., 2024, p. 102705).

The focus here will be on how marine resources can be utilized to combat hunger while addressing the challenges inherent in this approach. Unlike land, which must support population, infrastructure, and agriculture and is further strained by climatic extremes and soil degradation, the sea offers untapped opportunities. However, harnessing its potential is not without difficulties, and these will also be explored. The path to achieving Zero Hunger should focus on solutions that are tailored to specific locations, adaptable to changing conditions, and involve active participation from local communities. These solutions must address local institutional capacities, promote diverse agricultural ecosystems, support ecological management, and enhance the quality of local diets. Two key frameworks—socio-ecological systems and sustainable diets—provide integrated perspectives for analyzing agriculture and food security. These frameworks can guide the development of effective policies that are both practical and sustainable, ensuring long-term progress toward eradicating hunger (Aransiola, Akinsola, et al., 2024; Aransiola, Oyewole, et al., 2024).

The Earth's land-to-water ratio is approximately 1:2, meaning there is significantly more water than land available (Lehmköster & Maribus, 2011). This prompts an important question: what if we could utilize the sea as a space to grow food? This could include cultivating plants, farming animals, or even harvesting insects—essentially exploring all viable options for food production. While we already utilize some marine resources for food, the idea is to expand this usage to meet a greater share of nutritional needs, potentially filling up to 90% of the stomach, at least once a day if not twice. This perspective shifts the focus from land-based constraints to the vast, untapped potential of the ocean as a resource for food production.

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2. How can sea be used?

Regenerative sea farms are an intriguing alternative to traditional land-based farming even though they are small in scale. One compelling approach is creating farming areas in the ocean to cultivate marine plants and animals. For instance, Bren Smith, founder of Thimble Island Ocean Farm and the Connecticut-based nonprofit GreenWave, has developed a 3D ocean farming system that functions as an underwater garden anchored by a network of light nets, vertical and horizontal lines, and cages that grow a mix of oysters, mussels, kelp, and other sea vegetables and shellfish (Meyer et al., 2019) (Fig. 4.1). This innovation has a little carbon footprint but massive outputs, revitalizing ocean ecosystems and creating a new ocean economy.

Marine aquaculture makes use of natural resources like seawater and sunlight as energy sources to grow sea-based food making the process remarkably sustainable and efficient (Orcutt et al., 2011). This approach has promising prospects as an environmental solution, providing nutrient-rich food, creating job opportunities, and reviving coastal ecosystems. Sea greens can also serve as bioplastics, biofuels, and cattle feed additives that minimize methane release from livestock (McCay & Sunidhi, 2024) (Fig. 4.2). Kelps in particular are significant for their ability to absorb and retain carbon and nitrogen which helps in combating global warming and climate change (Filbee-Dexter & Wernberg, 2020).

Shellfish add to the ecological benefits. Shellfish reefs enhance coastal resilience by reducing storm surge impacts, while bivalves naturally filter pollutants from the water as they feed. This includes removing excess nitrogen, often caused by fertilizer runoff from industrial farming (Coen et al., 2011). However, there are challenges, such as integrating sea vegetables and other marine products into the economy at a scale comparable to land-based agriculture. With careful planning, strategic leadership, and innovative approaches, these challenges are surmountable. Solutions include creative farm designs, targeted farmer training programs, and online support hubs for small-scale cooperative sea farmers. These efforts are rapidly building a nationwide network of kelp farmers who are implementing climate solutions, fortifying shorelines, and enhancing food security (Institute of Medicine, 1991). By embracing these practices, sea farming holds immense promise for both people and the planet. The vast array of ocean plants and animals offers immense potential for integration into our food systems, and in many ways, we have only scratched the surface of what is possible. However, this raises an important question "Is society ready to embrace nutrient-rich sea vegetables and shellfish as a larger part of our diets?"

The U.S. Census Bureau estimates the shore length at 12,000 miles, while the National Oceanic and Atmospheric Administration (NOAA) places the total coastline length at approximately 95,471 miles. This highlights the extensive reach of our coastal resources, which remain largely untapped for food production. "There is not a lot of water on Earth at all," remarked David Gallo, an oceanographer at the Woods Hole Oceanographic Institution in Massachusetts. Despite its abundance, the ocean covers the planet with a water layer spanning 15,000 miles (24,000 km) at an average depth of 3.2 km. This immense volume of water presents a compelling opportunity to expand our food sources by sustainably cultivating marine life, but it also underscores the challenges of managing and harnessing such vast resources effectively.

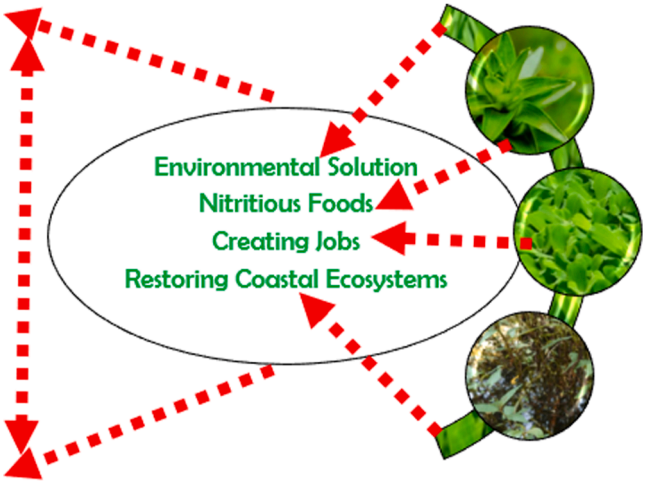

FIGURE 4.1 Benefits of 3D ocean farming system.

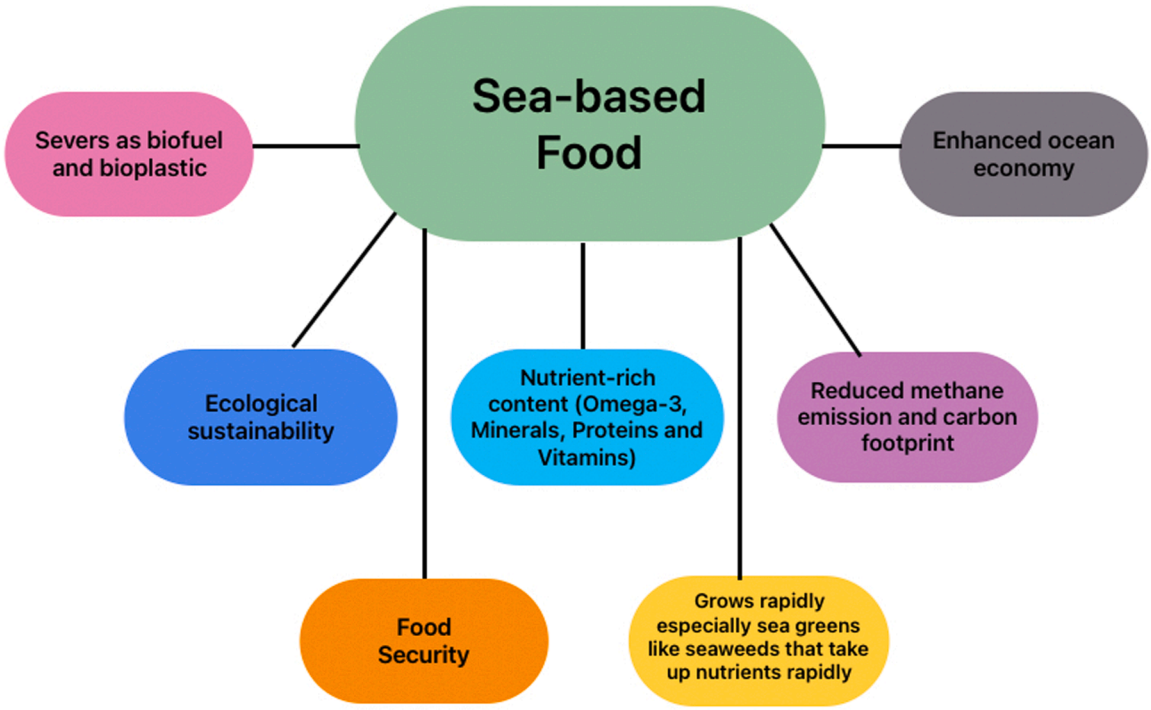

FIGURE 4.2 Sea-based food and potential benefits.

3. Tentative problems to use sea

The U.S. Census Bureau estimates the length of the shoreline at 12,000 miles, while the NOAA places the total coastline at approximately 95,471 miles (Gleick & Heather, 2021). However, utilizing the sea as a food source presents unique challenges, particularly due to the type of food we are accustomed to consuming. Staple grains like wheat, maize, and rice are rooted plants, making them unsuitable for cultivation in the ocean. On land, farming is better controlled, but in the sea, factors such as water currents, tides, and coastal dynamics make control far more difficult, even along shorelines.

With nearly half the world's population living within 65 miles of the ocean, coastal ecosystems are among Earth's most critical landscapes (Burkett et al., 2018). Yet, these areas are notoriously hard to map accurately. Until recently, there was no comprehensive high-resolution geospatial dataset of global shorelines. This gap has now been addressed by a new mapping and ecological inventory developed by Esri, the U.S. Geological Survey, and other partners (Sayre, Butler, et al., 2021).

While rooted crops like cereals and traditional vegetables cannot be grown in the ocean, marine resources such as sea plants, fish, shellfish, and even insects present viable alternatives for food production. Sea algae, in particular, has the potential to be a significant food source to combat hunger (Table 4.1). Addressing global hunger requires diversification of food sources, which calls for innovation and adaptability in utilizing the ocean's resources. However, the ocean poses unique challenges, particularly in monitoring and controlling the composition of marine food. On land, chemical analyses enable the regulation of toxins like heavy metals in crops, benefiting from extensive ecosystem studies. Meanwhile, these cannot be done in the ocean, as its vast realm and complexity make it difficult to carry out similar controls thereby posing a significant limitation. Meal preferences are deeply rooted in an individual's traditional background as they would prefer to continue with the food they have been used to, further complicating the adoption of sea-based foods into their diets. Staple foods like wheat, maize, and rice are core dietary components for many persons, and alternative foods may not provide the same sense of acceptance or satisfaction. This leads to both psychological and practical challenges in shifting toward sea-based diets. Also, while the ocean provides vast amounts of volume, it still poses issues that also involve critical issues of coastal erosion.

A worldwide challenge that has been of major concern is the need to balance the benefits derived from the ocean with its capacity to provide for future generations. To achieve sustainable management of the ocean and minimize environmental impact, overharvesting of capture fisheries and aquaculture facilities should be avoided. Failing to do so could reduce the marine ecosystem's ability to sustain food production and other societal benefits. Additionally, the social and

TABLE 4.1 Land-based food and their sea-based food equivalent with its potential benefits.

Land-based food	Sea-based food equivalent	Potential benefits	References
Wheat	Seaweeds, *Ulva*	Grows faster, occupies space more efficiently, and has a long chain of Omega-3 fatty acids, minerals and vitamins. A safer alternative to land-based wheat.	Hofmann et al. (2024).
Rice	Seagrasses (seed of *Zostera marina*)	More carbohydrates, iron, sodium, and calcium content. Higher vitamin B_{12} content. Used to make flour for bread and atoles production.	Pérez-Lloréns and Brun (2023)
Livestock	Bivalves (oysters, clams, mussels and scallops)	Filter feeders, high protein, minerals and healthy fat content, do not depend solely on feed input and have massive production capacity.	Costello et al. (2019)
Vegetables	Marine red algae	Contain protein, minerals, and polysaccharides and are used as food colorants.	Dumay et al. (2014)

economic goals of fisheries and aquaculture must adopt sustainable practices to protect and ensure long-term value. The gradual land loss along coastlines from natural processes like wave actions or human activities actually worsens these challenges. In some areas, natural erosion destroys property, interrupts economic activities, and even results in loss of life. Human actions—such as sand mining, land reformation, and building sea barriers, usually cause sediments to be transported along coasts. The changes in river catchments can also cause either an increase or decrease in the natural sediment flow to coastal areas. Global climate change compounds the gravity of these issues further, contributing to the change of wave patterns, rise in sea level, and recurring and severe storm incidents, all of which worsen coastal erosion and its repercussions. It is therefore critically important that the ocean's sustainability and coastal management strategies should be taken seriously to address these challenges.

Another significant aspect to consider is the dynamic nature of water, both in its quantity and its composition and how it interacts with its environment. Anthropogenic activities significantly affect coastal ecosystems causing global climate change, which is closely associated with rising sea levels (Jaagus, 2006; Johansson et al., 2004) and frequent storm events (Alexandersson et al., 1998; Lowe et al., 2001; Masselink & Russell, 2006; Meier et al., 2004; Morton et al., 2005; Suursaar et al., 2006; Tõnisson et al., 2011).

Coastal sedimentation and morphology are directly influenced by marine environments as well as regional landforms, their composition, and human activities such as agriculture, mining and urban development which alter the pattern of precipitation, runoff from both points (municipal and industrial discharge pipes) and nonpoint (agricultural runoff) sources, sea level changes, and storm behavior. These interactions influence the distribution and dynamics of sediments along coastal regions. Additionally, aeolian processes—such as wind-blown dust from deserts in Africa and Asia—can also impact some coastlines complicating further the delicate balance of these ecosystems. Such factors highlight the relationship between natural and human-induced changes in coastal and marine environments.

4. Some developments

Imagine a hypothetical underwater vessel where plants and animals coexist in a symbiotic system. In this system, aquatic plants and animals would live together and mutually benefit from each other. With a bottom layer of mud substrate or organic material, seeds are cultivated, and aquatic animals like fish are introduced into the environment. Plants provide oxygen and food for the animals, while the animals, in turn, provide organic nutrients that fertilize the plants. This concept reflects the principles seen in recirculating aquaculture systems (RAS), which efficiently produce significant amounts of food with minimal water use.

RAS technology is currently being explored to grow plants underwater within fish production systems, indicating initial potential. Integrating crop cultivation with aquatic species offers several benefits: plant roots absorb chemical organic compounds effectively, a large number of microorganisms maintain system health, and no chemicals or pesticides are required. However, scaling this method into a commercially viable model is challenging. Researchers are investigating ways to cultivate fish and plants together on a larger scale without disrupting existing fish production. Underwater

farming, by its nature, eliminates the need for pesticides, as pests cannot access the units unless introduced. Each biosphere in such systems is equipped with seedbeds and a 10-m coiled tube. Irrigation water and fertilizers are stored in a tank at the base of the coil and delivered to plants using a pump. All functions are remotely operated from an above-water tower powered by solar panels. These solar panels also power a fan within each biosphere to regulate humidity for the plants. This system is highly water-efficient; seawater inside the units evaporates and condenses to provide fresh water for the plants, and only in the initial planting stage is an external water source needed.

With this approach rooted plants can be cultivated in the sea starting with experiments on crops such as spinach. As progress is made, staple crops such as rice, wheat, and possibly even genetically modified maize. Although it might seem challenging, this vision offers a pathway to combat hunger and sustain many lives. Challenges like ocean pollution, global warming, and other environmental factors could limit its success but it should be noted that it represents a bold step toward sustainable underwater agriculture which could significantly contribute to global food security (Gimba et al., 2024).

5. What can an individual do?

As individuals, we all have a responsibility to use resources wisely and sustainably avoiding wastage and mismanagement. This means that we consciously have to take only what we need and leave the rest for others and future generations. Transformation takes time, but small, deliberate and consistent practice can make a huge difference. Imagine if each person on Earth chose to eat just one spoonful less at every meal—collectively, this result would make a significant amount of food become available for those in need.

There must be a personal effort within, made every day with every meal. It's not about comparing ourselves to others; the fight is solely with our habits and choices. If we cannot actively contribute to cultivating food, the least we can do is prevent waste and conserve what we have. While it may take a while, this shared, mindful approach from individuals around the world has the ability to impact lasting change.

6. Conclusion

The ocean holds significant potential as an alternative food source to tackle the world hunger crisis, especially as the limitations in land-based food production cannot meet the needs of the growing population. The thought of using the ocean as a farming ground to minimize hunger might seem difficult to achieve but taking a step one at a time and being consistent with our actions brings us closer to achieving a sustainable future in marine fisheries and aquaculture. Sea-based foods can be used as an alternative to their land-based counterparts, seaweeds can be used in place of wheat and Fish/bivalves in place of livestock. However, these opportunities also have some challenges in terms of overfishing and overharvesting, ocean pollution, and coastal erosion which should be addressed, and sustainable strategies should be practiced so that we can have a future where everyone can afford or access modest food. SDG 2 is achieved. Still a long way to go, yet one can begin from somewhere.

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Chapter 5

Remote sensing and geographic information system (GIS) in marine bioresources innovations and monitoring

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1. Introduction

As tools for gathering, analyzing, and storing geographic data, geospatial technologies are particularly well-suited to tackle these issues in marine planning (AAAS, 2018). The aforementioned factors facilitate multilevel perception (MSP) and are in line with the goals of natural resource management, conservation, and ecosystem health (Kirkfeldt, 2019). These factors also allow for the identification, gathering, and evaluation of geographic data at various levels. Global positioning systems (GPS), remote sensing (RS), and geographic information systems (GIS) are a few examples of frequently used GTs. The term "remote sensing" describes the process of gathering data and pictures from a distance. This includes not just satellite photos but also scanning tools like sonars that are used to map the seafloor. GPS, a satellite-based geolocation system, allows the public to follow mobile human users and tag mobile marine animals. GIS can be used to make maps and charts and to create, organize, and present data in a way that is spatially referenced. GIS also helps with decision-making, raising awareness of issues connected to marine water quality and developing sustainability with a national focus. Most previous studies on geographical technology solutions have focused on RS (El Mahrad et al., 2020) or a single technology in connection to MSP uses (Lee et al., 2019). Although GTs have previously been employed for planning and particular MSP requirements (González et al., 2020), their use for MSP is where they are lacking. This work aims to show how the innovations of RS and GIS-derived data are useful in the marine ecosystem. The importance of this analysis resides in how GTs explicitly address the demands of ocean managers, planners, and MSP practitioners by highlighting important resources available to them and thereby enhancing scientifically informed ocean use planning. Egypt's Mediterranean coastline is one of the longest in North Africa, spanning over 1050 km from El-Salloum in the west to El-Arish in the east. Even though the Egyptian Mediterranean coast is commercially significant and has witnessed major investments in a number of industries, including marine fisheries, the average annual fish production of this large area was just 60,000 tons (GAFRD, 2000–20). Using specific environmental indicators (Chl-a, SST, and productivity data), satellite RS has been used worldwide to locate and monitor the PFZs, according to a body of literature (Ali et al., 2022).

2. The marine life, resources, and economic value

2.1 GIS and biodiversity/habitat conservation

Marine and coastal resources management needs geography; though often seen as belonging to the biophysical sciences, its management is culturally and politically driven. Part of the methods of used in marine resources management includes centralized approaches (limiting access to oceans through permit, zoning of oceans, and enforcement of limits to catching

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fishes), community-based approaches, and the newly embraced spatial approaches. The later emphasizes ocean space regulation (Levine et al., 2015).

2.2 Geospatial technique and mapping in the marine region

In other to understand spatial pattern of human use, GIS, and mapping cannot be over emphasized. While GIS is used in illustrating spatial patterns in the field, a unique set of challenges is being presented by the mapping of the marine spaces because of its dynamic nature. This map shows the species distribution, the various habitat types, their importance in accessing economic value, and their integration in proper recording and accounting systems (Galparsoro et al., 2014).

The inventory and catchment of wetland/marine resources when conservation and management is being considered is of great importance. This is achievable with the digital maps that help in the aspect of monitoring and quantifying changes over time scale and also in decision-making. Maps preparation procedures starts with the surveying of the ground. This presents topographical maps that show various classes of land use/land cover including the marine/wetlands. Documented important tool for decision-making analyzing, viewing, and characterizing water, land, and component of the atmosphere is RS (Nath et al., 2020). Table 5.1 explains the various platforms, data types, processing software, and the applications of the acquired marine data necessary for monitoring the marine ecosystem.

2.3 GIS in the marine ecosystem

Inclusive in the wetland/marine boundary should be all open water, aquatic vegetation such as submerged, emergent, and floating weeds with satellite images giving an unambiguous mark of the wetland/marine extent. Vegetation presence in this region offers important information on the condition of the tropic (Nath et al., 2020; Okewu et al., 2024).

A host to varieties of habitat is the marine environment and are categorized below

1. Those occurring at the seafloor known as benthic habitats are reinforced by different types of base for example seabed composed of muds and sands, or the ones with firm base seagrass meadows, coral reefs of cold water and sponge aggregation
2. Those associated with water column for example pelagic habitats in the open ocean.

TABLE 5.1 Marine data acquisition plat form, processing software, and uses.

Platform	Data type	Processing software	Application/uses
Satellite/Radiometer (active and passive sensors)	Imageries	Geographic information softwares, oceanography software, Hydrographic software Fishery management software, statistical analysis software	Ocean color monitoring, chlorophyll detection, study carbon cycle, biogeochemical modeling, oil spillage
AUV (autonomous underwater vehicle)	Imageries		Conducts biological and geophysical surveys
Ship MBES (multibeam echo sounder)	Multispectral image and bathymetric chart		High resolution creation of maps of seabed
Echo sounder	Bathymetric charts and maps of seabed		Measure depth of water and the topography of the seabed.
Side scan sonar	Images of the seafloor		Seafloor feature mapping and underwater object detection
Bathymetric LiDAR	High resolution models of the coastal elevation		Water depth measurement and topography of the coast
Global positioning system (GPS)	Surveyed georeferenced data		Provides positioning and location data
Acoustic Doppler current profilers	Data of the direction and velocity of the current		Measures current of the ocean and the level of water
Sediment corers	Samples of sediment		Collection of the samples of the sea floor sediment

Habitat can be shaped primarily by physical processes and geology (geophysical) or by formation caused by living organism (biogenic).

2.4 The economic, social, and environmental benefit

Oceanography includes physical and marine bio-geochemistry and covers about 70% of the surface of the earth, which support the continuous life existence on the planet earth. It serves as source of food, means of transportation, recreation, source of energy, and minerals (Table 5.2). Of great importance also is the ocean to the weather and climatic condition of the earth surface. Some countries of the world depend on marine resources such as fishes to sustain their economy (Okewu et al., 2024). The pelagic habitat gives support to fishes with great commercial importance and also helps in maintaining the ecosystem functions (photosynthesis from phytoplankton).

In 2020, according to BPS (2021), 2.8% gross domestic product of Indonesia was from fishes. A larger and important influence to livelihood, nutritional security, foods, and well-being of many families was from the oceans (Gibson et al., 2020). Its mangrove forest area is the largest worldwide with 18% of the world's total, marine wild-capture fish second largest producer (Tran et al., 2019) and supplies demand for global fishes with about 25% (BKPM, 2018). Indonesia has the only route that connects diverse tropics ocean basin, and its water also play a significant role in the climate and ocean system (Sprintall et al., 2014).

TABLE 5.2 Some countries across the continent with available marine resources.

Continent	Countries	Available marine resources
Asia	Indonesia	Coral reefs, fisheries, seaweed, oil, marine energy
	Philippines	Tuna, fisheries, pearls, marine energy
	Japan	Fish, invertebrates, seaweed and algae, marine energy
	China	Fish shrimp scallops, mussels, seaweed, oil
	India	Fish shrimp, oysters
	Thailand	Fish, invertebrates, seaweed and algae, marine energy
America	United State	Fish, invertebrates, oil, marine energy
	Canada	Fish, invertebrate, oil
	Mexico	Fish, invertebrates, seaweed and algae, marine energy
	Brazil	Fish, invertebrates, seaweed and algae, offshore oil, marine energy
	Chile	Fish, invertebrates, seaweed and algae
Europe	Norway	Fish, invertebrates, marine energy
	United Kingdom	Fish, invertebrates, oil, marine energy
	Spain	Fish, invertebrates, seaweed and algae
	France	Fish, invertebrates, seaweed and algae, marine energy
	Greece	Fish, invertebrates, seaweed and algae
	Denmark	Marine energy
	Netherlands	Marine energy
Africa	South Africa	Fish and invertebrates, marine energy
	Nigeria	Fish, invertebrates, seaweed and algae, oil
	Egypt	Fish, invertebrates, seaweed and algae, oil
	Morocco	Fish, invertebrates, seaweed, and algae
	Kenya	Fish, invertebrates, seaweed, and algae
	Libya	Oil
Australia	Australia	Fish, invertebrates, marine energy

Due to the presence of massive sulfide deposit rich in copper, gold, zinc, silver, and other metals at the seafloor, several attentions have been attracted to it (Hannington et al., 2010). Research has shown that hydrothermal activities on ridges could last longer and thereby leading to a great percentage of accumulation of sea floor sulfide mineralization, this approximates probably for 86% of the massive sulfide resources of the sea floor (Hannington et al., 2011).

As a result of the reduction in the on-land mineral resources, deposits of massive sulfide on the seafloor have the potential of becoming important for development, exploration, and mining as of those on land (Aransiola et al., 2024). Owing tom the difficulty involved in investigating the environment of the ocean and location of the massive seafloor sulfide deposit, it is therefore important to improve efficiency in prospecting by reduction of the exploration search space through mineral prospectivity mapping.

3. Application of remote sensing and geographical information system to marine environment

GIS and RS techniques have developed into sophisticated and indispensable tools for investigating and assessing marine environmental studies. They provide effective means of collecting, analyzing, and visualizing datasets over large areas, also, inaccessible areas where other techniques seem unattainable. RS technique can be classifies as one of the most reliable approach for data collection, particularly in the modern era where it looks impossible to obtain information immediately at real time owing to it complexity. Passive and active RS are the two broad categories into which RS systems can be classified. While most active RS systems (such as microwave systems) measure the reflected microwave signal from various objects on Earth at higher wavelengths when compared to passive systems. Passive RS systems record reflected electromagnetic signals in the visible, near-infrared (NIR), and shortwave infrared (SWIR) bands as well as emitted electromagnetic energy in the thermal infrared (TIR) bands (Amani et al., 2022). In the passive RS, it primarily records solar radiation reflected from the Earth's surface at visible wavelengths in the 400–700 nm, near infrared (NIR) 720–1300 nm, and shortwave infrared (SWIR) 1300–3000 nm portions of the electromagnetic spectrum. The main principle behind optical RS is that distinct objects at different spectral bands will reflect and absorb solar light in different ways. As a result, every object has a distinct spectral behavior, or "spectral reflectance signature," which makes it visible to identify features on the earth surface (Amani et al., 2020).

Active sensors are used in light detection and ranging (LIDAR), synthetic aperture radar (SAR), active radar (RS), and altimeters. These sensors often gather surface data in microwave domains, such as the Ku and C bands (altimetry). These radar-based technologies send microwave pulses to earthly features and capture the values in waveform echo. These waveforms can subsequently be used to detect topographic characteristics and other areas of interest (Abazu et al., 2018; Amani et al., 2022; Baba et al., 2023). LiDAR and satellite altimetry, as reported by LaRocque et al. (2020), are revolutionizing the use of active RS techniques. Particularly in the fields of mapping and other spatial analyses, these technologies make it possible to gather and comprehend subsurface potential and underground surface data in a thorough manner.

GIS are widely used in business, communications, healthcare, and almost every other aspect of life. GIS is now more valuable and dependable in all contexts due to its technology breakthroughs over time. The use of GIS data is growing as businesses realize the value of the information that GIS can offer. According to Srivas and Khot (2018), GIS is a tool for gathering, storing, verifying, and displaying environmental, geographic, and demographic data. This data can be used across range of industries to make well-informed decisions about their operations. GIS and RS technology combined will create a comprehensive tool for study and a problem-solving strategy directly related to the marine environment.

3.1 Ocean monitoring

When it comes to tracking ocean variables like sea surface temperature (SST), turbidity concentration, ocean color, and sea surface height (SSH), RS, and GIS are essential. Scientists can identify changes in marine habitats, thanks to real-time data on ocean conditions provided by modern RS satellites. However, GIS aids in the integration and analysis of these data, assisting in the tracking of pollution sources, sea level rise (SLR), and oceanic currents in addition to monitoring natural disasters such as hurricanes and tsunamis. For instance, sea surface height (SSH) data can be retrieved using the altimetry technique, which can be used to monitor the marine environment by modeling SLR as it affects the coastal ecosystem over time. GIS platforms allow the spatial analysis of the obtained data SSH to assess the impact level over time and recommend more effective mitigation strategies.

3.2 Bathymetric survey

Shipboard echo sounding has been the standard method used to chart bathymetry. While this technology can produce precise depth readings at specific locations or along transects, its limitations include high operational costs, inefficiency, and in applicability to shallow seas.

RS techniques, on the other hand, provide a more adaptable, successful, and economical way to map bathymetry over large areas (Saida et al., 2017). Bathymetric survey is use to estimate the topography map of the sea floor. Fig. 5.1 depicts typical optical satellite streaming pulse signal for ocean depth estimation.

To produce intricate maps of the seafloor, RS techniques like LiDAR and satellite-derived bathymetry are frequently integrated with GIS tools. The integration of high-resolution satellite imagery and LiDAR data with a GIS framework enables the creation of three-dimensional seafloor models, which are useful for predicting sediment transportation and ocean current behavior as well as facilitating safe navigation.

The depth estimation's accuracy depends on a few different variables. Starting with the data collection phase, the image dataset's resolution and the model used to process the data and also, the model used in processing in GIS platform.

3.3 Sea floor habitat

Seafloor habitats, such as coral reefs, seagrass beds, and mangrove ecosystems, can be mapped with the use of RS data collecting methods, high-resolution image data (hyperspectral and multispectral imaging), and GIS tools. GIS spatial analytic platform, acoustic tools like sonar and video surveillance offer full information on the kind, traits, distribution, and condition of these sea floor ecosystems. It provides adequate information about the structure and makeup of the reef. It also allows for the monitoring of the biophysical parameters of the seas and oceans where the reefs are found and facilitates the detection of changes in these parameters over time. RS is a highly useful tool for coral reef monitoring.



FIGURE 5.1 Optical remote sensing, light detection and ranging (LIDAR) and unmanned aerial vehicle (UAV) equipment use for depth data acquisition beneath the earth surface.

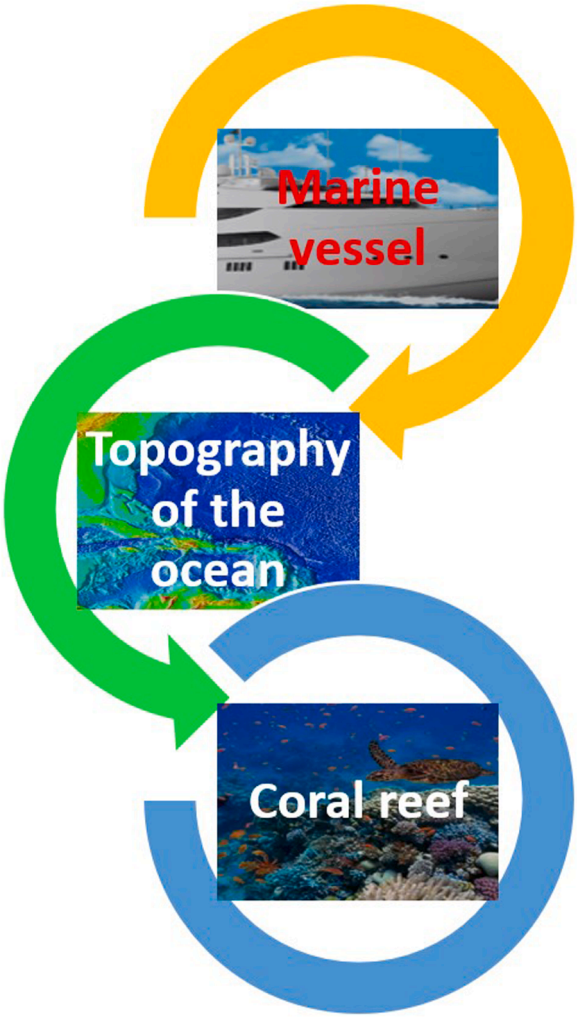

FIGURE 5.2 The use of remote sensing technique and onboard vessel in determining seafloor topography and coral reef and seagrass mapping using high resolution satellite data.

Along with other environmental data, this RS derived data are integrated into a GIS. In order to enable integrated coastal zone management (ICZM), the GIS is utilized to create an inventory of all available data as well as a tool for spatial analysis of that data (Goossens & Ghabour, 2005). Fig. 5.2 shows remotely sensed approach of streaming information about seafloor ecosystem.

Using sonar and high-resolution satellite image data in a GIS framework to assess coral reef area and damage as a result of climate change or human activity, protected marine areas are managed in part using these maps.

3.4 Fisheries management

RS and GIS are valuable for managing fisheries by tracking fish populations, monitoring their migration patterns, and assessing the health of aquatic ecosystems. RS technique can detect changes in water temperature, salinity, and phytoplankton concentrations and by extension the health condition of fish, which affect fish distribution and breeding cycles. According to Meaden and Corocci (2009), the problems facing fisheries and fish production in the world can best be viewed as state of instability in the spatial domain. However, the capacity to provide outputs from fisheries activities at an optimum level is dependent upon the variable factors controlling this output to be imbalance state. This has greatly influenced the output of its production. The used of hyperspectral image resolution data have made this task more visible and achievable. Wide fisheries at depth of about 20 m beneath water surface can be monitored efficiently from remotely areas (Tim et al., 2014). The use of GIS tools has giving more flexibility to the analyses of it ecosystem. The combination of both techniques will richly impact the fisheries production and effectively manage it ecosystem.

3.5 Climate change impact assessment

Understanding how climate change influenced the oceans depends heavily on RS and GIS. The entire globe is really concerned about climate change. The RS approach can be used to offer reliable data for tracking the effects of climate change in a global scale. Compared to other methods of gathering data, this method offers excellent precision coverage across a wide region. Satellite data from RS can be used to track climate change scenarios such rising sea levels, anomalies in temperature, and precipitation patterns. The spatial modeling of climatic scenarios and the display of their effects on human communities, coastal zones, and marine biodiversity are made possible by GIS. For instance, Remote satellite data on SLR and SST can be analyzed within a GIS framework helps develop model for monitoring coastal inundation and also predict future impacts on coastal infrastructure, biodiversity loss, and fisheries.

Using GIS and remotely sensed approaches together creates a platform that is valuable for controlling, charting, and monitoring marine habitats. By providing methods for preserving marine ecosystems, managing resources responsibly, and addressing the effects of climate change, these tools help scientists and decision-makers better understand the intricate and dynamic characteristics of the ocean.

4. Future perspectives and emerging technology of remote sensing in the marine environment

The marine environment, covering over 70% of the Earth's surface, is vital for regulating climate, supporting biodiversity, and sustaining human livelihoods. However, the pressing challenges of climate change, flooding, and overexploitation of marine resources require more accurate, timely, and comprehensive monitoring approach. RS technology has become a pivot in oceanographic research, where acquiring data about the Earth's surface and atmosphere can be achieve with high accuracy. Satellite-based sensors have advanced significantly over time, evolving from basic radiometers to sophisticated multispectral, hyperspectral, and radar sensors. Recently, emerging technologies such as artificial intelligence (AI), machine learning (ML) algorithm, and big data analytics are transforming the field, providing unprecedented and comprehensive capabilities for monitoring the marine environment.

4.1 Advances in remote sensing technologies

4.1.1 Synthetic aperture radar

SAR is another powerful technique in the active RS. SAR operates in the microwave spectrum, making it capable of collecting data regardless of the atmospheric condition of the study area. This is particularly important for marine applications, where cloud coverage is high, and monitoring must be continuous. SAR has proven highly effective in monitoring oil spills, sea level rise, and the dynamics characteristics of coastal zones. The European Space Agency's Sentinel-1 mission, equipped with SAR, is an example of the increasing reliance on radar data for marine applications. Fig. 5.3 depicts SAR satellite navigating at it orbit.

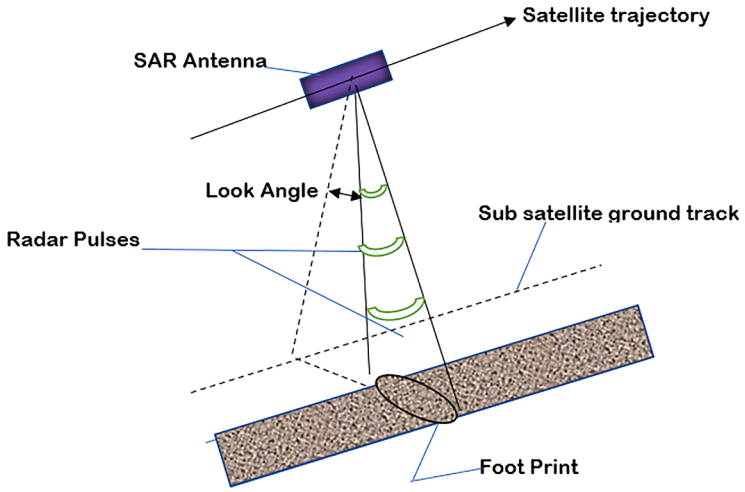

FIGURE 5.3 SAR satellite as it navigate in orbit, radar sends pulses signal to the target. The reflected signals returns to the radar where it is recorded as a function of time, range and, in the azimuth direction.

SAR's future advancements include higher-resolution imaging and polarimetric technology for enhanced surface feature capture. This technology could lead to better tracking of illegal anthropogenic activities such as fishing, mining, and more accurate monitoring of flooding activities and improved assessments of coastal erosion, all of which are vital for marine management and policy making.

4.1.2 High revolution image dataset

Hyperspectral imaging data are among the most advanced technological developments in RS. Unlike the conventional multispectral sensors that can only identify materials and processes with a limited level of detail since they only record data in a few wide spectral bands. Contrarily, hyperspectral sensors record information over hundreds of continuous spectral bands, enabling fine-scale distinction between various ocean characteristics with high level of clarity. Hyperspectral RS can be used to monitor coral reef and fish's health with high reliable result and also, detect changes in water quality and its characteristics in marine applications (Behrenfeld et al., 2020).

Additionally, oil spills and other contaminants can be detected with hyperspectral imaging, which provides vital information for environmental management. The high spectral resolution properties make it possible to monitor the biochemical characteristics of marine organisms, which could revolutionize the study of marine ecosystem health.

4.1.2.1 Miniaturized nanosatellite constellations

One of the most exciting developments in RS technology is the rise of small satellite constellations, particularly CubeSat. CubeSats are miniature satellites, typically less than 10 kg in weight that can be deployed in large numbers to provide frequent, high-resolution coverage of the Earth's surface. These satellites offer several advantages for marine RS, including lower costs of production, faster and less deployment times, and the ability to cover areas that are difficult to monitor with the conventional satellites (Sandau, 2010). One of the key advantages of CubeSats is their ability to provide high temporal resolution compared with the conventional satellites that require more time interval between successive satellite observations of the same location on earth. CubeSat constellations can offer near-continuous coverage, making them ideal for monitoring dynamic marine processes such as tides, ocean currents, and sea ice movements.

In the future, we can expect to see more specialized CubeSat missions focused on marine applications. These could include dedicated satellites for tracking illegal fishing, monitoring coral reef health, or assessing the impacts of ocean acidification. The combination of CubeSats with AI-driven analytics will enable near-real-time decision-making, offering unprecedented capabilities for managing the marine environment.

4.1.3 Enhancing data accuracy and resolution

Satellite-based RS offers a broad view of the marine environment; it often deficient in accuracy needed for certain applications. This is where in-situ sensors, deployed in the ocean itself, come into play. Autonomous underwater vehicles (AUVs), buoys, and drones equipped with sensors can provide high-resolution data on parameters such as temperature, salinity, and nutrient levels. By combining satellite data with in-situ measurements, researchers can achieve a more comprehensive and accurate understanding of marine processes.

4.2 Integration of artificial intelligence and machine learning

4.2.1 Automating data analysis

The vast amount of data generated by modern satellite missions requires advanced analytical tools for effective processing and interpretation. This is where AI and ML come into play. ML algorithms can process massive datasets, identifying patterns and anomalies that would be difficult or impossible for humans to detect (GoodFellow et al., 2016; Mitchell, 2017). In marine RS, ML is already being used to classify water quality, sea level, and track ocean wave pattern over time (Peng et al., 2018). The future perspectives in this area is the development of fully automated systems for real-time in monitoring marine environment. The algorithms are trained to automatically detect oil spills or sea level rise, triggering alerts to relevant authorities. This would drastically reduce response times and allow for more effective mitigation of environmental disasters. Additionally, AI can be used to enhance data simulation, combining information from multiple sources (e.g., satellites, drones, and in-situ sensors) to provide a more comprehensive situation of the marine environment and a better way of mitigation.

4.2.2 Predictive modeling and forecasting

Another exciting application of AI in marine RS is the development of predictive models. By analyzing historical satellite image to extract climate data, alongside real-time observations, ML algorithms can predict future ocean conditions. AI poses more advantage when compared to other parametric models for prediction. The training of the dataset gives the model an edge to comprehend the pattern of the features to be used. This is particularly useful for forecasting sea level rise, extreme weather events such as hurricanes, and changes in ocean currents that could impact global climate systems (Pauly & Christensen, 2020). These predictive models can be crucial for disaster preparedness and marine resource management, offering governments and organizations the ability to act proactively rather than reactively.

4.3 Big data and cloud computing in marine remote sensing

4.3.1 Data volume and storage challenges

Cloud computing platforms such as Google Earth Engine and Amazon Web Services (AWS) are increasingly being used to store, process, and analyze large-scale RS data. This is because it allows large data manipulations and facilitates flexible analyses. These platforms allow researchers and policymakers to access real-time data, perform complex analyses, and share results more efficiently. With the advent of high-resolution satellites and sensors, the volume of data being generated is growing geometrically. The conventional methods of storing and processing such are becoming obsolete and time consuming. The coverage of marine environment using satellite RS requires a large space for data collection and processing. Clouding computing approach has provided more improved ways of managing volume of data for the monitoring of marine environment.

4.3.2 Data sharing and collaboration

The future of marine RS lies in the collaboration between different players in marine industry. The stakeholders, include governments, research institutions, and private companies. Big data platforms allow for the sharing of satellite imagery and derived products across borders and disciplines. This data-shared will facilitate collaboration on a global scale, enabling coordinated efforts to tackle issues such as climate change, marine pollution, and oceanic ecosystem (Liu et al., 2019).

5. Conclusion

The future of RS in the marine environment is promising. With emerging technologies, it provides better and convenient ways on how to monitor and manage oceanic ecosystems. Hyperspectral imaging, SAR, AI and ML, big data, and CubeSats, are all set to play important roles in the next generation of marine RS systems. These technologies will enable more precise, real-time, and predictive monitoring of the marine environment, helping governments, organizations, and researchers tackle the pressing challenges of climate change related challenges and biodiversity. As these technologies continue to advance, they will provide the tools necessary for more sustainable and effective management of the world's oceans, ensuring their health for future generations.

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Section 2

Cosmos preservative power of marine lives

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Chapter 6

Marine bioresources for sustainable energy production and cleaner environment

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1. Introduction

The search for clean and sustainable energy sources has gotten more intense due to the world's growing energy demand and the urgent need to slow climate change. Marine bioresources offer a prospect in the search for sustainable energy sources because they comprise a diverse range of oceanic creatures. These resources include microorganisms, marine algae, and other aquatic biomass that can be used to produce bioenergy. By lowering the emission of greenhouse gases and reliance on fossil fuels, the use of marine bioresources not only provides a sustainable energy source but also aids in environmental protection (Maddela et al., 2024; Wijffels & Barbosa, 2019).

When compared to terrestrial biomass, marine bioresources are more plentiful and diverse. They escape the food versus fuel conundrum by avoiding land use competition with food crops (Demirbas & Demirbas, 2018). Furthermore, seasonal and climatic changes are less likely to occur in maritime habitats, guaranteeing a more consistent and steady supply of biomass (Gimba et al., 2024; Singh et al., 2011). The sustainability of marine bioresources, especially algae, is further enhanced by their rapid growth rates and their ability to be grown in a variety of water environments, including wastewater and saltwater (Chisti, 2007).

Seaweeds, or macro- and microalgae, are the most researched marine bioresources for energy production. Because microalgae have a high lipid content and can be used to make biodiesel, they are very promising (Aransiola, Oyewole, et al., 2024; Milledge & Heaven, 2013). Anaerobically digested macroalgae can yield biogas or fermented to make bioethanol. Given their quick rates of development and ability to do well in a variety of environmental settings, marine algae have great promise (Demirbas & Demirbas, 2018).

Through anaerobic digestion (AD), marine microorganisms like bacteria and archaea are essential to the creation of biogas. These microbes have the ability to decompose organic materials in marine biomass to produce biogas that is high in methane. This procedure promotes environmental sustainability by handling organic waste in addition to producing renewable energy (Chisti, 2007). It is also possible to convert aquatic biomass—which includes different kinds of marine plants and animals—into bioenergy. Waste from fish processing, for example, can be utilized to make biodiesel or biogas. Apart from being an environmentally friendly energy source, the utilization of such waste materials for energy production solves waste management problems and promotes environmental cleanliness (Singh et al., 2011).

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Recent technological advancements have significantly improved the feasibility and efficiency of converting marine bioresources into bioenergy. Photobioreactors, advanced cultivation systems for microalgae, optimize light and nutrient supply to enhance biomass yield (Wijffels & Barbosa, 2019). These systems are designed to maximize the surface area for light exposure and ensure optimal growth conditions, leading to higher biomass productivity. Improved designs for anaerobic digesters maximize biogas production from marine biomass. These digesters are engineered to enhance the breakdown of organic matter by anaerobic microorganisms, thereby increasing methane yield. The integration of advanced monitoring and control systems further enhances the efficiency and reliability of biogas production (Chisti, 2007). Biorefinery concepts, which involve the integrated processing of marine bioresources into multiple products, have also emerged as a promising approach (Fig. 6.1). Biorefineries can produce biofuels, biochemicals, and bioproducts, thereby improving economic viability and sustainability. This strategy is in line with the circular economy's tenets, where resources are utilized to their fullest potential, and waste generation is minimized (John et al., 2017).

Marine bioenergy has the potential to be a key component of the global shift toward sustainable energy systems by capitalizing on technology improvements and surmounting current obstacles. Sustainable development and environmental protection can be aided by the growth of marine bioenergy industries and technology, which can yield both economic and environmental advantages. This chapter provides an overview of the exploration, gains and limitations of marine bioresource in clean energy production.

2. Overview of marine bioresources

Over 70 percent of the Earth's surface consists of marine habitats, which are large and complex systems that are essential to the survival of life as we know it. These ecosystems are immensely varied from coastal regions and coral reefs to the open ocean and deep-sea depths. Beyond their biological value, maritime ecosystems are essential for controlling the world's temperature, cycling carbon, and supporting human economies. This thorough analysis delves into the physical attributes, biodiversity, ecological relevance, and human influences on maritime habitats.

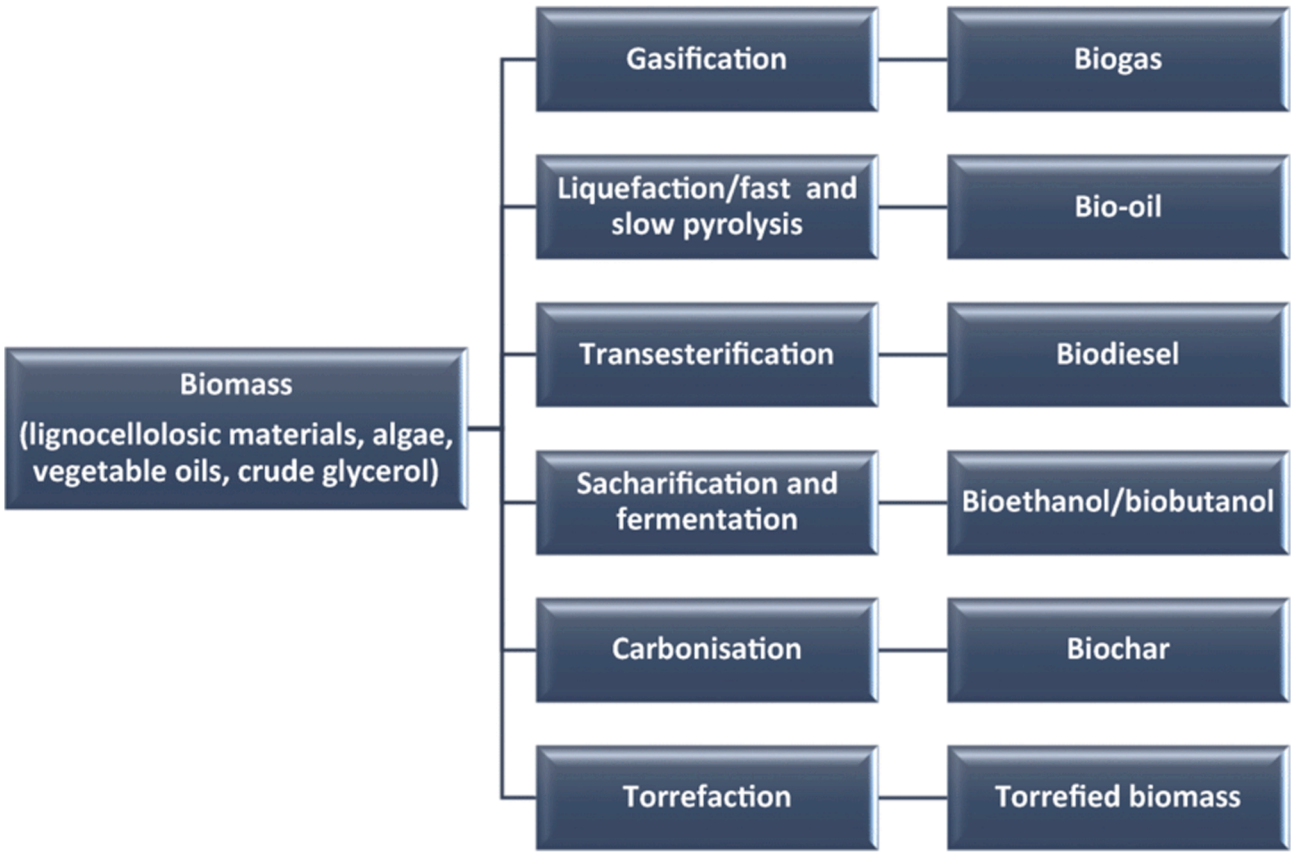

FIGURE 6.1 Energy extraction process from biomass resources. *Author.*

Several important physical properties that are dependent on depth and location, including salinity, temperature, availability of light, and pressure, characterize marine ecosystems. The four general zones that make up the ocean are the benthic zone, which contains the ocean bottom; the abyssal zone, which is the deepest section of the ocean; the pelagic zone, which includes the open ocean; and the intertidal zone, which is affected by tides. Different ecosystems and groups of species adapted to certain conditions can be found in each zone. For instance, deep-sea vents sustain distinct populations adapted to high pressure and darkness, while coral reefs flourish in warm, shallow seas with plenty of sunlight.

The vast array of life found in the ocean, from minuscule planktons to the largest creatures on the planet, like blue whales, is known as marine biodiversity. Marine mammals, fish, seabirds, mollusks, crustaceans, phytoplankton, and zooplankton, are among the many groups into which marine organisms are divided. Often called "the sea's rainforest," coral reefs are hotspots of biodiversity, supporting ‹1% of the ocean floor but an estimated 25% of all marine species (Hoegh-Guldberg et al., 2017). It has been discovered that the deep sea, which was previously believed to be lifeless, is home to a variety of ecosystems, including extremophiles that can endure extreme temperatures and bioluminescent organisms.

The health of Earth's ecological systems depends on marine environments. With the ability to absorb over 25% of the CO_2 created by human activity, the oceans constitute the planet's greatest carbon sink, adding to the slowing of climate change. The marine food chain's base, phytoplankton, is responsible for photosynthesis, which releases oxygen and stores carbon. In order to preserve water quality and the health of the ecosystem, activities like nitrogen fixation and the breakdown of organic matter are crucial to marine ecosystems' ability to support nutrient cycling. In addition to offering important ecosystem services like coastal protection, water filtration, and acting as nurseries for several marine species, coastal habitats including mangroves, seagrass beds, and salt marshes also provide other benefits (Barbier et al., 2017).

The maritime habitats are greatly impacted by human activity, which frequently results in major ecological problems. A serious danger that depletes fish stocks and upsets food webs is overfishing. Coral reefs and seafloor ecosystems can sustain significant harm from destructive fishing techniques including bottom trawling and dynamite use (Pauly et al., 2020). Marine life and ecosystems are seriously threatened by pollution, especially from plastics, oil spills, and agricultural runoff. Because microplastics are so common in the water, eating them can cause physical harm to marine life as well as introduce toxins into the food chain (Law & Thompson, 2014). The heat, acidification, and rising sea level originating from climate change brought on by human-caused CO_2 emissions have a negative impact on marine biodiversity and ecosystem health. Ocean acidification impairs the capacity of calcifying animals to form and preserve their shells and skeletons, while coral bleaching, a consequence of rising sea temperatures, has caused a widespread collapse of coral reefs (Hoegh-Guldberg et al., 2017).

The economy and welfare of humans depend on marine habitats as well. They supply a multitude of resources, such as minerals, food, energy, and medications. For millions of people worldwide, especially in coastal communities, aquaculture and fisheries are important sources of protein and a means of subsistence. Marine tourism, which encompasses pursuits like diving, snorkeling, and animal viewing, is a major source of income and raises public awareness of conservation issues. Ninety percent of world trade is carried out by sea, demonstrating the ocean's importance in international trade.

Sea ecosystems must be preserved for their ecological and economic benefits, which calls for conservation and sustainable management. The preservation of marine ecosystems and biodiversity is facilitated by establishing marine protected areas, or MPAs. MPAs impose limitations on specific activities, such as fishing and drilling, in order to save habitats and promote the recovery and well-being of marine populations. In 2020, over 7.5% of the world's seas will have been declared MPAs; nevertheless, the success of these areas varies greatly according on management and enforcement strategies. International collaboration and accords, like the United Nations Convention on the Law of the Sea and the Convention on Biological Diversity are essential for tackling transboundary marine problems and advancing worldwide marine conservation initiatives.

3. Technological transformation of marine bioresource to biofuel

Production of biofuel from microalgae is a promising, growing, and sustainable alternative to archetype fossil fuel, which is the central fuel of global warming. The global thirst for clean environment triggers the development and pacey growth of clean energy. The science of clean energy has been on trend for over a decade with a variety of technological application in different ways. The understanding and application of scientific and technological knowledge, both within and outside of industrial sectors, are fundamental sources of opportunities for technological advancements (Aransiola, Adeniyi, et al., 2024; Ediriweera & Wiewiora, 2021; Lederman & Lederman, 2020; Shin et al., 2023). Furthermore, the progress of fundamental science in biofuel generation from marine-sourced aquatic biomass necessitates the backing of cutting-edge technology (Shokravi et al., 2021; Vickram et al., 2023). Therefore, science and technology are mutually reliant. However, the global production of biofuels from diverse bioresources utilizing a range of emerging technologies

and biological processes is on the rise (Ambaye et al., 2021). The utilization of marine bioresources for the biofuel manufacture/generation has the potential to mitigate environmental burden (Sudhakar & Viswanaathan, 2019) and offer solutions to a multitude of environmental issues, such as the challenge, water contamination, and/or pollution (Gupta et al., 2022; Krishnani et al., 2023).

Of late, researchers have taken into consideration the need for technological advancement in biofuel production (third generation). The output of various studies has brought about three major technologies for efficient and high-volume biofuel production (Fig. 6.2) (Ambaye et al., 2021; Malode et al., 2021; Auta et al., 2024). Thermochemical, biochemical, and electrochemical methods are three major technologies for third-generation biofuel production from marine bioresources after pretreatment of aquatic biomass.

3.1 Pretreatment

Pretreatment processes are considered as the most energy-intensive step in the conversion of lignocellulose aquatic biomass (Wang, 2021). It involves modifying the structure of the material by breaking down the lignocellulosic matrix and removing the lignin component (Chandra & Madakka, 2019; Yuan et al., 2021). Numerous reports have addressed various pretreatment techniques for lignocellulosic aquatic biomass, including nontraditional methods, beating, physical, and chemical treatments to improve biofuel production (Cheah et al., 2020). Different pretreatment methods have been implemented on bioresources with varying degrees of success. Processes such as biological, chemical, mechanical, and thermal have been employed in the pretreatment of lignocellulosic materials. However, the complexity of these materials presents a challenge in selecting the most appropriate method and conditions for pretreatment. Thus, the optimal method and conditions for pretreatment are highly influenced by the type of lignocelluloses.

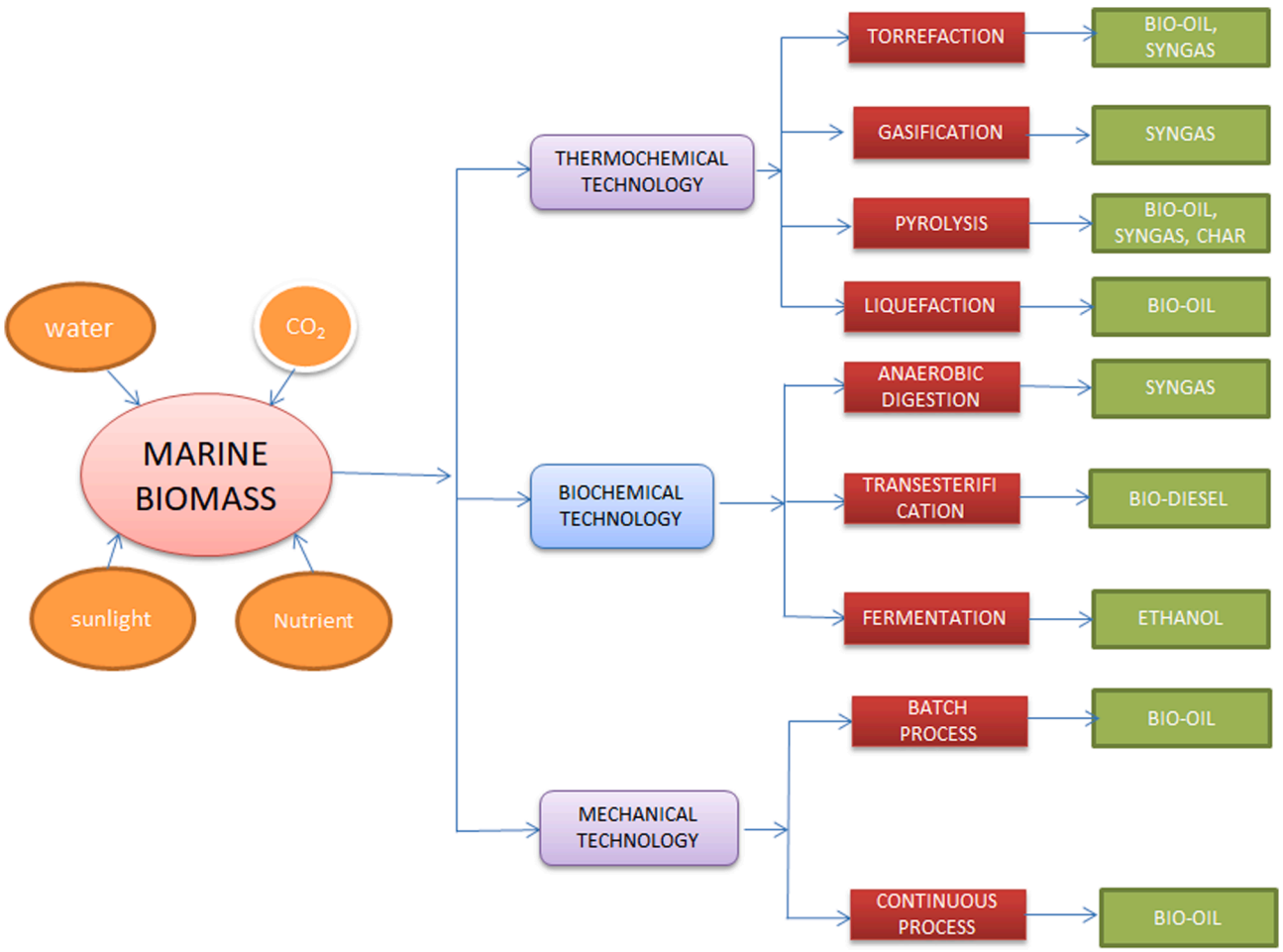

FIGURE 6.2 Pretreatment and technological method for marine biomass conversion. *Author.*

3.1.1 Mechanical pretreatment

Mechanical form of pretreatment is a widely employed approach that entails the utilization of knives, blades, as well as hammers to break down, pulverize, and mince aquatic biomass into minute particles before subjecting it to AD (Thompson et al., 2019). The mechanical pretreatment of lignocellulosic materials offers several advantages, including the particle size reduction, bulk density along with surface area increase, as well as a decrease in the amount of chemical waste produced (Jędrzejczyk et al., 2019). By increasing the ratio of reaction surface to volume, this method efficiently releases complex sugars for enzyme saccharifications. The result is an optimized bio-energy production process. Though there exist various mechanical methods for pretreatment, the most efficient ones are milling, extrusion, and microwave radiation.

Extrusion is a thermomechanical process used in various industries such as metal conformation, ceramics, rubber, and food processing. In order to generate high sharing forces, the use of one or more screws in a barrel as well as temperature control is employed. There exist two species of extruders: twin-screw and single-screw. Twin-screw type extruders can be further typed as corotating and counter-rotating (Dhaval et al., 2020). The development of extrusion machines dates back to the 19th century, as well as continuous refinement in design and functionality (Ek & Ganjyal, 2020; Prabha et al., 2021; Shuisheng & Kuangdi, 2023). Extrusion involves different processes, including alkaline extrusion, bio-extrusion, reactive extrusion, steam explosion and extrusion, and acid hydrolysis extrusion (Konan et al., 2022) of which are used in shortening the dry fermentation process for biofuel production to 10–20 days, increasing aquatic biomass utilization up to 65%–80% of dry weight. For bioethanol, sugar yields increase to $77 \pm 7\%$ of polysaccharides in the dry aquatic biomass (Ramachandra & Hebbale, 2020), with low concentrations of inhibitory products furfural and HMF, resulting in higher ethanol yields (Verma & Shastri, 2017). However, the extrusion performance is influenced by variables like the screw profile, screw speed, and extrusion temperature (Chandrahas et al., 2022).

Researchers are increasingly interested in using microwave radiation as an alternative to traditional heating methods. Microwave pretreatment involves using short electromagnetic waves to quickly heat aquatic biomass, causing water to boil and creating pressure that breaks hydrogen bonds within cells. Hoang et al. (2021) discussed that the amalgamation of microwave radiation as well as physicochemical methods for pretreatment of aquatic biomass in bioenergy synthesis has shown economic and environmental benefits. The study focused on the effects of this (microwave radiation and physicochemical) process of pretreatment on lignocellulosic structure as well as the achieved components ratio. Factors such as temperature, radiation time, components off initial feedstock, power of the microwave, and catalyst loading were found to have substantial impact on the pretreatment process. Also, microwaves were used to pretreat wet microalgal aquatic biomass by Rana and Prajapati (2021) in order to maximize the recovery of biofuel precursors. A response surface methodology was employed to evaluate the optimal conditions for pretreatment, which were found to be 5 min of irradiation time of microwave, 700 W of output power, as well as 2 g/L concentration of microalgal aquatic biomass. These conditions resulted in an increase of about 55.32% in lipid extraction relative to aquatic biomass that are untreated. The study also highlighted the significance of water as a green solvent for pretreatment of aquatic biomass under the process known as microwave irradiation, providing an environmentally friendly and economical method for pretreating wet microalgal aquatic biomass. Cogent benefit of employing mechanical form of pretreatment is the absence of chemicals needed during the processing stage, leading to decreased quantity of waste produced after postprocessing.

3.1.2 Chemical pretreatment

The utilization of chemical methods to alter the difficult structures of lignocellulose materials is referred to as chemical pretreatment. This process employs alkalines, organic solvent treatment, ionic liquids, acids, or oxidizing agents as the primary methods. The decomposition mechanisms of aquatic biomass may vary depending on the substances (chemical) employed during the process of treatment. The effectiveness of chemical pretreatment method has been evaluated by many researchers. A chemical pretreatment method was carried out on biomass samples by Pawłowska et al. (2023) in which 0.05 M solutions of NaOH and H_2SO_4 as well as distilled water were employed in soaking the samples for about 20 hours in a thermostated chamber (50°C) as well as room temperature (22°C). Analysis was done on the variations in pH, phenols, dissolved chemical oxygen demand (COD), electrolytic conductivity, and the content of volatile fatty acids (VFAs). The high efficiency of the methods, pretreatment, was determined by analyzing the concentration of COD dissolved.

A new additive called dicyandiamide (DICY) was proffered by Wu et al. (2024) to assist in the removal of lignin during alkali pretreatment of biomass (lignocellulose). Experiments showed that using DICY with KOH resulted in 15% higher lignin removal and increased enzymatic efficiency to 97% at a lower temperature compared to traditional alkali pretreatment. DICY dissolves lignin and helps alkali remove it by reducing resistance to diffusion as well as blocking the formation of "pseudo-lignin." DICY is an environmentally friendly additive that improves efficiency of enzymatic hydrolysis and removal of lignin, outperforming urea. Additionally, the waste liquid from DICY and KOH pretreatment can

be used to make agricultural fertilizers. Overall, DICY is a modern energy-saving option for lignocellulose alkali (chemical) pretreatment.

3.1.3 Biological pretreatment

The employment of microorganisms, specifically bacteria and fungi, which generate enzymes that can decompose the intricate composition of marine biomass, is a promising technique known as biological pretreatment (Kango et al., 2019; Álvarez & Ardisana, 2021). This method exhibits potential for the treatment of marine biomass to render it more suitable for the production of biofuel or other industrial applications (Vaishnavi et al., 2020). Varieties of marine biomass are available for biological pretreatment, comprising seaweed, microalgae, and marine plants. The microorganisms chosen for the next phase will be influenced by the type of aquatic biomass utilized. Most commonly employed microorganisms include: Fungi; *Trichoderma reesei*, *Phanerochaete chrysosporium*, *Aspergillus niger*, Bacteria; *Bacillus species*; and *Clostridium species*.

The marine *aquatic biomass* is made to undergo solid fermentation stage, while the microorganisms employed are made to grow on it. As the fermentation process proceeds, the microbes secretes enzymes that breakdown the aquatic biomass components (lignin or hemicellulose). Sulfahri et al. (2020) carried out biological pretreatment on marine biomass for bioethanol production, using algae. The study reveals that the application of fungal pretreatment before enzyme hydrolysis resulted in a 2.3-fold increment in yield of sugar compared to untreated algae. Furthermore, supplementing nutrients with the retrieved fungal aquatic biomass enhanced ethanol yields by approximately 38.23%. These findings indicate that incorporating fungi for supplementation of nutrient as well as pretreatment could significantly augment the economic feasibility of producing third-generation biofuels.

It was observed that microalgal biomass pretreatment by bacteria enhances liquefaction of about 18% and efficiently increases the macromolecular release (Sankaran et al., 2020). Biological methods of pretreatment have more advantages such as selective degradation, mild operating conditions, and mild chemical involvement (low environmental impact) over other form of biomass pretreatment. However, slow process, careful optimization, and biomass variability are some of the deficiencies associated with this method.

3.2 Thermochemical technology

The thermochemical form of converting biomass to biofuel encompasses a range of techniques that rely on thermal decomposition as the principal process. These methods can be divided into four types: torrefaction, gasification, liquefaction, and pyrolysis.

3.2.1 Torrefaction of biomass

The word "torrefaction" has its root from the French word "torrefier," which translates to the mechanism of roasting coffee beans. It is often used to describe thermal pretreatment, mild pyrolysis, or roasting (Zhang & Zhang, 2019). Solid form of biomass fuels has a lot of drawback that limit their industrial applications. Torrefaction has gained significant popularity over the past decade as it efficiently enhances the quality of fuel sourced from carbon-neutral solid materials. Torrefaction and similar techniques, say roasting, have been extensively utilized for the treatment of wood, production of coffee beans, and the enhancement of flavor and improvement of organoleptic properties of food.

However, torrefaction as a type of thermochemical technology for production of biofuels are classified into different types based on processes involved (Abdulyekeen et al., 2021; Olugbade & Ojo, 2020; Sarker et al., 2021). Wet and dry torrefaction are the main types of torrefactions with great efficiency and time maximization (Chen et al., 2021; Khempila et al., 2021). Wet torrefaction is a process of biomass upgrading, involves treating biomass in wet activator such as dilute acid as well as water. This process, which can be done without predrying, is corresponding to dilute acid type of pretreatment and can produce xylose and glucose for bioethanol production (Ajala et al., 2021). Wet torrefaction can achieve similar calorific value improvement as dry torrefaction but at lower temperatures. It also requires less energy for sampling but more energy for product harvesting compared to dry torrefaction (Cahyanti et al., 2020; Negi et al., 2020).

Nonoxidative (dry) torrefaction commonly uses nitrogen as a carrier gas to pretreat biomass, while oxidative torrefaction uses gases with oxygen (Brachi et al., 2019; Devaraja et al., 2022). Oxidative form of torrefaction has a higher rate of reaction but results in dwarfish solid yield as well as decreased heating value as regards to nonoxidative torrefaction. However, the higher heating value of torrefied biomass diminishes as oxygen concentration increases at 300°C (Jadsadajerm et al., 2024; Panahi et al., 2020; Riaz et al., 2022).

3.2.2 Gasification of biomass

In recent decades, interest in gasification of biomass has aggravated due to increasing thirst for sustainable energy and habitable clime. The process of gasification is widely recognized as one of the most effective methods of energy recoupment from biomass, as it produces syngas consisting primarily of CO, H_2, and CH_4 (Sapariya et al., 2021; Tezer et al., 2022). Biomass is a key renewable energy resource with significant benefits as regards of diversity, availability, and sustainability, making it a good source for energy supply in energy deficient areas (Amjith & Bavanish, 2022; Saleem, 2022; Siwal et al., 2021; Tareen et al., 2019). Numerous gasifiers based on agents and the gasifying process has been studied. The gas phase, commonly known as "syngas," can be employed for power or biofuel generation as a result of high heating power (Mishra & Upadhyay, 2021; Thomson et al., 2020). The solid state, known as "char," comprises the inert material found in the treated biomass as well as the organic unconverted fraction. This conversion involves a partial oxidation of the feedstock carbon and is typically conducted in the presence of a gasifying carrier, such as steam, air, carbon dioxide, or oxygen. Biomass gasification is regarded as an effective way to improve the use of biomass for the production of energy, facilitating widespread utilization of this valuable resource (Devi et al., 2020; Hameed et al., 2021; Nguyen et al., 2024). The three stages involved during the process of the gasification are: exothermic stage (oxidation), endothermic stage (drying, pyrolysis, as well as reduction), and tar decomposition.

The oxidation of a portion of the biomass is essential to produce the necessary thermal energy needed for the endothermic form of processes and to maintain the operational temperature at the desired level (Caballero et al., 2022; Siwal et al., 2021). This oxidation occurs under oxygen-deficient conditions with regards to the stoichiometric ratio, in order to selectively oxidize only a percentage of the fuel. The drying process entails the elimination of moisture from the feedstock through evaporation. The heat needed at this point is proportional to the feedstock moisture content and is typically obtained from other stages of the process (Gao et al., 2020; Kargbo et al., 2021). Drying is regarded as incomplete until biomass temperature reaches 150°C

3.2.3 Pyrolysis

The pyrolysis phase deals with the thermochemical decomposition of the matrix carbonaceous materials. In essence, it entails the breaking of chemical bonds through cracking, which result in molecule formation with a reduced molecular weight. Pyrolysis can yield various fractions, including a liquid/condensed fraction, solid fraction, and a gaseous fraction. The reduction process encompasses all the byproducts generated in the previous stages of pyrolysis and oxidation (Lopes & Astruc, 2021; Mishra et al., 2021; Yogalakshmi et al., 2022). The gas mixture and the char undergo a reaction, which leads to the creation of the ultimate syngas.

3.2.4 Liquefaction

Hydrothermal liquefaction (HTL) is a highly versatile technology that enables biomass feedstocks that are renewable, particularly in their wet state, to be converted into biofuel (biocrude oil) through a compact plant (Adeoye et al., 2023; Shahbeik et al., 2024). The direct processing of wet biomass by the HTL process results in significant energy savings, as it shut out the need for the processes like dehydrating or drying. In fact, processing of biomass that has approximate moisture content of $\geq$30% using hypercritical hydrothermal technology requires less energy than the conventional drying process (Prestigiacomo et al., 2022; Yang et al., 2020). With or without the assistance of enzymes or a catalyst, this process has an advantage over other thermochemical conversion forms in that it can convert wet biomasses straight into liquid biocrude or solid biocoal under less severe pressure–temperature conditions. The thermochemical reaction occurs on wet biomass in water at temperatures and process pressures that are close to critical, which are between 10 and 25 MPa ($<$2 MPa: HTC) and 280–370°C, respectively (Aragón-Briceño et al., 2021; Shafizadeh & Danesh, 2022). The effectiveness of HTL conversion of microalgae is dependent on a number of factors, including as temperature, feedstock content, and residence duration. HTL can be utilized to convert the microalgae's lipid fraction as well as its other organic components, like proteins and carbohydrates, unlike the algae-to-biodiesel pathway, which depends solely on the microalgae strain and lipid concentration (Khan et al., 2023; Saad et al., 2019).

3.3 Biochemical technology

Three different techniques can be used to convert microalgae biomass into biofuel: (i) biogas production and AD, (ii) photobiological H_2 or biohydrogen production, as well as (iii) bioethanol production. It is well-established that the fermentation process, which involves the transformation of biomass into biofuel in the presence of enzymes or microorganisms, is a crucial component of the biochemical transformation/conversion approach (Atiku et al., 2023). The

process of biochemical transformation/conversion is typically well suited for organic wastes with high-moisture content of >50% moisture and could be a suitable option for the conversion of wet algal type biomass.

3.3.1 Anaerobic digestion and biogas production

A crucial form of biochemical conversion is AD which is used for biomass with approximately high moisture content. The process helps in conversion of biomass organic matter into biogas and/or methane, ammonia (NH_3), carbon dioxide, with minute quantity of some inconsequential gases like hydrogen sulfide (Mutegoa & Sahini, 2023). The digestive process is a multistage mechanism that involves the sequential stages of hydrolysis, methanogenesis, and fermentation (acidogenesis and acetogenesis) (Fig. 6.3). *Hydrolysis* is a form of reaction/process that breaks down insoluble organic matter into simple monomers through the action of hydrolytic microorganisms. During this stage, lipids are changed into fatty acids, proteins into amino acids, carbohydrates into monomeric sugars, and starch into glucose. The subsequent stage, *acidogenesis*, involves the conversion of these acids and simple sugars into alcohols and VFAs by a complex consortium of bacteria, including bifidobacteria, bacteriocides, streptococci, clostridia, and enterobacteriaceae. These are the fastest steps in the salient AD process. In the *acetogenesis* stage, the VFAs are further converted into acetate, hydrogen, and carbon dioxide by acetogenic bacteria.

Finally, the *methanogenesis* stage involves converting/transforming acetate and hydrogen into carbon dioxide and methane by methanogenic bacteria. The maintenance of a stable consortium of these microbial populations is requisite to guarantee the stabilization of the AD process plus the enhancement of biogas production efficiency (Liu et al., 2021). The energy composition of the obtained digestion gas is reported to be approximately 20%–40% of feedstock lower heating

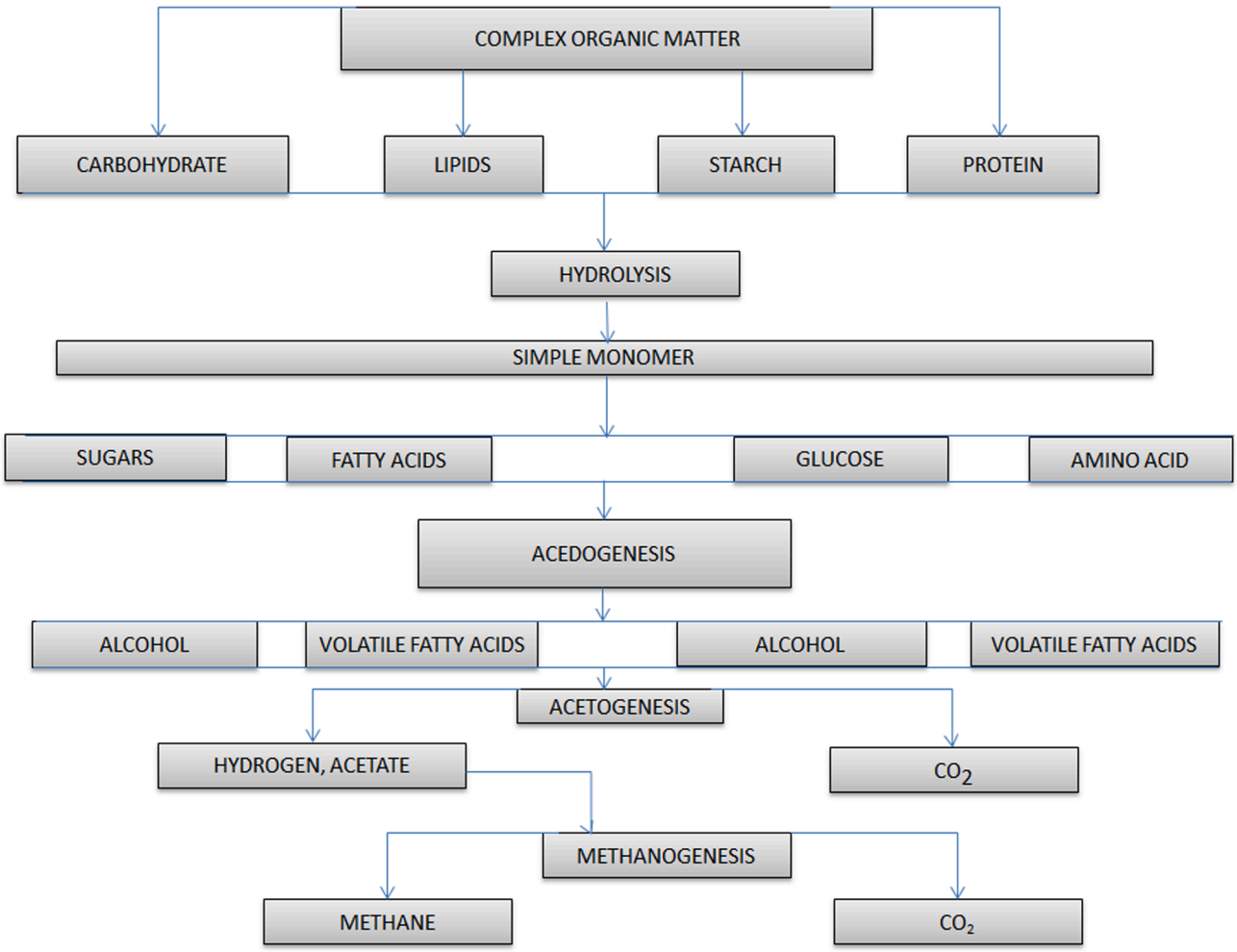

FIGURE 6.3 Biogas production and anaerobic digestion. *Author.*

value. Recent research has shown that transformation of biomass into methane (CH_4) can presumably recompense for the required energy of the unit where lipid is being extracted and result in a bio-waste (nutrient-rich) as a by-product (Yii et al., 2022).

The technical feasibility of marine microalgae, such as *Macrocystis pyrifera* and *Durvillaea antarctica*, as potential sources of biomass and renewable energy was investigated through laboratory-scale experiments. Using a two-phase digestion system, the study concentrated on the AD of *D. antarctica*, *M. pyrifera*, and their blend with 1:1 (wt/wt). An anaerobic batch reactor plus an upflow anaerobic filter made up this system. A substantial amount of the biogas, almost 70% of the total, was produced in the upper anaerobic filter, according to the data analysis.

Algal biomass is basically species-dependent, with lipid content ranging from 7% to 23%, protein content from 6% to 52%, and carbohydrate content between 5% and 23% (Di Lena et al., 2019; El-Sheekh et al., 2020). Methane production yield increased with a higher lipid content in the cells, rather than with higher carbohydrate or protein levels. Conversely, algae biomass that has high protein content (approximately 60%) undergoes AD, resulting in the release of a vital amount of ammonia (Parakh et al., 2023).

A lot of operating factors influences the AD method of producing biogas. These factors primarily include hydraulic retention time (HRT), pH, temperature, and organic loading rate (OLR). Additionally, other factors that affect the production of gas include volume of tank, type of feedstock, feeding pattern, and ratio of carbon-to-nitrogen (C/N) (Tg et al., 2022, p. 223–233). The HRT, can be defined as the average time the feedstock remains in the digester, is another essential factor that determines the level of organic matter degradation and proceeding biogas yield. The OLR, which represents the quantity of organic matter initiated into the system per unit of time, also significantly influences the biogas production process. The pH of the AD system must be upheld within an optimal range to certify the potent functioning of the methanogenic microorganisms (Wu et al., 2019).

Furthermore, the tank volume, the type of feedstock used, the feeding pattern (e.g., continuous or batch), and ratio of carbon-to-nitrogen in the feedstock has the affinity all impact the overall biogas generation in the AD process. Anaerobic digestion process temperature is important in the activity and growth of the microbial community responsible for biogas production (Sudiartha et al., 2024; Chen et al., 2024).

3.3.2 Transesterification

Biodiesel production through transesterification is a process that incorporates the reaction of lipids sourced from microalgae (triglycerides/FFA) with monoalcohols during catalysis (Bordoloi et al., 2022; Hossain, 2019). These reactions are equilibrium-based that requires a higher percentage/amount of alcohol/bio-oil ratio to increase reaction rate by the shift of equilibrium to the right hand side. Based on type of catalyst used, transesterification reaction is categorized into three types which are; acid-catalyzed, base-catalyzed, and enzyme-catalyzed reactions (Kalita et al., 2022; Maleki et al., 2022). Homogeneous transesterification and heterogeneous transesterification are two main subdivisions of each of the three types of transesterification. Due to low cost of catalyst, homogenous transesterification form of reaction is the most preferred. In contrary to this, in the heterogeneous transesterification form of reactions, the catalyst separation and revitalization is much easier, making it more palatable for extensive applications (Belousov et al., 2021).

The most common method of biodiesel production from biomass is transesterification of lipids through basic catalysts (heterogeneous and homogeneous) (Wang et al., 2023). These form reactions are the hastiest when compared to the enzyme- and acid-catalyzed type of transesterification reactions. The mechanism of reaction involved in base or acid-catalyzed form of transesterification is a reversible form of reaction. More often, a FAME (fatty acid methyl esters) 95%–99% yield is plausible through acid induced transesterification reaction. Although a comparatively lower oil-to-alcohol ratio of (1:9 to 1:166) is required to propel equilibrium to the product side (Ahmed & Huddersman, 2022; Makareviciene et al., 2020). The cosmic amount of mono-alcohol makes the fractionalization process more knotty, while a minute quantity of alcohol in the feed needs an increased reaction temperature to obtain the maximum product yield. Since it is advisable to employ the least temperature of reaction possible for lipids transesterification, a lower molar ratio of oil-to-alcohol is usually used to prevent material deterioration and dampen the selectivity to undesirable product (Chozhavendhan et al., 2020).

The transformation of microbial oil through lipases to biodiesel by transesterification is a modern process that is both environmental and economically friendly. Also, this process is proficient in alleviating the potential knots related to basic and/or acidic transesterification. The promising benefits of enzyme-supported transesterification reactions include no saponification, formation of high-purity biodiesel, low cost of operation, and stress-free recycling and separation (Hossain et al., 2020; Srivastava & Srivastava, 2021). Therefore, the production of biodiesel through enzyme induced/catalyzed transesterification is a sustainable option for our ecosystem and can potentially substitute for petro-diesel. Lipases are

usually involved in both heterogeneous (immobilized form) and homogeneous (free form) form of transesterification (Mandari & Devarai, 2021).

3.3.3 Fermentation

Fermentation enables transformation of biomass into viable bio-derived products, like biogas, bio-ethanol, and bio-hydrogen, through the utilization of microorganisms (Bhatia et al., 2021; Chavan et al., 2022). During this process, the microorganisms typically release a specific enzyme (E), which is also a biocatalyst to facilitate the release of the desired bio-product. Consequently, the understanding of fermentation of active parameters, including microorganism cultivation kinetics and bio-based formation kinetics, is crucial in the design of process optimization, bioreactors, and scale-up operations. When selecting the appropriate marine biomass type, several criteria must be considered, including cost, accessibility, ease of usage, durability, the impact on the fruition of the process, including product dejection, and environmental issues, such as the food versus fuel debate.

Polysaccharides and oligosaccharides are commonly hydrolyzed to fermentable monosaccharides using enzymes and, in some cases, acid catalysts. *Saccharomyces cerevisiae*, commonly referred to as baker's yeast, is the predominant microorganism employed in the fermentation of ethanol (Kruschitz & Nidetzky, 2020; Saini et al., 2022). Baker's yeast inherently possesses the AD-vantage of secreting the enzyme that hydrolyzes sucrose, invertase. Another benefit of using baker's fungus includes rapid and straightforward growth, the capacity to effectively complete the conversion of a range of C_6 monosaccharides into ethanol and carbon dioxide, and its exceeding microbial protection. Consequently, fermentation of ethanol has been done by utilizing baker's fungus.

However, alternative microorganisms or genetically engineered strains of *S. cerevisiae* are being considered, as baker's fungus does not ferment certain essential polysaccharides and C_5 monosaccharides naturally (Favaro et al., 2019; Sodré et al., 2021), and its fermentation is limited to temperatures up to 50°C.

4. Challenges associated with biofuel production

The concept of biofuel production through various bioresources is a major potential means of meeting the global energy demand. Enriched compounds created by biological agents or by using live organisms, such as bacteria and microalgae, can be used to manufacture biofuels (Rodionova et al., 2017). Although algal biomass has recently been demonstrated to be a viable bioresource for the synthesis of various biofuels, plant biomass has long been considered the best source of biofuels (Rodionova et al., 2017). Numerous methods have been thoroughly studied and acknowledged for the manufacture of biofuels, including the use of microalgae or cyanobacteria. Microalgae offer several benefits when it comes to manufacturing biofuels, one of which is their higher productivities when compared to other bioresources. Amid these several advantages, there are still many limitations associated with the production. Some major challenges faced by the biofuel industry, reflecting the complex interplay between technological, environmental, economic, and societal factors are presented in Table 6.1.

4.1 Environmental challenges

Biofuel production presents several environmental challenges despite being a renewable energy source. Biofuel production often leads to deforestation and land conversion, especially in biodiverse regions. This process produces significant amounts of carbon dioxide and reduces biodiversity. The cultivation of marine bioresources for biofuel can disrupt local marine ecosystems. Large-scale algal and seaweed farming may interfere with natural habitats, affecting biodiversity and the functioning of marine ecosystems. For example, the physical structures used in farming can alter water flow and light penetration, which are crucial for native marine species (Merlo et al., 2021). Although marine bioresources do not compete with freshwater resources directly, they require clean, uncontaminated seawater, which can be a limiting factor. The process also involves managing salinity levels and ensuring that the water used does not introduce pollutants back into the marine environment. This can be particularly challenging in coastal areas where water quality varies (Chisti, 2016).

Marine bioresource cultivation often requires the addition of nutrients to boost productivity. If these nutrients are not properly controlled, they may cause eutrophication, a condition in which water bodies become excessively enriched with nutrients and minerals, which results in an excessive growth of algae and oxygen depletion. Dead zones may emerge from this, making it impossible for aquatic life to exist (Markou & Monlau, 2019). The production process of marine biofuels, including harvesting, drying, and processing, can lead to the emission of greenhouse gas. Additionally, if the biomass

TABLE 6.1 Some of the challenges associated with biofuel production.

Challenge	Description
Feedstock availability	Availability and competition with food crops for land and resources.
Land use and deforestation	Potential for deforestation and biodiversity loss due to land conversion
Water usage and quality	High water demands for irrigation and potential impacts on local water quality
Energy intensity	Energy required for planting, harvesting, processing, and transportation.
Economic viability	Cost-effectiveness compared to conventional fuels and market fluctuations.
Greenhouse gas emissions	Actual emissions reductions depend on lifecycle analysis and feedstock type.
Food versus fuel debate	Competition with food production, impacting food prices and security
Technological challenges	Efficiency of conversion processes, scale-up of production, and innovation
Land tenure and ownership	Land rights issues, especially in developing countries
Infrastructure compatibility	Compatibility with existing fuel distribution and storage infrastructure.
Policy and regulatory framework	Supportive policies, incentives, and regulations affecting biofuel markets
Public perception and acceptance	Social acceptance, environmental concerns, and perceptions of sustainability.

Author.

decomposition is not properly managed, it can release a potent greenhouse gas (methane). The lifecycle analysis of marine biofuels shows that while they can lower the emission carbon compared to fossil fuels, the overall effect is dependent on the efficiency of the production process (Wei et al., 2023).

4.2 Technological challenges

One of the significant technological hurdles in marine biofuel production is the efficient harvesting and dewatering of biomass. Algae, in particular, are suspended in water at low concentrations, making the extraction process energy-intensive and costly. Developing energy-efficient and cost-effective harvesting techniques, such as centrifugation, flocculation, and membrane filtration, remains a major challenge (Milledge & Harvey, 2016). Cultivating marine bioresources requires optimizing growth conditions, which can be complex and resource-intensive. Algae, for example, need specific light, temperature, and nutrient conditions to thrive. Achieving these conditions consistently on a large scale is difficult. Additionally, controlling contamination from other microorganisms poses a significant challenge (Daniotti & Re, 2021). Converting marine biomass into biofuels takes place in multiple steps, including drying, extraction of lipids or carbohydrates, and subsequent conversion processes such as transesterification for biodiesel or fermentation for bioethanol. Each of these steps requires significant energy input and optimization to improve yield and efficiency. For instance, the high water content of algae makes drying a particularly energy-demanding step (Osman et al., 2021).

Scaling up marine biofuel production from laboratory and pilot scales to commercial levels poses substantial challenges. Large-scale operations need to maintain optimal growth conditions and efficiency, which is technologically demanding. Infrastructure development for large-scale cultivation systems, such as offshore algal farms, involves high initial costs and sophisticated engineering solutions (Singh, 2024). Advances in genetic and metabolic engineering can potentially enhance the productivity and resilience of marine bioresources. However, the development of these technologies is still in progress. Modifying algae and seaweed to improve growth rates, lipid content, and stress tolerance involves complex genetic manipulations and extensive field testing to ensure stability and effectiveness (Khoo et al., 2023). Integrating marine biofuel production with existing marine and coastal systems, such as fisheries and wastewater treatment, offers potential benefits but requires sophisticated technological solutions. Creating integrated multitrophic aquaculture systems, where by-products from one process serve as inputs for another, demands precise control and management (Chisti, 2016).

5. Environment impact of clean energy

It has been established by various researchers that energy generated from fossil fuel sources have various negative environmental impact of global warming leading to climate change, which stems from increase in greenhouse gases in our

environment thereby resulting into various health hazards in the society. The quest for a safe environment necessitates the search for clean energy. The term clean energy is usually refers to as energy generated from non–fossil fuel sources. Recently, clean energy has become more popular as many nations, and economies look to lessen their need on highly polluting fossil fuels. In keeping with the promise of a sustainable "green" energy supply in the future, clean energy consumption can guarantee a favorable effect on economic development. Since emission greenhouse gas has a negative impact on global warming and must be optimized by lowering contributing variables, the idea of clean energy will aid in lowering overall carbon emissions (Masa et al., 2020). There is a short- and long-term correlation between clean energy and economic growth, suggesting a sound feedback hypothesis (Mohsin et al., 2021). According to the results, clean energy sources have a notable effect on reducing greenhouse gas emissions and helping to control them. Fig. 6.4 highlights the positive environmental impacts of utilizing marine bioresources for clean energy purposes. It emphasizes sustainability, biodiversity conservation, greenhouse gas reduction, improved water quality, and enhanced energy security. Each aspect contributes to a more comprehensive knowledge of how marine bioresources can be beneficial in the context of clean energy initiatives.

Through the process of CO_2 sequestration, the production of various biofuels from the biomass of microalgae contributes to the atmospheric CO_2 balance and maintains a clean and healthy environment. By producing sustainable and renewable biomass for biofuel production and lowering greenhouse gas emissions, microalgae biomass offers two advantages (Kumar et al., 2021). When biofuels are produced from biomass, the leftover byproducts can be employed in agriculture as manure or fertilizer (Jaiswal et al., 2021). Utilizing waste products primarily controls and minimizes careless landfilling and waste disposal methods.

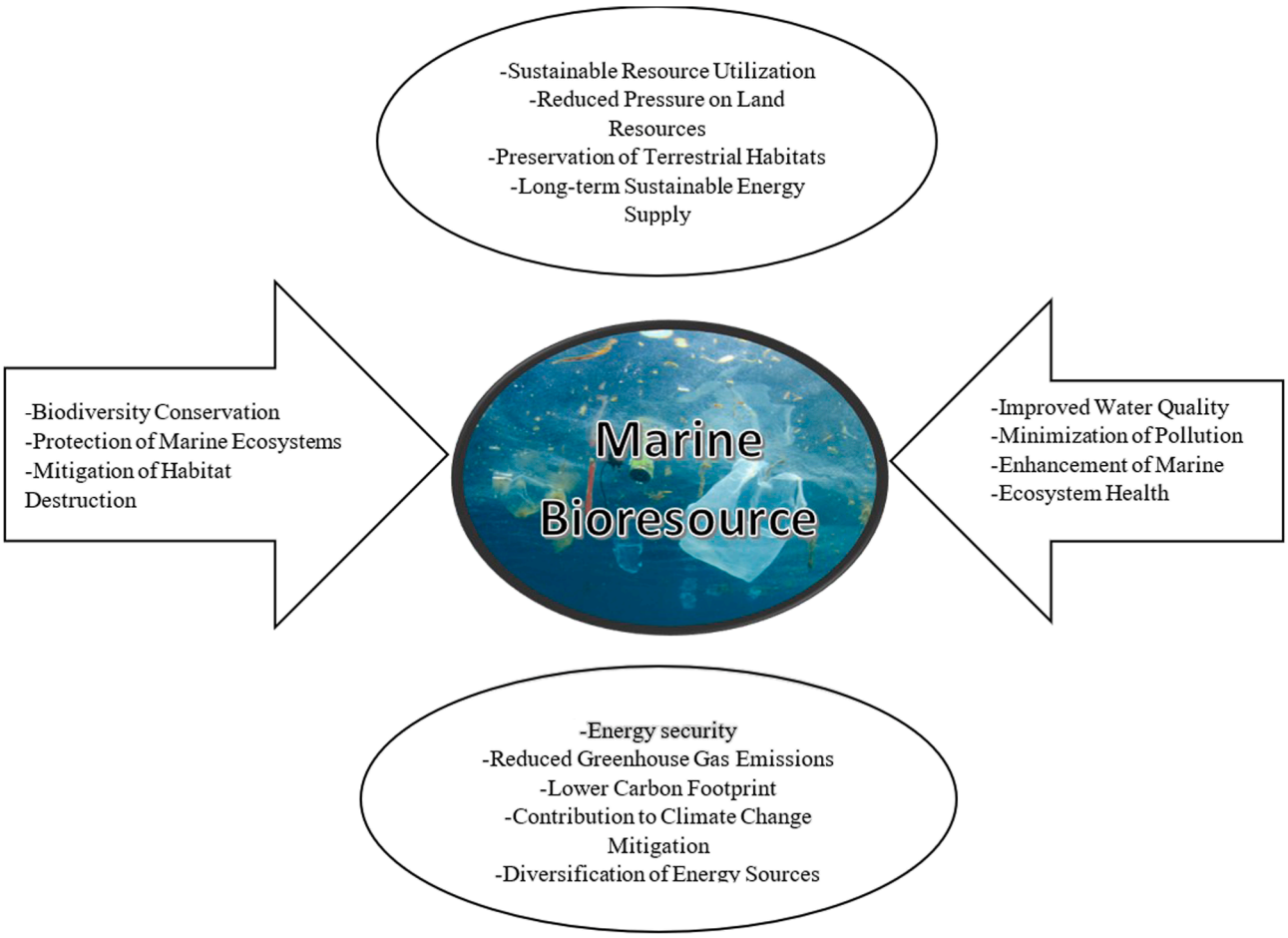

FIGURE 6.4 Positive environmental impacts of marine bioresources for clean energy purposes. *Author.*

5.1 Impact on zooplanktons and phytoplanktons

Marine bioresources hold promise as a renewable energy source; their cultivation and extraction methods can potentially affect marine ecosystems, including zooplankton and phytoplankton. The environmental implication of marine bioresource-based clean energy generation on zooplankton and phytoplankton populations can differ based on conditions such as cultivation methods, species selection, and location. Phytoplanktons are the primary producers in marine ecosystems and are important in global biogeochemical cycles and food webs (Sun et al., 2022). Algae are often considered as a potential precursor for biofuels due to minimal land use requirements and their high productivity. However, cultivating algae for the production of biofuel can have ecological consequences, including changes in nutrient levels, light penetration, and oxygen concentrations in marine ecosystems, which may indirectly impact zooplankton and phytoplankton populations (Makareviciene & Sendzikiene, 2022; Thevarajan et al., 2024).

Studies have shown that algal blooms, whether natural or induced by cultivation practices, can alter the composition and abundance of zooplankton communities (Glibert et al., 2010). Nutrient runoff from algal cultivation sites or processing facilities can introduce excess nutrients into marine ecosystems, potentially leading to eutrophication and harmful algal blooms that can impact phytoplankton communities (Zhou et al., 2022). Seaweed cultivation for bioenergy purposes is another emerging area of interest. While seaweed cultivation can provide habitat for some zooplankton and phytoplankton species and enhance local biodiversity, it can also lead to habitat modification and changes in nutrient dynamics that may influence zooplankton and phytoplankton populations (Duarte et al., 2022). Introducing nonnative seaweed species for cultivation purposes can also potentially disrupt native zooplankton and phytoplankton communities through competition or predation (Duarte et al., 2022; Jagtap & Meena, 2022, p. 493–501). Studies suggest the importance of conducting thorough environmental assessments and monitoring programs to evaluate and mitigate potential impacts on zooplankton, phytoplankton, and other organisms in the marine environment (Lomartire et al., 2021; Tazikeh et al., 2022).

5.2 Impact on terrestrial resources

The environmental effect of clean energy produced by marine bioresources on terrestrial resources is a multifaceted issue that involves various factors such as land use, water usage, nutrient cycling, and potential indirect effects on terrestrial ecosystems. While the focus of marine bioresource-based clean energy generation is primarily on marine environments, there can be indirect impacts on terrestrial resources. Although marine bioresource-based clean energy primarily operates in marine environments, there can be land-based infrastructure associated with the production, processing, and distribution of bioenergy products. Large-scale cultivation of marine bioresources such as algae or seaweed for bioenergy purposes may require land-based facilities for processing and refining biofuels, potentially impacting terrestrial ecosystems and land use patterns (Kamyab et al., 2023).

Some marine bioresource-based clean energy technologies may require significant amounts of water for cultivation, processing, or cooling purposes. Depending on the source and availability of water, large-scale water withdrawals for bioenergy production could potentially impact terrestrial water resources, including freshwater ecosystems, by altering flow regimes or depleting groundwater reserves (Bala et al., 2016). Cultivation of marine bioresources such as algae or seaweed for bioenergy purposes can involve the use of fertilizers or other nutrients to enhance productivity. Runoff or leaching of excess nutrients from cultivation sites into adjacent terrestrial environments can lead to nutrient pollution, eutrophication, and potentially impact soil and terrestrial ecosystems (Racine et al., 2021). Changes in marine ecosystems resulting from marine bioresource-based clean energy generation, such as alterations in nutrient dynamics or food web structure, can have indirect effects on terrestrial ecosystems. For example, shifts in marine biodiversity or productivity may influence migratory patterns of terrestrial species that rely on marine resources for food or habitat, leading to potential cascading effects on terrestrial ecosystems (Nater et al., 2021).

6. Conclusion, future prospects, and recommendations

The potential for marine bioresources to meet the world's energy needs and advance environmental sustainability is enormous. The ability of algae, seaweed, and other marine biomass to function as a clean, renewable alternative for conventional fossil fuels is demonstrated by their use in the production of biofuel, biogas, and hydrogen. The potential benefits of marine bioenergy in terms of lower greenhouse gas release and environmental sustainability make it a promising field for exploration, even though there are still many unanswered questions. Even though a lot has been accomplished, more developments in infrastructure, technology, and policy support are still required to fully utilize marine bioresources for the production of clean energy.

With a number of studies and technological advancement in the works, the use of marine bioresources in producing clean energy appears to have a bright future. Innovations in biotechnological like genetic engineering and strain optimization of algae could boost biomass yields and improve biofuel production efficiency. Enhancements in the methods of harvesting and processing could lower expenses and increase scalability. Furthermore, the combination of marine bioresources with other sources of renewable energy, like solar power and wind, can result in hybrid energy solutions that have an even smaller environmental impact. Marine bioresources are anticipated to be essential to reaching net-zero emissions targets, promoting energy security, and maintaining ocean health as global decarbonization efforts pick up steam.

Prioritizing research to fill knowledge gaps in areas like energy extraction efficiency, environmental impacts, and marine organism cultivation is recommended as it can help maximize the rich potential of marine bioresources for a clean environment. This entails maximizing the growth of algae and seaweed, enhancing the process conversion of biofuel, and investigating new marine organisms for potential energy uses. Also, in order to prevent overexploitation and ecological disruption, marine bioresources must be cultivated and extracted sustainably. To identify and reduce potential risks related to marine bioenergy projects, environmental impact assessments should be carried out. To further advance the field, a multidisciplinary approach involving marine scientists, energy experts, economists, and environmentalists is imperative. To speed up the development and commercialization of marine bioenergy, cooperation between governments, universities, businesses, and nongovernmental organizations should be promoted. It is important to think about developing and putting into effect laws and policies that encourage the sustainable harvesting of marine resources. Through the implementation of these suggested actions, society can fully utilize marine bioresources for the production of cleaner energy, thereby making a positive impact on a future that is more resilient and sustainable.

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Chapter 7

The marine antimicrobial agents in food preservation

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1. Introduction

The two primary goals of food preservation are ensuring microbiological safety and preserving food quality (Tibolla et al., 2019). According to Mahmud et al. (2021), food packaging is essential for maintaining food quality and ensuring microbiological safety. By facilitating the handling, transportation, and storage of a variety of food goods while shielding them from physical, chemical, and microbial damage, packaging extends shelf life and preserves quality (Youssef et al., 2019).

However, most polymeric materials used in food packaging are also known as plastic petroleum-based materials, and these materials' recycling, biodegradation, use, and biocompatibility are limited (Adrah et al., 2020). Because of the ban on plastic packaging, there is an enormous quantity of waste produced, which is generating major environmental pollution (air, sea, and soil) as well as animal mortality worldwide (Mahmud et al., 2021). According to Hahladakis et al. (2018), the extensive ocean contamination by plastics is also expected to pose a danger to aquatic life.

The plastic packaging sector is nonetheless booming due to its low manufacturing prices of plastic food packaging, its use as a global marketing tool, and its significant role in food safety (Adrah et al., 2020). In the course of searches for effective and environmentally friendly means of food preservation, marine antimicrobial agents were identified as a possible solution (Mahmud et al., 2021). These compounds have some characteristics that qualify them to be very efficient against foodborne diseases (Olatunde et al., 2020). It is derived from marine sponges, algae, and bacteria. Despite the fact that most of these bioactive compounds have not been discovered, they have the possibility of being used in food preservation and safety (Mahmud et al., 2021). These compounds possess unique properties that make them very effective against foodborne diseases (Olatunde et al., 2020). They are obtained from marine sponges, algae, and bacteria. Although majority of these bioactive compounds are yet undiscovered, having the potential for food preservation and safety (Bose et al., 2023).

2. The food industry and marine bioactive compounds

Many bioactive substances with distinct biological properties that can be used as functional food additives can be found in the marine environment (Villamil et al., 2017). Marine products consist of polysaccharides, chitin, chitosan, protein, essential and non-essential amino acids, vitamins, minerals, carotenoids and other bioactive compounds (Suleria et al., 2015).

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These bioactive substances can be present in all foods derived from marine creatures in varying quantities, and they can be incorporated at all stages of food production—processing, as well as storage (Villamil et al., 2017). The modern-day consumer is also much more conscious about how a proper diet can help prevent diseases. Thus, since they enhance the nutritional and monetary value of the food, biologically active components derived from sea produce demonstrate great potential to be the best ingredients to put into foods (Villamil et al., 2017).

In recent years, a variety of functional foods that come from marine sources have been introduced to the world market (Bose et al., 2023). Vitamins, probiotics, minerals, fiber, polysaccharides, antioxidants, carotenoids, and protein hydrolysates are examples of functional components that may be added to these diets (Bose et al., 2023).

Seaweeds aid in reducing cholesterol and blood pressure, fighting obesity, and neutralizing free radicals and they are used in meat, dairy, confectionery, bread, and pasta products (Bose et al., 2023). Marine-derived proteins like chitosan, alginate, and carrageenan are applicable in edible films and coatings which generate attention from researchers due to their accessibility, efficacy, and affordability (Abdelhedi et al., 2022).

3. The sources of marine antimicrobial agents

Marine antimicrobial agents are bioactive polymers that are extracted from marine organisms, marine, and algae and seaweed (Mahmud et al., 2021). Marine sources are increasingly being sought as emerging sources of novel biopolymers including proteins and polysaccharides (Jumaidin, 2023). The facts that these biopolymers are nontoxic, biodegradable, and biocompatibility have made them so popular for use in the formulation of food packaging materials (Jumaidin, 2023). Most sectors today rely heavily on the abundance of species in the aquatic environment (Cedeño Muñoz et al., 2024; Westlake et al., 2023).

3.1 Marine antimicrobial agents obtained from seaweed

Seaweed polysaccharides are becoming well-known due to their qualities and abundant renewable sources. A variety of seaweeds may be found in the ocean (Yang et al., 2021). The variety of advantageous polysaccharides that are generated by marine macroalgae has potential uses that serve as a cornerstone of the emerging blue economy (Bose et al., 2023). Marine biopolymers derived from seaweed are found in phaeophytes (brown algae), rhodophytes (red algae), and chlorophytes, that is green algae (Cedeño Muñoz et al., 2024; Yang et al., 2021).

Macroalgae is increasingly being seen as a possible source of bioactive compounds as a result of increased knowledge of the functional components of food (Bose et al., 2023). The mechanical, thermal, and physical properties of artificial polymer matrices have been improved by the use of seaweed as a filler in polymer composites. In summary, seaweed is a valuable renewable resource that may be utilized to make goods that are both ecologically friendly and biocompatible (Bukhari et al., 2023).

Agar is a complex carbohydrate extracted from red algae which is incorporated into its medium because it creates gel structure (Yang et al., 2021). In food industry, composites from polysaccharides of seaweed have been investigated in literature because of their availability and biocompatibility (Bose et al., 2023). Seaweed derivatives (agar, carrageenan, and alginate) have many uses, and they are mostly found their utility in food industry because they are easily available and biocompatible (Bose et al., 2023). The applications of seaweeds derivatives (agar, carrageenan, and alginate) are often used in the food industry.

Sulfated polysaccharides and algae-based polymers are relatively diversified polymers that possess various characteristics and utilities in the market (Deniaud-Bouët et al., 2017). These polymers are used as stabilizers, viscosifiers, gelling, and emulsifying agents (Bose et al., 2023).

An assortment of food products applies supplementation of alginate, carrageenan, and agar because it enhances meals' texture, consistency, and longevity by acting as stabilizers (Mahmud et al., 2021). These polymers enable various meals; sauces, dressings, sweets, and dairy products to exhibit thickening, gelling, and emulsifying properties.

3.1.1 Agar

Agar comprises D-galactose and 3,6-anhydro-β-galactose; which comes with functional groups of sulfate groups including, agarose and agaropectin, and is extracted from red algae (Bose et al., 2023). Agar forms gel structure that builds up into a three-dimensional network that holds onto water and allows it to turn liquid at temperatures over 80°C with application in the food, pharmaceutical, and microbiology industries (Puvvada et al., 2012).

Plastic food packaging choices are being replaced with a well-known and sustainable substitute: continuous, translucent agar gum film (Mostafavi & Zaeim, 2020).

Agarose is a neutral polymer whose rheological properties can be changed by mixing it with ethylene glycol or glycerin which may be used as a biopolymer coating on the cellulose-extract paper substrate for use in food packaging applications (Roy & Rhim, 2019).

3.1.2 Alginate

Alginate is a marine antimicrobial agent found in species of brown algae and some bacteria that lend their cell walls strength and flexibility (Mahmud et al., 2021). Alginate contains M and G residues forming M-G blocks or copolymer (Mahmud et al., 2021). The gel is a linear chain polymer composed of 14-linked-ß-D-mannuronate and 14-linked-L-guluronate units (Mostafavi & Zaeim, 2020).

Alginate is derived from brown seaweed such as *Ascophyllum*, *Durvillaea*, *Ecklonia*, *Laminaria*, *Lessonia*, *Macrocystis*, and *Sargassum*; it can therefore be regarded as useful substance in the food industry as well as in the control and treatment of diabetes and obesity (Chee et al., 2011). Alginate-based films are applicable in the packaging of coffee and tea (Bose et al., 2023).

Alginates, obtained from capsular polysaccharides of *Pseudomonas aeruginosa* and *Azotobacter vinelandii*, are not widely applied industrially (Roy & Rhim, 2019).

3.1.3 Carrageenan

Carrageenan consists of D-galactose and 3,6 anhydrogalactose moieties in turn and connected by α-1,3 and β-1,4 glycosidic link (Mostafavi & Zaeim, 2020). Applications involving food and nonfood items benefit from the wide range of rheological properties that arise from the structural diversity of these polysaccharides (Bose et al., 2023).

The first tested as a food thickening agent was the red algal species *Chondrus crispus* commonly referred to as "Irish moss" (Mostafavi & Zaeim, 2020). Carrageenan originating from seaweed is said to have been first employed several hundred years ago. Carrageenan is produced via a series of steps including precipitation, drying, concentration, extraction, and purification (Mahmud et al., 2021).

After gelatin and starch, the food industry considers carrageenan to be the third most important hydrocolloid (Mahmud et al., 2021). Carrageenans are generally water-soluble colloids, but their insolubility in majority of the organic solvents is a well-known property. Carrageenans are obtainable in two quality; the semi-refined and refined quality (Bose et al., 2023).

Carrageenans are gelatinized at 75°C by using an aqueous solution of potassium hydroxide instead removed by extraction from the seaweed in the manufacture of the semirefined carrageenans (Matheus et al., 2023). While potassium attaches itself to carrageenan and promotes the gel-forming process by inhibiting the dissolution of the hydrocolloid chains, hydroxide reacts with the sulfate esters production of κ- and ι-carrageenan, which strengthens the final product's gel (Bose et al., 2023).

Puvvada et al. (2012) outlined some applications of carrageenan as follows:

I. Carrageenan acts as an active pharmaceutical ingredient in various pharmaceutical industries and as a matrix-forming polymer in many oral controlled released tablets.
II. It is highly used because it is used as a food preservative agent and also in the preparation of diverse food products.
III. It is also used in thickening and solidifying food items.
IV. It helps in improving food flavor and binding water to encourage the development of gels.
V. It is also useful in dairy products, beverages, and pet food.

3.1.4 Ulvans

Ulvans are green marine microalgae which are soluble in water. They are sometimes referred as **sea lettuce** used in agriculture, medicine, and human nourishment (Azeem, Batool, & Iqbal, 2017). Xyloglucan and glucuronan are two linear alkali-soluble polysaccharide groups that are commonly found in Ulva cell walls (Bose et al., 2023).

Ulva has been linked to a decrease in the prevalence of chronic illness and has a high dietary fiber content that promotes digestive health (Bose et al., 2023). Ulvan has some desirable biological and physiochemical characteristics, and it is widely accepted for its potential application in food science, medicine, agriculture, and chemistry disciplines (Azeem, Batool, & Iqbal, 2017).

3.1.5 Fucoidans

Fucoidans can be isolated from various systems including the cell wall matrix of numerous brown marine algae species (Azeem, Batool, & Iqbal, 2017). Brown macroalgae generate the fucoidan polysaccharide. Brown seaweed contains significant amounts of fucoidans (Azeem, Batool, & Iqbal, 2017). Since its initial isolation from brown algae by Kylin in 1913, fucoidan has been marketed as a nutritional supplement in the food industry (Azeem, Batool, Iqbal, et al., 2017, p. 1–31). Interest in fucoidan has increased since it protects against problems with the liver and urinary system (Bose et al., 2023).

Particularly in Asia, several Asian diets increasingly incorporate fucoidan-containing brown seaweeds (Ali et al., 2022). It is water soluble, and its toxicity has confirmed that it does not produce allergic reactions and has multiple biological properties which qualify it for therapeutic uses (Azeem, Batool, Iqbal, et al., 2017, p. 1–31).

3.1.6 Laminarins

Laminaran was first isolated in 1885 by Schmiedeberg, and it is also known as leucosin (Goyal et al., 2016). Brown algae have a low-molecular-weight bioactive polymer, which is an essential component of laminarin (Bose et al., 2023). The polysaccharide Laminarin is extracted from roots *Laminaria* and *Saccharina* (Mahmud et al., 2021). The brown marine alga was *Laminaria digitata* from which laminarin was extracted and subsequently sulfated by treatment with chlorosulfonyl pyridine at between 0°C in liquid sulfur dioxide (Azeem, Batool, Iqbal, et al., 2017, p. 1–31).

Bose et al. (2023) have identified several bioactive properties of laminarin that need further investigation and may find practical uses in industry. Utilizing the algal biomass to its fullest potential, laminarin extraction from brown algae can be done concurrently with the extraction of other polysaccharides from the cell wall. *Ecklonia kurome*, *Laminaria japonica*, *Laminaria digitata*, and *Eisenia bicyclis* are among the algae species that contain laminarin (Goyal et al., 2016). Laminarin can be hydrolyzed into glucose and other simple sugars, which microorganisms may ferment to produce ethanol as a byproduct (Goyal et al., 2016) (Fig. 7.1).

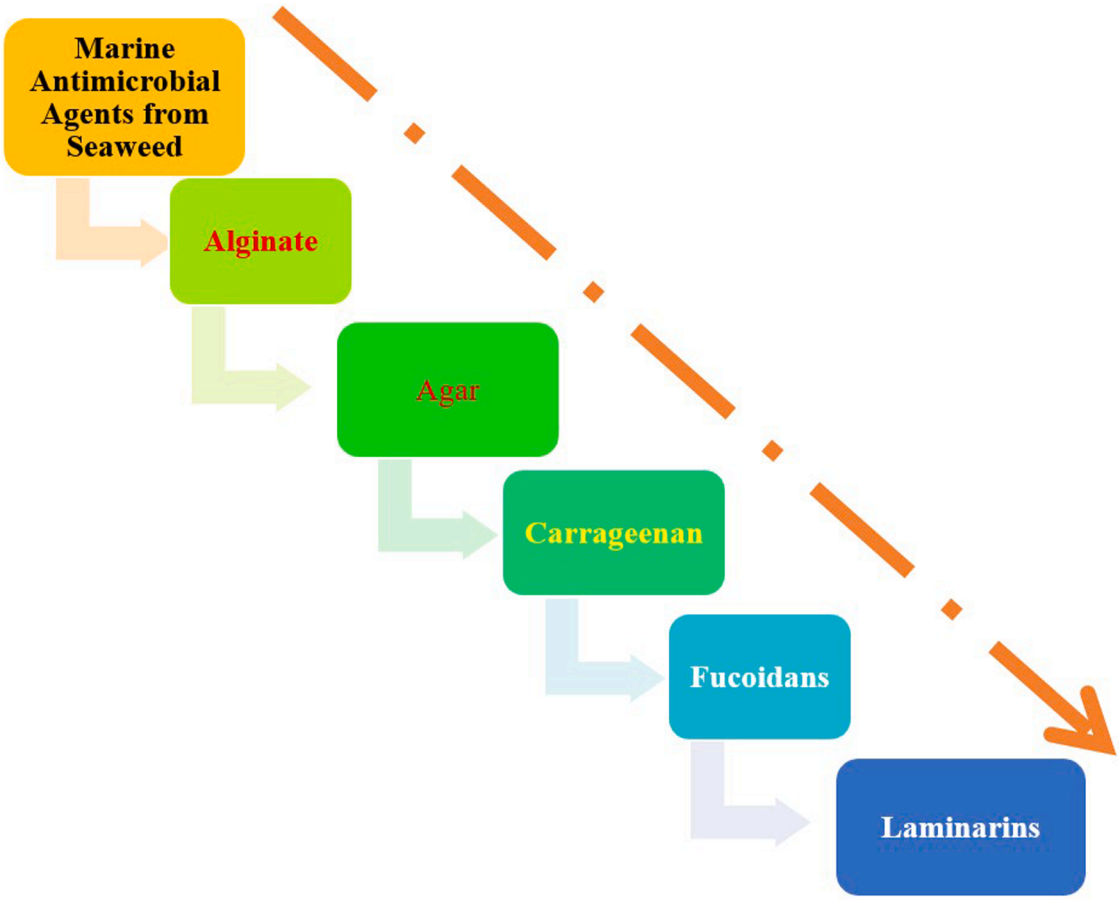

FIGURE 7.1 Flow chart depicting marine antimicrobial agents from seaweed.

4. Marine animals that yield biopolymers

The biodiversity of marine is reflected in the vast variety of different organismic species that inhabit environments from the periphery to the core of the sea (Mahmud et al., 2021). As noted by Bose et al. (2023), marine animals show an incredible array of both "form and function"; thus, they may be a rich source of bioactive compounds and may provide joy to various approaches. The term "aquatic" refers to animals like, jellyfishes, sharks, fishes, whales, sea otters, crabs, octopuses, mussels, dolphins, and so on that largely thrive in water resources and so on (Abdulazeez et al., 2024, p. 355–370).

4.1 Chitosan and chitin

A naturally occurring biopolymer named chitin, available prior to BC production, is derived from different organisms (Abdulazeez et al., 2024, p. 355–370). Most frequently, it is obtained from the leftovers of shellfish, such as prawns, crabs, and lobsters (Abdulazeez et al., 2024, p. 355–370). According to Mahmud et al. (2021), it amounts to about 13%–15% and 14%–27% of the dry weight of waste from the processing of prawns and crabs, respectively.

There is some furan species have chitin, which is an unbranched high-crystalline homo polysaccharide. This structure is assembled from N-acetyl glucosamine residues connected at positions −1 and 4 in antiparallel (α), parallel (β), or mixed (γ) orientations; type α orientation is the most frequent. It is not soluble in water and most of the organic solvents (Castillo et al., 2017). The neutral point of chitin leading to poor solubility is attributed to some cause such as hydrogen bonding (Goyal et al., 2016). In order to avoid this problem, analogs of chitin are routinely synthesized and used. Chitin may be used to make gels, membranes, and colloids (Mahmud et al., 2021).

Biological therapies employ bacterial strains for demineralization and deproteinization (Castillo et al., 2017). *Lactobacillus plantarum* has been investigated for the demineralization process for removing calcium from chitin and for deproteinization bacterial strains that produce proteases including *Bacillus subtilis*, *Pseudomonas aeruginosa*, and *Serratia marcescens* (Baron et al., 2017).

The *Rhizopus japonicus* has also been used as an agent for the conversion to chitosan from chitin process due to sufficient deacetylation activities inside and outside the framework (Sedaghat et al., 2017).

Chemical treatments are not suitable for modifying the physicochemical properties of chitin because such treatments are non-eco-friendly as they require extensive volumes and concentrations of acid and alkali solutions to be heated, the biological treatments are relatively eco-friendly methods (Castillo et al., 2017).

In addition, the extraction of the compound using the combined approaches was analyzed on its impact on the environment by Lopes et al. (2018) through a pilot study. Two other inventions spanning the length of the approach of chemical treatments are the soft-alkaline treatments employing NaOH and the possibility of recovering using water and hydrolyzed fish protein. Two types of chitosan can be distinguished: LMW (less than 300 kDa) and MWW (more than 300 kDa). The origin of chitosan may affect its molecular weight. Its physicochemical characteristics, including as its viscosity, dissolution, elasticity, tear resilience, and biofunctionalities, can be inferred from its weight (Ibrahim & El-Zairy, 2015).

Industrial settings provide difficulties when handling more viscous solutions with greater molecular weight chitosan. A chitosan film's viscosity was standardized by using glycerol molecules with varying molecular weights. Non-Newtonian behavior is shown by a high-molecular-weight chitosan film (Mahmud et al., 2021).

Source of chitin determines the properties of chitosan. Seaweed chitin, when extracted, is thick, stiff, and insoluble (Issa & Tahergorabi, 2020). The extensive reactivity, high flexibility, and water solubility of chitosan that is derived from marine source chitin might be highly beneficial for packaging (Roy et al., 2017).

Demineralized and deproteinized chitosan sourced from marine is applied in the industry as an antioxidant, coating, and preservative (Abdelmalek et al., 2017).

Yeast and fungus chitin and chitosan have been shown to have adsorption, antimicrobial, and biocompatibility qualities (Lee & Mooney, 2012). The US FDA has given clearance for select countries to utilize chitosan as a food additive (Lee & Mooney, 2012).

However, food packaging can employ their nanoparticles since chitosan and its derivatives are harmful to bacteria, fungi, and parasites (Issa & Tahergorabi, 2020).

4.2 Marine gelatin

Gelatin is obtained from hydrolyzation of collagen. It contains large amounts of proline, glycine, and 4-hydroxy proline residues. Food packaging frequently uses gelatin from bioactive films as an environmentally friendly substitute for manufactured ones (Bose et al., 2023).

The demand for seafood, especially fish, has increased dramatically on a global scale in recent years. Mammalian sources provide the great bulk of collagen products available on the market origins. While gelatin gotten from fish has certain drawbacks compared to mammalian-sourced gelatin, its homogenous amino acid content, color, smell, and functional qualities make it a suitable substitute (Rathod et al., 2023).

4.3 Collagen in marine

The most consumed animal proteins are collagen and other connective tissues—skin, bones, tendons, ligaments, and cartilage (Chinh et al., 2019). Two identical homologous α1 chains and another composed of α2 chains, which is formed from polypeptides that are cross-linked (Coppola et al., 2020). Some of the fish leftovers which are believed to contain high collagen include sea urchins, starfish, and sea cucumbers (Blanco et al., 2019).

In their study, Chen et al. (2016) identify demineralization—the removal of calcium or any other inorganic material using ethylene-diamine-tetraacetic acid, and raw material pretreatment, that is, the removal of noncollagenous proteins and lipids using alkaline and alcohol pretreatment as the most vital steps of extracting collagen.

Collagen is versatile in the production of films and coatings, beverages, foods and seasonings, supplements, and carriers (Chinh et al., 2019). The production of nutrient-dense meals has raised the need for collagen. Collagen production in the body decreases with aging and poor dietary habits (Blanco et al., 2019). The market for collagen supplements has expanded because of its potential health benefits (Coppola et al., 2020). The main compound and its derivatives have been identified to serve a key role in the construction of the human diet as primary protein and nutritious fibers sources because of their moisture absorption capability (Bose et al., 2023). Collagen supplements are utilized to retain their clients' bodily tissues such as skin, hair, and nails, according to Vilarinho et al. (2018).

According to Meneghetti et al. (2015), increased collagen can speed up the growth of lean muscle mass, recovery times, joint structure repair, and cardiovascular function. Collagen films are mainly applied as an extensive support and an appropriately permeable film to the support of food products and as a barrier in relation to the transport of solutes, moisture, and oxygen (Chinh et al., 2019) (Fig. 7.2).

5. Muscle proteins

The food industry has been adopting protein biomaterials more and more in recent years due to remarkable gel-forming ability, benign responses, and biodegradable nature (Arfat et al., 2017). Marine stromal and myofibrillar proteins have been focused on for many applications due to the fact that they may develop edible films to act as a barrier to gases, lipids, and organic volatiles (Nie et al., 2017).

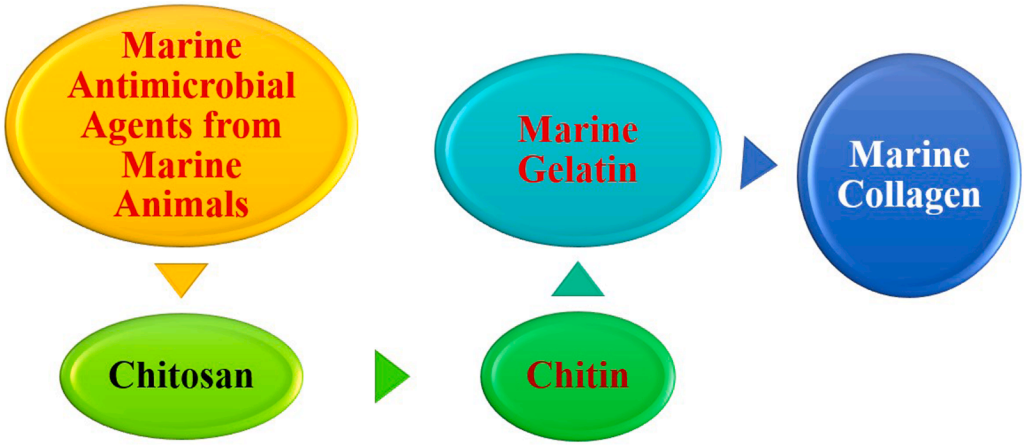

FIGURE 7.2 Flow chart showing marine antimicrobial agents from marine animals.

Sarcoplasmic, stromal, and myofibrillar are the muscle proteins, which might be sourced from marine resources (Nie et al., 2017). It is reported that 65%–75% of the entire muscle proteins is formed from myofibrillar proteins, which include contractile and regulatory proteins (Medina & Pazos, 2010). Proteins muscle and fiber require a more strong solution to be extracted and solubilized. About 20%–30% of all muscle proteins are sarcoplasmic proteins, according to Medina and Pazos (2010). Stem proteins, such as collagen and elastin, comprise a negligible portion of total muscle proteins, according to Kaewprachu et al. (2018). Most frequently, a denaturing solution containing sodium dodecyl sulfate, urea, beta-mercaptoethanol, and thiourea is used to extract myofibrillar proteins. Generating, actin, myosin light chains 1 and 2, tropomyosin, troponin-T, and other LMW proteins and fragments may all be efficiently removed using the denaturing procedure (Kaewprachu et al., 2018).

High-molecular-weight proteins such as desmin, α-actinin, and myosin heavy chain may be effectively solubilized by nondenaturing method using KCl phosphate (Della Malva et al., 2018). They may be incorporated into films and coatings with very valuable properties, like translucency, enhanced barrier to oxygen and carbon dioxide, and resistance to UV light (Nie et al., 2017).

6. Marine antimicrobial agents: Their application in food preservation

The nondenaturing extraction method is less time consuming and less toxic compared to the denaturing approach (Bowker et al., 2008). Edible packaging solutions often incorporate proteins and polysaccharides from organisms, plant and animal/saltwater resources, and food processing residues (Cedeño Muñoz et al., 2024; Díaz-Montes & Castro-Muñoz, 2021).

Surprisingly, the synthesis of packaging materials for enhancement of packaging films targets biopolymers from the marine environment. Package food hails attempt to increase the shelf-life by applying coatings and films from the biopolymers extracted from marine resources (Lionetto & Esposito Corcione, 2021).

Films and coatings as mentioned before extend food shelf life and quality qualities as they do not let gases, oxygen, and vapors pass through the barrier (Bowker et al., 2008).

However, several modifications are required to guarantee that the films and protective coatings derived from marine antimicrobials function as packaging materials before selecting a packaging application (Mahmud et al., 2021). The packaging materials must ensure avoidance of deterioration of the products (Mahmud et al., 2021).

The active ingredients used in marine antimicrobials such as plant extracts, nanoparticles, essential oils, organic acids etc., and functional and technical characteristics of packaging materials result in an improvement of finished packaging quality (Mahmud et al., 2021). Owing to the changes in the biopolymers-active agents, the packaging has some active properties, which enhances its shelf life (Kaewprachu et al., 2017).

7. Technological properties of biopolymers from fish waste in food preservation

Food preservation is essential for preserving food to avoid deterioration, especially from oxidative and microbiological means (Jariyasakoolroj et al., 2020). To increase its barrier, mechanical, and durability features, food packaging today has to serve other purposes beyond the traditional ones of marketing, information, and preservation (Kozłowicz et al., 2019). According to Lionetto and Esposito Corcione (2021), biopolymers derived from fish source could achieve better result in replacement of the traditional method of preservation to enhance smart/smart packaging.

This packaging incorporates the communication between the packaging, food, or the atmosphere within the box (Goyal et al., 2016). Within smart packaging are two types of packaging: active and intelligent. Active packaging interacts in an active manner with the food and the headspace of the active packaging to enhance the shelf life of food, it is nutritional value, sensor qualities, as well as safe microbiological status (Demitri et al., 2015).

Foods are sprayed or immersed into edible coatings to act as a barrier to moisture, oxygen, carbon dioxide, tastes, or fats in order to transfer food ingredients or bioactive compounds (flavor, antioxidants, and antimicrobials) or to enhance the food mechanical properties (Listrat et al., 2016).

WVP is one of the most critical indicators of packing material so that the food packed does not get dehydrated (Lionetto & Esposito Corcione, 2021). It is affected by the relative humidity, pressure, and temperature, as well as the film permeability porosity (Lionetto & Esposito Corcione, 2021).

To maintain the moisture level of dry food, fruits as well as vegetables low or moderate WVP films are needed (Goyal et al., 2016). Strong oxygen barriers that control the flow of oxygen between food and the environment are necessary for films and coatings to stop food from spoilage due to color change or surface softness (de la Caba et al., 2019).

As for oxygen barrier properties, oxidation of highly unsaturated food lipids, for instance fish and sea foods, results to rapid spoilage of foods—change of textures, loss of nutritional values, and undesirable odors and flavors (de la Caba et al., 2019).

Lionetto and Esposito Corcione (2021) note that packaging material that has direct contact with foodstuffs requires additional characteristics in addition to the typical sensory attributes, biochemical, physicochemical and microbial stability, absence of toxins, and safety.

Antimicrobial and/or antioxidants active compounds are incorporated in food packaging materials to retard the oxidation of food-derived pigments and lipids and also microbe growth (Kumral et al., 2016; Gómez-Estaca et al., 2011).

8. Safety issues with edible packaging made by marine biopolymers

It is possible to avoid utilizing common food packaging by employing edible films and coatings, which are ecologically and biodegradable-friendly (Mahmud et al., 2021). There is also likely that with benefits over traditional packaging foods themselves are better protected and have a longer shelf life because of edible films and coatings (Castillo et al., 2017).

The concentration gradient leads the active ingredients to pass through from packaging into food materials (Mahmud et al., 2021). If an antimicrobial with a high concentration is released, the food product will deteriorate, which may lose its original flavor and color and become hazardous to consume Therefore, for antimicrobial chemicals to serve their intended function, their release should be minimized (Rojas-Graü et al., 2009).

Nanoparticles as active agents improve their barrier qualities (Bukhari et al., 2023). Nanoparticles may be ingested and have antimicrobial potency when added to food surfaces (Chawla et al., 2021). Edible coatings and films contain significant amounts of nanoparticles that, if ingested, can penetrate the body and subsequently cause harm due to their tiny size (Chawla et al., 2021).

In edible packaging, the size and quantity of nanoparticles are crucial considerations (Chawla et al., 2021). Food additives must also meet the high standard of purity laid down in the Food Additive Purity Directive 2008/84/EC (Chawla et al., 2021).

9. Challenges and future trends

Foods derived from marine sources are driven by consumers' growing attention to healthy dietary components (Bose et al., 2023). Several functional foods originate from marine products; hence, their effectiveness in enhancing health should be scientifically supported and the barriers that hinder commercialization of foods with marine based components should be formally negated internationally to ensure that people embrace the nutrients in marine food hence improving utilization of the abundant resources in marine microorganisms (Rioux et al., 2017).

In spite of this, several bioactive compounds within the marine environment are well known and within their potential applications, especially within the food processing industry (Bose et al., 2023), several issues need to be resolved, some of which are listed below;

I. The assessment of sensory attributes to win over customers and the standardization of analytical procedures to guarantee product quality.
II. Well-organized clinical trials to produce strong proof for health descriptions.
III. While the industry has made considerable progress in using microalgae as a source of food ingredients, its full biotechnological potential is not being fully realized.
IV. A multitude of variables contribute to the complex matter of assimilating seaborne nutrients into the human diet.
V. Global issues including cultural and ethnic preferences and habits related to cuisine, environmental worries like worries about ocean pollution, and sustainable resource usage are all included in these restrictions.
VI. Food's sensory attributes and legal conformance.
VII. One possible barrier for the new functional foods, mainly those produced from marine sources, is national regulation, which is subject to frequent change and occasionally necessitates complicated processes.
VIII. Researching and using functional foods obtained from marine sources should be in line with food grade compatibility and sustainable harvesting methods.
IX. Conducting clinical research on humans to confirm the unique health advantages of these functional components and to assess their stability and bioavailability.

10. Conclusion

Natural antimicrobial marine agents are of great potential to become a real alternative to food preservatives. Their wide-spectrum functionalities against foodborne pathogens along with their biodegradability and low toxicity make them appealing candidates in increasing shelf life and food safety. Other food compounds that have proved to inhibit contact of microbial growth in foods include chitosan, bacteriocins, and marine peptides. With ongoing research, the use of these marine antimicrobials as part of the commercial food preservative method holds the possibility of helping in eliminating or lowering the use of synthetic preservatives and satisfying the rise in popularity of clean-label foodstuff. Further study and research are necessary to further realize their competency and regulatory and consumer safety.

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Chapter 8

Marine resources in green hydrogen production and storage

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1. Overview of marine energy resources and green hydrogen production and storage

Marine resources include the biological, mineral, and energy assets found in the ocean, covering nearly three-quarters of the Earth's surface. The biological components refer to living entities, while material components encompass physical resources. They range from biodiversity and ecological benefits from marine habitats, such as coastal and coral ecosystems, to aquatic life, seafood, minerals, oil, natural gas, and sustainable energy sources like ocean power. They also include opportunities for exploration (Elegbede et al., 2023). These resources are vital for global economies, ecosystems, and human livelihoods.

Energy from the sun and wind remains the predominant source of renewable power used worldwide. Nevertheless, the continuous rise in human energy demands calls for the utilization of all available renewable energy sources (Pérez-Vigueras et al., 2023; Maddela et al., 2024). Marine energy resources comprise a variety of technologies that utilize oceanic and sea energy to produce renewable energy. They are generally classified into various forms, such as tidal power, wave power, ocean thermal energy conversion, salinity gradient power, and offshore wind power (Thorson et al., 2022). Tidal energy harnesses the gravitational forces between celestial bodies to produce electricity from sea-level fluctuations. Two primary categories of tidal power systems are tidal stream devices and tidal dams. Tidal stream devices utilize the dynamic energy of flowing water to drive turbines, while tidal dams harness the stored energy generated by variations in elevated and low tides (Shetty & Priyam, 2022). Wave energy harnesses the power of oceanic waves to produce current (Veerabhadrappa et al., 2022). Marine thermal energy conversion converts the temperature disparity between the heated top water layer and the colder deep layer into electric current. Blue energy or saltwater gradient power, leverages the power created by the imbalance in saline levels between seawater and freshwater (Thennakoon et al., 2023). Offshore wind power uses wind turbines situated in aquatic environments to generate electric current. With a significant fraction of the world's inhabitants residing near the shores (UN, 2017), oceanic energy offers an effective approach to addressing climate change and advancing toward an eco-friendly future. Climate Change International Governing Panel identified marine renewable energy (Gimba et al., 2024) as a strategy for combating climate change and a key prospective contributor to the marine economy (IPCC, 2019). Ocean currents possess a yearly global potential of 800 TWh (Fig. 8.1).

Presently, green hydrogen is the exclusive option for decarbonizing sectors like chemicals, steel, and cement. Its production requires electrolyzers which separate water into its basic elements, oxygen and hydrogen using renewable energy. Sustainably powered electrolytic water decomposition creates green hydrogen, providing a green fuel substitute for various industrial uses. However, this process remains complex due to the significant amount of energy required and the challenge of matching supply with demand for green hydrogen. As nuclear and hydropower resources are nearly maximized a wider variety of consistent renewable options is necessary to complement the variable outputs of wind and solar energy, providing continuous carbon-neutral energy. Marine power can plug that void as a consistent, reliable, and

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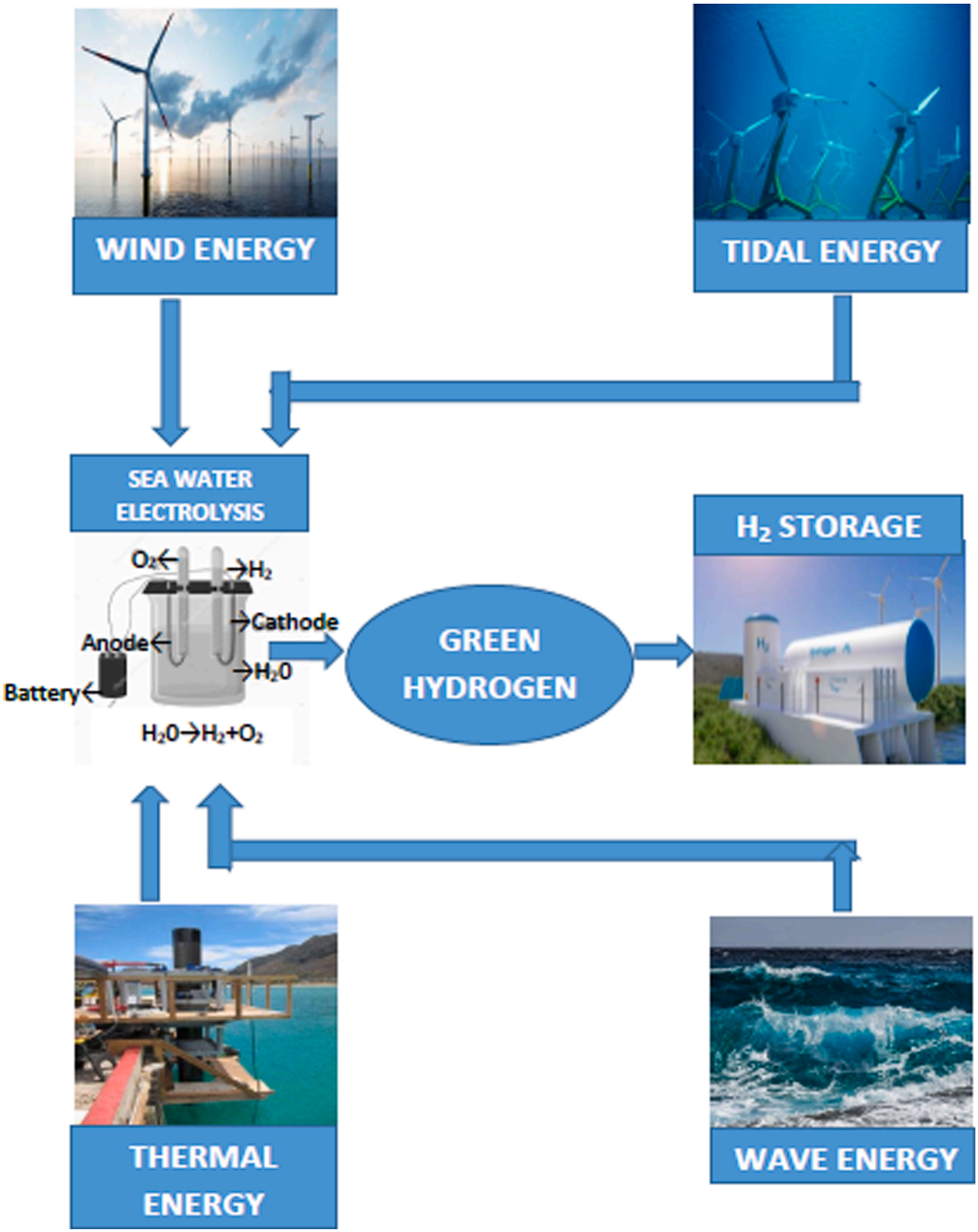

FIGURE 8.1 Marine energy resources and green hydrogen production and storage.

scalable power source (Raj et al., 2022). Marine power represents a vast, largely untapped resource that, when paired with advanced electrolysis techniques, can produce hydrogen on a large scale. This hydrogen can then be stored and transported to meet various energy needs, acting as a versatile and clean energy carrier that helps reduce emissions across multiple sectors.

Integrating marine energy resources into the production and storage of clean hydrogen offers a promising route toward a sustainable and decarbonized energy future. Continued research, innovation, and the implementation of pilot projects and commercial-scale operations will be key to overcoming existing challenges and optimizing these green energy solutions.

The outlook for marine energy and clean hydrogen is bright, fueled by ongoing technological progress, supportive government policies, and growing investments in renewable energy infrastructure.

Marine energy resources and clean hydrogen generation are pivotal in the shift to an eco-friendly and low-carbon power system. Integrating synergistic sustainable energy resources like wind and solar with marine energy resources can lead to a more reliable and steady energy supply for green hydrogen production. The green hydrogen produced can be stockpiled in different forms like pressurized form, liquefied form, or embedded in chemical substances (D'Amore-Domenech & Leo, 2019).

2. Advantages and challenges of using marine resources for green hydrogen production

2.1 Advantages

Promoting sustainable developments: This is particularly crucial for the oceanic sector, which has historically relied significantly on fossil fuels. The development of sustainable green hydrogen technologies is promoted by the application of hydrogen energy cells in maritime sectors. This has led to reduced dependence on nonrenewable energy sources (Inal & Deniz, 2020).

Energy security: The application of cells powered by hydrogen can boost power stability. Unlike oil and gas, which are sometimes sourced from volatile regions, hydrogen can be manufactured locally, thereby minimizing dependence on external energy imports and reducing the effects of unstable power prices and tense cross-border political situations on the maritime sector (De-Troya et al., 2016).

Enhanced safety: Since hydrogen fuel cells do not need combustible fuels to be stored on board, they are safer for maritime applications. This eliminates the dangers of fuel spills, leaks, and explosions frequently connected to conventional petroleum-based engines. Moreover, because hydrogen energy cells are not vulnerable to the fire risk brought about by the buildup of flammable gases in restricted areas, they provide a more reliable choice for ships.

All things considered, cells powered by hydrogen provide the marine sector with a more reliable, efficient, and sustainable energy source that helps lessen maritime transportation's negative environmental effects while enhancing crew and vessel safety (Luckose et al., 2009).

Ecological Benefits: The ability of cells powered by hydrogen to lower the release of greenhouse gases is one of the main advantages. Fuel cells greatly reduce the production of dangerous pollutants and greenhouse gases because they only emit heat and water as by-products in contrast to conventional marine driving technologies that depend on nonrenewable energy sources. Emission reductions can assist the shipping sector in meeting legal obligations such as goals for lowering greenhouse gas emissions (Sürer & Arat, 2022). Moreover, hydrogen serves as a sustainable energy resource that may be generated from biomass, natural gas, and renewable electricity, among other sources. This indicates that the market's reliance on fossil fuels can be lessened and a greener energy paradigm can be achieved by utilizing hydrogen energy cells in maritime applications (Van Biert et al., 2016).

Productivity: Fuel cell efficiency has the potential to be higher than that of conventional engines, which would reduce fuel usage and maintenance expenditures. This is because hydrogen energy cells transform their chemical energy into electricity more effectively than traditional devices, which initially transform chemical energy into mechanical energy, and then electrical energy. According to Tse et al. (2011), hydrogen energy cells offer a better affordable, and more energy-saving substitute over marine power technologies.

2.2 Challenges

Fermentative hydrogen production: Fermentative biohydrogen production requires expensive substrates. However, costs for operations can be reduced by substituting cattle, food, and agricultural wastes for simple sugars. Bioremediation and

energy production can also be managed by using effluent and sewage sludge as substrates. Utilizing pretreatment techniques on both substrates and inoculum can increase hydrogen yields. To convert complex sugars into simple sugars that ferment more readily, pretreating complex substrates is required. However, because it might impact the hydrogen yield, choosing the right microbe is also crucial for the design of the fermentative process. Furthermore, these fermentative processes produce biofuel gas, which is a combination of hydrogen and carbonic gas (Aransiola et al., 2023). As a result, a purification process is required to extract hydrogen from the mixture. In addition, the process must be carbon neutral since CO_2 must be drawn in and stored to stop emissions into the atmosphere. The primary disadvantage of the dark fermentation method is limited hydrogen output, which results from the several byproducts that are created during the reaction, even though it is more rapid than photo fermentation or bio photolysis. This process also produces CO_2 and hydrogen, in addition to metabolite byproducts (Aransiola, Adeniyi, et al., 2024). Further products of the process could be methanol, butanol, or acetone. The resulting biogas could also consist of trace levels of methane and hydrogen sulfide, based on the kind of microorganism and base materials involved (Sarangi & Nanda, 2020). Even if these by-products might be utilized as base materials for different ways of synthesizing hydrogen, like in a hybrid hydrogen production system, their formation reduces hydrogen output by 1–2.5 mol of H_2 per mole of glucose (Łukajtis et al., 2018). The process and reactor parameter optimization, pretreatment techniques, and appropriate microbe selection can all help to improve both the rate and volume of hydrogen generated in fermentative processes.

Microbial electrolysis cell (MEC): This is an inventive bioremediation and energy-generating system. The electrode materials, inoculum type, substrate type, applied potential, methane production, material and operating costs all affect how well MECs operate. Before scaling up and commercialization, some challenges need to be cleared. Electrochemically active bacteria (EAB) must first be optimized for use as biocatalysts. The precise processes by which electrons are transferred from a microorganism to the electrode are still not entirely known. Secondly, the poor Hydrogen output can be attributed to the methanogenic activity. Methanogens are microorganisms that produce methane from organic materials. Hydrogen is absorbed by the anode and cathode methanogens in addition to competing with the EAB for the biological matter in the base material. Therefore, more research is needed to find strategies for inhibiting the functioning of the methanogens prior to the advanced application of MEC for large-scale synthesis of hydrogen (Kadier et al., 2019). Although they have been effective in stopping methanogens, chemical inhibitors have increased operating expenses (Chae et al., 2010). To increase hydrogen generation, more studies on methanogen suppression must be done. Ultimately, more materials for electrodes need to be investigated. High electric conductivity materials at cheap cost are highly desirable for high-end applications. The substantial upfront costs of the cathode component as well as the catalyst, is an additional barrier to the MEC system, making up 47%–85% of the overall cost. Generally, the best catalyst for hydrogen synthesis, platinum (Pt) is located at the cathode side of the cell. Finding a more economical and ecologically friendly cathode has attracted significant interest because platinum is an expensive precious metal (Jeremiasse et al., 2010; Jafary et al., 2015, 2017; Jafary et al., 2017; Kundu et al., 2013). On the other hand, bio cathodes, also known as microbial cathodes, consist of more affordable materials and contain self-sustaining microbial populations capable of harnessing electrons for hydrogen synthesis (Croese et al., 2011). For exclusive applications, an MEC design that can combine cheap costs and high hydrogen yields is very desirable.

Biophotolysis: Low hydrogen yield is a characteristic of biophotolysis, which is primarily caused by the responsiveness of the process to oxygen and the poor ability to convert light. It is possible to regulate the oxygen evolved during photosynthesis by blocking the synthesis of oxygen and employing proteins that bind oxygen. Lowering the oxygen levels in the reactor can also be accomplished by sparging the headspace with an inert gas. Nevertheless, this necessitates higher running expenses. Studies have also indicated that nutrient deprivation can occur when specific nutrients, including sulfur and nitrogen, are absent from the green algae culture medium. This can lead to a reduction in oxygen evolution and an increase in hydrogen yield. Changing the cyanobacteria's metabolism to stop hydrogenases from consuming hydrogen is another method of increasing the amount of hydrogen produced (Ding et al., 2016). Previous studies on cyanobacteria and genetically modified green algae revealed a rise in light conversion efficiency (Volgusheva et al., 2013; Ghirardi, 2015). Furthermore, direct biophotolysis creates safety issues because hydrogen and oxygen can react explosively. Additionally, only hydrogen is synthesized by light-activated reactions once the microalgae are illuminated. Despite being a cost-effective light energy source +/−, artificial lighting is required for closed systems, which increases energy costs and necessitates the use of more expensive bioreactors (Das et al., 2014, p. 55–79). The microalgae's ability to capture light and fix Carbon dioxide are two other parameters that influence the output of biohydrogen. Numerous strategies to enhance H_2 production through biophotolysis are being investigated (Nagarajan et al., 2017). These include bioprospecting and bioreactor design (Kumar et al., 2019), microalgae metabolic and genetic engineering (Khetkorn et al., 2013), optimization of culture and process parameters (Tamburic et al., 2013), and enhancement of light use efficiency (Kosourov et al., 2017).

Safety considerations: Hydrogen leaks in fuel cells are another possibility that could cause flames or explosions because it is extremely combustible, therefore, using fuel cells in maritime environments could raise safety issues. To guarantee that hydrogen is transported and stored properly, safety precautions must be put in place (Baccioli et al., 2021).

3. Technologies for extracting green hydrogen from marine resources

Over the years, hydrogen has been considered a versatile fuel that has been used in chemical industries, aerospace and automotive industries. Since the boost in fossil fuel usage, most hydrogen fuels have be obtained from fossil fuels. However, due to increased environmental degradation, many industries are now considering other clean and sustainable sources of hydrogen fuel and green solutions have been seen as efficient (Teh & Sumaila, 2015).

Green hydrogen has been described as hydrogen that can be manufactured through renewable energies. Thus, green hydrogen is considered a clear, zero-pollution index and sustainable energy source (Fakhrulrezza et al., 2022). Green hydrogen is very effective in limiting the effect of climate change as it's clean and has the ability to replace fossil fuels. There are several technologies through which green hydrogen can be achieved, which include a technology involving an electrolysis process that is energized with the help of various renewable energy sources. This model uses electrical charges to break water molecules into two molecules of hydrogen and a molecule of oxygen, leaving the oxygen with an extra electrode. Some of the technologies for producing green hydrogen from marine resources can be summarized as follows (Aransiola, Oyewole, et al., 2024):

Through electrolysis of seawater: Recently, it has been documented that electrolysis of water accounts for roughly 4% of global hydrogen output (Chatterjee et al., 2022). According to previous literature, there are four main techniques involved in hydrogen synthesis which include high-heat solid oxide, proton exchange membrane electrolysis (PEME), alkaline electrolysis (AE) (Dincer & Acar, 2015), and direct electrolysis seawater. For the synthesis of eco-friendly hydrogen from the sea, the first three approaches are the more appropriate, however, PEME and AE, are the most commonly used with 55% and 26% preference, respectively. This results from their advanced technology and increased effectiveness. Seawater can be used as a sustainable form of energy production following any of the above strategies (Malin et al., 2020). In areas with significant shorelines and high solar exposure, seawater technology is in its infancy, approaching maximum efficiency (Hodson & Lampinen, 2018).

Photo-electrocatalysis is an important substitute and a potent technique that harnesses solar energy reflected from marine resources to meet the necessary thermodynamic requirement of about 1.23 V for water decomposition and hydrogen synthesis (Aransiola, Oyewole, et al., 2024; Chatterjee et al., 2022). This way, solar energy obtained from marine resources is retained in hydrogen as chemical energy and is considered one of the technologies for producing green hydrogen from marine resources.

Thermal decomposition of water: This is another sustainable way of obtaining green hydrogen from marine resources. This method has been studied over time and documented as an effective and efficient approach for sustainable hydrogen synthesis. However, the elevated temperature of up to 2500°C during its splitting reaction is considered as one of its disadvantages.

Green hydrogen can also be produced from marine resources by utilizing organic waste obtained from marine organisms (Fakhrulrezza et al., 2022).

4. Environmental impacts of utilizing marine resources for green hydrogen production

The production of green hydrogen from marine resources can either have a positive or negative impact on the environment.

4.1 Positive impacts

The utilization of marine resources for hydrogen production offers numerous environmental advantages, including:

1. **Freshwater Production:** Water is produced as a byproduct during green hydrogen synthesis, and can thus, be a solution to water scarcity, support human consumption, agriculture and industry (International Energy Agency, 2020).
2. **Oxygen Deprived Zone:** Oxygen, which is also another byproduct of green hydrogen supports marine life and can be injected into oxygen-deprived zones to revive marine ecosystems (Anderson, 2018).
3. **Reduction in Greenhouse Gas Emissions:** Green hydrogen production using marine resources has zero carbon emissions and serves as a potential solution to climate change (IEA, 2019; Metz, 2019).

4.2 Negative impacts

The environmental challenges associated with marine-based hydrogen production include:

1. **Disruption of Marine Life:** Marine food chains and habitats can be disrupted by large-scale seawater usage and algae harvesting for green hydrogen production, potentially harming marine species and ecosystems (Goldenberg, 2017).
2. **Dead Zones:** Excessive nutrient pollution from green hydrogen production can lead to oxygen depletion, destroying marine ecosystems and biodiversity (National Oceanic and Atmospheric Administration, 2022).
3. **Water Pollution:** The physical and chemical processes that occur in the ocean can be altered by the introduction of contaminants during seawater processing, which in turn affects marine life and human health (Schiermeier, 2019).

5. Case studies of successful projects using marine resources for green hydrogen

Several researches have been conducted on the utilization of marine resources for the synthesis of sustainable hydrogen. Kubilay et al. assessed the potential of synthesizing sustainable hydrogen for eco-friendly marinas from renewable energy resources, with a central focus on the generation of electric current from sustainable energy sources. They were able to generate an average annual green hydrogen of 3.99 kt in the study. They used solar and wave energy resources in the calculation of the total hydrogen production potential. This study is one of the major case studies where marine resources have been used to generate green hydrogen to fuel ships in the marine habitat (Dinh et al., 2020). South Africa is still actively investing in green hydrogen and seeks to gain a large portion of the hydrogen market in the world. This will enable the country to fast-track economic expansion and employment opportunities. South Africa's hydrogen economy is anticipated to boost the GDP by 1.6% while generating thousands of employment opportunities in 2024. South Africa is positioned to emerge as a top green hydrogen producer. This is because about 12% of South African energy is produced from green hydrogen (Franzitta et al., 2016). Various countries are still searching for innovative companies in the public and private sectors that are efficient in the green hydrogen production business.

Several industries have tried to produce sustainable energies using marine green, since the discovery of the biodiversity of marine resources and its potential in green hydrogen production. Different industrial plans and innovative techniques are underway to solve environmental problems using a sustainable approach. Presently, the maritime environment is experiencing various levels of degradation due to human activities. There is a need to channel the maritime environment to sustainable energy production rather than degrading it (Ababneh & Hameed, 2022). In addition, green hydrogen is expected to be highly sought after as nations work toward lowering greenhouse gas emissions, particularly in the transport and industrial sectors (Lahnaoui et al., 2021).

6. Potential for scaling up green hydrogen production using marine resources

Pilot-scale approaches, which have been explored for different components of the hydrogen production and distribution network, require increased investment for scaling up and commercial expansion. Since 2010, there has been a 60% drop in the upfront investment in electrolysis (Hydrogen Council, 2020), leading to a reduction in hydrogen costs from USD 10–15/kg to as low as USD 4–6/kg during this period. Various approaches are available to further decrease the price and encourage broader adoption of hydrogen technology (IRENA, forthcoming). Achieving optimal green hydrogen production at lower costs entails using an electrolyzer that has a prolonged lifespan, minimal wear and tear, seamless compatibility with the fluctuating nature of renewable energy sources and high performance (Hou et al., 2017). Proton exchange membrane electrolysis has been heavily utilized due to its high efficiency, mature technology, quick response time, and environmental safety. Alkaline electrolysis is also in use, however, it is associated with electrolyte leakage that is highly caustic, which poses significant risks to both workers and the environment (Barakat et al., 2019). Recent innovations in electrolyzer technology are aimed at enhancing efficiency, lowering costs, and boosting scalability. These advancements enhance the overall competitiveness and sustainability of green hydrogen production.

Studies on operating conditions, environmental impacts, technical feasibility, and economic viability are essential for scaling up sustainable hydrogen synthesis from marine resources. The feasibility of electrolytic hydrogen production from marine energy resources was studied by Pérez-Vigueras et al. (2023), with a focus on four primary factors: operational parameters, technical requirements, financial viability, and ecological impact analysis. The findings of the research suggest that offshore wind turbines and ocean current systems are the most effective for hydrogen production in marine settings, which is attributed to high speeds, capacity factors and investment costs. The financial feasibility of sustainable energy projects, such as offshore wind farms, can be initially assessed using the Levelized Cost of Energy (LCOE) which

indicates the electricity price required for the system to achieve financial balance throughout its operational life. It is determined by dividing the yearly energy production costs by the yearly electricity output (Mohsin et al., 2018). A lower LCOE indicates that the project is more economically favorable (Rezaei et al., 2020), and it results from increased energy production by the offshore wind farm and lower project costs (Castro-Santos et al., 2018). Studies have shown that offshore wind energy has the smallest LCOE and potential global growth (D'Amore-Domenech & Leo, 2019).

Regulatory frameworks and standards are developed by governments and international organizations to facilitate the deployment of clean hydrogen and ensure its safe integration into current power systems. These benchmark regulations and standards are needed to create equal opportunities and foster investment in the green hydrogen sector. Standards concerning hydrogen purity, storage, transport and safety are also established. Regulatory frameworks provide long-term subsidies, including carbon pricing schemes and grants, which promote the use of clean hydrogen technologies (Bharadwaj & Millison, 2023).

7. Strategies for storing green hydrogen produced from marine resources

Hydrogen is a fairly light gas in the atmosphere, yet it has three times the energy of petrol per kilogram. It possesses an extremely elevated gravimetric energy density and low volumetric energy density. Hydrogen must therefore be kept in one of three forms: a cryogenic liquid, a compressed gas, or as an atom joined to another molecule. The several techniques for storing hydrogen are broadly divided into two categories: material-based and physical technologies.

Hydrogen is most often stored using physical methods, and it is commonly done in high-pressure and cryogenic tanks composed of different types of materials, the materials do not have contact with the hydrogen or perform any other reaction. In addition, the gas must be compressed, held in high-pressure cylinders or pipes, or liquefied to store the hydrogen as a liquid. The storage of hydrogen is classified as follows:

i. Storage in liquid form; and
ii. Cold/cryogenic pressurized hydrogen gas form.

Storing hydrogen as liquid and in cryogenic compressed form: Liquid hydrogen storage needs cryogenic temperatures due to hydrogen's nearly 71 kg/m^3 density and −253°C boiling point at normal atmospheric conditions. Because of these characteristics, retaining hydrogen at normal atmospheric pressure and temperature is quite challenging due to cost and safety concerns. It is regrettably nearly impossible to liquefy hydrogen at the normal temperature of 20°C, in contrast to other gases. Hydrogen must thus be compressed into cryogenic tanks capable of being pressured to 25–35 MPa. Because of this, larger tanks are needed for liquid hydrogen, roughly three times larger than those used for petrol at the moment.

Subsurface geological formations offer safe gas storage for hydrogen between the thermal and pressure limits of 25–130°C and 5–30 MPa. For subsurface storage, underground hydrogen storage requires the transportation of hydrogen to a wellhead. Pressurizing hydrogen to the appropriate pressure and temperature is essential for the in situ circumstances before being injected into the geological formation.

Underground storage of hydrogen is generally employed for bulk hydrogen applications. For light transportation, hydrogen gas is typically pressurized up to 700 bar. While volumetric density is less critical than in passenger cars, 350 bar storage is commonly used in hydrogen tanks for heavy-duty vehicles to reduce costs (Müller & Arlt, 2013). Hydrogen can be transported and stored via pipelines, including those carrying natural gas. Natural gas can already be stored in existing pipeline networks; adding hydrogen as a blend to the network would allow for substantial storage capacity. Numerous final-use applications that are currently powered solely by methane gas could benefit from the usage of a blended natural gas-hydrogen mixture. Around the world, various blending rates up to about 20% are being tested. Hydrogen-incorporating pipelines may be constructed from new, hydrogen-compliant infrastructure or by retrofitting already-existing infrastructure.

Cooling gaseous hydrogen below −250°C causes hydrogen to liquefy. Roughly 30% of the hydrogen's energy content is used during the energy-intensive process of liquefaction. Additionally, the thermal variation between the outside and the inner storage tank wall causes modest evaporative losses, often known as "boil-off." Liquid hydrogen is released onto storage tanks at the place of usage after being stored in extremely insulated cryogenic tanker trucks for long-distance transportation (Zen Clean Energy Solutions, 2019). The liquid is changed back into a gaseous state so that it can be kept in high-pressure tanks and used as fuel in fuel cells before being delivered to hydrogen-powered cars. Due to its cheaper cost per kilowatt-hour, liquid hydrogen is more often used in high-volume applications. For instance, liquid hydrogen powers most electric buses and trucks across North America (Stetson & Blair, 2011).

7.1 Materials based storage

If hydrogen molecules are bonded or adsorbed to a surface, the volume needed to hold hydrogen can be substantially decreased while maintaining the same temperature and pressure. This is known as the volumetric energy density. Porous polymers, zeolites, and materials based on carbon like graphite are examples of adsorption materials that can store hydrogen in a compact manner by holding it on their surface. Exothermic in nature, the adsorption process requires low temperatures to be maintained (Zen Clean Energy Solutions, 2019).

7.2 Chemical carrier storage

Strong chemical bonds can be used to store hydrogen, while chemical reactions or thermal breakdown can release it. Subsequently, a different process regenerates the reaction byproducts into their hydrogenated state. Two materials that are currently being developed are ammonia (NH_3) and methylcyclohexane (MCH) (Stetson & Blair, 2011). Chemical tankers are capable of handling MCH, which exists in a liquid state at atmospheric pressure. It is possible to free three H_2 molecules from MCH, which causes a reversible process that turns MCH into toluene. Dehydrogenation of ammonia (NH_3) produces 0.176 t of hydrogen per ton of NH_3. Though it is still in its early stages of development, this technology shows great promise, particularly for the export of H_2 to foreign markets (Air Products, 2020a).

7.2.1 Large scale geological storage

Hydrogen, an energy carrier for clean energy that needs energy storage devices in addition, is a promising way to assist balance the energy supply from intermittent renewable sources and demand. Hydrogen has several advantages over other fuels, including nontoxicity, high specific energy, and no carbon dioxide emissions during combustion. However, finding high-capacity materials for hydrogen storage is difficult (Air Products, 2020b). For many years, natural gas has been successfully stored underground on a large scale. Currently, 413 billion standard cubic meters of stored natural gas are located in exhausted gas reservoirs worldwide (80%), artificial salt caves (8%), and subterranean aquifers (12%) (Crotogino & Bünger, 2010).

A special chance to store significant amounts of energy for extended periods through suitable geologic formations is provided by hydrogen. The stored supply can be set aside for usage in the event of unplanned plant outages or shutdowns, or it can be used to buffer the intermittent generated sustainable electric current from both photovoltaic and wind power. This is a well-established procedure to store natural gas underground geologically in order to prepare for seasonal variations, plant outages, and shortages. There is enough fossil fuel reserves in Germany and France to last for about 2 months.

Energy storage will be essential as the Maritimes' electric system becomes more and more dependent on intermittent renewable electricity generation. Since wind energy is by its very nature sporadic, the area will need a durable, elevated-capacity power storage solution if it is to generate a substantial amount of its electricity from wind.

7.2.2 Salt caverns

The high-pressure gas storage facilities made possible by salt caverns are another subsurface storage alternative that could be used in particular circumstances and locations. The exhausted gas reservoirs and geological structures are the two most widely used natural gas storage methods. Since hydrogen may react with the mineral content or microorganisms within these structures, reducing the amount of hydrogen over time and blocking microporous pores, these options are less suitable for commercial storing of hydrogen. Because the compacted salt creates a tight seal that confines the stored hydrogen molecules and is inert, engineered salt caverns are the best choice.

Man-made salt formations are produced by drilling down to a designated storage depth and then building the storage area using solution mining. A cavern is formed by injecting fresh water which gradually dissolves the salt deposit and extracts the brine solution at the same time. If it is established that the rate and concentration of brine introduction have no negative impact on the environment, the brine may be disposed of using an effluent treatment procedure or discharged into surrounding water bodies. As an alternative, the brine stream can be used as a feed stream for chlor-alkali facilities or the manufacturing of salt.

Trucks or direct pipelines from the production source can carry hydrogen to the storage location. Before being injected through the borehole, the delivered hydrogen needs to be dried and compressed to the cavern's storage pressure.

8. Economic implications of utilizing marine resources for green hydrogen production and storage

A facility for producing hydrogen will be a crucial component of the eco-industrial park. The total footprint and cost of producing hydrogen can be reduced by combining accessible excess resources from other industries, such as water, renewable energy, waste heat, intermediates, and byproducts of marine resources, with the facility that synthesizes the hydrogen (Kazi et al., 2015, 2016, 2017). There are several unknowns associated with the cost of producing hydrogen, and they are mostly determined by feedstock pricing, present infrastructure availability, and production technological advancements. Aside from that, some difficult aspects for any solitary hydrogen production facility are increasing urbanization and industrialization, the use of energy and resources intensively, and land use patterns. Through more effective resource utilization, and industrial symbiosis, a portion of the industrial environment can help to resolve these problems without endangering the advancement of the economy. For instance, economic growth might result from the utilization of resources more effectively by policy-makers. For example, rather than building individual facilities for hydrogen synthesis in each sustainable industrial zone, policymakers ought to build a generalized plant for hydrogen synthesis. Feedstock can be used to create hydrogen atoms and resources from a variety of energy sources (AlNouss & Eljack, 2019). These energy supplies can be obtained through shared facilities from the adjacent industries.

Big central facilities, semicentral plants of a moderate scale, and smaller distributed facilities like fixed generators and gasoline pumps, or small units at the place of operation can all produce hydrogen. This provides decision-makers with additional leverage when scaling their plant in the sustainable industrial zone to produce hydrogen, taking into account with patterns of need for several related sectors, including transportation fuel, urban mobility, industry, and the international commerce side. The environmental advantages of industrial symbiosis in the hydrogen economy can be assessed by tracking changes in the use of natural resources and discharges to the environment as a result of enhanced circular usage of materials and energy (Kazi et al., 2015, 2016, 2018). On the other hand, the economic advantages ought to be measured by how successfully businesses can generate sources of income or reduce disposal expenses by utilizing byproducts, saving money on transit, and making efforts at a lower cost.

Inexpensive, lightweight, small, and safe hydrogen storage are essential requirements for the economic expansion of hydrogen. Due to the cryogenic temperature of hydrogen, the distribution chain system must consider the risk management involvements when discharging into the environment. Additionally, certain materials used to construct storage bins, conduits, regulators, and other machinery can be subjected to wear and tear by hydrogen. Sometimes this destructive power can be known as hydrogen embrittlement (Phull, 2003). However, none of the ordinary gaseous, liquid, or metal hydrides presently in use satisfy all the prerequisites for a viable hydrogen market. This is primarily due to safety concerns, financial issues, small-scale hydrogen storage and inefficient functionality. As a result, the integration of hydrogen storage systems from a technical and economic standpoint is still pending. Similar to methane gas sensors, which are often recommended for repair facilities and other structures in the common fire prevention standards, hydrogen gas sensors are necessary to protect indoor areas due to the dynamics and unmanageable temperatures in hydrogen uptake/release (Abe et al., 2019).

In terms of technology, hydrogen is a potential fuel for vehicles. For instance, minimal automobile emissions are guaranteed when hydrogen is used in conjunction with fuel cell technology (Al-shanini et al., 2014). Zhang et al., 2018 suggested that despite a number of sad and well-known hydrogen-related catastrophes, the risks and phenomena are now widely recognized. The physical properties of hydrogen have been better understood, and this includes modeling and predicting accidents. The 1937 Hindenburg combustible airship disaster research found that hydrogen in the air had a reduced concentration of 60–67% of its maximum combustible threshold, which is estimated to be 74%. This is an example of how awareness has improved. Still, the amount of hydrogen used each year has increased to more than 8 million tons. However, the amount of hydrogen used as a chemical reagent and rocket propellant has increased to over 8 million tons per year. According to some research, fuel spills from hydrogen vehicles increase the amount of flammable gas in an enclosed space, making them less dangerous than gasoline vehicles (Lasn & Echtermeyer, 2014).

Hydrogen has been used as a feedstock in many industrial sectors for years. Some industries, such as transportation, manufacturing, and the current natural gas use, would find it difficult to decarbonize by direct electrification. But hydrogen might be the "unidentified link" that provides these industries with significant volumes of renewable energy. By accelerating major funding for the creation and commercial development of renewable hydrogen applications and by assisting in the incorporation of different sectors, the hydrogen economy can support the energy transition. Hydrogen can distribute sustainable energy over long-range distances. Hydrogen can be produced in places with inexpensive and abundant renewable energy sources and transported to places with increased manufacturing costs and restricted capability for eco-friendly energy output. Transportation driven by hydrogen and sustainable energy could be developed on a variety of scales, from regional to global.

Collaborative efforts across different sectors will be necessary for the processes involved in producing, storing, moving, and distributing hydrogen in order to gradually adopt end-use applications. The technology exists; but, to save costs and maintain the economic feasibility of H_2 as a durable energy transition tool, a swift increase is currently necessary. Large-scale applications that can quickly produce large-scale economies, require little in the way of infrastructure and are the highest-performing option within a sector should be the primary focus of initial efforts. Regarding this, the best places to start are large industries (such as refineries, chemical plants, heavy-duty transportation (such as massive networks of buses powered by hydrogen, vehicles, etc.), methanol manufacturing, and so forth. Renewable hydrogen is a good way to meet climate goals. It's clear that in comparison Infrastructure to supply end users with clean hydrogen will require a substantial investment because of the fossil fuel industries. It is possible that recent rapid decrease in electricity pricing from renewable sources.

9. Policy frameworks and regulations supporting the development of marine-based green hydrogen technologies

Regulatory and policy frameworks essential for integrating marine energy into a country's power portfolio are insufficiently developed. Creating these frameworks necessitates early involvement with policymakers. However, there is a scarcity of marine energy associations and coordinating organizations with the capacity and expertise to develop the needed regulatory structures and engage in policy discussions with authorities. There is also an absence of government strategies and policy tools, which hampers progress in grid development, investment security, revenue pathway creation, and marine territory management. This is largely because these techniques are still emerging (Andreasson, 2021).

However, the development of clean hydrogen technologies from other sustainable sources, such as photovoltaic and sunlight, is increasingly supported by a range of policy frameworks and regulations globally. The European Union (EU) policy framework strategy to promote green hydrogen deployment is listed below (IRENA, 2020). Notably, offshore green hydrogen production is not included in the EU hydrogen strategy (Andreasson, 2021).

(2020–24): Expanding the size of the electrolyzer to 6 GW and generating about 1 million tons per annum of renewable hydrogen. The policy aims at reducing carbon emissions in different hydrogen sectors at the local level. Equipping existing hydrogen production facilities with carbon sequestration technologies (IRENA, 2020; World Bank and United Nations, 2017).

(2025–30): Expanding the size of the electrolyzer to 40 GW in EU countries and generating about 10 million tons per year of sustainable hydrogen. This will require collaboration with neighboring regions. A pan-European network for green hydrogen transport, primarily utilizing the existing natural gas pipeline system, will be essential (IRENA, 2020).

(2030–50): Green hydrogen becomes fully established and is implemented extensively across difficult-to-decarbonize industries, where other options are more expensive. A capital outlay of EUR 24–42 billion for electrolyzer size, alongside EUR 220–340 billion for 80–120 GW of extra sustainable energy production, EUR 65 billion for infrastructure, and EUR 11 billion for revamping current methane gas facilities, is required to drive this policy and make E-fuels from hydrogen accessible across a wide range of sectors (IRENA, 2020).

Policy support for electrolysis and the acceleration in the growth of electrolyzer capacity focuses on cost reduction in the manufacturing of electrolysis equipment by leveraging cost advantages, technological advancements, increased operational efficiency, increased support for research, optimizing and standardizing designs for large-scale electrolyzers, and cutting tariffs and charges on electricity consumed by electrolyzers (IRENA, 2020; World Bank and United Nations, 2017).

Policy recommendations for green hydrogen infrastructure entail deploying strategic measures to address limitations in green hydrogen transportation and storage. These measures include collaboration among different regions to pilot routes (pipelines) and carriers (transportation facilities) toward a global supply chain, primarily from countries with low-cost renewable resources. Additionally, establishing international standards to guide the functioning and configuration of cargo and transportation infrastructure required in transporting green hydrogen and associated products is crucial. The international guidelines should encompass benchmarks for sustainability, guidelines for safety management, mandates for pipeline durability, fuel quality parameters, and standards for device adaptability (IRENA, 2020; World Bank and United Nations, 2017).

10. Conclusion

The adoption of marine energy resources for electrolytic production of green hydrogen presents a crucial pathway toward achieving zero carbon emissions, a carbon-neutral ecological system and an energy future. This approach holds significant promise for various industries, with ample potential to expand production and enhance storage solutions through

technological advancements and insights gained from successful case studies. However, addressing associated challenges—such as environmental impacts, economic viability, and technological limitations—is urgent. Additionally, drafting strategic regulatory policies is essential to ensure the optimal efficiency and sustainability of green hydrogen production and storage systems derived from marine resources.

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Chapter 9

Foods of humans, feeds of animals: Safe marine bioresources, sustainable possibilities for food

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1. General overview of marine bioresources

The marine world contains immense and relatively untapped resources of huge biological and chemical significance, chief among which are marine bioresources (Aransiola, Oyewole, et al., 2024). These bioresources have a significant part in the ecosystem and earth's biodiversity, man's well-being, economic activities, health and functioning of marine ecosystems, and scientific research (Aransiola, Bamisaye, et al., 2024; Duarte et al., 2020). Marine bioresources comprise a diverse range of marine-related organisms; some of which include macro and microorganisms, nematode, fungi, sponges, molluscs, macroalgae and microalgae, fish and its co-products, plants, etc (Vasconcelos, 2019). They are found in marine environments such as oceans, seas, and coastal areas and can be utilized either as end products or as raw materials for the creation of novel, beneficial products.

Marine bioresources, according to (Peixoto et al., 2022), can be broadly grouped into the underlisted categories:

a. Marine macroorganisms: which comprise of finfish (fish), shellfishes (lobsters, shrimps, prawns, etc), and other marine animals (squids, octopuses, sea cucumbers, etc).
b. Marine microorganisms: made up of cyanobacteria, marine bacteria, marine fungi, marine viruses, and marine microalgae (phytoplankton).
c. Marine invertebrates: made up of corals, sponges, jellyfish, and sea anemones.
d. Marine vertebrates: made up of fish (also a macroorganism), sea turtles, and marine mammals (dolphins, seals, sea otters, manatees, etc).
e. Marine birds: made up of seabirds like penguins, albatrosses, and puffins.
f. Marine plants: made up of seaweeds, seagrasses, and mangroves.
g. Marine nematodes: which are composed solely of roundworms that live in marine environments.
h. Marine microbial communities: made up of biofilms and marine microbiomes.

Do note that this classification is not exhaustive, and also that some of these bioresources overlap in the various categories.

Marine bioresources render some important ecosystem services to the planet including biodiversity conservation (crucial for sustaining the balance of marine ecosystems and overall health of the planet), food security (via provision of sustenance for millions all over the world), climate regulation (which occurs via activities like photosynthesis, carbon sequestration, and nutrients cycling), coastal protection (entails the prevention and amelioration of coastal erosion, storm

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surges, etc., by marine ecosystems like mangroves and coral reefs), enzymes (during production of biofuels, biodegradable plastics; and bioremediation of polluted lands, etc), carbon sequestration (which helps in mitigating climate change), economic benefits (activities such as fisheries and tourism contribute to the well-being of communities dependent on marine resources), biodiversity and habitat provision (coral reefs, kelp forests, and seagrass beds provide critical habitats and nursery grounds for a multitude of marine species), nutrient cycling (helps during the cycling of essential nutrients like nitrogen, potassium, phosphorus, sulfur, etc), aquaculture and mariculture (the former deals with the farming of fish, shellfish, and aquatic plants in controlled environments, while the latter is a specialized branch of aquaculture that is concerned with the rearing of marine organisms in the open ocean or its enclosed sections, or man-made systems filled with seawater), and cultural and recreational benefits (crucial to the way of life of many coastal communities and indigenous groups) (Gimba et al., 2024).

Also, due to their unique properties, they have shown good potential in applications in various fields such as biomedical (in the development of treatments and therapies for various diseases and health conditions), food (to develop healthy and nutritious food products), pharmaceutical (to develop new medicines and supplements), cosmeceutical (to develop skincare and beauty products), and ecotourism (to develop sustainable tourism practices and promote conservation efforts) (Sanjeewa, 2024). Other applications include the production of biomaterials, textiles, animal feeds, and usage in a variety of industrial and manufacturing processes as co-adjuvants and enhancers to increase productivity and lessen their environmental impact.

Finfishes, shellfishes, molluscs, seaweeds, marine animals, etc., are a vital food source for man, providing essential nutrients and other numerous nutritional benefits (as a result of their being nutrient dense) to humans (Monteiro et al., 2024). These nutritional advantages include serving as a vital source of omega-3 fatty acids (beneficial against chronic diseases), providing bioactive food ingredients, and producing antioxidant peptides like glutathione and carnosine (Senadheera et al., 2023). It can therefore be seen that making marine bioresources a mainstay of the diet can provide a range of nutritional benefits, thus maintaining overall health and well-being.

Artemia, algae, insects, marine-based poultry feeds, etc., used as feed for animals, also come with numerous benefits (Zoya et al., 2020), some of which include the following: they are alternative protein products in feeds, their peptides can be modified to give the animals specific physiological benefits, they help minimize the strain on man's depleted food resources, and they also provide essential nutrients and are more nutritious than traditional sources of animal and aquatic feed (Mcdougal, 2023).

It is absolutely essential that bioresources used as foods and feeds be safe for consumption, so as to avoid getting sick from consuming contaminated seafood (most especially shellfish). For instance, the spread of SARS-CoV-2 to Antarctic marine species has caused worries (Barbosa et al., 2021) because it can lead to cross-contamination of our food supplies, with attendant deleterious consequences on man. Furthermore, since the marine world provides us with diverse essential resources, it stands to reason that we keep it healthy in our own best interests.

It is not farfetched to describe marine bioresources as a sustainable and underutilized resource, with the capability to bring global food security if well-handled. Mariculture and wild fisheries can help in this regard (Costello et al., 2020). Also, it has been posited that marine algae-based aquaculture can make a significant contribution to global protein demand by 2050 (Greene et al., 2022).

2. The diversity of marine bioresources

The diversity of living forms present in coastal and oceanic environments is referred to as marine biodiversity. Ecological balance, financial resources, and cultural identity all depend on it. The oceans cover over 70% of the Earth's surface and are home to an estimated 230,000 known marine species, with many more yet to be discovered (Costello et al., 2020). It encompasses all living organisms in oceanic and coastal ecosystems, including:

1. Fish diversity: Fish represent one of the most visible and economically significant groups in marine ecosystems. With over 34,000 recognized species, they range from the tiny, colorful reef fish to the massive whale shark. Fish play essential roles as predators, prey, and contributors to nutrient cycling within their ecosystems. The diversity of fish species also supports global fisheries, a critical resource for food security (Carlo, 2007).
2. Invertebrate diversity: Invertebrates make up the majority of marine species, with estimates ranging from 500,000 to several million, many of which remain unidentified. Key groups include: mollusks: such as octopuses, squids, and bivalves, they are vital for both ecological processes and as human food sources, Crustaceans: including crabs, shrimp, and lobsters, these organisms are important in nutrient cycling and utilized as a major source of food for numerous marine animals, echinoderms: starfish, sea urchins, and sea cucumbers contribute to the health of benthic environments and play critical roles in ecosystem dynamics (Lewbart & Zachariah, 2023)

3. Plankton: The ocean's microcosm: plankton, which includes both phytoplankton and zooplankton, forms the basis of the marine food web. A large amount of the oxygen on Earth is produced by these microscopic plants called phytoplankton, which also act as the main source of food for a wide variety of marine life. Zooplankton, ranging from tiny protozoans to larger jellyfish, serve as crucial food sources for larger marine animals.
4. Marine mammals: including whales, dolphins, seals, and manatees, are vital indicators of ocean health. These species exhibit complex social behaviors and play significant roles in their ecosystems. For example, baleen whales contribute to nutrient cycling through their feeding and migration patterns, enhancing productivity in various ocean regions.
5. Coral reefs: biodiversity hotspots coral: Thousands of species are supported by coral reefs, which are among the planet's most diversified ecosystems. Though they make up less than 1% of the ocean floor, 25% of all marine creatures find home among them. Coral reefs also preserve coastlines, support fisheries, and have significant cultural value. However, they are particularly vulnerable to climate change, pollution, and destructive fishing practices (Hoegh-Guldberg et al., 2017).
6. Marine plants and algae: Marine plants, including seagrasses and macroalgae (seaweeds), play vital functions in coastal ecosystems. They serve as habitat and food for a variety of marine species and contribute to carbon sequestration, helping to mitigate climate change. Seagrasses, in particular, are essential for stabilizing sediments and improving water quality (Macreadie et al., 2017).

Marine biodiversity contributes significantly to ecological functionality where ecosystem-related functions, including the cycling of nutrient, carbon sequestration, and the provision of habitats. Coral reefs, for example, support a high diversity of species and provide critical nursery habitats for fish, contributing to fishery productivity (Hoegh-Guldberg et al., 2017). Reduced resistance to environmental changes and ecosystem deterioration can result from biodiversity loss. It also has economic value as marine bioresources are vital for global economies, particularly through fisheries, tourism, and biotechnology.

The Food and Agriculture Organization (FAO, 2020) estimates that over three billion people get a substantial amount of their protein from fish. Moreover, marine organisms serve as a source of new pharmaceuticals; for instance, compounds derived from marine sponges have shown promise in treating cancer (Ortigosa-Palomo et al., 2024). There is also the cultural significance of marine biodiversity where many coastal communities depend on marine biodiversity for their livelihoods and cultural practices. The traditional knowledge and practices related to marine resource use are integral to the identity of these communities and must be recognized in conservation efforts (Holly et al., 2022).

There is little focus on how the biodiversity of the oceans is changing. Nonetheless, there is already a significant amount of human influence on the oceans, particularly in coastal regions but also more and more in the open ocean. Marine biodiversity faces multiple threats, primarily due to human activities. These threats include:

1. Overfishing is one of the most severe dangers to marine biodiversity. Unsustainable fishing practices deplete fish stocks, alter marine food webs, and lead to the depletion of entire fisheries. By catch, the unintentional capture of nontarget species, further exacerbates the problem by removing important species such as turtles, sharks, and marine mammals from ecosystems (Pauly et al., 2005). Global fisheries effects can be seen in the decline of large fish, sharks, turtles, crustaceans, and plants, the resulting rise in smaller fish species, sea urchins, etc., and their phytoplanktonic or macrophyte food, coccolithophorids, and pteropods. Fisheries focus on the top predators and herbivores of the food web (Carlo, 2007).
2. Habitat destruction: Marine habitats are being destroyed or degraded by activities such as coastal development, dredging, and bottom trawling. Coral reefs, seagrass meadows, and mangroves are particularly vulnerable to physical damage from these activities. Destruction of these habitats results in the loss of biodiversity and the ecosystem functions they provide, such as carbon sequestration and nursery habitats for marine species (Paul et al., 2012).
3. Climate change and ocean acidification: Changing climate and acidified oceans are long-term risk to marine biodiversity. Coral bleaching is caused by warming ocean temperatures. The sea surface temperature is rising due to global climate change, and species migrations northward have been observed in fisheries and through the use of special data from the continuous plankton recorder. High carbon dioxide (CO_2) concentrations can have substantial effects on calcifying organisms including corals, molluscs, coccolithophorids, and pteropods by lowering the pH of seawater and increasing the solubility of calcium carbonate (Carlo, 2007).

While it is understandable that people would concentrate their attention on the loss of biodiversity on land, marine biodiversity also has to be immediately addressed in order to preserve a healthy interaction between humans and the sea. The oceans have no owner, and no one nation or international agency is answerable for their health. The pressure on the waters is rising as a result. Due to overfishing of the top predators across a significant portion of the planet, humans are

seriously altering the oceanic food webs, contaminating coastal waters, and eroding coastlines and their ability to withstand flooding. These days, marine protected areas and nature reserves are being created quickly but not in places outside of national borders that are still open to unchecked exploitation. This encompasses the majority of Earth's deep-water ecosystems and open oceans, making up the majority of the globe overall (Carlo, 2007).

3. High-value utilization of marine bioresources

Covering over 70% of the Earth's surface, oceans harbor a diverse range of organisms that serve as a critical reservoir of bioresources. These marine bioresources are increasingly acknowledged for their potential in various high-value applications across sectors such as pharmaceuticals, nutraceuticals, cosmetics, and biotechnology. The diverse utility of marine bioresources underscores their economic, environmental, and societal benefits. Marine organisms synthesize a plethora of bioactive compounds with distinctive properties, thereby presenting substantial opportunities for innovation across multiple industries (Arrieta et al., 2010).

Marine bioresources include a diverse array of products, such as seafood, derivatives from seafood processing, and nonconsumable marine microbial resources. Different seafood categories—like marine fish, shrimp, crabs, scallops, oysters, squid, jellyfish, sea cucumbers, sea urchins, and various seaweeds—are abundant in proteins, enzymes, peptides, polysaccharides, astaxanthin, saponins, omega-3 fatty acids, and vitamins (Ozogul et al., 2021). However, the full economic potential of seafood remains unrealized when it is solely consumed as food. Consequently, advanced processing techniques, valorization of seafood by-products, and the exploration of marine microbial resources are critical for maximizing the value derived from these biological assets. Several species of green algae, known for their production of polyunsaturated fatty acids, are being utilized in aquaculture as feedstock. Given their resilience to extreme environmental conditions including variations in pH, temperature, salinity, and exposure to infrared radiation, these algal species are also incorporated into cosmetics and personal care products. They serve as antioxidants, emulsifiers, and humectants, enhancing skin resilience against abrasions and promoting overall skin health (Yarkent et al., 2020).

Although marine microorganisms are not directly consumable by humans, they produce a variety of specialized enzymes adapted to harsh environmental conditions characterized by high salinity, extreme pH levels, and varying temperatures and pressures. Enzymes derived from marine sources, including chitinase, chitosanase, alginate lyase, agarase, carrageenase, α-amylase, xylanase, lipases, proteases, and collagenases, can specifically hydrolyze substrates into low-molecular-weight oligosaccharides, monosaccharides, peptides, or lipids. These products have valuable applications across the food, healthcare, cosmetic, agricultural, and pharmaceutical industries (Ghattavi & Homaei, 2023). By harnessing these diverse marine organisms such as microorganisms, algae, and fish, we can develop innovative products and sustainable practices that foster human well-being and drive economic growth.

Marine bioresources hold immense promise in pharmaceutical development. Marine organisms, particularly sponges, algae, and bacteria are rich sources of bioactive compounds with significant medicinal properties. A notable example is Yondelis, an anticancer drug gotten from the tunicate of marine *Ecteinascidia turbinata*, highlighting the therapeutic potential of marine compounds. Furthermore, marine algae such as Spirulina and Chlorella are renowned for their nutritional benefits, rich in proteins, essential fatty acids, and vitamins. These algae are increasingly utilized as dietary supplements and functional foods, contributing to health and wellness by enhancing nutrition and supporting disease prevention (Gouveia et al., 2008). Research indicates that regular consumption of these algae can boost immune function and improve cardiovascular health (Freitas et al., 2012).

In the cosmetic industry, marine bioresources are valued for their bioactive compounds that enhance skin health and aesthetics. Marine algae extracts are often incorporated into skincare products due to their antioxidant, anti-inflammatory, and even antiaging effects (Pangestuti & Kim, 2011). Studies have demonstrated that marine extracts can improve skin hydration, elasticity, and overall appearance (Freitas et al., 2012). Furthermore, marine peptides derived from fish waste are emerging as potent ingredients in cosmetic formulations, offering moisturizing and rejuvenating benefits (Freitas et al., 2012). These developments position marine bioresources as key ingredients in high-quality cosmetic products. Marine microorganisms, particularly extremophiles, are invaluable in biotechnology due to their ability to produce enzymes and other bioproducts under extreme conditions. These enzymes are instrumental in various industrial processes, including biofuel production, bioremediation, and food processing (Trincone, 2011). For instance, enzymes from marine bacteria are used in biodiesel production, while marine-derived biopolymers are gaining traction in sustainable packaging solutions. Their unique adaptations to high salinity, temperature variations, and pressure conditions allow for applications that conventional enzyme cannot fulfill, paving the way for innovative industrial solutions.

The high-value utilization of marine bioresources presents significant opportunities for economic development, environmental sustainability, and enhanced human well-being. By leveraging the unique properties of marine organisms,

we can develop innovative products and sustainable practices that contribute to a healthier planet. However, realizing this potential requires a balanced approach that integrates technological advancements with sustainable management strategies. Ongoing research, investment, and collaborative efforts are essential to harness the full benefits of marine bioresources, ensuring that they continue to provide value for future generations.

4. Marine bioresources as food for humans

Marine bio-resources encompass a vast array of organisms found in oceans, seas, and other bodies of water. These resources have long been an essential source of food for coastal communities and are increasingly recognized for their important need to address global low food production challenges. They include fishes, invertebrate, aquatic plants, seaweeds, crustaceans, sponges, 2 marine mammals, and seabirds. Globally, people from history feed on seafood as part of their daily nutrition (Kim & Wijesekara, 2010). Most people from history already believe in all the nutritional values of sea food, some even believe it can add to life expectancy. People who consume seafood in high quantity see it as a way to boost their lifestyle and prevent common diseases, even though this belief has scientific backings (Aransiola, Akinsola, et al., 2024; Cencic & Chingwaru, 2010). Some of the nutritional benefits of seafood consumption include the prevention of chronic heart disease. Many other benefits have also been described by Lavie et al. (2009).

Marine bio-resources offer a rich source of essential nutrients, including protein, omega-3 fatty acids, vitamins, and minerals. Fish such as salmon, mackerel, and tuna are renowned for their high protein content and omega-3 fatty acids, which are beneficial for heart health and brain function. Additionally, shellfish like shrimp, oysters, and crabs provide essential minerals such as zinc, iron, and selenium, contributing to overall health and well-being. Seafoods have also been noted to have high polysaccharides, which have been observed to have many applications in food technology industries. For example, certain products of seaweeds such as carrageenan and agar are known to produce hydrocolloids, which can also be an edible product and source of protein. In addition, vegetables from deep sea also contains fucanoids, which can function as antioxidant, anticancer, antiarteriosclerosis and antitumor (Cencic & Chingwaru, 2010; Freitas et al., 2012; Lavie et al., 2009) (Some substances derived from crustaceans such as chitosan have also been used in various applications especially as emulsifying agents.) The food technology industries have also received ingredients from seafoods such as collagen and gelatin (Ngo et al., 2012). Also, studies have shown that there are many other enzymes sources from seafoods that have proven to show better and more effective applications compared to the enzymes sourced from terrestrial environment (Freitas et al., 2012). The nutritional value of proteins that are obtained from sea-weeds have proven to have more of the essential amino acid composition than even the terrestrial cereals and vegetables (Cox et al., 2013; Freitas et al., 2012; Holdt & Kraan, 2011; Ngo et al., 2012). In addition to all the important applications of seafoods, even the microorganisms from sea environment have been documented to have high potential in food science and technology; this is because it has proven effective even in the fermentation industry (Cencic & Chingwaru, 2010).

It is a known fact from time immemorial that seafood materials such as fish, shellfish and seaweeds have been consumed as important food delicacy and also in other industries globally (Samarakoon & Jeon, 2012). According to Fernandes (2010), Holick (2009), Zimmermann (2010) and Wu et al. (2009), seafood has also shown significant levels of bioactive peptides, free amino acids, enzymes, vitamins, minerals, and other functional ingredients. Some common seafood and their potential benefit are highlighted below:

Seaweed: This is a versatile marine bio-resource that people from all over the world believe in its consumption and nutritional benefits. This food class has high vitamins, minerals, and antioxidants. It also offers various benefits in the food technology industries. For example, nori which is obtained from seaweed can be used as food such as sushi and kelp. It can also work as an additive to soups and in preparation of salads.

Krill: These are small crustaceans that are found in the oceans. They are known to be part of the marine environment because they live all their life in the marine region. The krill is rich in omega-3 fatty acids, protein, and antioxidants. Krill are usually used for human consumption.

Algae: Algae encompass a diverse group of organisms found in marine and freshwater environments. Certain algae species, such as spirulina and chlorella, are cultivated for their high protein content, vitamins, and minerals. These microalgae are used in various food products, including protein powders, snacks, and beverages, offering a sustainable and nutritious alternative to traditional protein sources.

Sustainability of marine bio-resources: Sustainability is a critical consideration in harvesting marine bio-resources to ensure the long-term health of ocean ecosystems. Practices such as overfishing, by catch, and habitat destruction can deplete marine populations and disrupt marine ecosystems. However, sustainable fishing methods, such as selective harvesting, aquaculture, and marine protected areas, can help mitigate these risks. For example, aquaculture of seaweed and shellfish requires minimal inputs and can be conducted in an environmentally friendly manner, providing a sustainable source of food and reducing pressure on wild fish stocks.

Marine bio-resources represent a valuable source of food to humans. From nutrient-rich fish and shellfish to versatile seaweed and algae, the diversity of marine organisms offers a wealth of culinary and nutritional benefits. By promoting sustainable harvesting practices and exploring innovative food technologies, marine bio-resources can play a vital role in addressing global food security challenges while safeguarding the health of marine ecosystems.

5. Marine bioresources as feeds of animals

Seafood of all kinds, by-products of seafood processing, and marine microbiological resources that are not edible are examples of marine biological resources. According to Ozogul et al. (2021), as a result, high-value applications of marine biological resources will include deep-processing seafood, which includes a variety of proteins, enzymes, peptides, polysaccharides, omega-3 long-chain polyunsaturated fatty acids, astaxanthin, taurine, saponin, vitamins, and other substances. Examples of seafood include marine fish, shrimp, crab, scallops, oysters, squid, jellyfish, sea cucumber, sea urchin, kelp, wakame, sargassum, and seaweeds, valuing low-value and by-products of seafood processing, and creating and utilizing marine microbial resources (Aransiola & Maddela, 2024).

Seafood may not be fully absorbed and exhibit its activities in our bodies without additional processing, despite the fact that it is packed with nutrients and bioactive compounds. Deep-processing seafood involves using cutting-edge processing techniques like supercritical fluid extraction, microencapsulation, ultra-micro pulverization, membrane separation, enzyme, and fermentation to create a range of high-value, healthful foods, functional foods, and distinctive medicinal foods technologies.

Marine bioresource may be possible to use structurally varied bioactive substances with significant medicinal and pharmacological potentials as useful, health-promoting additives in animal meals. In addition to species, environmental factors including location, season, and harvesting time affect the bioactive components of marine macroalgae. Studies have demonstrated the impact of including macroalgae or macroalgal extracts into the diet on the intestinal health and immunological function of many monogastric farm animal species, such as pigs, broiler chicken, and fish. It has been proposed that bioactive components from macroalgae, such as fucoidan and laminarin derived from Laminaria, can be used as environmentally friendly substitutes for in-feed antibiotics or as a healthier alternative to therapeutic dosages of zinc oxide in pig diets because of their growth- and health-promoting properties. Studies that have assessed the health effects of feeding intact macroalgae to diets for monogastric animals are scarce, but those that have, have shown that feeding extracts from algal species—particularly Laminaria—has positive impacts on animal health. Weanling pigs were given dietary supplements containing Laminaria spp. or extracts containing laminarin and fucoidan, which enhanced intestinal health. Weanling pigs were given dietary supplements containing Laminaria spp. or extracts containing laminarin and fucoidan, which enhanced intestinal health, alleviated frequent postweaning issues, and decreased postweaning diarrhea (Gahan et al., 2009; Reilly et al., 2008).

By-products of the processing of seafood are typically thrown out as waste or turned into cheap animal feed or fertilizer, which can pollute the environment and deplete marine biological resources. Fish cartilage, chitin in shrimp and crab shells, leftover proteins, enzymes in animal visceral organs, fucoidan in algal waste, and minerals in scallops are just a few examples of the numerous bioactive components found in seafood processing by-products (Ozogul et al., 2021). Using contemporary food processing methods, these active ingredients can also be isolated from those by-products of the seafood processing to create useful materials, high-quality marine health food, and marine pharmaceuticals. Furthermore, several low-value species of marine creatures and plants, like fish Engraulis ringens, seaweed Ulva prolifera, shrimp Antarctic krill, and jellyfish, are not preferred by humans to eat because of their small size or unattractive flavor. However, those marine plants and animals are also rich in bioactive components that can be used as raw materials to produce high-value products like shrimp oil, which includes omega-3, EPA, and DHA, and chitin, chitosan, and chitooligosaccharide, as well as jellyfish and fish peptides and surimi.

According to Garcia-Vaquero and Hayes (2016), marine macroalgae that are brown, red, or green are rich sources of structurally diverse bioactive components that hold great potential for use in medicine and biotechnology. They might be used as useful components in animal feed that improve health. In addition to species, environmental factors including location, season, and harvesting time affect the bioactive components of marine macroalgae. Studies have demonstrated the impact of including macroalgae or macroalgal extracts into the diet on the intestinal health and immunological state of various monogastric farm animal species, such as fish, broiler chickens, and pigs. Laminaria-derived fucoidan and other bioactive components from macroalgae have been shown to have growth- and health-promoting properties. As an environmentally friendly substitute for in-feed antibiotics or as a means of reducing the amount of zinc oxide given to pigs as part of their therapy, fucoidan can be used. Although there is a lack of study on the health advantages of feeding monogastric animal's entire macroalgae, it has been demonstrated that animals benefit from extracts from algal species,

especially Laminaria. Laminaria species or extracts containing fucoidan and laminarin supplemented diets improved intestinal health in weanling pigs (Reilly et al., 2008), relieved frequent postweaning issues (Gahan et al., 2009), and decreased diarrhea after weaning.

Enzymes derived from marine sources, including enzymes that can recognize and convert substrates into extremely active, low-molecular-weight oligosaccharides, monosaccharides, peptides, or lipids: chitinase, chitosanase, alginate lyase, agarase, carrageenase, α-amylase, xylanase, lipases, proteases, and collagenases. Numerous industries, including food, medicine, cosmetics, agriculture, and pharmaceuticals, can benefit from the use of these enzymes (Sun et al., 2020).

6. Marine bioresources as energy source

Algae are an ideal source of biofuel. Algal oil may be treated in conventional refineries to create biofuels. Based on the method and portion of the cell used, algae can produce different types of biofuels. The lipids in algae may be extracted and refined into biodiesel. The carbohydrate component of the algae is then fermented to produce butanol fuel and bioethanol. Table 9.1 is a list of the algae that are utilized to produce biofuel.

6.1 Biodiesel

Commercial biodiesel is produced by transesterification or alcoholysis of triglycerides derived from plants and animal fats. Biodiesel is made from lipids and a high concentration of free fatty acids extracted from macro algae. Macro algae are not widely utilized to produce biodiesel because they lack triglycerides. In comparison to microalgae, the yields of biodiesel produced from macro algae are much lower and are only seldom documented (Aransiola et al., 2023; Chen et al., 2015).

The cavitation formed during the ultrasonic irradiation-assisted transesterification speeds up the reaction rate of an oil and alcohol emulsion to boost the yield (Chen et al., 2015). In another study, wet biomass produced 10 times less biodiesel than dry biomass, suggesting that water adversely affects the transesterification process.

Dehydration is therefore required to obtain a high yield. The conventional technique for producing biodiesel involves several steps, such as oil extraction, purification (degumming, deacidification, and dehydration), and transesterification. As opposed to the two-stage process of producing biodiesel, direct transesterification, or in-situ extraction, reduces the overall production costs by bringing the oil-bearing material directly into contact with alcohol instead of allowing it to react with extracted oil. On the other hand, microalgae can collect 20%–50% of their cellular weight in triglycerides (Chen et al., 2015). It is contingent upon the strain type and conditions of cultivation. The microalgae used to produce biofuel are

TABLE 9.1 Biofuels produced from marine resources.

Microalgae	Macro algae
Tetraselmis suecica	*Enteromorpha compressa*
Chaetoceros calcitrans	*Ulva fasciata*
Dunaliella tertiolecta	*Dictyota adnata*
Phaeodactylum tricornutum	*Centroceras clavulatum*
Nannochloropsis oculata	*Acrosiphonia orientalis*
Isochrysis galbana	*Lobophora variegate*
Phormidium sp.	*Valoniopsis pachynema*
Chlamydomonas reinhardtii	*Padina tetrastromatica*
Phormidium sp.	*Sargassum wightii*
Botryococcus brauna	*Bryopsis pennata*
Spirogyra sp.	*Ulva lactuca*
Tetraselmis suecica	*Bryopsis pennata*
Cyanobacteria	*Caulerpa peltata*

Source: Baskar, G., Abarna, I., Selvakumari, E., & Aiswarya, R. (2018). Marine algae—future source of biofuels. *International Journal of Modern Science and Technology* 3(4), 72–82.

first cultivated under ideal growing conditions. After that, they are placed on nutrient-rich growth media with a restricted diet, which causes them to produce more oil.

Different circumstances can be applied to the growing microalgae in these species to promote the synthesis of triacylglycerols (TAGs). It involves subjecting the microalgae to stresses related to temperature, pH, salinity, starvation, algal culture age, and nutrients, which include nitrogen, sulfur, phosphorus, zinc, and iron. The quality of biodiesel is determined by the saturated and unsaturated fatty acids found in TAG, and higher TAG content increases biodiesel yield and efficiency. Biodiesel produced from microalgae can be improved through genetic modification or molecular engineering by increasing photosynthetic efficiency, biomass growth rate, oil content, and reducing photoinhibition. Photo bioreactors, which offer a controlled environment to increase the microalgal biomass needed to make biodiesel, should be used to achieve a consistent annual oil yield.

6.2 Bioethanol

Bioethanol produced from macroalgal feedstock can also be used as a liquid algal fuel for automobiles. Macroalgae can be utilized as an effective substrate for the fermentation process to produce bioethanol because they are low in lignin and high in carbohydrates (Hamelinck et al., 2005). In aquatic environments, buoyancy permits upright development without lignin crosslinking in organisms with different cellulose structures than those in terrestrial environments. It has a substantial number of sugars (at least 50%) that could be utilized in the fermentation of bioethanol because of its low lignin concentration. The procedure is comparable to the standard ethanol production method technologically. A pretreatment step is crucial for the saccharification and fermentation processes that occur in the synthesis of bioethanol from macroalgae. This is because macroalgae do not readily release their carbohydrates; therefore, a mechanical or acidic pretreatment could increase the reaction space and enhance the accessibility of hydrolytic enzymes to the sugars that are trapped in structural polysaccharides. Despite its apparent economic benefits, acid hydrolysis pretreatment has the drawback of causing glucose to break down during the hydrolysis process (Horn et al., 2000). Saccharification is therefore enhanced by an acid and enzymatic pretreatment combination; however, the right enzymes must be used to achieve high hydrolysis and enzyme recovery efficiency (Demirbas, 2008). Thus, the two primary obstacles to using macro algae as the feedstock for bioethanol production are efficient fermentation and a highly efficient hydrolysis process. As noted by Horn et al. (2000), the red algae *Gelidium amansii*, which is primarily composed of cellulose, glucan, and galactan, can be a productive feedstock for the synthesis of bioethanol. Mannitol and laminarian are commonly used as substrates in the synthesis of bioethanol because they are the main components of other brown algae species like Alarie, Saccorhiza, and Laminaria that store energy.

In addition, every species of microalgae produces a vast amount of carbohydrates in different combinations that can be fermented to produce bioethanol. Since carbohydrates are the main material that stores energy, other than lipids, pretreatment of the microalgal biomass is also required for the successful extraction of fermentable sugars. Hydrolysis is a low-cost and easily managed energy technique that can be used to achieve this. Enzymes or diluted or concentrated acids are frequently utilized for the hydrolysis of algal biomass. To effectively release fermentable sugars from the biomass, it is vital to take temperature, algal loading, and acid content into account (Harun & Danquah, 2011). Green algae like *Spirogyra* sp. and *Chlorococcum* sp. have complex cell walls that store high levels of polysaccharides. This accumulation of starch can be utilized to produce bioethanol (Harun & Danquah, 2011). According to reports, samples that are pre-extracted for lipids can provide ethanol concentrations that are 60% higher than those that are left as dried, complete cells by *Chlorococcum* sp. This indicates that by using microalgae to produce ethanol and lipid-based biofuels from the same biomass, it may be possible to increase the overall economic value of biomass (Harun & Danquah, 2011).

Numerous attempts have been documented to construct genetically engineered microalgae by inserting ethanol-generating genes to increase the production of bioethanol (Ross et al., 2008). A private business established a photosynthetic ethanol manufacturing technology and described how microalgae can produce bioethanol using photosynthetic processes. Despite this, research and development efforts are focused on the commercial production of bioethanol from microalgae. Furthermore, because microalgae are good hydrogen generators, biohydrogen can be produced as a pollution-free, renewable green fuel.

6.3 Biogas

Anaerobic digestion converts the organic components of macroalgae, such as protein and carbohydrates, readily into biogas. As a result, macroalgae can create a substantial quantity of biogas, and their biodegradation is facilitated by the decreased lignocellulose content. Nevertheless, there are a number of challenges associated with producing biogas using

this method, including an incorrect C:N ratio, elevated ammonia levels, pretreatment techniques, and the existence of alkaline metals in macroalgae that could hinder the anaerobic process. Therefore, a proper C:N ratio must be maintained to obtain improved methane production; a lower ratio may cause ammonia to build up in the bioreactor, which would ultimately reduce the yield of biogas (Yen & Brune, 2007). The next step that limits the pace of biogas production is hydrolysis treatment. Several pretreatment techniques, like milling, maceration, and thermal pretreatment, have been shown to effectively break down cell walls and produce biogas (Leh-Togi et al., 2018). Furthermore, a considerable concentration of saline, sulfur, and halogens prevents anaerobic microorganisms from growing and producing as much, which leads to fouling problems. For this reason, pretreatment in both water and mild acid is required to eliminate a sizable portion of the mineral contents.

Together with other carbonaceous feedstock, the microalgal biomass can also be utilized to produce biogas. Because of this, biomass can be used directly without drying and with a high energy yield, making all types of microalgal biomass suitable for use as feedstock in anaerobic digester. Common pretreatment procedures, such as acid-base hydrolysis or mechanical pretreatments, include the use of autoclaves, homogenizers, microwaves, sonication, and enzymes. The C/N ratio is a crucial factor to take into account when producing biogas. Because algal biomass is unfavorable for anaerobic digestion, it may limit the methane output due to its low C/N ratio. The resolution of this problem came from the effective co-digestion of carbon-rich wastes with algae, which resulted in a high C/N ratio and enhanced methane generation by bringing ammonia levels below their inhibitory thresholds (Mussgnug et al., 2010).

It has also been noted that anaerobic co-digestion of corn straw in continuous feed digesters increases biogas output. Additionally, it has been found that the best microalgae for the biogas production process are those with minimal intracellular nitrogen or sulfur content. For instance, microalgae cultivated in growth media that limits the amount of nitrogen or sulfur or those harvested during the stationary phase can enhance the biomass quality for the production of biogas.

7. Exploring safe marine bioresources

The ocean, which encompasses 71% of the world total surface area, is home to a wide range of living resources that we collectively term marine living resources; these are: aquatic animals and plants, in addition to microorganisms useful for human economic purposes. Some of these animals can be employed in the food processing industries or sometimes as food without further processing.

Marine resources entail the physical and biological resources that are domicile in the marine environment and have great benefits to human. The Sustainable Development Goal (SDG) 14 majorly talks about "Life beneath water," which is a major part of the 17 SDG signed by the UN in 2015 during their assembly. The statement of the goal officially is to "conserve and sustainably use the oceans, seas, and marine resources for sustainable development which will serves as food, raw materials, and development of additives."

The global population surpassed 8 billion and is expected to balloon to 9.7 billion by 2050. The challenge to the global food supply will be enormous. Seafood is a vital part of the food consumed worldwide. The global production of marine animals was 112 million tons, while that of marine algae was ~34 million tons (wet weight).

It offers high-quality protein and other essential nutrients for mankind. Yet the edible part of seafood is generally minuscule. Spoilage of by-products or waste view point, maximum 70% for fish or Crustacea harvested from marine waters substrate with in fishery management area Hence, the exploitation in seafood by-products valorization, which is also a bull boost for global food supply (Sandström et al., 2022). Nowadays more and more people worry about which nutrient support rather than an energy, a meal. The oceans are home to vast numbers of marine biological resources, which have promise as sources of bioactive molecules for human health. Using substances from marine environment and the extraction valuable nutrient has been extensively researched on in recent times. This will help in developing and new nutritional benefits of the marine animals, especially in food industries, cosmetics industries, and other important additive industries.

8. Marine bioprospecting

Marine bioprospecting, also known as marine bioprospection, is the systematic study of how novel bioactive substances can be searched in the marine environment (Olsson, 2013). This process involves the exploration of marine biodiversity to identify and isolate valuable genetic and biochemical resources with potential applications in medicine, agriculture, industry, and environmental conservation. The objective of marine bioprospecting is to identify and isolate bioactive compounds from marine sources that can assist in new drugs development, in cosmetics and other industrial products.

Marine bioprospecting also tries to understand marine ecosystem dynamics and how it converts various sources of energy. Marine bioprospecting has helped in the discovery of new medicines (e.g., antibiotics, anticancer agents), development of sustainable agriculture practices, and creation of eco-friendly industrial products and has also assisted in job creation and economic growth.

Bioprospecting processes involves sampling and collection of biological samples from marine ecosystems, then screening and isolation of bioactive compounds from the collected samples, then characterization and structure elucidation of the chemical structure and biological activity of the isolated bioactive compound, and then bioassay and efficacy testing of the biological activity and efficacy and ends with the patenting and commercialization of the isolated bioactive compound. Even though marine bioprospecting offers great opportunity in the biosciences industries, researchers in this field face several challenges such as causing harm to the marine environment during sampling collection. Propensity for intellectual property theft and some regulations and policies form various countries. However, the slow development in technology witnessed in the developing countries also affects the development of marine bioprospecting field.

9. Sustainable production and utilization of marine bioresources

At present, fossil fuels make up approximately 80% of total energy consumption, with transportation representing 58% of this portion (Escobar et al., 2009). The fossil fuel and oil reserves are depleting rapidly, and it has been found that they play a major part in emitting harmful gases into the air. Adverse effects caused by these gases involve rising sea levels, loss of biodiversity, melting glaciers, and changes in climate. One result of the significant demand for crude oil is an increase in its prices, which is also affecting global economic activity. The rapid pace of the modern world is driven by motorization and industrialization, key contributors to the changing fuel consumption trends. Biofuels are one of many alternative energy sources that are currently available. Researchers are consistently focused on developing biofuel from sustainable biomass as a reliable alternative to nonrenewable fuels (Weldemichael & Assefa, 2016). Biofuels offer a variety of benefits compared to traditional petroleum fuels, such as convenient retrieval from organic materials, eco-friendly characteristics for sustainability, combustion reliant on the carbon-dioxide process, and improved environmental impact. Due to its environmental benefits, the use of biofuel in the automotive industry is projected to grow significantly in the next decade. This will definitely result in a substantial growth of the agriculture industry to boost production and its associated by-products. Algae can be categorized into two main groups: macro algae, also known as seaweeds, comprised of green, brown, and red algae, and microalgae, made up of blue-green algae, dinoflagellates, and bacillariophyta (diatoms). Marine algae were the first type of vegetation to appear during the pre-Cambrian period. They play a crucial role as primary producers in the oceanic food chain and make up 90% of total marine plant species (Mussgnug et al., 2010).

As seaweeds found in the ocean contain a high amount of cellulose and minimal lignin, they are being utilized as a useful source of biomass for generating sustainable energy. The minimal amount of lignin suggests that biomass could progress toward biofuel production and transition into a third-generation method with significant benefits. Anaerobic digestion has been attempted using algal biomass in order to generate methane. Recent research has focused on the effective utilization of algal biomass in producing sugar through enzyme hydrolysis and fermentation by microorganisms, leading to the production of liquid biofuels such as ethanol and butanol. Around 8.6 million metric tons of algal biomass are believed to be utilized each year for various purposes such as phycocolloids, fertilizers, nutritional supplements, medication, as well as human and animal food and feed supplements within different industries (FAO, 2020). Due to the incredible health benefits of seaweed, people in developed countries are incorporating more natural ingredients into their diets. Nevertheless, the main objective of seaweed cultivation in advanced countries is to harvest carrageenan, agar, and alginates. Denis et al. (2010) stated that most marine vegetable species are composed of red and brown algae. Marine macroalgae have been used for centuries as traditional and folk medicine in various countries, especially in Asia and the Caribbean. Seaweeds have been recognized for their medicinal properties in Chinese literature as early as 2000 years ago, known as “Pen TsaeKan Mu.” From 300 BCE onward, Chinese and Japanese cultures have utilized seaweeds to treat parasite infections and various other illnesses, as highlighted by Moo-Puc et al. (2008). In the field of medicine, it has been utilized in ointments and dressing solutions, specifically in the field of gynecology.

Blue-green algae, dinoflagellates, and diatoms are types of microalgae that can have a lipid content ranging from 8% to 31% of their dry weight. Several research studies have found that microalgae are a superior and more hopeful option for oil extraction compared to conventional biofuel crops. According to Ramachandra et al. (2013), microalgae have a potential net energy output exceeding 9000 Lt/ha/year. Cyanobacteria, a diverse group of autotrophic microorganisms, can be found in both freshwater and marine phytoplankton. They play a significant role in producing atmospheric carbon dioxide via photosynthesis. Due to its rapid growth rate compared to plants and its ability to thrive without land like macro

algae, the microorganism could be utilized as a source for pyrolysis in order to produce bio-oil. Cyanobacteria are the most suitable organisms for genetic engineering, as they can either produce biofuel from CO_2 or utilize it for carbohydrates. There is ongoing research to develop biofuel for economic and environmental purposes in the near future (Xiong et al., 2015). There are two methods to extract energy from seaweed and agricultural waste based on the initial drying process. There are various methods to produce biodiesel from dry biomass, including direct combustion, pyrolysis, gasification, and trans-esterification. Anaerobic digestion, hydrothermal treatments, enzymatic hydrolysis, fermentation for bioethanol, bio-hydrogen, or bio-butanol production, and fermentation are some techniques used to generate energy from moist biomass (Milledge et al., 2014).

For the purpose of pretreating lignocellulosic materials, physical, physiochemical, chemical, and biological methods have been employed. The processing of lignocellulosic materials is also not simple due to their complexity. The optimum pretreatment technique and parameters are highly dependent on the kind of lignocelluloses (Fig. 9.1).

The cellulose molecules present in the cell walls of plants that produce biomass are tightly bound within the amorphous molecule lignin and hemicellulose. Lignocellulose is a complex substance found in plant cells, comprising about 90% of their dry weight, formed as polymers establish powerful noncovalent connections. Enzymatic hydrolysis is one proposed technique for transforming biomass. Cellulase refers to a group of three primary enzymes responsible for breaking down cellulose. Cellulases are mainly responsible for breaking down the cellulose polymer into glucose monomers (Gan et al., 2003). All three enzymes are necessary to fully degrade the cellulose molecule. Endoglucanase (EG) is the initial enzyme to hydrolyze cellulose, also known as 1, 4-ßD-glucan-4-glucano-hydrolases; EC3.2.1.74. It operates on the haphazardly distributed glycosidic connections found within cellulose molecules. Following this, exoglucanase (EC 3.2.1.91 and EC 3.2.1.74) continues to degrade the ends of cellulose, resulting in the production of glucose or cellobiose. The hydrolysis process would not reach its full potential without the presence of the enzyme β-glucosidase (BGL) (EC 3.2.1.21). BGL acts on cello-dextrins and cellobiose, triggering the activation of other enzymes to convert them into glucose (Jeya et al., 2009). However, a major progress in researching how to digest cellulose in different biomass sources will greatly impact the worldwide fuel supply and economy.

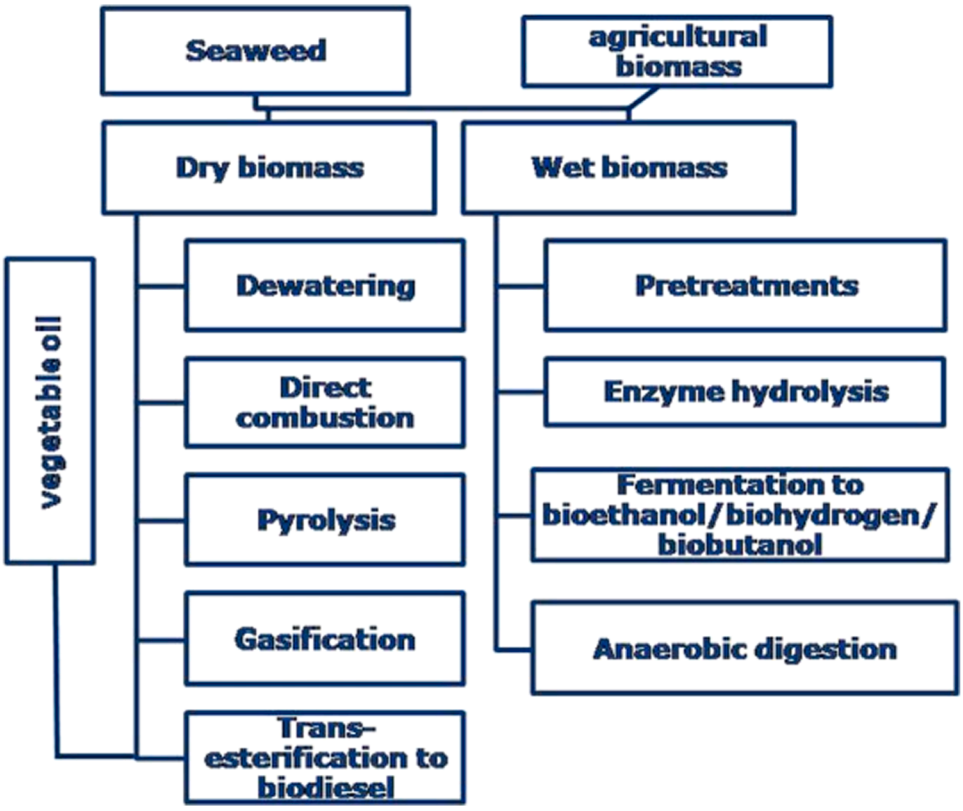

FIGURE 9.1 Process of energy extraction from bioresources.

Xylan, the main hemicellulose present in angiosperm wood, is receiving increased focus in the enzymatic degradation of hemicellulose in biomass. The intricate composition of the xylan molecule consists of D-glucuronic acid, L-arabinose, and xylose, among other components. For years, scientists have attempted to develop conversion enzymes for biomass. When grown on specific substrates like cellulose/hemicellulose, various natural bacteria, actinomycetes, and fungi have been discovered to secrete hydrolytic enzymes. Genetically modified bacteria are currently the primary focus of advanced biotechnological studies to enhance the production of enzymes at a rapid pace. The exploration for novel species that create hydrolytic enzymes remains ongoing in biofuel studies. However, studies have investigated the extracellular enzyme system of Trichoderma sp. as well as the organism's capacity to manufacture enzymes on a large scale.

Studying how cellulase is produced in various microorganisms could also lead to ways to use it for breaking down polysaccharides. Investigation on utilizing agro-industrial biomass like apple pomace, coconut oil cake, cassava waste water, grape pomace, ground nut shell waste, rice straw, wheat straw, wheat bran, sugarcane bagasse, banana pseudo stem, coir pith, bamboo, etc., for cellulase and xylanase production by fungi like *Aspergillus awamori*, *A. niger*, *A. fumigatus*, *A. nidulans*, *A. oryzae*, *A. terreus*, and *Melanocarpus* sp. In recent decades, the cultivation of *MTCC 3922 Penicillium* sp., *Rhizopus stolonifer*, *Scytalidium thermophilum*, *Trichoderma* sp., etc. has been initiated and maintained. Various studies have explored the cost-effectiveness and sustainability of using both solid state (SSF) and submerged (SmF) fermentation for enzyme production. The conversion of carbohydrates like glucose, fructose, and sucrose into cellular energy and the production of hydrogen, ethanol, and butanol are also referred to as fermentation, a biological process. Many microorganisms including fungi, yeast, and bacteria utilize fermentation of carbohydrates to generate energy. Researchers are intrigued by bacteria due to their rapid fermentation process. Bacteria typically need a shorter fermentation period compared to yeast. Each microorganism possesses specific limitations, like limited final product yields or the incapacity to break down both pentoses and hexoses.

Biofuel production consists of three generations: first, second, and third. The traditional method for creating ethanol and biodiesel is considered part of the initial generation production process. The process of transesterification is employed to remove oil from oil-rich plants and change vegetable oil into a type of fuel that can be directly used in engines to generate biodiesel. The modified engines can operate using straight vegetable oils as fuel. Enzymatic catalysts or acids, alkaline, ethanol, or methanol are used in the process of transesterification to produce glycerin and fatty acids as by-products (Hassan & Kalam, 2013). The breakdown of cellulose through hydrolysis and the following fermentation of sugar form the basis of second-generation biofuel production techniques. The gasification process can be utilized to create syngas from biological materials, proving to be quite beneficial. Various catalytic techniques can be utilized to convert this syngas into liquid biofuels. The process of anaerobic digestion can produce methane and natural gas. Crop waste or agricultural waste decomposes during the process (Elshahed, 2010). Currently, biofuels made from algae are produced using third-generation techniques. Algae have the capability to produce oil efficiently, which can be refined into diesel fuel and specific compounds found in gasoline. Genome and metabolic engineering techniques can guide the carbon metabolic pathway toward producing ethanol as the end product. Algal biomass can be produced using both open raceway ponds and photo bioreactors. A downside of the third-generation approach is that its biofuel production is not as consistent as that of the alternative methods.

Despite the even distribution of renewable resources globally, both nuclear and fossil fuel resources are depleting rapidly and have restricted accessibility. The energy generated from renewable sources exceeds the current worldwide energy usage. There is much doubt about the long-term viability of the existing energy systems because of worries about the economy, equality, and environment. Many conservation initiatives and projects for alternative fuels are being created to protect the environment, societies, and variety of species. Entities from the public, private, and nonprofit sectors have taken part in these initiatives. An urgent requirement exists for the merging of public and private investment to drive the commercialization of biofuels. Countries such as Brazil and the Netherlands are on the forefront of creating sustainable biofuels from crops and have made deals to collaborate on biofuel production. The US government provides funding to accelerate research and development for biofuels in the market. China ranks as the third biggest energy producer globally, following the US and Brazil. The primary focus of China's government is on the production of industrial ethanol. The goal of India's "National Biofuel Policy" is to substitute biodiesel for diesel to fulfill 20% of the country's diesel consumption. Furthermore Hassan and Kalam (2013) have recommended the substitution of 10%–20% of gasoline with bioethanol.

10. Conclusion

Marine bioresources are a vital component of the world's ecosystem, offering an array of benefits for human well-being, economic growth, and environmental sustainability. This overview has highlighted the significance of marine bioresources, showcasing their diversity, high-value utilization, and potential applications. The diversity of marine

bioresources is staggering, encompassing various species, habitats, and ecosystems. Effective conservation and management strategies are crucial to maintain this biodiversity. High-value utilization of marine bioresources has transformed industries such as pharmaceuticals, cosmetics, and food. Innovative technologies and research continue to unlock new opportunities. Marine bioresources serve as a vital source of nutrition for humans, providing essential proteins, omega-3 fatty acids, and micronutrients. Sustainable fishing practices and aquaculture ensure food security. As feed for animals, marine bioresources support the growth of aquaculture, agriculture, and livestock industries. Marine bioresources also hold promise as a renewable energy source, with potential applications in biofuels, biogas, and tidal power. Ensuring safe marine bioresources requires rigorous monitoring, regulation, and responsible harvesting practices. Marine bioprospecting has emerged as a critical tool for discovering novel compounds, driving innovation and economic growth. Ultimately, sustainable production and utilization of marine bioresources depend on integrated approaches, balancing human needs with environmental stewardship.

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Chapter 10

Production of biofuel from marine biomass

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1. Introduction

Biofuel is an energy that is produced rapidly from biomass, as opposed to the extraordinarily slow processes in nature that produce fossil fuels like oil. Plants or biowaste from homes, businesses, or agriculture can be used to make biofuel (Mahapatra et al., 2021). Although they may also be utilized to generate heating and electricity, biofuels are mostly employed for transportation. Renewable energy sources include biofuels and bioenergy in general. In light of the "food versus fuel" controversy, differing opinions on its sustainability, and the potential loss of forests and ecosystems brought on by the production of biofuel, the usage of biofuel has come under fire (Lark et al., 2022). A number of biomasses have made considerable strides toward becoming viable eco-friendly base products and are among the most intriguing fossil fuel substitutes (Aransiola, Oyewole, et al., 2024; Maddela et al., 2024). The act of transforming biomass via methods of converting biorefineries into many economic items, such as fuel and chemical substances (Aransiola, Adeniyi, et al., 2024; Estebsari et al., 2020). A typical biorefinery energy source derived from biomass is biofuel. Biofuels are classified as first, second, or third-generation fuels depending on the types of feedstock used. The feedstocks used to make first-generation biofuels are foods used for human consumption. Many biomasses are part of the most interesting alternatives to fossil fuels and have come a long way toward being sustainable, environmentally beneficial base goods (Godvin Sharmila et al., 2021). Biofuel is a common biomass-derived energy source used in biorefineries. The classification of biofuels into the three stages of generation fuels is based on the kind of feedstock that is utilized. Foods intended for consumption by humans serve as the raw materials for the initial generation of biofuels (Panchal & Brown, 2024).

Large fuel supplies are running out quickly and unpredictably due to a number of factors, including population growth and the need for renewable energy, which is mostly brought on by the world's fast development and industrialization. The main, nonrenewable source of energy is fossil fuels. The careless ecology is negatively impacted by the use of fossil fuels, deteriorating air quality, and worldwide climate change, all of which are major contributors to environmental imbalances and health consequences (Urtamo et al., 2019). Between 2010 and 2040, there will likely be a 40% increase in consumer demand for fossil fuels. Thus, supplying a unique supply of environmentally friendly energy is a top priority (Aransiola, Adeniyi, et al., 2024; Wells et al., 2017).

Due to they can produce larger yields using fewer resources, seaweeds, cyanobacteria, and maritime resources are attractive sources of third-generation biofuel.

Arguably, the most potential nonconsumable biofuel providers are macroalgae, which can grow quickly in hard conditions and salty water. The biofuel made from algae is sulfur-free, perfectly biodegradable, and safe (Guo et al., 2022). The ash (18%–55%), carbohydrates (25%–60%), protein (5%–47%), and lipids (<5%) content of each group varies according to the species and is heavily impacted by both biological and environmental habitat development factors

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like temperature and light. Depending largely on the method and type of algae utilized, algae can even be converted into a range of fuels (Adarshan et al., 2023; Gimba et al., 2024). Algal biofuels, which are regarded as third-generation fuels, have the potential to address the energy issue due to their quick growth, high CO_2 collection, and ease of cultivation even on barren soil. The fatty acids and acyl glycerides found in algal biomass are utilized to produce biofuel, which reduces the need for fossil fuels. Algal oil may be extracted and used to produce biodiesel, while the leftover biomass has a significant amount of sugar that is capable of producing bioethanol (Aransiola, Bamisaye, et al., 2024; Schumacher et al., 2024). To enable commercial biofuel generation from algae at a scaleup that is adequate to significantly reduce energy requirements, a number of obstacles must be overcome. This review's goal is to talk about various methods for producing biofuel from macroalgae (Auta et al., 2024; Jeswani et al., 2020). Additionally, in-depth information has been given regarding the patent for the production of macroalgal biofuel. The paper finishes with a review of some of the challenges that macroalgal biorefineries face and future research directions that should be investigated in order to support further industrial growth (Granic et al., 2018) (Fig. 10.1).

2. Macroalgae: Feedstock for the generation of biofuel

The macroalgae are a type of aquatic eukaryote that are both varied and nonphylogenetic. They are classified into three families: Algal species that are green are called Phaeophyta, red-colored algae are called Phaeophyta, and brown-colored algae are called Phaeophyceae. It is feasible to grow algae in practically any kind of water, even wastewater (Bortz et al., 2023). Additionally, the Macroalgae's oil concentration is almost 30 times higher than that of conventional feedstocks, and the growth rate of algal biomass is 20–30 times faster than that of fertilizer for crops. The algae-derived material is entirely sulfur-free and biodegradable, and the oil extracted from it is of higher excellence. Additionally, the absence of lignin in aquatic algae makes it easier for their conversion into biofuel more readily than in plants that grow on land and makes them simpler for bacteria to digest throughout the biorefinery procedure (Morales Bayetero et al., 2022). Following the conversion procedures, biomass leftovers can be utilized to produce fertilizer, fuel, and other products for heating. Because macroalgae are high in water content and low in protein (7%–15%), fat (1%–5%), and carbohydrates (25%–50%), they are a suitable feedstock for producing biohydrogen, ethanol from biomass, and biodiesel.

Similar to this, macroalgae can be utilized as fertilizers, feed for animals, hydrocolloids, food additives, and medicinal substances. Macroalgae make up 83 percent to 90 percent of the global seaweed market and bring approximately $5 billion annually to the food business. Utilizing macroalgae as a raw material to create biofuels, such as biodiesel, ethanol from biomass, biohydrogen, biomethane, and bio-oil, has been the subject of extensive research (Aransiola et al., 2023; Cavelius et al., 2023). Most of the results gave a positive summary of the macroalgae-based biofuel production method. Numerous techniques can be used to develop macroalgae both onshore and offshore. As seen in Fig. 10.2 below, Kelp development, floated cultivation, and rafts cultivation are examples of offshore cultivation techniques. Because it is less

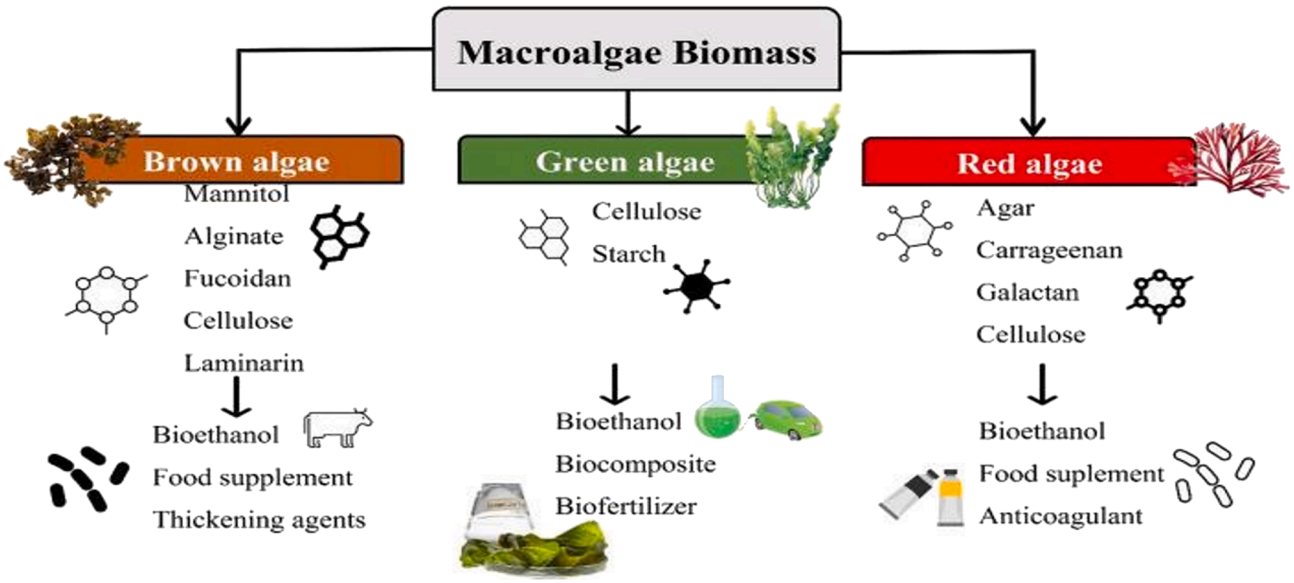

FIGURE 10.1 The idea of a third-generation biorefinery using microalgae biomass.

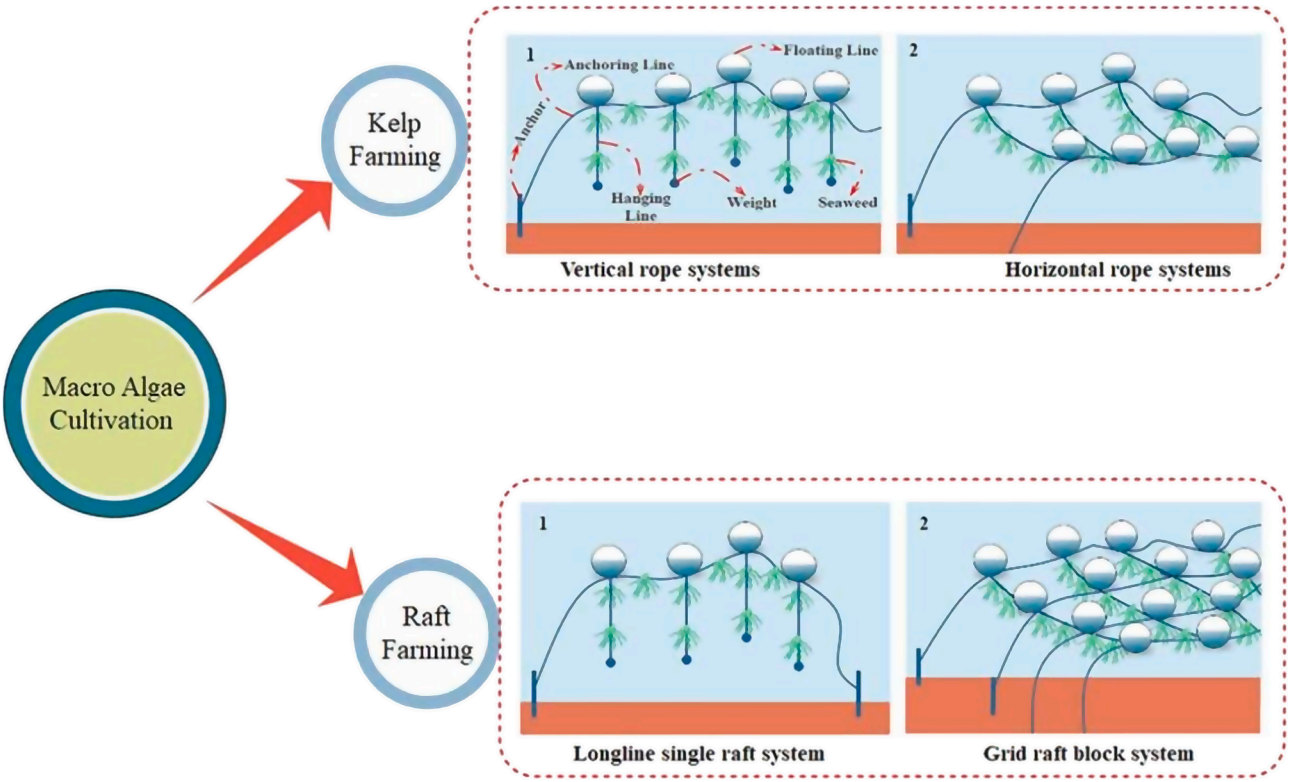

FIGURE 10.2 Various systems for cultivating macroalgae (Fukuda et al., 2001).

expensive to install and maintain, ropes or netting cultivation is considered a prevalent cultivation approach (Fukuda et al., 2001). Macroscopic algae may be cultured in lagoons because the nutrients come from the saltwater. Long lines, fixed-off-bottom, and rock-based cultivation are some more techniques for growing macroalgae. A further kind of cultivation is called transplantation, whereby plant saplings have the ability should be cultivated in tanks after being grown within the house, afterwards being moved using ropes into the sea (Houghton et al., 2006).

Seawater gardening has been widely employed in onshore approaches because of its high production of products and very large control over safety. Onshore farming is more environmentally friendly than offshore culture since it does not harm marine species and provides excellent adaptability for a wider variety of macroalgae (Lilonfe, Davies, et al., 2024). Furthermore, one element that can encourage improved algal development in this kind of culture is mixing. Although it costs more, appropriate agitation or circulation is the most effective method of mixing algae cultures. Currently, there is no low-cost, sustainable, creative method for large-scale deployment of this onshore agriculture. It's also conceivable that open farming could encroach on an abiotic and biotic ecology (Pontrelli et al., 2018). As a result, the algae lose quality and are no longer appropriate to be utilized in the chemical in nature, cosmetic, and pharmaceutical industries. Sebok et al. created a ring-shaped culture method for cultivating algae on land. This method significantly reduced costs by reducing the amount of growing media needed (Lilonfe, Dimitriou, et al., 2024).

This technology not only supplies nutrients and CO_2 separately, but it also drains the heat generated during agitation, resulting in an improved growth phase. Furthermore, the cultured algal biomass's growth rate is crucial for demonstrating the effects of the growing techniques. Macroalgae provide marine species with a good, special environment that supports and nurtures ecosystems (Knothe, 2010). Algal growth is influenced by a number of variables, including salinity, pH, turbidity, light intensity, water temperature, and nutrient concentrations. However, algae harvesting proves problematic and harms the ecology. Furthermore, inorganic fertilizers such as phosphorus and nitrogen have been utilized to promote the development of macroalgae. This nutritional enrichment causes algal blooming, which is observed throughout the shoreline and upsets the surrounding ecosystems, most likely leading to hypoxia (Ryckebosch et al., 2011).

Following the process of photosynthesis macroalgae sequester a significant portion of inorganic carbon, which is then broken down into carbon dioxide, HCO^{-3}, and carbon dioxide once more. Carbon will be replenished in saltwater by processes like respiration, photorespiration, and carbon trapping (Greenwell et al., 2010). A portion of the carbon is

transformed into carbon dioxide by biological deterioration, while the remainder lingers as organic carbon particles in the water until they sink to the bottom. Phosphate has a limited time to be captured by macroalgae before it becomes dilute in deep seas (Dinh et al., 2009). The use of seaweed cultivation as a potential method for removing nutrients has grown over time. Moreover, a decrease in the amount of light in the water beneath macroalgae cultivation sites could negatively impact other marine organisms in locations that are shallow. In the coordinated multitrophic aquaculture sector, macroalgae cultivated in both onshore as well as offshore marine ecosystems can use fish farming nutrients as fertilizers (Ajayebi et al., 2013).

3. Macroalgae and biofuel production

Any fuel made from biological matter, whether it be liquid, gaseous, or solid, is referred to as biofuel. These biofuels can be utilized in a range of industrial processes as well as in cars. The specific kind of biomass used determines the biofuel produced in all three generations (Yang et al., 2011). Numerous biochemical and thermochemical processes can be used to extract biofuels from macroalgae. The most widely used processes for producing biofuel are the process of fermentation, the liquefaction transesterification process anaerobic digestion, and pyrolysis. However, the complex organization of the algal biomass may affect the hydrolysis processes over a prolonged limited rate phase (Demirbas, 2011).

Therefore, it has an impact on biofuel output, thus it can be decreased by adding an appropriate pretreatment. Pretreatments increase solubilization by dissolving molecular bonds and depolymerizing complicated structures (Rodionova et al., 2017). The solubilized samples facilitate the process of transformation process and improve the yield of biofuel. Several pretreatment techniques, including chemical, biological, mechanical, and combinatorial approaches, are employed to solubilize complex substrates in macroalgae. Table 10.1 lists several macroalgal species that produce biofuel (Aro, 2016). The dissolved materials facilitate the transformation procedure and improve the yield of biofuel. A variety of pretreatment techniques, including mechanical, biological, physical, chemical, and combinatorial techniques, are employed to solubilize the complex substrates in macroalgae. Table 10.1 lists the several macroalgal species that produce biofuel (Abdullah et al., 2019).

3.1 Production of biodiesel

A mixture of long-chain fatty acids and monoalkyl esters made from algae biomass is called biodiesel. Biodiesel has remarkable igniting properties and 78% lower carbon dioxide and greenhouse gas emissions than fossil fuels (Xu et al., 2018). Osman and colleagues investigated the manufacture of Ulva intestinal biodiesel and discovered a yield of 32.3 mg/g dw. *Gracilaria corticata* and *Chaetomorpha antennina* yielded 2.4 and 2 mL of biodiesel each 10 g of biomass from algal cells, accordingly, according to Sharmila et al.'s study. Two steps were then developed for the production of biodiesel after Tamilarasan esterified the Free fatty acids of Enteromorpha condensed algal oil to reduce it from 6.3% to 0.34% (Kougias & Angelidaki, 2018). An acid catalyst was used in the first phase to generate the FFAs, and in the second step, the oil was converted to biodiesel. In a different effort, *Cladophora glomerate* produced glucose, which was then converted to FFA-producing biodiesel. The largest lipid content achieved by Xu's recent attempt to make biodiesel utilizing macroalgae to supply oleaginous yeast with carbon was 48.30%. In the meantime, the oleaginous yeast can be cultured using the accompanying FFAs (Zhang et al., 2014).

3.2 Bioethanol production

A transformation yield rate of 89% was achieved by Borines et al. when producing bioethanol from Sargassum spp. Bioethanol synthesis via the fermentation from the red seaweed *Gracilaria verrucosa* yields 0.43 g/g sugars Yoza and Masutani conducted experiments on the manufacture of bioethanol from Ulva reticulate, a macroalgae biomass (Bryngemark, 2019). One gram of material yielded 0.37% v/v concentration of bioethanol. The aforesaid results, according to the scientists, also roughly represent that for every dry ton of macroalgae, 90 liters of ethanol, are generated. The generation of bioethanol from *Ulva intestinalis* yielded 0.081 g/g dw, according to a study by Osman et al. A 90.9% bioethanol conversion yield was achieved by processing seaweed trash using saccharification and fermentation methods (Forsberg, 2009). An anaerobic fermentation within an entire reactor, *B. custersii* converted 90 g/L of glucose into 11.8 g/L of ethanol, but in a running reactor, the same amount of sugar produced roughly 27.6 g/L of ethanol. Additionally, Offei et al.'s findings suggested that *E. cottonii* would be a viable feedstock for the production of bioethanol. Red algae, *Palmaria palmata*, which are primarily composed of carrageenan, subsequently acid hydrolyzed (0.4 M H_2SO_4 at 125°C for 25 minutes) to liberate glucose, galactose, and other sugars, which were subsequently fermenting to produce

TABLE 10.1 Macroalgal production for biofuel (Lü et al., 2011).

Kinds of biofuels	Kind of species	Procedures for pretreatment or conversion	Conditions for the prior to treatment or process of conversion	Potential for generation or yield of biofuel	Refs.
The biodiesel	The Ulva fasciata	Transesterification by catalysis	Methanol to oil molar ratio is 9:1. 6 hours; temperature: 80–100°C	88%	Khan et al. (2016)
	Anamorpha Chaetomorpha	The process of transesterification	Ethanol-chloroform solvent: 1:20 (w/v)	2.1 mL/10 g Biomass	Sharmila et al. (2022)
	Gracilaria corticate	The process of transesterification	Hexane-ether solvent—1:20 (w/v) 2 mL/10 g biomass	2 mL/10 g biomass	Sharmila et al. (2022)
	Ulva-intestinalis	Transesterification	–	32.3 mL/10 g biomass	
	Enteromorpha compress	Base transesterification	Base—1% NaOH, methanol–oil ratio—9:1,—60°C: Time—70 minutes	90.6%	Suganya et al. (2013)
Bio-oil	*Laminaria digitate*	Oven drying	−70°C, time −72 hours	235.4 ± 14.1 mL/gVS	Kostas et al. (2019)
	Saccharina japonica	Pyrolysis in a fixed-bed reactor	450°C	47% conversion	(Choi et al., 2016)
	Ulva lactuca	Microwave pyrolysis	500°C	18.4 wt.%	Amrullah et al. (2023)
	Porphyra tenera	Packed tube reactor pyrolysis	500°C	47.4 wt.%	Bae et al. (2011)
	Laminaria japonica	Packed tube reactor pyrolysis	500°C	45.8 wt.%	Bae et al. (2011)
	Undaria pinnatifida	Packed tube reactor pyrolysis	500°C	37.5 wt.%	(Bae et al., 2011)
Bio-hydrogen	*Laminaria japonica*	Microwave	−160°C, time—30 minutes	15.8 mL/g TS	Chen et al. (2022)
	Laminaria japonica	Ultrasonic	Sonication frequency—20 kHz	23.56 ± 4.5 mL/g	
	Laminaria digitate	Hydrothermal	−140°C time—20 minutes	4.0 ± 1.2 mL/g VS	Ding et al. (2020)
	Chaetomorpha antennina	Surfactant-aided microwave pretreatment	Microwave power—0.36 kW ammonium dodecyl sulfate—0.00	0.003574.5 mL/g COD	Kumar et al. (2019)
	Ulva reticulate	Microwave-H_2O_2 alkali pretreatment	Microwave power—0.36 kWH_2O_2 dosage—24 mg H_2O_2/g biomass pH—1	1087.5 mL H_2/g COD	Kumar et al. (2019)
Biomethane	*Palmaria palmata*	Anaerobic digestion	Microwave power—0.36 kWH_2O_2 dosage—24 mg H_2O_2/g biomass pH—10	7.5 mL H_2/g COD	
	Chaetomorpha antennina	Ozone disperser pretreatment	Semi-continuous anaerobic digestion disperser g force −1613 g, treatment time—30 minutes, ozone dosage −0.00049 g O_3/g TS0.20	320 mL CH_4/gVS	Tamilarasan et al. (2017)

Continued

TABLE 10.1 Macroalgal production for biofuel (Lü et al., 2011).—cont'd

Kinds of biofuels	Kind of species	Procedures for pretreatment or conversion	Conditions for the prior to treatment or process of conversion	Potential for generation or yield of biofuel	Refs.
	Chaetomorpha antennina	Thermo-chemo disperser	Disperser g-force of 1613 g,−80°C, NaOH—1 N, pH—11	TS0.20 g COD/g COD	Tamilarasan et al. (2017)
	Laminaria digitate	Heat	104°C	215 mL/g VS	Ding et al. (2020)
	Laminaria digitate	Oven drying	−70°C, time −72 hours	Dried biomass—97.66 m^3 CH_4/ Fresh biomass—67.24 m^3 CH_4/t	Adams et al. (2015)
Bioethanol	*Chaetomorpha linum*	Wet oxidation method	200°C	44 g ethanol/100 g glucan	Schultz-Jensen et al. (2013)
	Saccharina japonica	Low acid pretreatment	Acid—0.06% (w/w) sulfuric	6.65 g/L	(Offei et al., 2018)
	*Saccharina japo*nica	Thermal acid hydrolysis	Acid temperature −170°C, Time—15 minutes	7.7 g/L	Jang et al. (2012)
	Laminaria digitate	Oven drying	Acid—40 mM H_2SO_4 temperature—121°C time—60 minutes	13.6 ± 0.2 μL/gDS	
	Ulva linza	Mild acid hydrolysis	Temperature—70°C, Time −72 hours	12.01%	Robak & Balcerek (2018)

ethanol (Searchinger et al., 2008). The biomass of *Kappaphycus alvarezii* was saccharified at 100°C in 0.9 M H_2SO_4, with the best the saccharification process yields occurring at the bench (16 kg) and laboratory (250 g) scales, accordingly, at 26.2% and 30.6% (w/w). According to Stefan Kraan et al. cleansing macroalgae at 65°C in an acidic solution (0.09 M HCl in H_2O) improved laminarin hydrolysis (Sawyer, 2008).

3.3 Generation of biohydrogen

Biohydrogen is widely regarded as a renewable energy origin with a high energy yield that will be the primary fuel source of the future. Yin et al. treated *Laminaria japonica* with thermal treatment at 170°C, yielding a hydrogen yield of 109.6 mL/g chemical oxygen demand (COD). Kumar et al. administered Ulva reticulate, an algal biomass, using a disperser therapy, yielding a biohydrogen yield of 45.5 mL (Righelato & Spracklen, 2007). Algae Laminaria japonica was treated with an alkaline procedure that yielded 15 mL/g of biohydrogen. Additionally, biohydrogen yield of 63 dm^3/kg VS was obtained by treating the macroalgae with the use of hydrogen peroxide chemical-based. In a different attempt, glucose was produced by *Cladophora glomerata* and subsequently transformed into free fatty acids suitable for biodiesel. The highest lipid concentration was 48.30% when Xu recently tried to use macroalgae as a carbon source for oleaginous yeast to create biodiesel. Furthermore, the oleaginous yeast could be cultured employing the byproducts FFAs that precede mannitol (Heselton, 2005).

In their microwave pretreatment experiment, Yin et al. treated the macro-algae *Laminaria japonica* for 30 minutes at 160°C, yielding 15.8 mL/g TS of hydrogen. Kumar and colleagues treated *Ulva reticulate*, an algal biomass, with a disperser to produce 45.5 mL of biohydrogen. 15 mL/g of biohydrogen was produced by treating the algae *L. japonica* with an alkaline solution (Sasongko et al., 2017). Additionally, the macroalgae were treated with the chemical hydrogen peroxide to provide a biohydrogen output of 63 dm^3/kg VS. Wang and colleagues investigated the mixed microwave and acid pretreatment approach for *L. japonica* and produced 28 mL/g TS of biohydrogen in 15 minutes at 140°C with 1% H_2SO_4 (Hongyan & Guangce, 2014).

3.4 Production of biomethane

After treating the algae, the biomass of *C. antennina*, with a chemo disperser, 47.25 mL/g COD of biomethane was produced (Michael Fredenslund et al., 2023). By treating the red macroalgae *P. palmate*, Jard et al. investigated the synthesis of biomethane and obtained a high biomethane output of 308 ± 9 mL/g VS. Gurung et al. investigated the generation of biomethane from brown and green algae and found that the yields were 256 ± 28 and 179 ± 35 mL/g VS biomethane, respectively (Le Mer & Roger, 2001). An anaerobic digestion method was used to treat Laminaria hyperborean, resulting in a 70% biomethane output. With yields ranging from 140 to 280 mL of methane per gram of VS (volatile solids) for green and brown algae genera like Sargassum, Gracilaria, Laminaria, Ascophyllum, and Ulva, marine biomass has demonstrated potential for steady methane generation. Some research even suggests that for Laminaria sp., Macrocystis sp., and Gracilaria sp., biomethane recovery can reach 260–500 mL methane per g VS (Le Mer & Roger, 2001).

3.5 Bio–oil production

Bio-oil is capable of being used as a chemical or straight as fuel for internal combustion engines. Pyrolysis, which involves heating algal biomass without oxygen, is thought to be one of the most feasible conversion methods to create bio-oil (Mahapatra et al., 2021). When the green macroalgal species *Enteromorpha prolifera* was hydrothermally liquefied at 300°C for 30 minutes with Na_2CO_3 acting as a catalyst, 23.0% dw of bio-oil (with an energy density of 29.89 MJ/kg) was produced (Malode et al., 2021). The same liquefaction was also studied by Anastasakis and Ross in the brown macroalgae *Laminaria saccharina*, which influences reaction parameters. A maximum bio-crude of 19.3% was obtained with an algal/water ratio of 1:10 at 350°C and a residence time of 15 minutes without catalyst (Anastasakis & Ross, 2011).

4. Biofuel production: Contemporary issues

An increasingly important method for improving the production of biofuel in a variety of industries is nanotechnology. Its function in macroalgal biorefinery facilities is to create nanoparticles for the purpose of moving components inside the algal biomass because of its large surface area (Singh, Langyan, et al., 2022). The encapsulation of cellulase by nano-materials is a novel strategy to improve the production of biofuel from macroalgae, which may reduce the amount of

hydrolyzed enzyme used. Additionally, magnetic nanoparticle biosynthesis is underway for the generation of biofuel. The ability of macroalgae, which are bio-nano manufacturing facilities, to produce metallic nanoparticles that come in wet and dry forms is astounding. Integrated techniques are developed to create sustainable and affordable biofuels (Raj Singh et al., 2022). Previous studies have demonstrated that by promoting direct interspecies electron transmission in complex marine communities, the conductive nanomaterial graphene can enhance AD performance. Conversely, excessive graphene is ascribed to the microbial restriction brought on by a high nanometer concentration. Even if the production of biomethane has significantly increased, the exorbitant cost of graphene may prevent its widespread use (Leong et al., 2021). Generally speaking, integrated approaches favor processes like pyrolysis, fermentation, hydrothermal liquefaction, etc. Pyrolysis and anaerobic fermentation combined increase the output of bio-oil by 10% and methane by about 17%. Hydrothermal liquefaction is another exciting technology in the field of producing biofuel. The macroalgal species quickly use up 80%–85% of the moisture they contain undergoing hydrothermal converting, also known as liquefaction, to generate fuel. Additionally, by depolymerizing the algae into the presence of sugars this hydrothermal liquefaction process is coupled with microwave technology to provide fuels that are affordable. In order to yield biofuels from macroalgae for the aviation industry, microwave pyrolysis can be used to generate the perfect microenvironment (Kumar et al., 2018). Methane production is increased by 17% and bio-oil yield is increased by about 10% by the integration of fermentation in anaerobic conditions and pyrolysis. Additionally, the production of biomethane and biodiesel is improved by agar extraction prior to the aerobic breakdown of algal biomass. In macroalgal biorefineries, genetic and metabolic engineering techniques have lately become more significant, providing a breakthrough in biotechnology and innovative tools (Li, Zhang, et al., 2020).

4.1 Enhancing biofuel production from microalgae via genetic engineering

The amount produced from algal biomass can be increased through technological breakthroughs utilizing metabolic and genetic engineering. By rerouting the transfer of carbon and lowering equivalents from other routes, the generation of oil from microalgae can be increased by modifying the synthesis of lipid enzymes or any competing alternative pathways (Al-Zuhair, 2007). Changing particular genes that regulate different phases of the metabolism is the most popular method. However, due to the complex regulation of microalgae's lipid production, the efficacy of this approach varies. The green-colored algae *Chlamydomonas reinhardtii* has been the subject of genetic investigation. Consequently, the majority of gene knockdown techniques have been created for this species. However, diatoms and other more important algae that are useful for industry are increasingly being produced as tools. Controlling the lipid production for a certain strain can have a significant impact on both the amount and the grade of biofuel produced (biodiesel) (Korkhovoy et al., 2016). Genetic screening using genome-scale mutant datasets and their high-throughput examination may help develop efficient methods for enhancing microalgal strains. As a result, microalgae strain bioengineering requires this understanding. The enhancement of the microalgae strain is typically achieved through the integration of several information sets. In the procedure of strain augmentation with genetic engineering, molecular techniques for precise gene targeting, specific screening, and stable transformation are crucial for carrying out genetic manipulation (Radakovits et al., 2010).

Lipid synthesis in microalgae is initiated by acetyl-CoA carboxylase (ACC). Roessler's work found that overexpression of the ACC gene from *Cyclotella cryptic* microalgae boosted the enzyme activity by two to three times. Enhancing the entire lipid production process might need more than just raising ACC gene expression according to Sheehan et al. By limiting competing processes, lipid production may also be enhanced (Chauton et al., 2021). Deactivating genes directly related to triacylglyceride (TAG), free fatty acid activation and fatty acid oxidation increased lipid content. Either mutation or RNA silencing would need to be used to inactivate the gene. Eliminating genes involved in lipid catabolism may have detrimental effects on cell division and development as well as possibly raising fat storage. In order to help with cellular ATP requirements and/or cell division, a number of microalgae begin to accumulate TAG throughout the day and deplete its stores at night during diel light-dark cycles (Andreotti et al., 2020).

Thus, inhibiting oxidation would prevent TAG from being lost overnight, but this would probably result in less development. Thus, this method may not work well for microalgae grown in open ponds outside, but it may work well for increasing the production of lipids in microalgae produced in photobioreactors that have constant light and/or exogenous carbon sources. Additionally, an investigation revealed an overexpression of malic enzyme (ME), that has been previously recognized for its function in metabolic pathways like photosynthesis, energy metabolism, and lipogenesis, leading to increased lipid accumulation and a profitable biodiesel supplier. Scholars can use transcriptome evaluation employing next-generation sequencing, or to gather and identify any programming or noncoding in order to get a deeper understanding of the genetic structure and metabolites of microalgae. Using transcriptome data from the latest generation of sequencing has shown the capacity to reveal intriguing metabolic pathways and intriguing targets for metabolic

modification in microalgae, as well as to support functional genomic research for the manufacture of next-generation biofuel (Barros et al., 2015).

The transcriptome's annotation for the function was effective in identifying the gene expression for important enzymes that regulate *Dunaliella tertiolecta's* fatty acid production and degradation (*D. tertiolecta*). The transcriptome of *D. tertiolecta* comprises most of the enzymes essential for the process of biosynthesis elongation, and degradation of fatty acids. The biochemical and molecular knowledge essential for the physiological alteration of microalgae fatty acid synthesis is expanded by these findings. Additionally, transcripts for the enzymes that break down TAG were discovered (Barsanti & Gualtieri, 2018). Furthermore, it was discovered that *D. tertiolecta* contains an important amount of transcriptions that encode digestive enzymes that participate in the biosynthesis and catabolism of starch. Accumulated starch is a promising supply for the manufacture of ethanol, butanol, and hydrogen for different biofuels. The blockade of TAGL and other TAG-degrading enzymes may lead to an increase in the TAG content (Broch et al., 2019).

Making biofuel from microalgal starch could solve the preprocessing and environmental problems associated with using plant-based starches and lignocellulosic materials for ethanol synthesis. De novo transcriptome assembly and sequencing of the microalga Eustigmatos cf. polyphem additionally revealed metabolic pathways involved in the generation and breakdown of carbohydrates, fatty acid TAGs, and carotenoids, as well as the identification of transcripts encoding essential enzymes. The substantial number of transcripts detected enables thorough genome annotation and provides a strong basis for the next genomic research on oleaginous microalgae. The genetically modified version of this organism to expand the availability of biomass for commercial microalgae biofuel production is greatly aided by these discoveries (Bruhn et al., 2019).

4.2 Commercialization and expansion of biofuel

The emergence of the previously described intriguing prospect of macroalgal biological refineries has brought attention to the potential of creating innovative biological products from macroalgae, as numerous of their biochemical components have already demonstrated economic utility. The output of these bio-fuel products offers significant commercialization and product allocation prospects, despite the fact the creation of these processes in biology is still in its early phases (Cheregi et al., 2019). The main practical feedstock for the synthesis of biofuels and other biochemicals through biorefinery activities is macroalgae. Because of the cost-effectiveness of the processing methods and the growing popularity of the intermediates generated throughout the biorefinery procedure, the manufacture of biofuels from macroalgal biomass is still in its infancy. Biomethane, biobutanol, bioethanol, and biodiesel are the main forms of biofuels that are typically made from macroalgae (European Commission, 2018).

Additionally, even while research continues, biofuels, especially some hydrocarbon derivatives like bio-oil, have grown less common. A swift expansion of effort is being made to replace gasoline and diesel in the transportation sector with liquid biofuels, particularly biobutanol, bioethanol, and biodiesel, to increase government subsidies (Galasso et al., 2019). One of the most important biofuels has been thought to be bioethanol in particular. Fortunately, a lot of remedies have been put forth for the production of macroalgal bioethanol because an important barrier to its commercialization is the complexity of employing conventional fermentation in conjunction with using strains of bacteria to produce bioethanol from macroalgal polysaccharides and monosaccharides. Applying metabolic and bioengineering techniques, strong stressors have been produced by exploiting the natural macroalgal monosaccharides in order to make bioethanol. Although it has been a difficult process, biofuels made from macroalgae have recently spent some years recording a few patents to market the method in the industry (Goecke et al., 2020).

Therefore, there is no suitable upscaling of biofuel production employing these biotechnologies principles that can be accomplished using a practical technique with the right infrastructures. Fig. 10.3 displayed six patents detailing the biological procedures that produced a range of biofuels and bioproducts with industrial applications (Hafting et al., 2015). Biofuels including Examples of renewable energy sources and platform chemicals include bio-oil, bio-butanol, biological methane, the fermentation process sugars, sugar acids, alcohols made from sugar, levulinic acid, hydroxymethylfurfural, and the formic acid compound (US9452993B2). Other examples include ethanol from biomass (CN101024847, US201300500 9A1), biological products fertilizer, and agricultural products feed (CN101024847, US2013005009A1, US10000579B2). A specific patent specifically suggests a method for extracting a range of diverse, commercially desirable bioproducts from the red seaweed *G. corticata* (US10000579B2), including lipids, pigments that are present in agricultural feed, and hydrocolloid component agar. Although patenting is typically a time-consuming and costly process, there is a chance that the application will be denied, as well as the much more challenging possibility that only a small portion of the bioprocess will be patented, depending on its uniqueness and inventiveness (Lähteenmäki-Uutela et al., 2021).

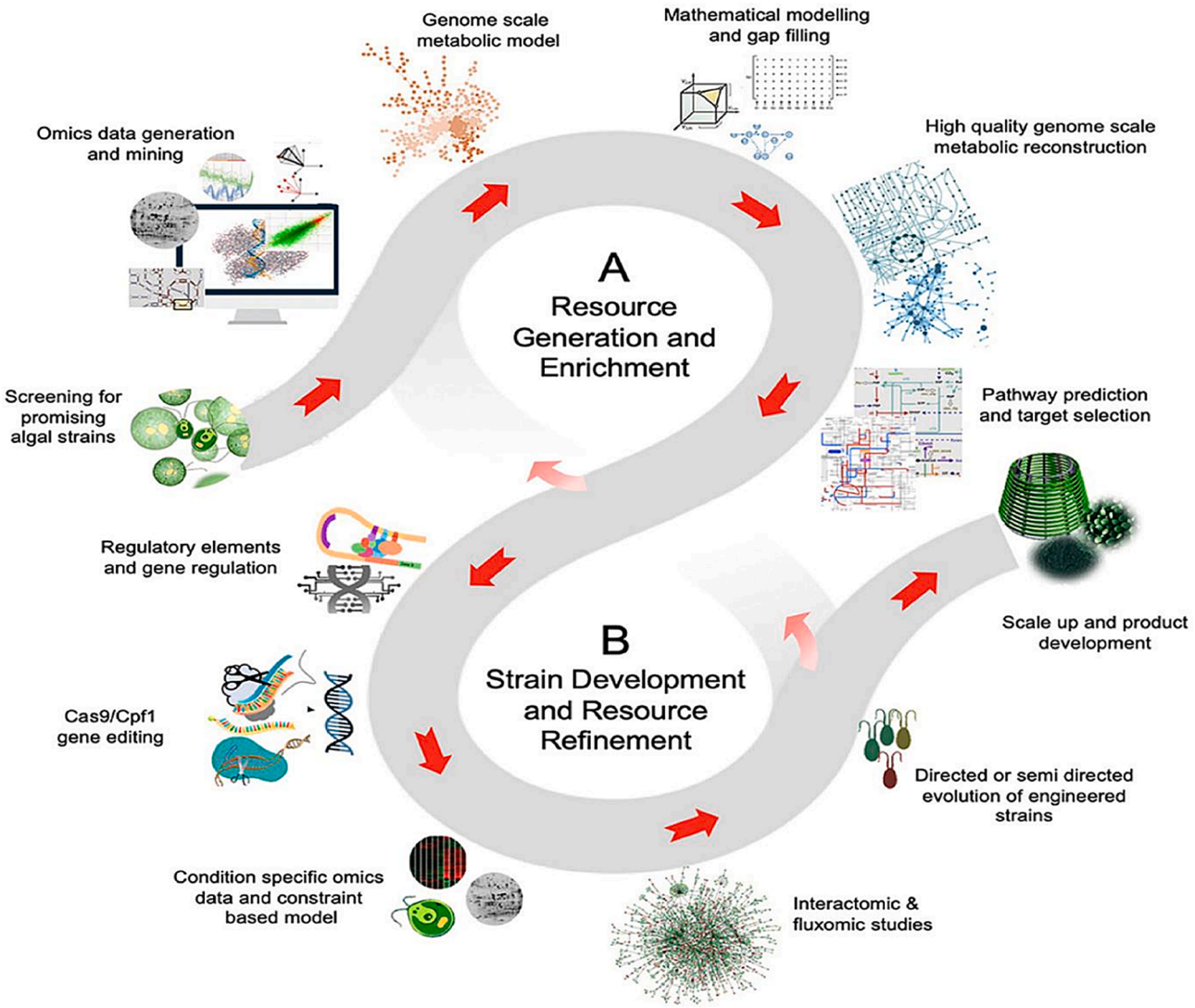

FIGURE 10.3 (A) Resource development and enrichment: Excellent curated data can be produced via high-throughput technologies, comprehensive bioinformatic analysis and computing, and a strong scientific interest in microalgae. (B) Microalgae strains can be produced with the aid of metabolic model results and cutting-edge technologies such as genome editing and a high-through variant selection. Metabolic flux changes in mutants typically indicate that a living thing evolved to optimize flux reconfiguration. It is possible that the goal of the flux balance shift is to boost the manufacturing of desirable items (Zhang, Xue, et al., 2023).

Patent US8167959B2 makes it evident that the development of kelp based on a bioprocess *Macrocystis pyrifera* may use technology like energy-secured lubrication and associated additives, nontoxic medical equipment, biochemicals, biofuels, sorbents and dispersing agents for oil medication, cosmetics, and nutraceuticals, pharmaceutical products/ingredients, and fertilizer or supplements for aquaculture and horticulture (Ljubic et al., 2019). Research on the area relevance of producing macroalgal biofuel is growing daily, and investment in research and development is also required for the entire biorefinery process. Although the concept of producing bioenergy from macroalgae was first introduced in the 1970s, the number of pilot-scale and funded projects related to producing biofuels from macroalgae increased starting in 2010, with a focus on the practical aspects of producing biofuel, food additives, and chemicals. Among the tasks that have recently been finished were the Sea-Gas Project, Macro-Fuels, Macro-BioCrude, and Global-Seaweed (Novoveská et al., 2019).

5. Production of biofuel: Challenges and limitations

Macroalgae cultivation and harvesting present difficulties, as does the accessibility of a continuous fuel source delivery chain. Species selection and the hydrolysis, transformation, and utilization of certain polysaccharides by common microorganisms are further challenges. The growth of macroalgal biorefineries may be hampered by the scalability of the biotechnologies employed to enable ongoing research (Roleda et al., 2018). Biorefineries must be complete to make more than two products and combine every component on a much larger scale. As an outcome of the scale-up, the bioprocess's effectiveness and the bioproduct's output will both be reevaluated to track any losses. Freshwater usage increases as the biorefinery process moves through its bioprocessing stages, which is also a major problem considering the global freshwater crisis. Depending on the different techniques used, between 1.5 and 10 L of water was used for each liter of bioethanol produced that was produced (Sathasivam & Ki, 2018). Seawater can also be included in bioprocesses in another way. The most appealing and practical fuel sources to transition to a blue bioeconomy are macroalgae, which have shown great promise as sources of bio-based products and biofuels. According to studies, seawater can be utilized for bioethanol fermentation as well as macro-algal hydrolysis and fractionation. A few studies have shown that employing saltwater in a particular process is feasible, but this has not yet been verified in a macro-algal biorefinery process that involves several interrelated steps and processes (Sebök & Hanelt, 2020).

5.1 Economic-technological barriers

Despite the potential for producing biofuel using microalgae technology, their commercialization is hindered by the high costs involved. The economic disparities between the production of first-, second-, and third-generation biofuels and fossil fuels are shown in the figure below. Economically feasible technological advancements must be developed, such as the improvement of microalgal strains for increased oil production (Shannon & Abu-Ghannam, 2019). Furthermore, methodological limitations like the expensive expense of scaling up equipment may prevent research from progressing as quickly as it could. Another obstacle is the collecting and dewatering of microalgal cells prior to the generation of biofuel. Diluted cell suspensions are very difficult and time-consuming to dewater, and certain approaches are expensive. Studies show that the cost of harvesting biomass ranges from 20% to 30% of the cost of downstream microalgal operations. One of the biggest obstacles to the commercialization of microalgal biofuel is still the technology gap. Another issue with large-scale biomass production is the excessive use of water, nitrogen, and phosphorus. Contamination from pathogens, bacteria, and chemical compounds found in wastewater is a growing concern when using it as an alternative source of nutrients (Su et al., 2017).

The largest technological challenges the energy-intensive and costly procedures of microalgae dehydration, drying out, oil extraction, and the elimination of naturally occurring fatty acids and inorganic materials are used in the synthesis of biodiesel from microalgae contaminants. Additionally, it was found that tubular PBRs require the most energy during the culture phase, while ponds that are open use the least throughout their entire cycles (Wahlen et al., 2020). The result was determined by an assessment of how much electricity the open pond, tube PBR, and column PBR used throughout the course of their various life cycles. PBRs are nevertheless advantageous and frequently result in larger biomass concentrations, despite the fact that they use more electricity, which raises the expenses. One aspect that needs to be adjusted is the expense of employing lamps to illuminate microalgae cells and give a sufficient amount of light. Compound parabolic concentrators are one way to improve microalgae lighting (Yu et al., 2019). Glass and plain tubes without compound parabolic concentrators (CPCs) were used to culture *Chlorella vulgaris*, and the concentrator-equipped system was contrasted with the plain tube method. The concentrator system increased the average light intensity of the cells by 462% and the radiation level of the culture by 351%. In the categories of biological material dry weight, proteins, carbohydrates, and lipids, the CPC system produced greater amounts of biomass than the tube-based system between days two and four of cultivation, even though *C. vulgaris* grew more quickly in the tube structure compared to the concentration system throughout the phase of exponential growth (0.98 div/day). Its cells were also larger in the concentrating device system (11.23 m) than in the tube system (6.28 m) (Zabed et al., 2019).

5.2 Environmental barriers

Fossil fuels are widely used as the main energy source in the world. To meet the world's fuel needs, alternative energy sources must be sufficient. The daily oil consumption in the United States was approximately 19 million barrels in 2008.

The production of microalgae requires around 30 million acres of land in order to supply this need for biofuel feedstock. Compared to first- and second-generation biofuels, microalgae, which may develop and multiply on nonarable land using wastewater and brackish water, have fewer land-use concerns. However, one of the biggest obstacles to using microalgae in the manufacture of biofuel is water (Wu et al., 2021). To avoid water and fuel trade-offs, water utilization is crucial for large-scale microalgae cultivation. The location, conversion pathways, and production systems are the primary determinants of microalgae's water consumption for biofuel generation. For example, the water consumption of microalgae in a sealed photo reactor was estimated to be 8 m^3 GJ^{-1} in the Netherlands. On the other hand, it was calculated that microalgae grown in open pond systems in Hawaii used 193 m^3 GJ^{-1} of water (Griffiths et al., 2021).

Biofuels derived from microalgae are seen as clean and renewable substitutes for fossil fuels. However, a number of studies have been carried out to evaluate how microalgal biofuels more especially, biodiesel—affect greenhouse gas emissions. According to the majority of research, biodiesel made from microalgae currently emits more greenhouse gases than fossil fuel. This is because growing, harvesting, and preserving microalgae requires a lot of energy and results in a little harvest. Numerous studies have shown that a variety of processes, such as pumping, lipid extraction process, dewatering, and thermal drying, necessitate a large amount of energy for microalgae-based biofuels (Zhang, Ding, et al., 2023). However, the energy needed to grow microalgae in ponds with raceways is less than 1 MJ MJ^{-1}, which is significantly less than what photobioreactors require. Furthermore, the use of pesticides, including insecticides and herbicides, causes the production of molecules called organochlorine, which depletes the ozone layer. Fertilizers required for optimal microalgal growth also contribute to greenhouse gas emissions, along with insecticides. For optimum growth, microalgae need nutrients, fertilizers, or supplements. However, fertilizers are nonrenewable and composed of materials derived from fossil fuels. Microalgae have an impact on biodiversity in addition to natural resources. The ecosystem and biodiversity are at risk from the cultivation of microalgae (Singh, Tomar, et al., 2022). Large-scale microalgae deployment necessitates effective cultivation process management and control. Therefore, instead of growing invasive species that could jeopardize biodiversity, it might be wiser to rely on local plant species for the production of biofuel. The controlled eutrophication process is another name for the mass culture of microalgae. However, the overabundance of nutrients in the aquatic body caused by the mass cultivation of microalgae can endanger biodiversity. The decomposing corpses of microalgal biomasses absorb oxygen from the aqueous body as they wither (Ahmed et al., 2022) (Fig. 10.4).

Given the vast potential for environmentally friendly power, it is necessary to recommend pretreatment from this macroalgae that allows for proper separation of the stages of the entire coastal development, mainly for the generation of biofuel and for application as a food fixer nutrients, therapeutic, manure, and medication, which will increase the biorefinery's profitability (Snehya et al., 2022). The establishment of biorefineries is predicated on the reliable supply and large-scale production of an appropriate macroalgal species as feedstock. However, the macroalgal cultivation process is the biggest barrier to the development of biorefineries. Techno-economic evaluations and life cycle analyses of such methods have often shown that the system's culture component is possibly the most expensive and energy-intensive,

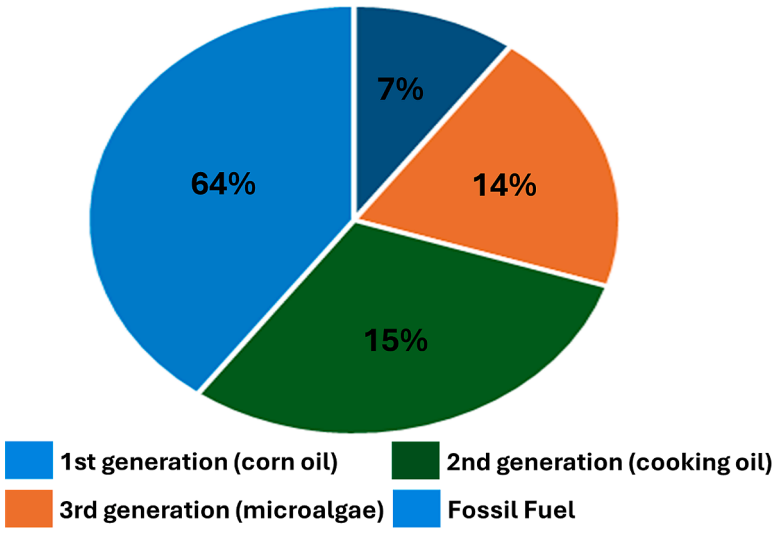

FIGURE 10.4 Comparing the economics of fossil fuels with biofuels from the first, second, and third generations (Shanmugam, Sekar, et al., 2021).

requiring more research and development in order to commercialize macroalgal biological refineries viable (Thanigaivel et al., 2023). Enhancements in understanding and acceptance of macroalgal growth cycles, as well as the development of new, efficient, and appropriate growing techniques (mostly for offshore production) for all kinds of macroalgae, are essential for successful development. The process's energetic balance or recovery rate is also essential for every species. It includes increasing and expanding biomass yields and the potential worth of biofuels while lowering operating and investment costs (such as labor, technology, and energy inputs) (Chaturvedi et al., 2020). There are currently 447 manufacturing facilities for algae and Spirulina species in Europe. Across the European nations, a wide range of species, production techniques, and commercial applications have been found. The most common method of producing macroalgae in Europe is the harvesting of wild stocks (68% of the manufacturing units mapped). Photobioreactors account for 71% of the production of microalgae, whilst open ponds account for 83% of the production of *Spirulina* spp. (Chaturvedi et al., 2020).

In order to improve the macroalgal biorefinery, international cooperation would be necessary to promote and develop the agricultural technological advances and experience of East Asian countries (China, Korea, Japan, Indonesia, and the Philippines), which are the main producers of macroalgal biomass. 95% of the global supply in 2010 came from these nations. The predominant species generated in the various countries vary due to ecological factors including climate (Fayyaz et al., 2020). Thirty percent and 85 percent of the world's production of *U. pinnatifida* and *L. japonica*, respectively, came from cultivation in China and Korea. Whereas similar red algae are primarily farmed in Indonesia and the Philippines, Porphyra sp. was grown mainly in Japan. Because of their decades of agricultural knowledge and methods, East Asian nations would be crucial in increasing the quantity of macroalgae cultivated globally for use as feedstock in biorefineries. The development of fully integrated electronic devices and internet access to facilitate the management, monitoring, and analysis of difficulties in macroalgal growth systems can be attributed to the preference for different kinds of sensors for predicting temperature, pH, etc. in the future. These days, this kind of technology is used in microalgal cultivation systems (Cao et al., 2020).

In order to separate the ocean's expanding biomass, creative and ecologically sound cycles are essential. Based on the data collected for this investigation, weak corrosive pretreatment is probably the most effective and feasible way to acquire fermentable sugars. The need for more environmentally friendly practices leads to research into prior treatments that use green solvents (like water, deep eutectic solvents, and so forth) that, when paired with efficient warming frameworks, may increase the appropriateness of these integrated ocean growth biorefineries (Singh & Das, 2018). There is also a need for inexpensive, environmentally friendly methods of saccharifying noncellulosic polysaccharides. One of the most significant challenges is the accessibility of catalyst-mixed beverages for specific ocean development polysaccharide hydrolysis. Given that cellulolytic compounds used in lignocellulosic biomass saccharification can be used, using deposits from phycocolloids companies is recommended as a viable choice in this regard. On the other hand, a unique pattern that may result in the identification of efficient proteins for the saccharification of noncellulosic kelp polysaccharides is the disengagement and presentation of novel chemicals from marine bacteria. Therefore, it seems sensible that advancements in biotechnology would make it possible to create microbes that can hydrolyze and age these sugars in a combined bioprocessing environment by using metabolic designing devices and genetic alterations. Proper fractionated pretreatment and solidified biological processing could help improve kelp biomass-to-biofuels measures (Hallenbeck & Ghosh, 2012).

The spectrum of potential bioproducts and biofuels, as well as the best, comprehensive, and integrated biological processing pathways, must be identified with regard to every macroalgae variety that can be farmed sustainably. The long-term sustainability and financial gain of the bioeconomy will depend on this data. The macroalgal industry will be able to thrive if all of the bioprocessing steps and the range of possible bioproducts are kept in a single database that is available to everyone. Strong ties between academia and industry, as well as multidisciplinary groups composed of experts in cultivation, bioscientists, marine biologists, engineers, and social science researchers make it conceivable, despite the fact that it might seem overly optimistic. Effective collaborations are essential to this field's progress (Hu et al., 2008). Following the identification and documentation of the optimal bio-processing pathways, it is also crucial that the bio-processing characteristics of each macroalgal species be thoroughly examined for improved sustainability using a variety of cutting-edge environmentally friendly assessment methods. These include energy, life cycle evaluation, and energy-based models, each of which could help advance the macroalgal biorefinery (Barati et al., 2021). To collect the native macroalgal species and make it affordable to produce superior biofuels using different biological processing technologies, offshore growing requires that each country's farming regulations and licenses be properly followed. Additionally, biorefineries would use native species in coastal waters, which could affect the bioproducts that differ from one country to the next. Additionally, by causing variation by taxonomic group, the biochemical makeup of macroalgae influences the possible bioproducts (Sanz Smachetti et al., 2019).

The bioeconomy of every nation or coastal area may be more significantly impacted by this. Furthermore, because national regulations differ, it may be challenging to obtain planning permission for the construction of a biorefinery in a coastal area. Additionally, the effects of global warming may cause a country's bioeconomy structure to drastically change over the next few decades. Studies have indicated potential differences in geographic distribution and massive macroalgae in different coastline environs as a result of the warmer temperatures brought on by climate change (Yang et al., 2017). The infrastructures, locations, employment, and overall viability of macroalgal biorefineries in the bio-economy will all be impacted by changes in macroalgal distribution. Therefore, simulating and projecting the commercially significant macroalgal species transition in climate change is crucial for species distribution. Further research into the creation of innovative macroalgal biorefineries is needed in the ensuing decades, primarily in agricultural regions that might be in opposition to the source of decreased feedstock or the invasion of new species as a result of distributional changes (Shanmugam, Hari, et al., 2021).

It's crucial to consider the macroalgal biorefinery's economic effects in addition to the general public's and local government's acceptance of it. The construction of massive biorefineries along shorelines (and off-shore macroalgae growing projects that might ideally be within the close neighborhood) may encounter resistance from certain governments and community groups. Innovative sustainable techniques are being studied and put into practice for bio-refineries that are embraced by the general public (de Carvalho Silvello et al., 2022). Before the construction of the biorefinery, coastal people may have been informed about biotechnologies and their impacts. Focus groups and/or workshops that have been open to everyone could still comprise participants from educational institutions, funders, sponsors, and the general public. Therefore, the following issues are addressed by the macroalgal ecological biorefineries:

- By using capture and storage of CO_2, waste biorefineries together with the cyclical biological economy constitute a low-carbon economy that can address worldwide issues.
- Another growing field of study using multi-feedstock culturing methods that focus on the scalability of macroalgal production is macroalgae and agribusiness.
- Unquestionably, large-scale biological refineries located along the coast will help society by creating jobs, ensuring energy security, and fostering economic growth through employment (de Carvalho Silvello et al., 2022).

6. Conclusions

One excellent alternative for the foreseeable future would be to show a combined method of biofuel generation from macroalgae, which has a lot of possibilities. Research studies have identified a number of unique macroalgae species from all three taxonomic groups as prospective biochemical extraction methods for the production of bio-fuels, bioproducts, and high-value biochemicals. The strong trend in the implementation of macroalgal property rights outlines its innovative interest in contributing to the biological economy and offering a sustainable renewable energy source (Li, Cao, et al., 2020). Additionally, there may be a growing need for support research projects that address the entire spectrum of macroalgal biorefinery pathways. There are numerous issues with using macroalgae to produce chemicals and fuels, primarily related to their availability and the significant seasonal variations in their nutritional and biochemical value. There are still certain restrictions, like inadequate technology and the unpredictable nature of macroalgae biomass in both quantity and quality. Species, geographical location, and season all affect macroalgae biomass, while processing technology has a major impact on the yields and product kinds produced (Bastos, 2018). The methods for treating biomass derived from the land are generally appropriate, and in fact, the creation of new technology or the application of emerging technologies may prove advantageous. It's also crucial to remember that research on bringing lab-scale techniques to an industrial scale for macroalgal biorefineries is still in its infancy (Kumar et al., 2021).

However, the legislative and regulatory framework of the government can still be influenced by bioenergy and other macroalgal products. These enabling nations should speed up the need to avoid using limited nonrenewable resources and concentrate on creating bioeconomic systems. Efficient knowledge sharing and openness between Government, industry, academia, stakeholders, and the general public will enable the commercialization of such biorefineries (Grama et al., 2022). To increase the effectiveness and efficiency of macroalgae in the future, priority should be given to the identification of new microbes, the advancement of technologies for metabolic modification and gene alteration, and the creation and optimization of processes for yield enhancement. Therefore, macroalgae have the potential to become the most potential biomass in the years to come and greatly contribute to an environmentally friendly economy (Goswami et al., 2021).

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Chapter 11

Marine biotechnology: a panacea for pollution control and human healthcare

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1. Introduction

Over the past decade, an increase in the toxicological impact of microplastics in the environment has been distributed globally, from coastal areas to deep-sea sediment. The term plastic encompasses a range of malleable synthetic materials that are to be transformed into solid substances (Musa et al., 2024). They are composed primarily of polymers, which are larger molecules composed of monomers, or repeating building blocks. The polymer can be natural (cellulose) or synthetic. The amount of plastic waste that enters aquatic ecosystems each year is estimated to be between 5 and 13 million tons (Burgos-Aceves et al., 2022; Narra et al., 2022). Marine microplastic pollution is the contamination of the marine environment by particles smaller than 5 mm in diameter. This microplastic originates from various sources such as primary microplastic source, known as small-sized plastics, including microbeads in personal care products, synthetic textile microfibers, and preproduction plastic pellets. The fragment of larger plastic debris leads to secondary microplastics through processes such as photodegradation, mechanical abrasion, and biological degradation. Polyethylene (PE), polypropylene (PP), polyamide (PA), polyvinyl chloride (PVC), polystyrene (PS), and polyethylene terephthalate (PET) are the common constituents of microplastics (Auta et al., 2022; Lundebye et al., 2022).

These challenging issues have posed a vital risk to marine environments by causing physical blockage, reduced feeding, and starvation to marine organisms if mistakenly ingested for food, thereby affecting the food web. The injection of seafood contaminated with microplastics and associated toxins poses potential risks to human health, including endocrine disruption; inflammation, and other chronic conditions; therefore, remediation efforts need to be put in place.

Biotechnology is the use of enzymes and microorganisms for the treatment of plastic waste (Aransiola et al., 2021; Feng et al., 2023). Biotechnological approach offers promising solutions by preventing the accumulation of plastics, which can consequently cause microplastics to accumulate in the marine environment. Leveraging biological systems for remediation can provide sustainable and efficient techniques to reduce the environmental and health impact of microplastics. This approach has been recorded to be eco-friendly, natural integration, which is the way of utilizing organisms that naturally occur in marine environments, scalability and efficiency, versatility, and adaptability. Certain microorganisms have evolved the ability to decompose polymers like polystyrene and polyethylene. Researchers are identifying and optimizing these microbes to enhance their plastic-degrading capabilities, potentially leading to bioremediation techniques that can be applied in contaminated environments (Amobonye et al., 2023).

Biotechnology is revolutionizing the field of medicine by providing innovative solutions to a wide range of health challenges. Through the use of living organisms, cells, and biomolecules, biotechnology enables the development of new therapies, vaccines, and diagnostic tools (Prajapat & Jain, 2022). It plays a critical role in areas such as personalized

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medicine, gene therapy, and regenerative medicine, offering potential cures for previously untreatable diseases. By harnessing the power of biotechnology, researchers can develop targeted treatments, improve patient outcomes, and address global health issues more effectively. As the field continues to evolve, biotechnology holds immense promise for shaping the future of healthcare and improving the quality of life worldwide.

2. Biotechnological approaches to remediation

2.1 Biodegradation by microorganisms

The disintegration of polymeric substance is largely attributed to microorganism's action. Biodegradation of plastics is the process by which microorganisms including bacteria, actinomycetes, and fungi change the chemical composition and physical characteristics of a plastic substance (Shinde et al., 2023). The biodegradation process consists of sequential degrading phases such as bio-fragmentation by enzymatic separation, product assimilation by microorganisms, and mineralization, which result in the creation of oxidized catabolites. Biodegradation of plastics involves the following processes. Different processes involved in the biodegradation of plastics are shown in Fig. 11.1.

Biodeterioration: Microbial communities that undergo decomposition are responsible for the natural imperceptible constituents and chemical deterioration of plastics, leading to alterations in their mechanized, chemical, and natural characteristics. Abiotic parameters are typically helpful either as an initiator or as a synergistic component. This process of

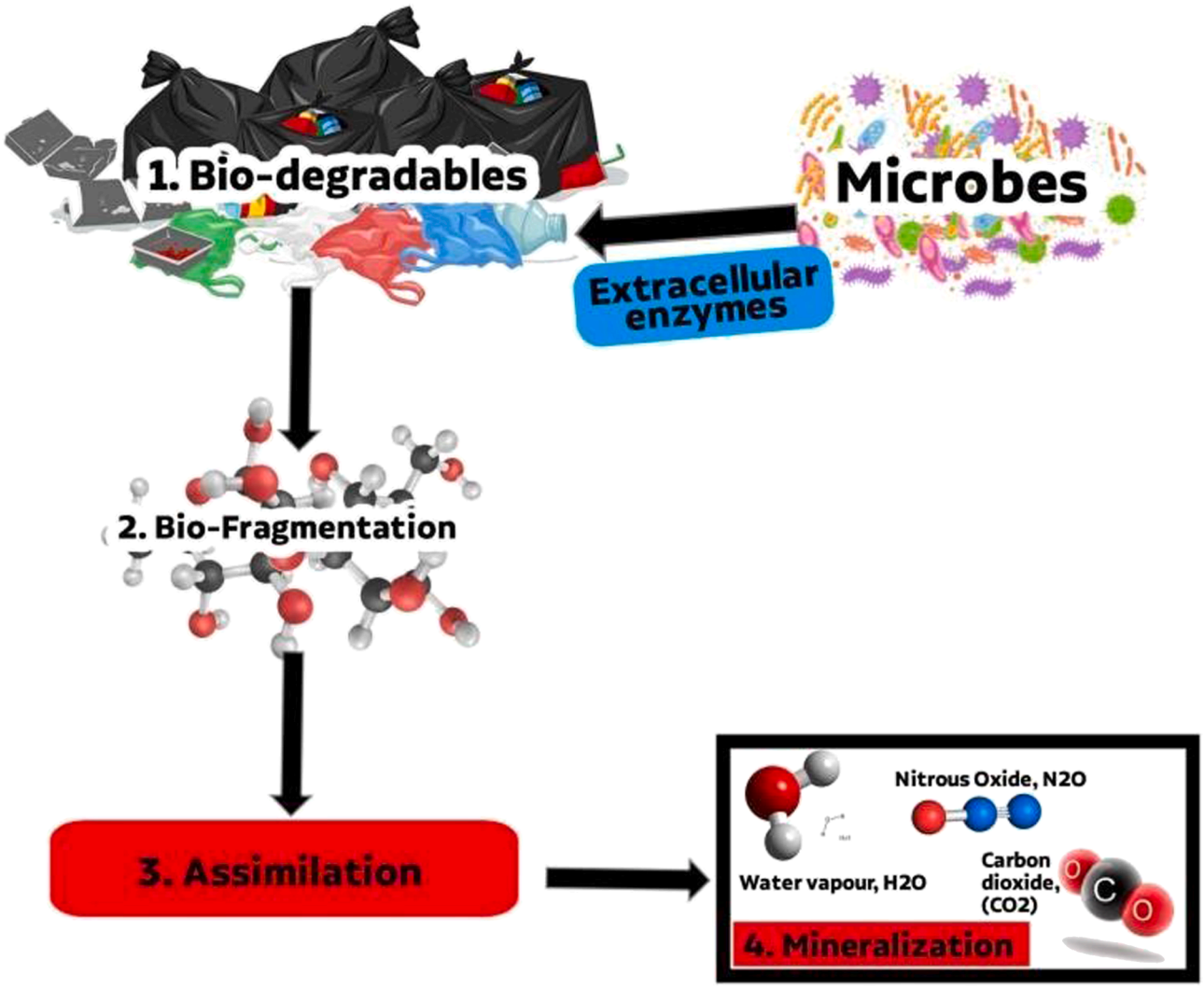

FIGURE 11.1 Varieties of processes in biodegradation of plastics. *Authors.*

apparent or outermost deterioration alters the chemical, physical, and even the involuntary/instinctive characteristics of plastic. The abiotic factors mostly aid in weakening plastic's polymeric structure. Occasionally, these abiotic features exhibit potential as catalysts or symbiotic elements in the biodegradation system. The formation of a microbiological biofilm is the first step in the bio-deterioration of the system. This biofilm multiplies within and on the outermost layer of plastic.

Biofragmentation is a catalytic process during which enzymes released by microorganisms disintegrate plastics into monomers (subunits) and oligomer for reasons, such as UV radiation, chemical, biological, mechanical, and/or thermal sources. Extracellular enzymes secreted by microorganisms stimulate responses at the plastic polymer's edges. Most bacteria that breaks down plastics consist of an enzyme called oxygenase, which is able to include oxygen to a lengthy carbon-carbon chain and cause it to cleave. The substrates are further broken down by the esterases and lipases following the production of groups of carboxylic compounds. The biological aspect is the main focus here. Plastics are polymers with larger molecular weights; they are unable to cross the cytoplasmic membrane. Certain extracellular enzymes, or exoenzymes, made by microorganisms accelerate certain chemical reactions around the plastic polymer's perimeter (Buragohain et al., 2020; Prasad & Aranda, 2018).

Assimilation: Only monomers that can enter bacterial cell wall and be taken up by the organism. Some monomers that use particular carriers to go past the cell wall are absorbed, while the other monomers do not change. Variety of the production of secondary metabolites occurs during assimilation and is transported outside of the cell for additional breakdown. The process known as metabolite mineralization leads to the generation of many chemical compounds, including CH_4, CO_2, N_2, and H_2O, following the complete breakdown of primary and subordinate metabolites.

Mineralization: The ultimate stage of biodegradation entails the complete disintegration of the molecules resulting from the process, leading to the emission of H_2O, N_2, CO_2, CH_4, and other substances. The whole breakdown of primary and secondary metabolites is indicated by mineralization, which also leads to the evacuation of completely degraded metabolites (CH_4, N_2, CO_2, and $6H_2O$) (Buragohain et al., 2020; Prasad & Aranda, 2018).

2.1.1 Identification of plastic-degrading microorganisms

Microbes that exist independently of other living things have the ability to modify various polymer kinds and adapt to almost any form of environment. Accordingly, bacteria that degrade microplastics can be found in a long-term contaminated environment. The decomposition of microplastics by fungi, bacteria, algae, and other microorganisms speeds up the biological breakdown of organic materials without posing a threat to the ecosystem. A number of locations have been identified where specialized microbes that break down plastic, mostly fungal and bacterial species, have been found. These include mealworm guts, landfills, wastewater treatment facilities, organic matter, coastal MPs-associated microbial films, and mangrove sediment (Chen et al., 2020; Hou & Majumder 2021; Lou et al., 2020). Many types of plastic polymers that can be biodegraded by fungi, bacteria, actinomycetes, and algae have been researched. Currently, there are approximately species of fungal and bacterial organisms from species that are known to metabolize polyethylene; these microbes primarily come from trash dumps and detritus (Cassone et al., 2020; Kundungal et al., 2021). Some bacteria were discovered to degrade PE, including, *Streptomyces ruber*, *Bacillus*, *Rhodococcus*, and *Pseudomonas* (Park & Kim, 2019; Zhang et al., 2021). According to a recent study, *Aspergillus Niger*, *Thermobifida fusca*, and *Bacillus subtilis* degrade PET (Yang et al., 2023). Moreover, it has been discovered that *Fusarium solani* and *Curvularia senegalensis* degrade PUR (Yang et al., 2023). Furthermore, newly identified biodegradable microorganisms from coastal water have been found to breakdown PE and PVC (Kumari et al., 2019).

Actinomadura species, *Actinomycetes* with a considerable potential for decomposing plastic include *Rhodococcus ruber*, *Thermoactinomyces*, and *Streptomyces*, which have been discovered in a range of habitats (Amobonye et al., 2021; Jabloune et al., 2020; Yang et al., 2023). One of the primary processes by which they proliferate on various plastic and convert high molecular weight into low-molecular-weight ones is the production of hydrolytic enzymes (Gohain et al., 2020). Among other chemical additives, it has been discovered that actinomycetes break down keratin, rubber fuel, PUR, p-nitrophenyl esters, and PET (Gaytán et al., 2020; Jabloune et al., 2020). It was also demonstrated that the enzymes or toxin systems released by algae, especially microalgae, may be used to degrade plastic (Chia et al., 2020). The application of blue–green algae *Anabaena spiroides*, green microalga *Scenedesmus dimorphus*, and diatom *Navicula pupula* as natural remedies for PE films has been studied. *Anabaena spiroides* demonstrated the highest rate of plastic degradation following 2 months of cultivation at ambient temperature ($27 \pm 2^{\circ}C$) and under direct light (12:12 h of light and dark). At a rate of 8.18%, it was able to degrade LDPE (Yang et al., 2023). Lowering activation energy causes PE polymer chemical connections to weaken and polymers to be used as a source of carbon during the microalgae's breakdown of plastic polymers (Chia et al., 2020; Khoo et al., 2021; Soong et al., 2022). Comparing fungal and microbial species, the

biodegradability of Spirulina sp. was noticeably inferior in their ability to metabolize PET and PP (Khoironi et al., 2019). One possible explanation is because, unlike bacteria, microalgae mostly get their own power from sunlight and only need atmospheric CO_2 as a carbon source (Dineshbabu et al., 2020). Because it effectively built PETase from *Ideonella sakaiensis*, *Phaeodactylum tricornutum* has been discovered to have increased rate of PET biological degradation (Moog et al., 2019). However, the industry's ability to use biodegradation of plastic effectively is hampered by the rate with which different microorganisms break down plastic (Amobonye et al., 2021). There is not yet an in vitro plastic breakdown method suitable for industrial use. Therefore, it would be possible to create delicately designed genetically altered microbes for use in real applications by incorporating effective plastic degrading catalysts (enzymes).

2.1.2 Mechanisms of microbial degradation

The results of the breakdown of plastic are water, carbon dioxide, carbon residue, and methane. Microorganisms use extracellular enzymes to secrete these polymers as an energy source because the majority of them are too big and soluble to enter their cells easily. These enzymes aid in biodegradation both inside and outside of bacterial cells by facilitating depolymerization outside of the cells. Depolymerization and mineralization are the two main procedures in the biological breakdown of polymeric polymers. Exo-enzymes, or enzymes made outside of cells, hydrolyze large polymers into smaller, soluble molecules. These substances are able to supply energy over the semipermeable bacterial barrier. The process of mineralization converts the resulting minerals into inorganic chemicals, such as CO_2, H_2O, as well as CH_4. The method of decomposing large polymers is called depolymerization (Shinde et al., 2023). Under aerobic conditions, products include biological biomass, CO_2, and H_2O. Apart from these trio of byproducts, the hydrolysis of polyethylene under sulfidogenic and anaerobic/methanogenic environments yields H_2S and CH_4. The ability to degrade plastic polymer substances is mostly determined by characteristics of the bonds binding monomers together. Amid the six main categories, when it comes to synthetic polymers, the most robust C–C networks are those of hydrolyzable PET and PUR, PS, PVC, PE, PP, and PET (Chen et al., 2020).

In order to hydrolyze plastic into molecules, environmental microbes can do one of two things: release a protein called hydrolase that binds specifically to receptors on the outermost layer of polymers, or the microbial organism may absorb the small molecules of lipids or acidic substances produced in the previous phase and participate in its physical metabolic processes, subsequently disintegrating into CO_2 and water, generating energy for proliferation of cells (Yang et al., 2023). Therefore, depending on the degradation method, effective plastic biodegradation can be accomplished. Microbiological degradation of C–C bonding polymers PE breakdown usually happens when secreted enzymes break down the PE polymers through a process called biofragmentation. This is succeeded by microbes assimilating small lytic particles through a process called bioassimilation (Montazer et al., 2019; Yang et al., 2023). Specifically, the bacteria changes the long-chain PE framework's –C–C– units into the –C═O– (carbonyl) category. It is then possible to transfer the microscopic aliphatic hydrocarbons straight into the cell membrane for destruction (Yang et al., 2023). The primary determinants of PS degradation efficiency are polymeric thickness and molecular weight (Yang et al., 2023). The vinyl at the network's boundaries is epoxidized by mono-oxygenase, breaking down styrene. Next, an epoxystyrene isomerase is used to transform styrene oxide into phenylacetaldehyde. According to Yang et al. (2023), the actinobacterium *Rhodococcus opacus* can break down styrene by using the aerobically generated phenylacetic acid (PAA) route to make styrene oxide. This process of breakdown involves a number of enzymes, such as styrene oxide isomerase (SOI), tricarboxylic acid cycle (TCA)-accessing enzymes of phenylacetate (PAA#) degradation, phenylacetaldehyde dehydrogenase (PAD), and styrene monooxygenase (SMO) (Yang et al., 2023). According to reports, the proteobacteria genera Xanthobacter and Pseudomonas use the side-network (chain) oxygenation route extensively for the aerobic breakdown of styrene (Yang et al., 2023). Furthermore, phenylacetaldehyde dehydrogenase has the ability to accelerate the rate of conversion or oxidization of phenylacetaldehyde to PAA. PVC's breakdown route differs from that of PE and PP due to the presence of Cl. Chlorine-based hydrocarbons are far harder to oxidize than PP and PE in addition to *T. molito* may also mineralize PE, PS, and PP; however, PVC processing is not as effective because of PVC's high conversion rate to chlorine-based intermediate chemicals (Peng et al., 2020).

There are currently very few research studies of the biological mechanisms underlying PVC breakdown, and the most of them have only looked at particular bacteria that are able to break down PVC. PVC is chemically stable and hydrophobic within the C–C structure. Information regarding the precise enzymes that break it down is not available. The only enzyme identified was laccase (Yang et al., 2023). According to Janusz et al. (2020), laccase is a type of oxidoreductase that is frequently utilized in the dissolution of toxic chemicals and phenolic compounds. Sumathi et al. (2020) demonstrated that laccase may create new C═O bonds and split PVC double-bonded chains, though the mechanism underlying this action is still unidentified. It was hypothesized that radicals lacking oxygen in laccase byproducts would damage C–C

bonds based on the processes by which lignin, cellulose, and numerous other macromolecules degrade (Yang et al., 2023). Other unidentified enzymes break down the short chain that this process produces, which microbes can use as an origin of carbon by using the process known as TCA cycle. Owing to their high level of hydrophobicity and chemical abrasion resistance (Yang et al., 2023), PP and PVC are challenging for microbes to break down. While it has been demonstrated that a number of microbial strains may break down PP and PVC (Yang et al., 2023), the basic disintegration pathway and necessary enzymes are still undiscovered. In the ester-linked PET decomposition process, bacteria from the genus *Ideonella*, specifically *Ideonella Sakaiensis* 201-F6, were discovered to decompose as well absorb PET. Kawasaki et al. (2020) suggest that to maximize the hydrophilic properties of PET and improve the efficacy of following enzyme-mediated hydrolysis, PET hydrolase and the PET may focus on the terminus or loop framework of the chains of polymers for enzyme dissolution (Yang et al., 2023). This is because MHETase and PETase efficiently breaks down PET into subunits that are harmless for the planet, such as ethylene glycol and terephthalic acid (Yang et al., 2023). This PET hydrolase is different from previous PET hydrolases in that it may entirely deteriorate PET, albeit possessing 45%–53% of its similarities with actinomycete keratinase (Wei et al., 2019). Its limited stability, however, prevents it from being widely used. PET is changed into MHET once the ester link is broken down by the enzyme. Then, MHET progressively hydrolyzed by MHETase to produce TPA and EG, which will unavoidably enter the TCA route (Peng et al., 2021; Yang et al., 2023). Polyols and di- or polyisocyanates are the constituents of polyurethane (PUR), a polymer joined by urethane linkages. According to earlier research, microorganisms can break down polyester polyurethane (PUR) with the use of their produced enzymes. Protein-dissolving enzymes produced by microorganisms, such as proteases, esterases and ureases, can hydrolyze the ester and urethane links in PUR. Whereas ureases may target urea linkages, proteases are thought to be able to break down urethane and amide bonds. Proteases and esterases' hydrolysis of ester bonds is one of the primary processes for PUR degradation (Yang et al., 2023). Enzymes that degrade PUR are classified as either membrane-bound or secreted based on where they are found. When the urethane link is hydrolyzed by the enzymes attached to the membrane, the PUR monomers are then released from the surface. Numerous secretases emerge to break down recalcitrant PUR.

According to Fesseha and Abebe (2020), polymers decompose mostly aerobically in the environment, in deposits, landfills, and partly under aerobic conditions in soil and compost. Polymer dissolving requires circumstances which are both aerobic and anaerobic in nature. Through aerobic biodegradation, microbes help break down huge organic molecules into smaller forms by acting as charged particle acceptors. The technique yields carbon dioxide and water as byproducts (Shinde et al., 2023). Anaerobic biological decomposition is the process by which bacteria break down chemicals without the presence of oxygen. The organic decomposition of contaminants still requires oxygen at potentially hazardous waste sites. Massive volumes of organic substances decompose into tiny particles by anaerobic bacteria by using CO_2 and various alternative electron receivers in place of oxygen, such as manganese, iron, sulfate, sulfur, and nitrate. The biodegradation pathway of plastic in the marine ecosystem is shown in Fig. 11.2.

2.1.2.1 Enzymatic breakdown

Enzymes are natural catalysts that operate on certain substrates, actively engage in the reaction, and quicken the substrate's transformation into a valuable product. All recognized enzymes that break down polymeric polymers belong to the class "hydrolases." When water is available, this group of enzymes participates in a catalytic activity that breaks down chemical bonds in its substrate (Tokiwa et al., 1976). Hydrolases are the main enzymes responsible for degrading ecological plastic compounds (Kaushal et al., 2021). Among the enzymes that comprise the third category is the hydrolase enzyme class (Kaushal et al., 2021). They help dissociate chemical bonds in the presence of water, fracturing bigger molecules into fragments. Enzymatic degradation is more particular than other forms of disintegration since it depends entirely on the interaction within the enzyme and the substrate. The active site is a special attachment region that the enzyme uses to engage with the substratum (contaminants) in order to carry out its catalytic action (Bilal et al., 2019; Karthik & Kim, 2021; Maddela et al., 2022). More benefits come from enzymatic breakdown than from microbiological bioremediation. In contrast to different bioremediation techniques, it has a more specialized, quick procedure, more adaptable operating settings, produces profitable outcomes even under adverse environmental circumstances, does not require nutrient delivery, and has fewer mass transmission and by-product generation restrictions (Saravanan et al., 2021). Despite the fact enzyme breakdown yields better results in comparison to conventional bioremediation techniques, choosing the right microbiological substrate is essential for producing enzymes, producing and purifying enzymes for use in manufacturing environments comes at a greater price. The cost of producing and purification enzymes may place a limit on the quantity of refined enzymes needed to facilitate the industrial-scale dissolution of enzymes. This can be accomplished by using genetic engineering, which produces the necessary number of enzymes at an amount that is far less expensive than the traditional method of producing

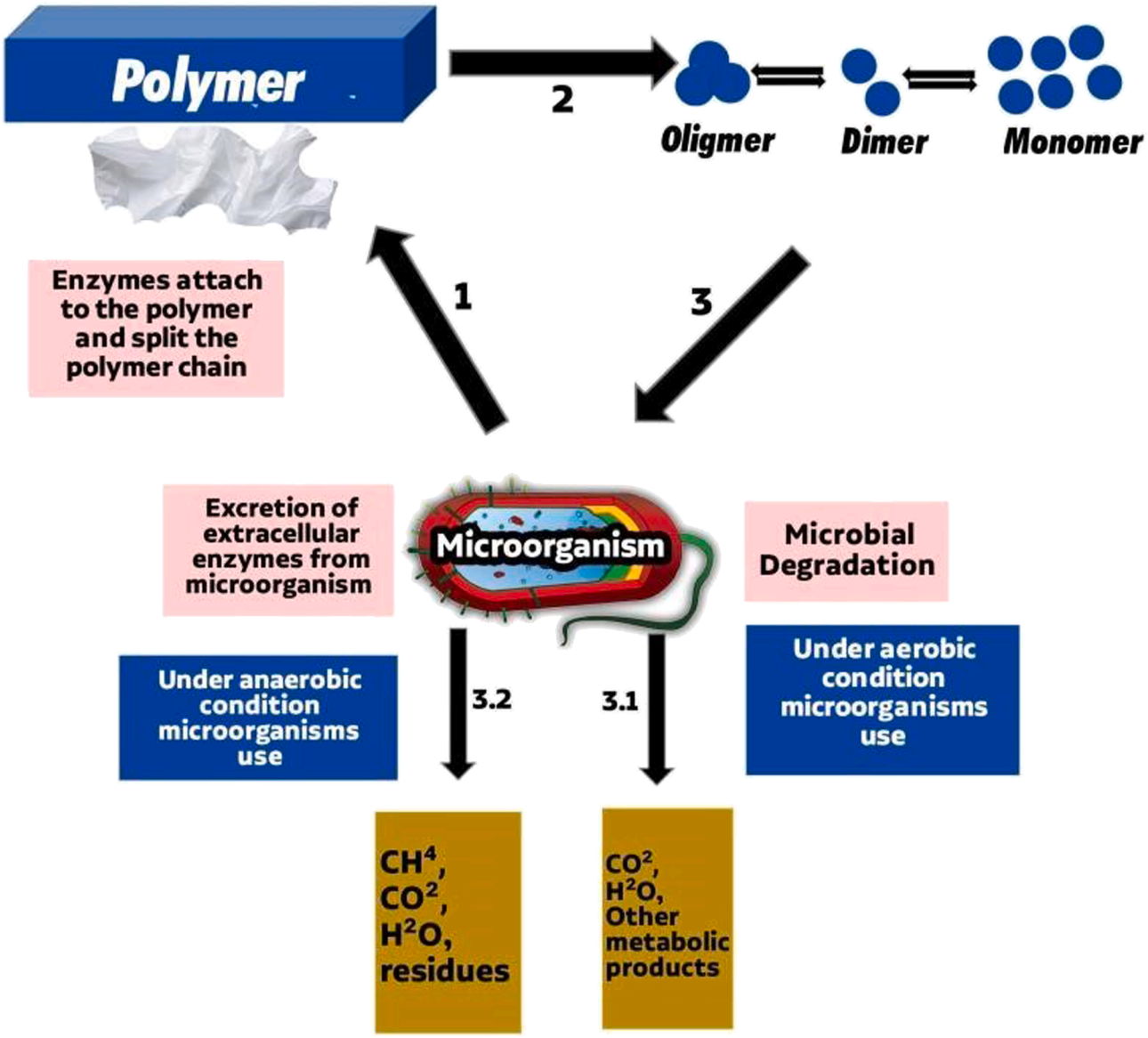

FIGURE 11.2 The biodegradation pathway of plastic in the marine ecosystem. *Authors.*

enzymes while maintaining a greater quantity of originality (Huy et al., 2021). Both internally and externally microbial enzymes contribute to the main disintegration process by breaking up the chains of polymers by interior absorption inside the cell and releasing metabolites such nitrogen dioxide (NO_2), carbon dioxide (CO_2), and carbon monoxide (CO) (Amobonye et al., 2021). Numerous enzymes which have been identified in bacteria, fungal actinomycetes, and algal may degrade different types of plastic molecules (Urbanek et al., 2020).

Since plastic's carbon–carbon backbone lacks hydrolyzable groups, it is challenging to break down using microbial enzymes. A combination of biotic and abiotic factors is used to reduce the molecular weight first. Microbial enzymes are facilitated by UV light exposure and can more easily target the carbonyl group of the polymer (Amobonye et al., 2021). A variety of enzymes are used in polymeric degradation, such as protease, urease, laccase, lipase, and manganese-dependent enzymes (which break down lignin). Fig. 11.3 shows the essential enzymes produced by various microbes for plastic degradation.

For instance, it has been shown that thermostable laccase may break down polyethylene (PE) in 48 h when it is incubated at 37°C (Kaushal et al., 2021). Biodegradation is the outcome of several microbial enzyme, enzymatic activity, and bond breakage. Enzyme adsorption on the polymeric interface and connect hydro-peroxidation/hydrolysis are the two

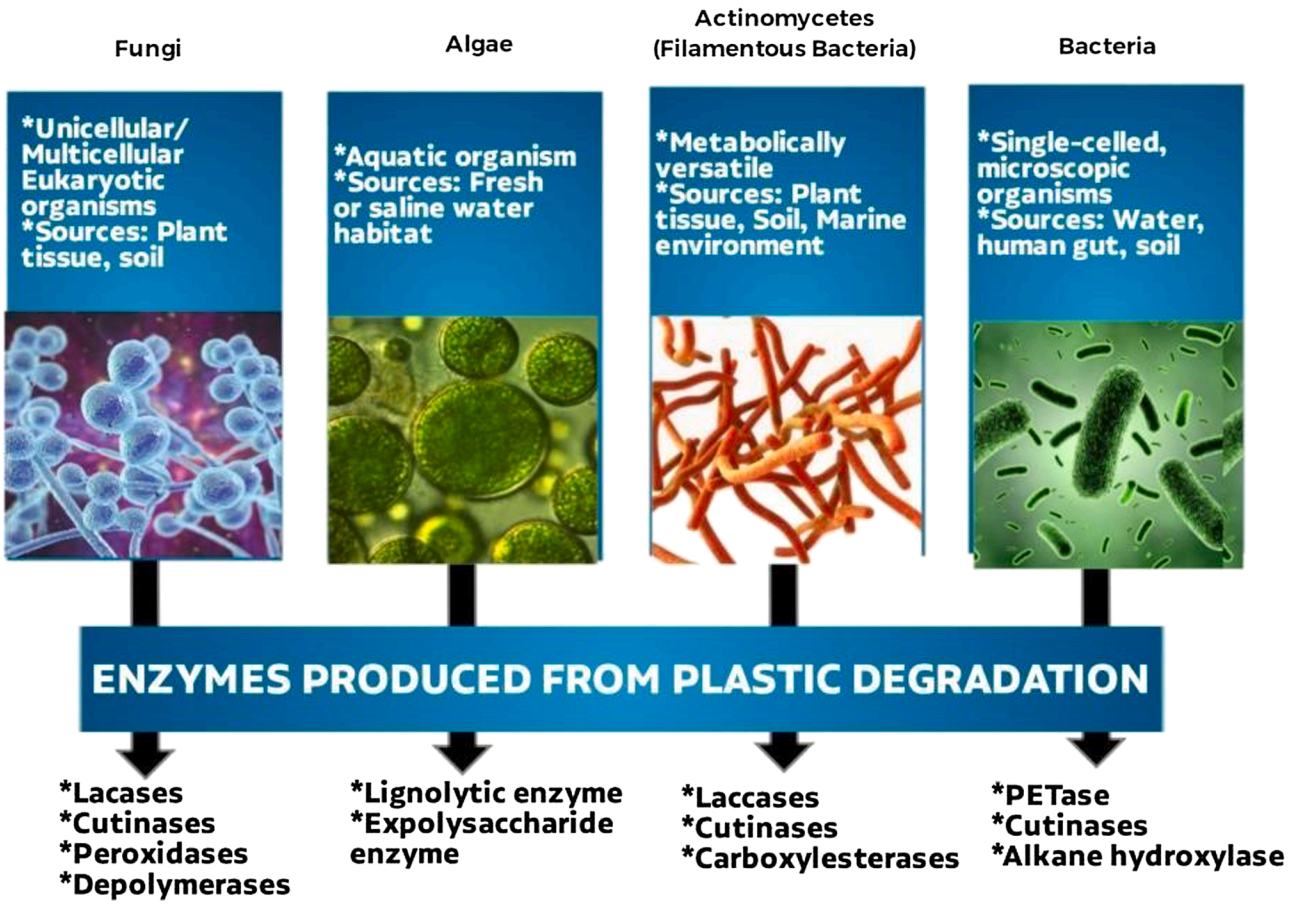

FIGURE 11.3 Essential enzymes produced by various microbes for plastic degradation. *Authors.*

phases of enzymatic degradation. This proves to be quite beneficial for controlling waste in the surroundings. Long carbon chains are broken up into shorter segments by the hydrolases that break down polymeric polymers in two different ways. By nature, all plastics in the ecosystem are hydrophobic substances. Enzyme–polymer interactions begin when the extracellular enzymes produced by different microorganisms adhere to the plastic surface through hydrophobic processes (Amobonye et al., 2021). The hydrophobic compounds in the polymer can be accepted by a hydrophobic gap present in many hydrolases close to the region of activity, increasing the enzyme's accessibility to the plastic (Kaushal et al., 2021). The enzyme's active site breaks down the lengthy chains of polymer into monomers of lesser size or dimers during the next stage of the reaction. The organisms involved can then concentrate these tiny monomers or dimers and use them as an alternative source of carbon (Kaushal et al., 2021).

Microbial communities have the ability to adapt by developing extensive biofilms and functional enzymes that catalyze on the exterior of plastic when they are exposed to settings exterior by plastic. The synthetic polymers can be broken down by these enzymes. Microbial enzymes have significant catalytic activity, which makes them useful in the degradation of man-made polymers. By lowering the activation energy of compounds, enzymatic processes quicken reactions, but microbial activity breaks down pollutants progressively. Bioremediation employs enzymes originating from various microorganisms as an even greater expedient option since they are very effective biocatalysts for a range of biochemical reactions involved in the systems leading to the breakdown of pollutants. The reduction of the activation energy of molecules leads to the acceleration of the process. The oxireductases (peroxidases, oxygenases, and laccases) and hydrolases (haloalkane dehalogenases, carboxylesterases, lipases, phosphotriesterases, and cellulases) are the two primary categories of enzymes which have demonstrated the capacity to biodegrade materials (D'Souza et al., 2022). In relation to various other biological remediation methods, enzyme-mediated breakdown has numerous benefits over microorganism bioremediation. These benefits include being more particular, faster, and adaptable in functioning, able to produce beneficial outcomes irrespective of harsh environmental circumstances, requiring no supply of nutrients, reducing the production of byproducts, and having fewer mass transfer constraints (Saravanan et al., 2021). Even though enzyme

breakdown yields better results than other bioremediation techniques, choosing the right bacterial origin is essential for producing enzymes, and producing and purifying enzymes for use in commercial applications comes at a greater expense. Researchers are now using immobilization approaches to produce and purify enzymes more efficiently and at a lesser cost in order to address these issues (Saravanan et al., 2021).

2.1.2.2 Metabolic pathways

Microorganisms secrete extracellular enzymes that facilitate the disintegration of plastic by dissolving complex polymers into their constituent As a result, short-sized oligomers can be carried through the membrane that covers the cytoplasm (Ghosh, Gangadharan et al., 2019). The internal enzymes additionally use these as sources of both energy and carbon (Ghosh, Gangadharan et al., 2019). Direct internalization of oligomers is possible, most likely with the help of biosurfactants made by bacteria so that beta-oxidation can begin alternatively, prior to internalization, can undergo further cleavage by abiotic mechanisms (Ghosh, Gangadharan et al., 2019). As a biofilm forms, biosurfactants are created. In addition, these monomers additionally have the ability to systematically degrade into a cycle known as TCA basic metabolite that penetrates core carbon homeostasis. During the natural breakdown of styrene, it was found that pyruvate, acetaldehyde, 2-phenyl ethanol, and 2-vinylmuconate appeared. Such compounds undergo further biosynthesis to produce phenyl-acetyl-CoA, which is then incorporated into the Krebs cycle/citric acid cycle, also known as the core carbon biosynthesis. On the other hand, PCL's molecular mass and quantity of crystalline structure determine the extent of its degradability. The amorphous portion was degraded by two fungus strains faster than the crystalline portion. Furthermore, it is impossible to overlook the part that a number of proteases play in the degradation of polymers. By examining breakdown of poly (L–10 lactide) PLA using three proteases: proteinase K, pronase, and bromelain, it has been demonstrated that proteinase K, which is derived from *Tritirachium album*, is the most effective of them at rupturing polymer chains. A portion of L-PLA that was amorphous was hydrolyzed more quickly by proteinase K, speeding up the disintegration process. In the crystalline region, it was smaller, albeit (Ghosh, Qureshi, & Purohit, 2019). Still, some strains have unique enzymes for a certain polymer. *Ideonella sakaiensis* secretes PETase in the event that PET is broken down. At the center of its catalytic triad is a Ser-His-Asp using engineered microorganisms is less expensive and safer than other methods. Bacteria are genetically modified to become gene-engineered microorganisms, or GEMs, by producing a stronger protein that supports a desired characteristic genetic modification of microbes (Ghosh, Qureshi, & Purohit, 2019).

Many different types of microbes exist in the environment that can break down dangerous compounds, although most of them do so slowly. Several chemical components present in the majority of pollutants prevent bacteria from biodegrading them as the catabolic pathways needed to break down harmful pollutants are absent, microbial species' capacity to detoxify or break down the particular contaminant must be increased. In order to create novel microbial strains with distinct traits and broad-spectrum bioremediation capabilities in comparison to native microorganisms, genetic engineering techniques can be used to achieve it (Kaur et al., 2020). Compared to other approaches, using modified microbes is safer and less costly. By genetically engineering microorganisms to generate an even stronger protein that promotes a desirable trait, one can develop gene-engineered microorganisms, or GEMs. Using GEMs such fungi, bacteria, and algae, it has been feasible to break down various pollutants such as oil spills, toluenes, naphthalenes, xylenes, halobenzoates, octanes, and trichloroethylene (Arunraja et al., 2023). Genetic engineering is the process of employing biotechnological technologies to manipulate an organism's genetic material in order to change its traits. The act of transferring an interesting gene from one creature to another in order to produce the desired result is known as genetic engineering. Any biological structure whose genetic composition has been altered using genetic engineering techniques is referred to as a recombinant living thing, also sometimes called a genetically modified organism. Recombinant bacteria can also be created naturally by genetic exchange between microbes (Kaur et al., 2020). Microorganisms (including bacteria, yeast, and fungi) that have undergone genetic alteration, or GMO, using in-vitro methods utilizing molecular biology are explicitly referred to as "genetically engineered organisms" (GEMs). Multiple microorganisms can be created by inserting genes into a single microorganism. The use of GEMs is vast, as it has been found to be very useful in bioremediation. In order to totally eliminate pollutants and the poisons they produce from the environment, this technique uses bacteria or their systems of enzymes (Hou et al., 2020; Liu et al., 2018). Genes relevant to breakdown pathways or those responsible for transforming resistant substances could be introduced into the microorganisms used in bioremediation procedures through genetic engineering. Because biotechnologically produced bacteria may co-metabolize or swiftly adapt to novel contaminants, they are more effective rather than native ones. Poisons also degrade faster in their presence. Genetic engineering is an area with tremendous promise to improve environmental and human health.

A class of methods referred to as "bioremediation" cleans up or restores damaged ecosystems using biological systems, such as those found in nature or genetically modified microorganisms (GEMs). The majority of indigenous bacteria

may effectively restore the environment by using mechanisms such as oxidation, immobilization, or other processes to transform contaminants into carbon dioxide and water. Researchers are considering bioremediation with GEMs as a significantly less hazardous and more economical method of treatment than traditional methods as pollution rates grow. GEMs can break down toluene, naphthalene, camphor, halobenzoates, trichloroethylenes, other chemicals, etc (Arunraja et al., 2023). These modified microbes seem to be more efficient than regular strains and exhibit higher degeneration tolerance. Additionally, they are able to quickly adapt to a wide range of contaminants as substrates by co-metabolizing. The use of plants, either directly or indirectly, to remove contaminants from soil, sediment, water, or sludge is known as "phytoremediation." A method called phytoremediation was developed to boost plant productivity and effectively remove harmful metals from ecosystems. Volatilization, rhizo-degradation, stabilization, rhizo-filtration, and extraction/accumulation are methods for removing metals from plants (Arunraja et al., 2023).

2.2 Genetic engineering of microorganisms

Biodegradation by microorganisms on plastic are relatively slow, and they cannot destroy some types of polymers (Prasad & Aranda, 2018). In comparison to natural strains, genetically modified microbes are more effective and exhibit more debasement flexibility. They can also swiftly adapt to various pollutants as substrates or co-metabolize (Arunraja et al., 2023). The amount of refined enzymes required for industrial-scale enzyme breakdown may be limited by the costs associated with generating and purifying enzymes. This can be achieved by using genetic engineering, which generates the required amount of enzymes at a comparatively lower cost than the conventional way while also manufacturing them with a higher degree of specificity (Huy et al., 2021). Under some settings, genetically engineered microbes have a higher degradative capacity for a variety of dangerous substances. Genetic engineering technology is now frequently employed as a possible aid in bioremediation. Bioremediation studies the diversity of microorganisms' metabolisms and gene diversity (Srivastava et al., 2021). Because of their genetic makeup, these bacteria aid in bioconversion, decomposition, and biosorption. These microorganisms' extrachromosomal and chromosomal DNA contains the basic gene blueprint for biodegradative enzymes. Recombinant DNA methodologies speed up the advancement of an organism's propensity for breaking down a xenobiotic by facilitating the detection of the aforementioned degradative genes and their conversion into a particular host utilizing the appropriate vector within careful oversight by appropriate promoters. Genetic information exchange and alteration susceptibility are necessary for it. Pollutant-degrading microorganisms have recently been enhanced by recombinant DNA biotechnology through strain alterations and mutations of particular regulatory and metabolic genes. The advancement of bioremediation techniques that are successful, safe, and economical depends on these discoveries. Important methods in the field of recombinant DNA development are particle bombardment, electroporation, site-directed mutagenesis, the chain reaction of polymerase (PCR), and the use of antisense RNA technology. Despite bioremediation is not effective solely for the decomposition of dangerous compounds, also it might be employed to clear undesirable pollutants from the atmosphere, water, and soil and materials that originate from commercial waste.

2.3 Enzymatic treatment

An environmentally acceptable, economical, and sustainable substitute for physicochemical separation of micropollutants is enzymatic treatment. One of its main advantages is that it requires few reagents to degrade a variety of substrates (Hussaan et al., 2021; Prasad et al., 2019; Rasheed et al., 2019). Microbial enzymes have a several limitations, including relative poor stability (temperature, storage, and pH), a decreased capacity for reuse, and a difficult technique for extracting them from the reaction fluid (Babaniyi et al., 2023; Hussaan et al., 2021). The factors that affect enzyme-assisted degradation, such as pH, enzyme concentration, temperature, and the presence of certain redox mediators, represent another disadvantage. Due to its effects on bacterial physiology and the speed at which enzyme activities proceed, temperature was found to be a significant factor in the breakdown of micropollutants. It was noted that at 3040°C, the rate of degradation reached its maximum. The bacterial membrane stiffens as the temperature drops toward its ideal range. The amino acids in bacteria become denatured at higher temperatures.

By altering the shape of bacteria and the characteristics of their membranes, pH also affects the process of decomposition (Hussaan et al., 2021). One possible disadvantage of employing enzymes in bioremediation is their susceptibility to denaturation when exposed to harsh conditions and certain hazardous organic compounds. By denaturing the proteins of the enzymes, surfactants such as urea and EDTA can decrease their activity. When urea is present, laccase activity drops by about 50%. On the other hand, certain surfactants, such as ethylenediaminetetraacetic acid (EDTA), totally eliminate enzymatic activity (Hussaan et al., 2021). Also, a variety of organic contaminants can be broken down by some enzymes, such peroxidase, but not by others that are more tenacious. One study claims that cyanide binds to the pronated

site of the enzyme, blocking other chemicals from activating it. Other studies revealed that the function of enzymes is impacted by the presence of salts and chloride ions (Hussaan et al., 2021).

Intermediate chemicals produced by enzyme-based biodegradation may be more hazardous than the original degrading agent. By intensifying the competition for active sites, a number of interfering substances lower the activity of microbial enzymes. Some chemical substances, such phenols, can accelerate the pace at which the active site of the enzyme breaks down triclosan. But the estrogen hormones E1, E2, E3, and E4 also exhibited a similar effect and decreased the pace at which the enzymes metabolized (Hussaan et al., 2021). The presence of some chemical solvents, such as acetone, ethanol, and methanol, which decrease enzyme activity, also affects the breakdown of natural contaminants. The rise of polymeric and oligomeric compounds in wastewater poses a risk to microbial-based enzymatic bioremediation because they can readily obstruct the active sites of the enzymes.

2.3.1 Discovery and optimization of plastic-degrading enzymes

Enzymes that break down plastic can have their activity enhanced through protein engineering. This optimization may include increasing the enzyme's degree of thermostability, strengthening the binding between the active site and the substrate, improving the surface–substrate exchange, and adjusting the catalytic capacity (Zhu et al., 2022). Enzymes aid in the sustainable and efficient handling and recycling of waste plastic, biocatalytic depolymerization, which minimizes adverse environmental effects. Proteomics and metagenomics can be employed as useful instruments to extract plastic depolymerizing enzymes from varied environments and settings. Given the widespread presence of polymers in biological systems and the remarkable metabolic and genetic variety of microorganisms, it is plausible that the capacity to degrade and utilize plastics has developed in bacterial colonies in two different environments (Zhu et al., 2022).

It is plausible that the enzymes associated with environmental plastic depolymerization bear little or no resemblance to the enzymes identified to date that break down plastic. However, because of their low catalytic function and inadequate thermostability, naturally existing polymer-degrading enzymes are not particularly suitable for the decomposition of synthetic plastic in industrial applications. Specifically, when contrasted with biogenic polymers, synthetic polymers generally possess distinct chemical and physical properties (such elevated crystallinity) that enhance their ability to withstand enzyme disruption (Zhu et al., 2022). As a result, protein engineering is being used more and more to create plastic-degrading enzymes that have improved resilience and catalytic effectiveness. The utilization process of protein engineering has allowed for great improvement and alterations in plastic-breaking enzymes (Zhu et al., 2022). In general, there are two types of techniques in protein engineering: logical engineering and focused evolution. Based on computational modeling, simulation, molecular properties, and knowledge of protein structure and rational, 34 designs alter the target protein. Because many of these enzymes have a lot of mechanistic and structural data available, almost all recent studies on the development of plastic-degrading enzymes incorporate rational design. The absence of effective high throughput screening methods is a major barrier to the controlled development of plastic-breaking enzymes (Zhu et al., 2022).

2.4 Biofilm formation for microplastic aggregation and removal

There are theories that suggest that microbiological on microplastics are not restricted to any particular substrates, that is, they are not substrate-selective when it comes to biofilm formation (Jacquin et al., 2019). Any kind of biofilm has its own unique growth and synthesis depending on the substrate, place, and time: the production of biofilms can be more geographically restricted than it could be restricted particularly to the substrate (Bolan et al., 2020). Initial biofilm growth can see fluctuations in abundance, microbial cell size, and carbon biomass; develop biofilms; and on the other hand, exhibit stable data for these variables (Aransiola et al., 2022; Hossain et al., 2019).

Under various circumstances, the biogeochemical environment can differ significantly. Microbes can interact with MP particles in two different ways: actively and passively. The microorganisms utilize MPs as a source of carbon when there is active exchange. The microbial population is influenced by the redox environment, leading to their active interaction with recipients of free electrons. The bacteria use the carbon from MPs by interacting with easily accessible nitrate, oxygen, and/or ferric ions, which function as electron receivers in water (Jacquin et al., 2019). The redox environment has a big impact on how the microbe colonizes plastic particles. According to Jacquin et al. (2019) and Kettner et al. (2019), the breakdown of plastic and the release of hydrocarbon gases and DOC are caused by abiotic processes including photodegradation, which releases electron donors into the surrounding water that bacteria can use to produce biofilms. Passive interactions are those that occur when microbes use MP fragments as a basis for the development of biofilm whether through biochemical or physical means. Both freshwater and coastal settings are likely to experience a similar

biofilm development process on plastics, which may involve a number of phases including physical attachment, monolayer growth, chemical adsorption, dispersion, excretion of EPS, and multilayer growth (Bolan et al., 2020). Free-floating microbes may attach to the surface of plastic through chemical and physical adsorption mechanisms (Koelmans et al., 2019). Physical adsorption would occur from the attachment of bacterial cells on bases containing EPS; chemical adsorption would result from polymers and microbial population's exhibit surface-charge-governed electrostatic attraction (Aransiola et al., 2024; Kumari et al., 2019). The EPS's proteins, carbohydrates, and nucleic acids aid in the adhesion of microorganisms within the colony (Kumari et al., 2019). Microorganisms that create biofilms primarily invade plastic's exterior in marine habitats. Interactions between polymer and biofilm may affect the polymer's chemical and physical characteristics, which could cause it to deteriorate. As a result, research is being done on biofilms as possible means of repairing marine environments in order to lessen the anticipated rise in microplastic contamination (Debroy et al., 2022; Sooriyakumar et al., 2022). In an aqueous solution, microorganisms swiftly colonize the outermost layer of MPs and create a durable biofilm. Certain bacteria have the ability to break down organic pollutants in biofilms and promote adhesion to contaminants via MPs (Ali et al., 2021). Even more crucially, the interaction between biofilms and MPs can change the physical and chemical characteristics of the polymer surface, potentially resulting in the breakdown of MPs and the presence of bacteria that form biofilms for MP biological degradation (Ali et al., 2021; Narciso-Ortiz et al., 2020).

MPs coated with biofilms degrade significantly at high quantities of methane gas, potentially contributing to bacterial aggregation (Faheem et al., 2020). Only CO_2 and H_2O are produced during MP breakdown as metabolites, and neither of these substances is hazardous to the environment (Sutkar et al., 2023). Microbial accumulation, which is facilitated by an elevated level of methane gas in the surrounding environment, can cause significant degradation of MPs infused with biofilms (Faheem et al., 2020). MP degradation is enhanced when glucose is utilized as an external carbon source as opposed to natural biofilms (Niu et al., 2023). On the other hand, biofilms can increase MP adherence to naturally occurring toxins, acting as conveyors and increasing the environmental risk associated with MPs (He et al., 2022). Bacteria rapidly colonize MPs' outermost layer and develop biofilms when they are placed into a watery environment. This increases MP adsorption to nearby pollutants (Enfrin et al., 2021). However, the issue can be greatly mitigated if a biofilm is developed and generated in controlled conditions before being contacted with MPs. Many factors influence biofilm formation on MP surfaces, such as UV exposure, pH, salinity, and temperature. It was discovered that a maximum degradation of 20% might occur (Faheem et al., 2020). The primary cause of this phenomenon is the time it takes for bacteria to change the inherent features of MPs. Although biofilms being formed have the ability to degrade MPs, the present efficacy is limited.

MPs are broken down by biofilm-forming bacteria because they are unable to consume macropolymers directly. As MPs pierce the biofilm, extracellular hydrolases and oxidases break down the big macromolecular polymers into smaller monomers and oligomers. These shorter-chain polymers are then absorbed by the bacteria in the biofilm, which then starts to convert them (Zhang et al., 2021). When bacteria are present, MPs can mineralize and produce CO_2 and H_2O. The biofilm approach typically eliminates MPs in four stages (Shabbir et al., 2020). At first, bacteria cluster on MP surfaces, changing their molecular composition. The bacteria subsequently broke down the chemicals and parts of the MPs. Thus, the bacteria produce free radicals or enzymes that assault the MPs and their component parts, resulting in their degradation and loss of long-term activity. Ultimately, microorganisms degrade MPs by dissolving microbiological filaments and allowing water to infiltrate the plastic matrix. The most essential stage of disintegration is expected to occur in the second phase (Shabbir et al., 2020). A variety of additives are commonly used in plastic goods to modify or enhance their mechanical and chemical qualities. These compounds are released when plastic waste is converted into MPs, which significantly impairs MP breakdown. Before the succeeding degrading phase, the additives will have to be leached via the MPs' structures to be eliminated. Microorganisms degrade polymer additives, facilitating biofilm development and early bacterial attachment to the fragments' external layer (Sun et al., 2023). This sixth phase aids in the breakdown of additives and MPs and promotes the production of biofilms. Finding and growing bacteria that have a significant impact on the process and utilizing them to get the best results can simplify the breakdown of MP.

2.4.1 Natural biofilms in marine environments

Biofilms in ecosystems are almost often defined as diversified or containing multiple species at once (Tuck et al., 2020), and this has significant implications for both research and downstream attempts at management. For example, typical mono-species simulations in vitro may often prove insufficient for elucidating ecological dynamics or recreating environmental occurrences (Tuck et al., 2020). Biofilms in their more complicated ecological condition, such as on minerals distributed in marine habitats, are even more difficult to treat using antimicrobial agents and biocides, as different species may exhibit distinct tolerance characteristics. Biofilms emerge rapidly in marine settings and renewal times are short,

especially when contrasted with monospecies laboratory models. Microeukaryotic and prokaryotic biota can be found in naturally formed microbial biofilms in marine and estuaries. Maritime biofilms are abundant in the maritime setting. These intricate microbial communities respond quickly to environmental changes because they comprise a wide range of distinct microbial structures, activities, and metabolic processes (Qian et al., 2022). The marine industry is greatly impacted by marine biofouling, which is largely caused by marine biofilms. Plastic waste can aid in the spread of dangerous algae, barnacles, bryozoans, and deadly Vibrio species. Plastics act as homes for marine microorganisms, which quickly colonize them and form vast biofilms on the plastic exterior known as the plastisphere.

The lifespan of plastics in marine environments is a subject of debate; estimates vary from 700 to thousands of years, depending on the chemicophysical characteristics of the material. Biofouling is the unwelcome development of biotic contributions on a surface and can have a major impact on the control of plastic buoyancy. Biofouling, which can also result in the disintegration of polymers, can cause larger plastic objects to crack and dissolve (Kirstein et al., 2019). According to Kirstein et al. (2019), the microbial communities on marine plastic garbage exhibit consistent differences from those in the nearby waters. Seasonal and regional conditions affect these polymer-associated communities' organization (Kirstein et al., 2019). The variety of substrate and plastics biofilm makeup influence the community makeup, as does the habitational conditions, such as harbor versus offshore (Kirstein et al., 2019). Overall, a special fusion of various elements, including the kind of substrate, the surroundings, seasonal variations in environmental conditions, and geographic location, is most likely responsible for the chemical makeup of marine plastic biofilms. On the other hand, it is generally known that the generic plastic biofilm community is made up of several different bacterial populations. *Erythrobacteraceae, Flavobacteriaceae, Rhodobacteraceae*, and *Hyphomonadaceae* are prevalent environments in the North Sea, Baltic Sea, North Atlantic, and freshwater systems (Oberbeckmann et al., 2021; Kirstein et al., 2019).

2.4.2 Engineered biofilms for enhanced aggregation

In both natural and artificial environments, bacteria typically produce biofilms, also known as formed extracellular polymeric substances (EPSs) (Flemming & Wuertz, 2019). Engineering biofilms entails understanding the principles underlying the creation of biofilms and utilizing the advantageous characteristics of bacterial communities. Beneficial biofilms' usage is limited by their variety in form and activity, as well as the inability to manage biofilm dynamics. Controlling biofilm shape and dynamics can improve biotechnology uses, such as efficient and regulated chemical synthesis through biofilm-mediated biocatalysis. Engineering biofilm is still in its early stages, despite various published techniques for enhancing biofilm-mediated bioprocesses over the past 5 years (Flemming & Wuertz, 2019). Biofilm formation is governed by sophisticated systems of regulation that coordinate the many phases of the biofilm development process (Mukherjee & Cao, 2021). The assistance of quorum sensing (QS) signaling molecules in the development of bacterial biofilm is one of their most important roles. Davies et al. (1998) state that although quorum quenching (QQ), or altering QS, prevents the formation of biofilms, intense QS encourages the creation of highly organized biofilms (Mukherjee & Cao, 2021). Thus, QS is one goal in regulating biofilm growth. For instance, water purification membranes were engineered using QS-based biofilm engineering to prevent the production of biofilm. Mukherjee and Cao (2021) found that the modified *E. coli* biofilm developed nitric oxide, which prevented other bacteria from forming biofilms on membranes.

Synthetic biology has significant potential for managing biofilms by refining and broadening preexisting molecular equipment, bringing additional activities into the system, protein production, and altering gene regulation (Mukherjee & Cao, 2021). The lack of well-defined gene transcription techniques in various bacteria limits synthetic biology applications in biotechnological fields (Cao et al., 2019). Synthetic biology tools are commonly used to generate and regulate microbial populations through changing gene expression, regulating regulatory systems, and constructing cell-to-cell communications. It may be feasible to create extremely programmed and manageable complicated synthetic systems by fine-tuning gene circuits that have been designed to generate desired output or performance by adjusting various input signals. The expression of planned gene circuits is frequently regulated by biochemical stimulants; however, their uses are limited by their possible toxic effects, absence of spatial regulation, and irreversibility (Liu et al., 2018). Chemical catalysts would make it more difficult to purify chemical compounds later on in the biocatalysis process for chemical synthesis. Light can now be used to influence bioactivities, thanks to recent developments in synthetic biology instruments. Optogenetic techniques are preferred over chemical inducers for regulating cellular behaviors because light is easily controlled, noninvasive, and economical (Mukherjee & Cao, 2021). By using optogenetic techniques, biofilm relevant genes can be accurately controlled by manipulating light-responsive switches, offering a potential approach to biofilm dynamics management (Mukherjee et al., 2018).

Changing the functions of important regulatory proteins and/or enzymes that regulate the formation of biofilms is another method of biofilm engineering. A prior work used random mutagenesis to create an evolved version of the SdiA

protein, and the variant increased the development of biofilms when QS signals were present (Mukherjee & Cao, 2021). The controlled development is a powerful protein engineering technology that gives an alternate way to create proteins with superior or unique capabilities through the use of mutation and selection (Kan & Joshi, 2019). Improving synthetic gene circuit function through directed evolution could be a potent method for biofilm engineering to increase biofilm-mediated activities. Biofilms are usually composed of very diverse microbial communities in environments that are both artificial and natural (Mukherjee & Cao, 2021). In contrast to single-species biological films, multispecies biofilms exhibit greater durability and resilience against environmental stressors (Mukherjee & Cao, 2021).

3. Biotechnological tools and techniques

3.1 Omics technologies in microplastic degradation research

Omic techniques have been effective in research on agriculture, food, and medicine (Oliver, 2019; Walsh et al., 2017). Without isolating the bacteria, omics-based technology has made it possible to quickly identify new genes, enzymes, and pathways involved in the breakdown of hydrocarbons. These developments have improved our profound knowledge of how the microbial communities living in the plastic environment change over time, particularly with the help of the rapid refinement of next-generation sequencing (De Tender et al., 2017). Numerous biological entities, including proteins (proteomics), microbes (microbiomics), mRNA transcripts (transcriptomics), and metabolites (metabolomics), have been studied using the omics approach. To fully comprehend toxicity pathways, it is common practice to integrate these different omics techniques. Advanced omic technology to assess environmental contaminants' toxicity has rapidly increased within the past 10 years. Technological developments in the fields of sequencing, laboratory techniques, and comprehensive data integration have significantly boosted the number of toxicological studies conducted (Fröhlich, 2017).

In the modern world of plastic pollution, where humankind is fighting to combat it, it is imperative to comprehend the toxicological pathways associated with microplastic. Novel insights on the biological reactions of microplastics to the exposed model have been made possible by the introduction of omics technology in toxicology. Toxicological data from acute and chronic exposure investigations, as well as from molecular to environmental levels, are being integrated using omic techniques. Using omics technologies allows for a deeper knowledge of the biomarkers and toxic mechanisms behind the reactions of the body to various forms of microplastics. Omic offers a high-throughput analysis that may be utilized to create plans for assessing the toxicity of related pollutants and microplastics (Bhagat & Vakhlu, 2022). Molecular marker high-throughput investigations have been made easier by the omics approach. Studies on exposure to microplastics at realistic environmental concentrations typically do not reveal any phenotypic alterations. Thus, far greater concentrations of these particles have been used in the majority of nonomics research. However, the negative impacts at low particle concentrations may now be identified, thanks to the advent of omics studies. The use of omics techniques, such as metabolomics, microbiomics, proteomics, and transcriptomics, to study aquatic species, including fish and shellfish that are edible and the impact of microplastics, has grown in popularity in recent years. The toxicological reaction of prawns (Duan et al., 2021), mussels (Cappello et al., 2021; Khalid et al., 2021; Gardon et al., 2020; Green et al., 2019) oysters (Teng et al., 2021), and clams (Jiang et al., 2021) exposed to microplastics has been studied using omics technologies.

3.1.1 Metagenomics

Important insights can be gained by employing metagenomics to analyses the metabolic processes and the phylogenetic, functional, and microbiological diversity of uncultivable bacteria. By studying microbial communities from severely contaminated areas, the use of combined metagenomics and molecular biology has improved our understanding of the microbiome and its biological systems in contaminated environments (Brahney et al., 2020; Kumar et al., 2021). It is possible to extract different microbial populations that may aid in the degradation of microplastics through the enzymes they produce. Not every enzyme that the microbial population produces is effective enough to take part in the processes of breakdown. The microbial population engaged in the biodegradation of plastic: a metagenomic analysis is suggested as a remedy for this issue in order to comprehend the characteristics determine the microbial community's potential for in-situ biodegradation (Purohit et al., 2020). Due to the developments in bioinformatics and sequencing techniques, it is now feasible to perform detailed metagenomic investigation of microbiomes to mine related genes and enzymes involved in biodegradation. Thus, metagenomics may be a useful technique for identifying efficient genes and enzymes that break down plastic in populations of uncultivable microorganisms (Basak & Meena, 2022; Ufarté et al., 2015). The investigation assessed both the levels of protein expression and the aquatic plastic biofilms' genetic potential (Oberbeckmann et al., 2021). According to Purohit et al. (2020), certain enzymes that are effective at breaking down microplastics in a lab

setting may not necessarily be appropriate for carrying out the precise mechanism in the environment of nature. For instance, one of the most common methods for disposing of PET polymers in marine environments is PETase hydrolysis. *Ideonella sakaiensis* produces PETase, a distinct version of the same enzyme. Plastics cannot be broken down by this enzyme in an aquatic environment. Scientists are now tackling this challenge by obtaining Homologs of PET hydrolase from several microbiological sources utilizing a functional metagenomic approach. PET hydrolases can be used in a variety of genetic engineering strategies to modify the target organism, and they are anticipated to have a wide distribution in both terrestrial and marine metagenomes according to conserved amino acids (Kirstein et al., 2019).

3.1.2 Proteomics

Proteomics, which is frequently carried out in conjunction with transcriptomics, examines structural and functional changes that occur during and after translation of proteins. For detecting cellular proteins, LC-MS/MS is most often used technique. Protein–protein interactions can be studied, and the target protein can be quantitatively detected with the use of isotopes (Granby et al., 2018). Research has indicated that the proteomes of *M. edulis* (Green et al., 2019) and *Litopenaeus vannamei* (Duan et al., 2021) are changed by exposure to MP/NP. D. after being exposed to microplastics, D. *rerio* larvae's expression of genes involved in signaling and fin regeneration at the protein level (TNF-α, IL-10, and NF-κB) *rerio* was measured.

3.1.3 Metabolomics

With the help of the potent bioanalytical technology known as metabolomics, thousands of metabolites can be thoroughly and quickly characterized. This is a very valuable addition as a tool for toxicology for researching microplastics mode of action in fish. Metabolite patterns change can reveal crucial details about the toxicological processes underlying the toxicity of microplastics. LC-MS and NMR are the two most often utilized analytical methods. In metabonomics, NMR is typically used, while metabolomics refers to MS-based study. Studies on metabolomics show how exposure to contaminants alters an organism's functional state. When significant alterations in the metabolism of tyrosine, purine, and the pathways for the manufacture of monobactam, novobiocin, and vancomycin group antibiotics, and so, quinoline alkaloids have been reported when *O. niloticus* is exposed to MP/NP. With shotgun metagenomics, high-throughput sequencing techniques, next-generation sequencing (NGS), and a variety of contemporary omics, including tools and software for proteomics, genomics, and bioinformatics, metagenomics provides a solution to the microplastic crisis (Brahney et al., 2020). Using metagenomics to analyze metabolic processes as well as the functional, phylogenetic, and microbiological diversity of bacteria yields important discoveries. Our understanding of the use of metagenomics and molecular biology has led to an improvement in the understanding of the microbiome and its biological processes in contaminated environments, which have made it possible to investigate microbial communities from severely contaminated locations (Kumar et al., 2021).

3.1.4 Identifying degradation pathways and key enzymes

MPs are depolymerized by microorganisms, which releases biodegraded polymers, which are catalytically broken down into smaller components by free radicals and extracellular enzymes. Generally speaking, the process of microbiological degradation of plastics involves the polymer being broken down into smaller molecules or shorter chains.

Depolymerization of the polymers results in monomers that might be required for microbial uptake, growth, and passage through semipermeable membranes, as well as for eventual mineralization in cells. In aerobic environments, the cells' monomers form into CO_2, H_2O, or under anaerobic conditions, CO_2, H_2O, and CH_4. The foundation of enzymatic degradation is the microbial destruction of polymers, which begins with microbial colonization on plastic surfaces by adhesion or exposure. Enzyme and polymer matrix are combined in the second phase, hydrolysis, which is followed by catalytic hydrolysis and cracking. The hydrolase that is linked to the material catalyzes the decomposition of organic materials (Tokiwa et al., 2009). Microbiological enzymes are essential for environmental biodegradation, which contributes to ecological health and remediation, engages in biotransformation and biodegradation processes, and combines the benefits of functionality and efficiency, making biocatalytic processes more efficient, safe, clean, and environmentally friendly (Carmen, 2021). Three technological outcomes primarily determine the degradation evidence: (1) structural changes in plastics or MPs; (2) physical mass loss of plastics or MPs; and (3) the production of plastics or MPs metabolites. These findings gathered together certainly provide the most reliable proof of plastics' and MPs' biodegradation.

The most used thermoplastic material is PET; it is produced in the largest amount—nearly 70 million tons annually—and is mostly used as packaging and textile fiber, with a tiny amount also going into the film and engineering industries. The database contains information on several signature enzymes for PET metabolism, including PETase, MHETase, TPA

dioxygenase, and PCA dioxygenase (Maity et al., 2021; Yoshida et al., 2016). There are currently very few bacteria and fungi that can partially degrade PET. It would seem, therefore, that only a few numbers of bacterial phyla display characteristics associated with PET degradation, and the bulk of isolates capable of doing so to Gram-positive phylum Actinobacteria (Kawai et al., 2019), which comprises the genera Thermomonospora and Thermobifida (Hu et al., 2010).

3.2 Synthetic biology approaches

By using engineering principles, synthetic biology creates programmable cells, biomolecular parts, and synthetic gene circuits with precisely defined dynamics and functions (Khalil & Collins, 2010). This method has led to the engineering of sophisticated biological systems that allow for biological computation, cellular spatial patterning, population coordination, living materials synthesis, and ecosystem functioning. This capability results to its application in environmental remediation. By utilizing synthetic biology technologies, creative engineering methods could be employed to enhance the innate ability of ocean biological systems to adjust to the rapid changes brought about by MPs (Nguyen et al., 2023).

The development of artificial microbial consortia is the main goal of the second wave of synthetic biology, which has garnered significant interest because to its rapid development (Purnick & Weiss, 2009). Advantages of exploring membrane consortia are: (1) Several strains are functionally split to do numerous complex tasks simultaneously, (2) dynamically balanced cell connections result in greater stability and flexibility to the changing environment, and (3) different strains can be constructed with components and modules with a range of functionalities and sources, which prevents the cross-influence of many functions and lowers the metabolic load on a single chassis (Shong et al., 2012).

Consortia of synthetic microorganisms can be designed and built in primarily two methods. The first is a top-down approach called re-engineering naturally occurring microbial consortia. In other words, using numerous omics analysis, one can investigate the maintained systems' molecular mechanisms by parsing the system principles and working their way up to the macroscopic microbial consortia. The other is a bottom-up approach that involves designing and building artificial microbial consortia. This refers to the process of creating enhanced stability, controllability, and efficiency of microbial consortia through the rational application of engineering principles, based on metabolic networks, circuits, modules, and genetic components (Jia et al., 2016). Fazzini et al. (2010) used proteome analysis to compare pure cultures with a co-culture of *Achromobacter xylosoxidans* and *Pseudomonas reinekei* under concurrent oxidative and chemical stress during the wastewater management process with consortia (Fazzini et al., 2010).

4. Wound healing and dermatological applications of marine plant-derived products

Wound healing is a critical aspect of dermatology, involving the repair of skin tissue after injury. This process is complex and can be impacted by several kinds of factor, such as the type of wound, the patient's overall health, and external interventions. A wound can be described as any disruption with the integrity of living tissue. The skin, recognized as the body's largest organ, is essential for protecting the moisture-laden internal organs from the arid conditions of the external environment (Almadani et al., 2021). Skin plays a pivotal role in human survival by mediating environmental interactions, regulating physiochemical and thermal homeostasis, storing essential nutrients, providing defense mechanisms, and responding to injuries. To maintain these vital functions, robust methods are required to shield the skin from harm, repair damages, and restore its essential roles when compromised. Across the annals of time, humans have consistently attended to their injuries, frequently making use of easily accessible materials like water, soil, plants, and animal byproducts. Conventional methods of wound care, which encompass ceremonial customs, are widespread in various societies globally. In areas such as Asia, Africa, the Middle East, and Latin America, indigenous flora, fauna, and natural cures function as the mainstay of wound management for countless people and, in certain cases, the exclusive form of treatment (Alexandra, 2019). The process of skin repair requires the coordination of multiple cell types in a precise sequence. The skin comprises various layers, including the epidermis—a protective barrier with sebaceous glands, sweat glands, and hair follicles. Beneath lies the dermis, rich in extracellular matrix, blood vessels, and sensory receptors, supporting the skin with strength and nutrients. The subcutaneous adipose tissue acts as an energy reserve and a source of growth factors. Each skin layer houses immune cells that monitor for damage. When the skin is injured, these cell types in the layers must work together in a specific order for healing. Angiogenesis, growth, re-epithelialization, remodeling, inflammation, and hemostasis are intricately coordinated during skin repair, making it among the human body's complex biological functions. At first, blood vessels undergo constriction, leading to the formation of a clot by platelets to halt the bleeding. This clot provides a platform for inflammatory cells like neutrophils to defend against bacteria. Monocytes transform into macrophages, and the adaptive immune system activates to combat antigens. Understanding the roles of different immune

TABLE 11.1 Marine plant–derived product for wound healing and dermatological applications.

Marine plant-derived product	Key components	Wound healing applications	Dermatological applications
Brown algae (e.g., Fucus vesiculosus)	Alginates	Hydrogels for moisture retention in wounds	Moisturizers, anti-aging formulations
Red algae (e.g., Chondrus crispus)	Carrageenan, antioxidants	Promotes cell proliferation and reduces inflammation	Treatments for burns and skin irritations
Seagrasses (e.g., *Zostera marina*)	Bioactive compounds	Stimulates skin repair and healing	Anti-inflammatory treatments for chronic conditions
Marine sponges	Bioactive peptides	Antimicrobial properties aiding wound healing	Anti-inflammatory creams
Corals	Calcium carbonate, bioactive compounds	Enhances tissue regeneration	Sunburn relief and skin repair products
Sea Cucumber (Holothuroidea)	Saponins, glycosaminoglycans	Anti-inflammatory, accelerates wound healing	Treatment for skin ulcers and infections
Spirulina (*Arthrospira platensis*)	Proteins, vitamins, antioxidants	Supports wound healing through nutrient supply	Skin rejuvenation, acne treatments

cell populations and their heterogeneity in clearing debris and resolving infection is of growing interest. As inflammation decreases, angiogenesis begins, forming new blood vessels through the expansion and movement of endothelial cells (Honnegowda et al., 2015).

Marine plant–derived products have garnered significant attention for their potential in wound healing and various dermatological applications. These products, often rich in bioactive compounds, can promote skin regeneration, reduce inflammation, and enhance healing processes. Marine organisms are abundance of bioactive substances with possible uses in the pharmaceutical and cosmetic industries. Recent investigations dedicated to exploring the benefits of collagen extracted from these marine sources have been published. Marine collagen stands out due to its solubility in water, compatibility with the human body's metabolism, and ease of availability, making it a valuable biomaterial. Studies have shown that marine collagen is versatile, playing a role in skin wound healing and slowing down the aging process. Both in laboratory settings and real-world scenarios, collagen has demonstrated its ability to enhance skin cell migration, promote tissue vascularization, and contribute to the treatment and prevention of diseases such as osteoarthritis and osteoporosis. Moreover, marine collagen is effective in improving bone density, facilitating mineral deposition, and supporting the development and growth of bone-forming cells. This examination underscores the advantages of marine collagen over collagen derived from terrestrial animals, underscoring its significance in skin and bone health applications. Dermatological conditions have a significant psychosocial impact, greatly affecting patients' lives. The use of topical therapy is crucial in managing such conditions. Traditional topical delivery methods often lead to either excessive or inadequate medication, resulting in adverse effects or reduced therapeutic efficacy. As a result, researchers have been exploring alternative delivery systems for dermatological treatments. Microsponges have become a viable alternative in recent years for topical delivery due to their unique particle size, offering superior benefits compared to current microcarriers (Mahant et al., 2020). Table 11.1 shows a list of marine plant-derived product for wound healing and dermatological applications.

5. Cardiovascular health benefits of marine plant compounds

Natural substances obtained from flora, fauna, microorganisms, and geological materials have historically played a vital component in the treatment of human illnesses. Although the exploration of natural products for pharmaceutical applications encountered various obstacles in recent decades, advancements in analytical methodologies, spectroscopy, and high-throughput screening techniques have revitalized interest in the discovery of drugs produced from substances in nature, particularly those originating from marine environments. The marine ecosystem, characterized by its extensive biological diversity, offers a promising pathway for the identification of innovative therapeutic agents. Increasingly, chemicals originating from aquatic environments are now advancing into clinical trials, reflecting the growing influence of this domain within the pharmaceutical sector (Pravin et al., 2019).

Marine bioactive compounds, characterized by their varied chemical structures and biological activities, offer compelling therapeutic opportunities for addressing age-related illnesses. A plethora of marine-derived substances has demonstrated potential in the treatment of type 2 diabetes (T2DM) and cardiovascular diseases (CVD); however, the pathway to their clinical utilization is protracted. These compounds are particularly noteworthy in the realm of aging, as they address critical components of the aging process, including inflammation, oxidative stress, and the gut microbiome. Their low incidence of adverse effects and the capacity to exert a wide array of beneficial impacts render them particularly suitable for elderly populations, who frequently require long-term management with multiple medications (Giuliani et al., 2024). In addition, compounds derived from marine sources, such as saringosterol, xyloketal B, asperlin, and omega-3 acid ethyl esters, have demonstrated encouraging efficacy in the treatment of various cardiovascular conditions. Historically, synthetic pharmaceuticals have dominated the interests of pharmaceutical companies; however, since the early 2000s, there has been a notable revival in the exploration of natural products, which now occupies a significant role in biomedical research. This renewed focus can be attributed to the enhanced biocompatibility of natural compounds in comparison to synthetic drugs, alongside the remarkable diversity and therapeutic potential of these natural substances (Akram et al., 2023).

Individuals who successfully manage their cardiovascular risk linked to excessive triglyceride levels may still exist for low-density lipoprotein (LDL) levels. Research has indicated that heightened fasting triglyceride concentrations are independently linked to the occurrence of new cardiovascular events. Furthermore, recent genetic investigations have provided substantial evidence supporting the involvement of triglyceride-rich lipoproteins (TGRLs) in the process of atherothrombosis. Omega-3 fatty acids, including docosahexaenoic acid and eicosapentaenoic acid (EPA), have been shown to lower blood triglyceride levels and may confer additional protective benefits against atherosclerosis when administered in higher doses. Additionally, omega-3 fatty acids play a role in T-cell maturation, facilitate the production of different prostaglandins, and produce specific proresolving lipid mediators that aid in the healing of inflammation and tissue damage.

REDUCE-IT trial, formally known as the Reduction of Cardiovascular Events with Icosapent Ethyl–Intervention Trial, revealed a significant 25% decrease cardiovascular events among patients with diabetes, heart disease, and other related risk factors, utilizing an EPA-only formulation. This observed clinical benefit is thought to stem from a variety of molecular mechanisms, as EPA is easily integrated into atherosclerotic plaques in humans, which may reduce the risk of events in clinical practice. Notably, the effects of docosahexaenoic acid and EPA on membranes architecture, inflammatory markers, lipid oxidation rates, endothelial function, and tissue distribution are different. Research involving omega-3 fatty acids that include docosahexaenoic acid has not demonstrated the same level of benefit as that observed with EPA in the REDUCE-IT study (Sheikh et al., 2019).

6. Conclusion and future prospect

Biotechnology offers a promising pathway to tackle some of the most pressing global challenges, from pollution control to healthcare innovation. By harnessing the capabilities of microorganisms, plants, and bioengineered organisms, biotechnology has already demonstrated its potential to address environmental degradation and enhance public health. As research and development in this field continue to advance, the future holds even greater possibilities. New biotechnological breakthroughs are likely to lead to more efficient methods for detoxifying polluted environments, improving waste management, and creating sustainable solutions for industries. In healthcare, continued innovations in gene therapy, regenerative medicine, and personalized treatments promise to revolutionize the way we treat diseases, offering targeted and more effective solutions. With ongoing advancements and a growing understanding of biological systems, biotechnology has the potential to become a cornerstone of global sustainability and human well-being in the years to come.

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Section 3

Innovations and applications of marine bioresources

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Chapter 12

Microbial bioactive molecules applications

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1. Introduction to microbial bioactive molecules

1.1 Definition and importance

Natural substances have long been used to cure and prevent illnesses globally. Natural product medications are derived from a variety of sources as secondary metabolites, including plants, microbes, marine species, and terrestrial organisms (Chin et al., 2006). Both in their natural form and as models for synthetic alteration, organic substances derived from terrestrial and marine microorganisms have been extensively used in the past and present to cure an array of disorders.

The majority of the planet's diversity is found in the oceans, which make up more than 75% of the planet's surface. Marine organisms are diverse and include phytoplankton, sponges, green algae, red algae, brown algae, cnidarians, bryozoans, crustaceans, echinoderms, tunicates, and various benthic plants and microbes. Microbes in marine habitat can tolerate high salt concentrations, pressure, nutrient depletion, and low temperatures. Because of their adaption to this distinct habitat, they create a wide range of primary and secondary metabolites that have proven substantial biological activity against cancer and inflammatory illnesses, anesthesia, immunity modulation, allergies, and antiviral properties assays. For bioremediation, biosurfactant synthesis, and the chemical composition of "psychrophilic" enzymes produced by microorganisms suited to low temperatures, a variety of marine bacteria are of great biotechnological interest (Kang et al., 2015). These materials have great promise for biotechnological uses in the food and detergent industries, as well as in the manufacturing of chemical reagents and pharmaceuticals. Furthermore, a plethora of novel antibiotics have been discovered from marine microbes.

The MarinLit database identifies over 42,000 compounds with a marine origin (http://pubs.rsc.org/marinlit/). Therefore, the potential of marine species as sources of new pharmaceuticals has yet to be fully investigated.

1.2 Historical background

The first cephalosporin C antibiotic was developed from a marine fungus in 1949, but until the 1980s, the discovery of biologically active chemicals from marine microorganisms was extraordinarily sluggish. Since 1985, marine organisms have developed over 15,000 new metabolites, some of which have shown fascinating bioactivities (Han et al., 2003).

It is now well established that different marine populations exist, even though it has long been known that common soil-inhabiting actinomycetes may be easily recovered from marine samples (particularly ones taken close to land). This was made clear in 1984 when *Rhodococcus marinonascens*, the first marine actinomycete, was described taxonomically. In the past few decades, at least three marine species have been identified. Among these is the genus Salinispora, which needs salt—more specifically seawater—to thrive. The first seawater-obligate marine actinomycete, *Salinispora* sp., was not described until 2005, despite the fact that sampling for marine actinomycete had started in the late 1960s (Wang & Lei, 2018). In 2003, researchers reported the discovery of a potent anticancer drug, salinisporamide A, from *Salinispora tropica*. This substance shares chemical similarities with omuralide, a recognized inhibitor of proteasomes (de Castro et al., 2020).

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1.3 Sources of microbial bioactive molecules

Most bacteria discovered in saltwater fall into five genera: *Flavobacterium* sp., *Vibrio* sp., *Pseudomonas* sp., *Achromobacter* sp., and *Micrococcus* sp. According to Shivale et al. (2018), nonribosomal peptides (NRP) or a polyketide-nonribosomal family of peptides make up about 70% of marine bacteria's secondary metabolites. These peptides serve a variety of biological functions. Of the 58 species tested, nine strains of marine bacteria from the genera Actinomyces, Bacillus, Micrococcus, and Serratia were shown to produce antibiotic compounds and interact negatively with Gram-positive microorganisms. However, Streptomyces has developed the majority of novel chemicals thus far (Brennan & Owende, 2010). Streptomyces sp. S2A, a marine actinobacterium, was isolated from sea sediment. This organism's extract inhibited the enzymes a-glucosidase and a-amylase, as well as having antioxidant and cytotoxic properties against different cell lines and antibacterial properties against pathogenic bacteria and fungi (Mubarak et al., 2015).

Marine algae: Marine species face harsh conditions in their natural habitats and adapt differently than terrestrial organisms. Algae are one of the oldest groups of creatures. Microalgae are photosynthetic microorganisms, both prokaryotic and eukaryotic. Microalgae are abundant in biodiversity and include bioactive components like as proteins, lipids, pigments, and vitamins that have a variety of biological functions, including antiviral, antibacterial, antioxidant, and anti-inflammatory properties. Chlorella, Arthrospira (Spirulina), and Dunaliella salina are the most common commercial microalgae (Mojaat et al., 2008). The most common carotenoid is β-carotene, which comes from *Dunaliella salina*. It is widely utilized in the food industry as a natural colorant and provitamin A. β-carotene can be used in medicines as an antioxidant to prevent cancer. *Haematococcus pluvialis*, a green microalga, includes astaxanthin, the second most prominent carotenoid found in microalgae.

Algal biomass can be used to make biodiesel, as microalgae store 100 times more lipid than terrestrial species do, particularly in the form of triacylglycerides (TAGs) within their cells. High-energy-density fuels like biodiesel, which is produced by transesterifying TAGs to produce fatty acid methyl esters, and green gasoline, which is produced by combining hydro processing and catalytic cracking to produce alkanes, could both be started with TAGs (Hattab et al., 2007). The Table 12.1 below lists several categories of metabolites that come from marine sources.

1.4 Method of extraction

To increase the isolation and production of bioactive compounds, a number of strategies, like metabolic engineering and different extraction procedures, have been designed. Conventional extraction techniques that involve liquid and solid extraction steps are commonly used in industry and laboratories to separate solid matrix components. The foundation of

TABLE 12.1 Metabolites from various marine microbes.

Marine source	Metabolite	Activity	References
Bacteria species 1. Bacillus sp. 2. Bacillus amyloliquefaciens 3. Photobacterium sp. 4. Streptomyces sp.	• Bogorol A, Loloatin B • Macrolactin S, Macrolactin V • Unnarrmicins A, C • Ngercheumicins A–D • Solonamidin A. • Anthramycin	Antimicrobial activity	Jang et al. (2010) Rahman et al. (2010) Tuin et al. (2009) Agrawal et al. (2017) Hu et al. (2007)
Fungal species 1. Alternaria sp 2. Phialocephala sp 3. Penicillium sp. 4. Trichoderma	• Altertoxin VII • Scirpyrone K • Phenalenone, • Herqueinone derivatives • Aminolipopeptide trichoderins	• Anticancer activity • Antioxidant • Anti-angiogenetic and Anti-inflammatory activities, • Antibacterial activity	Pang et al. (2018) Zhang et al. (2018) Park et al. (2019) Pruksakorn et al. (2010)
Algal species 1. Dictyota ciliolate 2. Dunaliella tertiolecta 3. Padina pavonia 4. Sargassum patens	• Dictyodial, dictyol C and dictyol H • 7-dehydroporiferasterol (phytosterol) • Sulfated galactan • Sulfated polysaccharide	• Cytotoxic, antiviral, and algicidal activities. • Neuromodulatory activity • Antiviral activity • Antiviral activity	Manzo et al. (2009) Francavilla et al. (2012) Mohamed and Agili (2013) Zhu et al. (2004)

TABLE 12.2 Extraction of bioactive from various microorganisms.

S. No.	Method of extraction	Bioactive compounds	Bioactivity	Microorganism	References
1.	Solvent extraction	β-Carotene Volatiles and essential oils	Antioxidants	Dunaliella salina Dictyopteris membranacea	Mojaat et al. (2008) Hattab et al. (2007)
2.	Pressurized liquid extraction	Carotenoid and chlorophyll extract	Antioxidants	Chlamydomonas	Montero et al. (2018)
3.	Microwave-assisted extraction	Polyphenolic-rich extract	Antimicrobial activity	Ascophyllum nodosum	Silva et al. (2022)
4.	Subcritical fluid extraction	Vitamin E and Short-chain fatty acids	Antioxidant and antimicrobial properties, respectively	Haematococcus pluvialis	Rodríguez-Meizoso et al. (2010)
5.	Supercritical extraction	Lipids	Biodiesel production	Chlorella protothecoides	Viguera et al. (2016)

these techniques is the extraction of the molecules using suitable solvents in accordance with their differences in polarity. The properties of the matrices, the solid/liquid ratio, the temperature, the pressure, and the duration of extraction are additional variables that significantly affect standard procedures. Some of the classical extraction techniques are solvent extraction, subcritical fluid extraction, supercritical extraction, pressurized liquid extraction, and microwave-assisted extraction. Table 12.2 below displays the bioactive extracted from different microorganisms.

2. Types of microbial bioactive molecules

2.1 Antibiotics

The substances that bacteria make that either stop other microbes from growing or eradicate them are known as antibiotics. Antibiotics not only treated infectious infections but also paved the way for many modern medical treatments, such as cancer therapy, organ transplants, and open-heart surgery. Unfortunately, inappropriate usage of these beneficial substances has led to a large development in antimicrobial resistance (AMR), making many illnesses almost incurable. Given the relatively poor success of introducing efficient synthetic antibiotics into the clinic, the best chance of developing a new generation of anti-infective medications is to discover new microbial bioactive molecules that are unparalleled in their chemical diversity and potency as antibiotics (Hutchings et al., 2019).

A multitude of microbial metabolites exhibit distinct antimicrobial properties and selectively act at specific target areas as shown in Fig. 12.1, making them a valuable resource for biotechnological applications, particularly in the fields of medicines and nutraceuticals (Rani et al., 2021). Deep-sea creatures account for around 2% of the over 30,000 marine natural products (NPs) discovered in the previous 50 years (Skropeta & Wei, 2014). Antibiotics are among the most intriguing microbial nanoparticles (NPs), having applications in biotechnology and medicine. New antibiotics are needed to avoid the emergence of multidrug-resistant (MDR) microorganisms (Ventola, 2015). New antibiotics may be found by investigating hitherto unknown deep-sea creatures such as bacteria and fungus, as well as the products they produce. Around 50% of natural medicines were discovered between 1981 and 2010 as a result of the late 1980s transition in drug discovery from nature to the laboratory bench—a process known as chemical synthesis (Sanseverino et al., 2018). Among them was prodigiosin, an antibacterial pigment that causes *Bacillus subtilis* to undergo autolysis and is generated by the marine bacterium *Vibrio ruber*.

Because of their vast genetic diversity and capacity to produce different metabolites, marine microorganisms are an essential source for the discovery and development of new antibiotics. A considerable number of taxonomically odd species have been identified as promising new sources of bioactive compounds (Goodfellow & Fiedler, 2010). Deep-sea sediment-derived marine microorganisms have been shown to provide a rich source of secondary metabolites with distinct structures and superior biological activity, such as antimicrobials (Abdel-Mageed et al., 2010).

High GC Gram-positive bacteria produce the vast majority of naturally occurring antibiotics. Actinomycetes, in particular, are the principal source of natural bioactive chemicals with potential medicinal or therapeutic applications

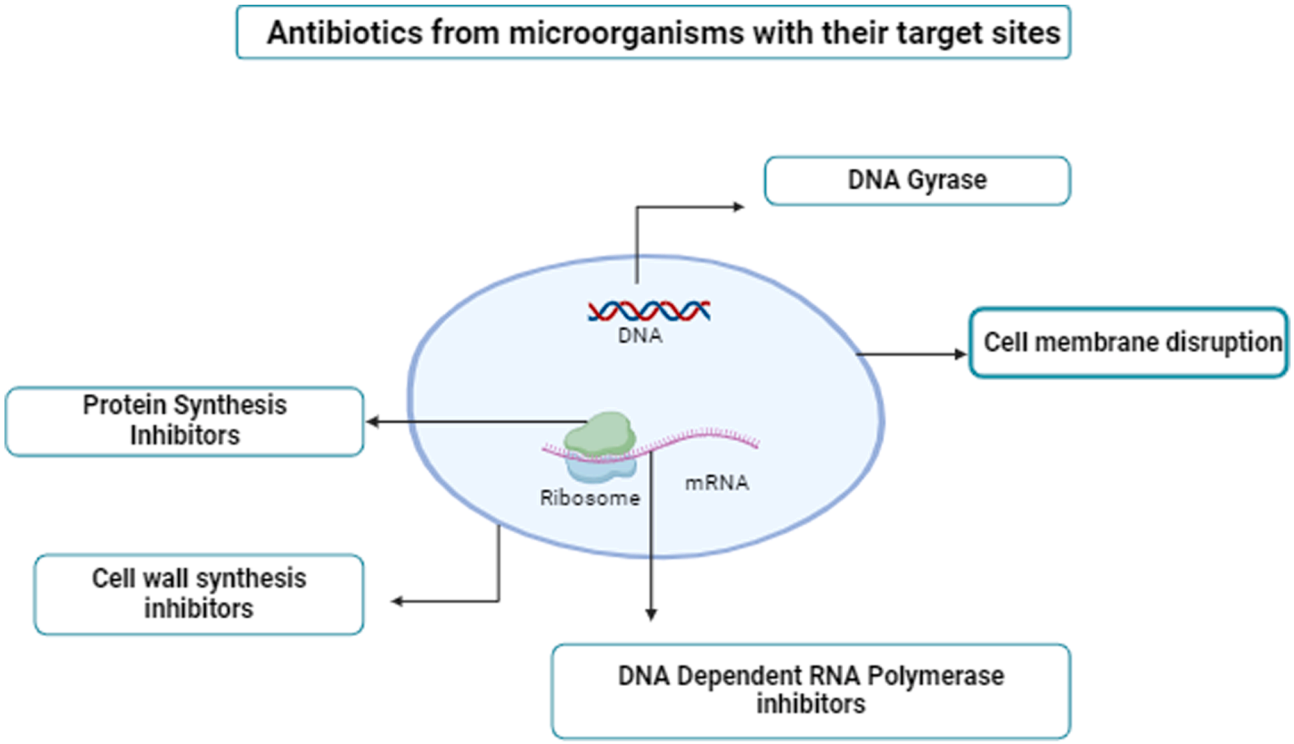

FIGURE 12.1 Antibiotics reported from different microorganisms with their target sites.

(Bérdy, 2005; Bister et al., 2004) identified three new polycyclic polyketide-type antibiotics, known as abyssomicins B, C, and D, from the rare actinomycete Verrucosispora strain AB 18-032, which was found in a sediment sample from the Japanese Sea at a depth of 289 m. Abyssomicin C effectively treated MRSA and a vancomycin-resistant *S. aureus* strain, with MIC values of 4 μg/mL and 13 μg/mL. abyssomicin C is considered a representative member of the class I spirotetronate. Abyssomicin C and its atropisomer suppress the formation of para-aminobenzoic acid (pABA), making them the first known bacterial-derived chemicals to do so.

PABA biosynthesis is an intriguing target in the realm of novel antibiotic development since it is found in numerous bacteria but not in humans. Blocking the pABA pathway is harmful to bacteria since it is a biosynthetic precursor of folic acid, which is necessary for DNA synthesis/repair and cell viability (Lacoske & Theodorakis, 2015).

2.2 Antifungals

Since the discovery of the antibiotic cephalosporin in 1948, marine fungi have been recognized as an important source of bioactive compounds. Gliotoxin was the first antibacterial agent discovered in an Aspergillus sp. strain isolated from deep sea. It inhibits the growth of Gram-positive bacteria like *S. aureus* and *B. subtilis*. The fungus was found in soil from Japan's Seto Inland Sea. Following this finding, deep-sea fungi were found to generate additional antibiotics; however, they are tiny in comparison to those produced by marine fungi isolated from surface waters. (Blunt et al., 2014; Zhang et al., 2013) discovered 13 distinct fungus species in deep-sea sediments in the South China Sea, including several novel phylotypes. Several of these species, including *Micrococcus luteus*, *Pseudoaltermonas piscida*, *Aspergerillus versicolor*, and *A. sydowii*, were shown to generate antibiotic substances against harmful bacteria and fungus (Zhang et al., 2013).

2.2.1 Fungal endophytes

Since W. Flemming discovered Penicillin from *Penicillium notatum* in 1928 and the anticancer medication "Taxol" from *Taxomyces andreanae* in the early 1990s, scientists have been searching for novel microbial-derived medicinal molecules. The two medicines were isolated from the fungus. Taxol was originally isolated from *Taxus brevifolia* and then from *Taxus wallichiana*, both of which include endophytic fungus called *Taxomyces andreanae* and *Pestalotiopsis microspore*, respectively. The discovery of these antibiotics and anticancer drugs created new opportunities for the development of

biologically derived therapeutics. Endophytic fungi generate various antibacterial compounds that are highly effective against antibiotic-resistant illnesses. Many substances having antibacterial characteristics have been found and isolated, including linoleic acid, R-glycerol monolinoleate, fumiquinazoline-F and fumiquinazoline-D, deoxy-thymidine, and cerebroside A (Z,Z).-N, N0-[1-[methylene-(4-hydroxyphenyl)]-2-[methylene-(4-methoxy-phenyl)]-1,2-ethanediyl]-pyrazolineand bisformamide, three-one trimester A. fumigatus, an endophytic fungus, produces Tricho-9-ene2a,3a,11a, and 16-tetraol (Hashem et al., 2023).

Endophytic Aspergilli crude ethyl acetate extracts show promising antibacterial and antifungal properties as shown in Table 12.3. They show antioxidant potential through the synthesis of active secondary metabolites such alkaloids, terpenoids, and ρ-terphenyls (Hashem et al., 2023).

2.3 Antivirals

Antivirals are bioactive substances that selectively restrict the ability of viruses, a subclass of microbial pathogens, to proliferate and propagate within their host cells. Antivirals, in contrast to antibiotics, act on viruses by interfering with different stages of the viral life cycle without necessarily causing death to the host cells.

The research of marine microbial-derived antiviral lead compounds has advanced significantly in the literature between 2015 and 2019. Over 30 of the 89 secondary metabolites that have been identified show strong antiviral properties. Considerable research should be done on two secondary metabolites that show strong broad-spectrum (HIV, HCV) antiviral activities trypilepyrazinoland-3β-hydroxyergosta-8,14,24(28)-trien-7-one. Marine microorganisms have yielded several molecules with notable antiviral activity, and it is anticipated that they will remain a valuable source of antivirals

TABLE 12.3 Various fungal endophytes and their bioactive compounds.

Endophytes	Host plant	Bioactive compounds	References
A. alternata AE1	Azadirachta indica A. Juss	Phenolics and flavonoids	Chatterjee et al. (2019)
A. alternata KT380662	Passiflora incarnata L	Flavone chrysin (5,7-dihydroxy flavone)	Chatterjee et al. (2019)
Ampelomyces sp	Urospermum picroides	3-O methylalaternin, altersolanol A, 6-O-methylalaternin andAltersolanol A	(Baker & Satish, 2012; Seetharaman et al., 2017)
Aspergillus aculeatus	Rosa damascena	C32H30O15	Aly et al. (2008)
A. awamori	Acacia nilotica	Peptide lectin (N acetylgalactosamine	Farooq et al. (2020)
A. flavus	Solanum nigrum	Solamargine	Adeleke and Babalola (2021)
A. fumigatus	Sweet-potato (ipomoea batatas)	Linoleic acid, R-glycerol monolinoleate, bis-dethio-(bis-methyl-thio)-gliotoxin, fumiquinazoline-F, fumiquinazoline-D, deoxy-thymidine, cerebroside A, (Z,Z)-N, N0 -[1-[(4-Hydroxy-phenyl)- methylene]-2-[(4-methoxy-phenyl)-methylene]-1,2-ethanediyl]-bisformamide, pyrazoline-3-one trimer, Tricho-9-ene2a,3a,11a,16-tetraol	El-Hawary et al. (2016)
A. terreus	Solanum xanthocarpum and carthamus lanatus L. (Asteraceae),	Lovastatin, (22E,24R)-stigmasta5,7,22-trien-3-β-, Aspernolides F	(Parthasarathy & Sathiyabama, 2015; Shaaban et al., 2013)
Berkleasmium sp	Dioscorea zingiberensis	Diepoxin, Palmarumycin C11, Palmarumycin C12, Cladospirone B, Palmarumycin C6, 1,4,7β-trihydroxy-8-(spirodioxy-10,80—naphthyl)-7,8-dihydronaphthalene and Palmarumycin	Shan et al. (2014)
Botryosphaeria sp	Melia azedarach L and Huperzia serrata	Stemphyperylenol, Pycnophorin, chaetoglobosin C, Djalonensone, Alternariol, β-sitosterol glucoside.	Ibrahim et al. (2015)

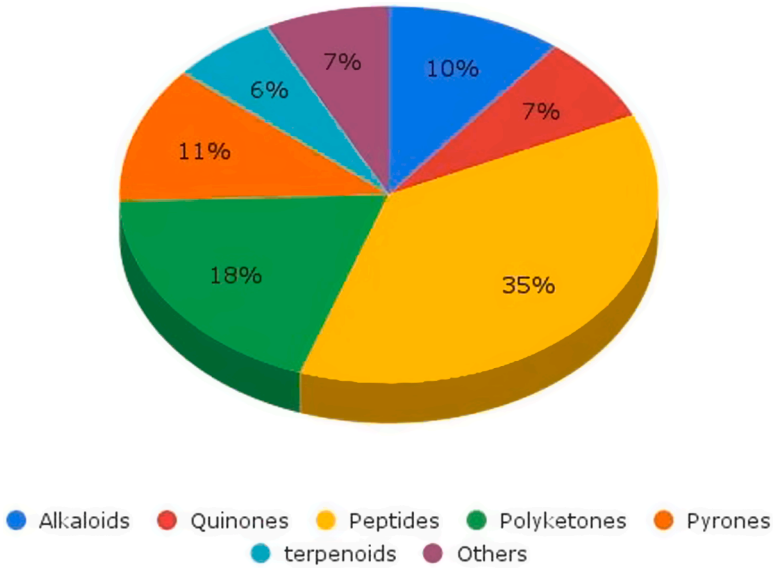

FIGURE 12.2 Antiviral chemicals produced from marine microbes.

in the future. Fig. 12.2 depicts eight biosynthetic categories: alkaloids, quinones, peptides, polyketones, pyrones, sterols, terpenoids, and others, which may be used to identify the antiviral compounds produced by the marine bacteria discussed in this article ( ). Peptides are the most common type of secondary metabolite, and many of them have potential benefits. Ten viruses, including RSV, EV71, HBV, HIV, HCV, H1N1, HSV, H3N2, H5N1, and DENV, were used as screening viruses to determine the compounds' antiviral activity. Furthermore, the majority of antiviral compounds showed anti-H1N1 activity, followed by anti-HIV and anti-HSV activity. Trichobotrysins A and D, aspergilols H and I, eutypellazines E, I–K, and 3β-hydroxyergosta-trien-7-one shown potential anti-HIV activity. Truncateol M showed strong anti-H1N1 action. Trypilepyrazinol, raistrickindole A, raistrickin, and asteltoxins E and F had strong anti-H3N2 action. These offer direction for the subsequent evaluation of novel drugs' antiviral efficacy.

These molecules can be produced on a large scale using microbial fermentation and genetic engineering approaches, which makes them a viable substitute for synthetic or plant-based antiviral medicines. Microbial bioactive chemicals are therefore becoming more and more acknowledged for their potential in medication research, particularly in view of the worldwide demand for powerful antiviral treatments (Carvalho et al., 2016).

2.4 Anticancer agents

Novel and promising cancer therapeutics have been investigated in natural substances and their structural analogs, exhibiting remarkable chemical diversity. Unfortunately, some chemotherapy medications might not target less active cancer cells effectively, which would have a detrimental impact on prognosis and overall survival (Teng et al., 2020).

Natural products are defined as compounds produced by marine organisms, plants, and microbes. Natural ingredients have always been essential to the development of cancer therapies. Natural products are used in research on anticancer medications due to their wide range of chemical composition, unique structural features, and lower toxicity biological activity (Teng et al., 2020).

Live, nonpathogenic marine bacteria can grow preferentially within tumors and impede their growth. On numerous cell lines, more than 70 substances with anticancer properties have been demonstrated. These substances include polyketides, indolocarbazole, isoprenoids, macrolides, and nonribosomal proteins.

They relate to different structural groupings of marine microorganisms (Zong et al., 2023). Because of their specificity for tumor tissues, these marine bacteria and their spores provide good vectors for delivering therapeutic proteins (Zong et al., 2023). Toxins produced by marine microorganisms have also been found as a possible cancer treatment (Rommasi, 2022). The most promising and possibly beneficial approach is gene-directed enzymatic prodrug treatment with marine microorganisms. This approach has been shown to be successful in cancer therapy in vivo (Jha & Zi-Rong, 2004). Marine microorganisms produce distinct macrolactins that limit the growth of melanoma B16–F10 cells in rats, decrease the reproduction of mammalian herpes simplex viruses, and protect T cells against HIV.

3. Pharmaceutical applications

Novel structures and unique modes of action are exhibited by compounds derived from marine creatures that influence human disease targets. About 15–20 chemicals originating from marine sources have received approval for use in clinical settings to treat heart disease, cancer, pain, and viral infections. Certain highly effective substances target cancer cells by binding to an antibody. The authorized marine-derived medications are made by (semi)-synthesis; however, a potential option for making those substances is to express the gene clusters involved in biosynthesis in a microbial host. Industry is showing a renewed interest in this field as a source of novel mechanisms of action for pharmaceuticals to treat unmet medical needs. This is due to advancements in technology that have sped up the discovery process in the extraction, isolation, and structural characterization of compounds derived from marines, as well as the reduction of effort wasted in isolating known compounds.

Additionally, marine sources have shown remarkable potential in the production of secondary metabolites that combat inflammation and viral disorders as well as anticancer chemicals. According to Blunt et al. (2004), the primary marine environments' suppliers of biomedical chemicals include sponges (37%), coelenterates (21%) and microorganisms (18%), with algae (9%), echinoderms (6%), tunicates (6%), mollusks (2%), and bryozoans (1%), among others (Blunt et al., 2004).

3.1 Success in clinic

The arabinose-linked nucleosides were the first marine-derived precursors of human-use medicines. The Pettit group isolated a collection of linear peptides from the Sea Hare *Dolabella auricularia*, which was the second compound family to get major attention. The development of brentuximab vedotin, which was first approved in 2011 for the treatment of anaplastic large-cell lymphoma and Hodgkin's lymphoma, was a milestone. In 2017, brentuximab vedotin was approved for the treatment of Hodgkin lymphoma with CD30 positivity.

4. Agricultural applications

4.1 Biopesticides

Biopesticides refer to biological methods of control that involve the entanglement and action of living organisms. Microorganisms produce bioactive compounds that are beneficial and can be used in the defense of plant diseases and insect pests. In the global agricultural industry, the use of these bioactive compounds as pesticides has the potential to substantially add to crop protection (Thakur et al., 2020). The pathogen is suppressed by bioactive compounds by many processes such as the release of pest-specific toxins, antibiosis, antagonism, inducing parasitic activity in the pests, and enhancing the host plants' systemic resistance (Kumari et al., 2022, p. 301–317). Due to their great effectiveness, species specificity, and environmental friendliness, pesticides derived from microbes and their byproducts have become an integral part of pest control strategies worldwide.

4.1.1 Applications of bioactive compounds in agriculture

4.1.1.1 Marine micro-algae bioactive compounds

Macroalgae, often known as seaweeds, are commonly found in aquatic environments including seas and oceans. They are an excellent source of bioactive compounds with a wide range of biological activities, including antibacterial, antifungal, and antiviral properties, as seen in Fig. 12.3. They are also often known as plant stimulants. They have been utilized as foliar sprays to encourage plant growth in cold, dry, and salty environments (Hamed et al., 2018). Active antibacterial extracts from diverse brown algae contain both saturated and unsaturated fatty acids, with a high concentration of myristic, palmitic, oleic, and eicosapentaenoic acids. The kind and quantity of free fatty acids are linked to antibacterial activity, which plays a role in overall defenses against pathogenic Gram-positive and -negative bacteria.

4.1.1.2 Bacterial bioactive molecules

Chemical pesticides have been employed in agricultural systems to boost crop yield; nevertheless, their prolonged use has led to insecticide resistance in major pest species, pesticide residues in the food chain, and a loss in ecosystem quality and human health. With this concern in mind, biopesticides have been offered as a green solution. Microbial secondary metabolites are low-molecular-mass secondary metabolism products that are frequently produced during the late development phase (Keswani et al., 2020). These secondary metabolites lower the pathogen's disease potential by directly

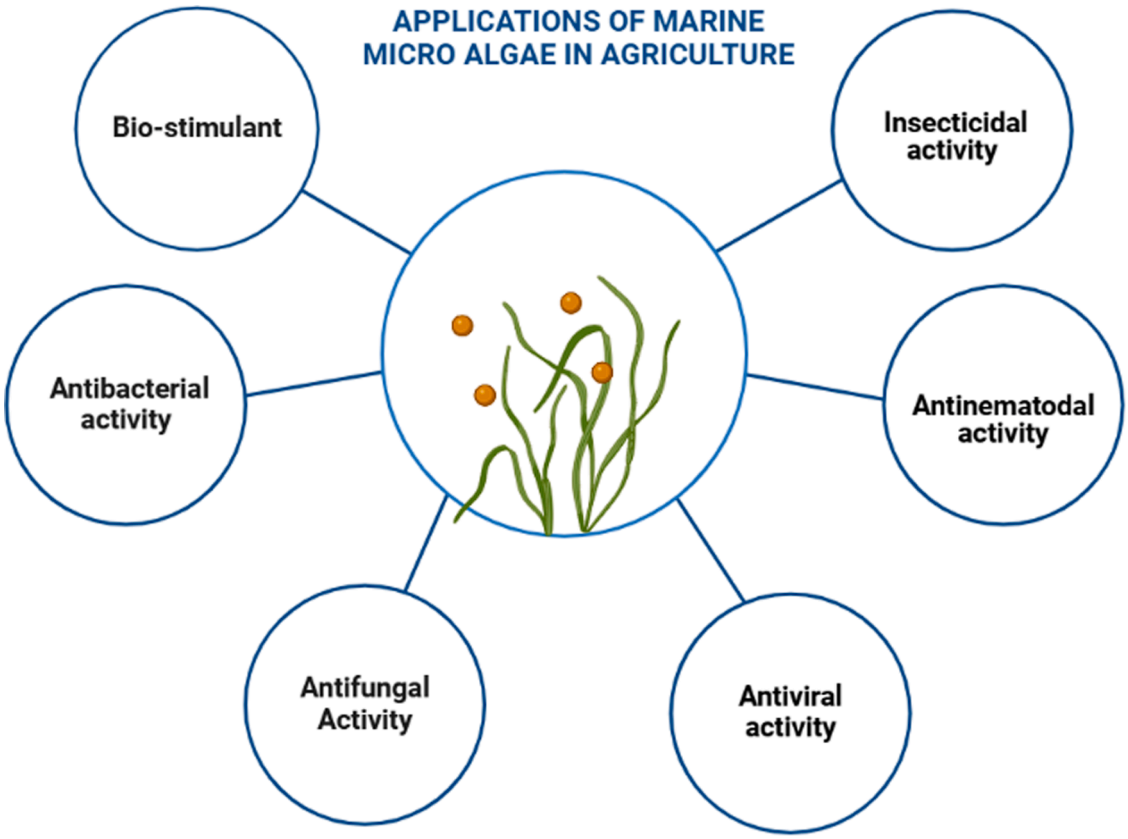

FIGURE 12.3 Application of marine microalgae in agriculture. *Created in BioRender.com.*

suppressing pathogen growth or stimulating plant defense. Siderophores, for example, are small organic molecules produced by bacteria in iron-limited environments that increase iron absorption (Saha et al., 2016). Fig. 12.4 shows the function of siderophores in the inhibition of pathogenic microbes.

Pseudomonas has the capacity to colonize roots and maintain large population densities. These microorganisms regulate fungal infections in crops by lowering disease severity and promoting plant growth. Table 12.4 lists the many metabolites produced by pseudomonas species and their applications (Spago et al., 2014).

4.1.1.3 Fungal bioactive molecules

Fungi produce a variety of secondary metabolites and antimicrobials to a variety of pigments. Antimicrobial potential of peptaibols is by forming pores in lipid membranes, which causes ion leakage across the membrane leads to osmotic imbalance and finally results in insects' cell death.

Fungi in the genera Beauveria and Metarhizium spp. help to defend hosts from primary pests by encouraging the creation of plant defense chemicals, which have been shown to have a variety of bioactivities and functions. They are well-known for their capacity to produce a diverse range of secondary metabolites with antibacterial, antifungal, and insecticidal effects (Bamisile et al., 2021). Table 12.5 below showcases various fungal bioactive molecules and their application in agriculture.

4.2 Plant growth promoters

Plant growth promoters enhance plant development directly by creating bioactive chemicals. During seed germination and seedling growth, the plant interacts with a diverse range of microorganisms in the soil. As seeds germinate and roots travel through the soil, the release of organic material promotes the formation of active microbial communities in a zone that is only a few millimeters thick and includes the plant root and surrounding soil. The phenomenon is referred to as the rhizosphere effect. Microorganisms contribute directly to plant growth by synthesizing bioactive components.

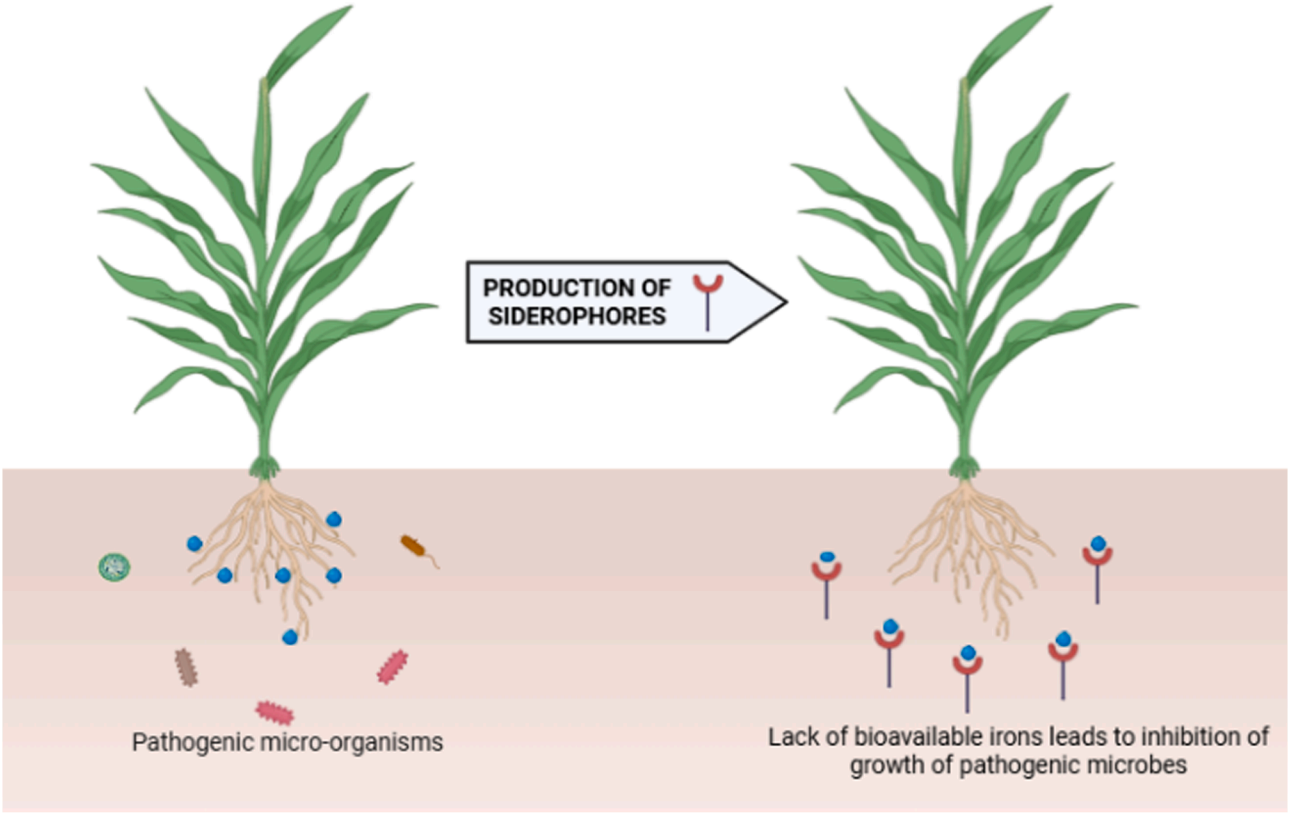

FIGURE 12.4 Role of siderophores as iron chelating bioactive molecules.

TABLE 12.4 Various metabolites produced by pseudomonas species and their applications.

S. No.	Metabolite	Strain	Application	References
1.	Phenazines	*P. fluorescens, P. chlororaphis,* and *P. aeruginosa*	Broad antibacterial and antifungal activities	Guttenberger et al. (2017)
2.	Phloroglucinols	Strains of P. fluorescens	antibacterial and anthelmintic activities	Rezzonico et al. (2007)
3.	Dialkylresorcinols	Different strains of Pseudomonas	antifungal and antibacterial activities	Schöner et al. (2015)
4.	Pyrolnitrin	Fluorescent Pseudomonas	Inhibitor of fungal respiratory chains	Putri et al. (2024)
5.	Pyoluteorin	Different strains of Pseudomonas	control of many soil-borne diseases.	Brodhagen et al. (2005)
6.	Mupirocin	Different strains of Pseudomonas	Highest level of antibacterial activity toward gram-positive pathogens	Gross and Loper (2009)
7.	Hydrogen cyanide	*P. aeruginosa, and Chromobacterium violaceum*	Inhibition of cytochrome C oxidase and other metalloproteins	Ramette et al. (2003)
8.	Rhizoxins	*P. fluorescens*	phytotoxic, antifungal, and antitumoral properties	Gross and Loper (2009)
9.	Oxyvinylglycines	*P. aeruginosa, P. fluorescens*	Blocks the germination of a large variety of grassy weed species	Banowetz et al. (2008)

TABLE 12.5 Various fungal bioactive molecules and their application in agriculture.

S. No.	Bioactive molecule	Strain	Application	References
1.	Peptaibols	*Trichoderma brevicompactum*	Insect cell death by causing pores in lipid layer of cell membrane	Suga et al. (2015)
2.	Linoleic acid	*Arthrobotrys oligospora*	Biocontrol of plant-parasitic nematodes	Keller (2019)
3.	Destruxins	*Metarhizium anisopliae*	Insecticide	Brousseau et al. (1996)
4.	Bursaphelocides	*Mycelia sterilia*	Nematicidal activity	Degenkolb and Vilcinskas (2016)
5.	Anisaldehyde, 3-chloro-anisaldehyde	*Pleurotus pulmonarius*	Wood and forest-litter degradation	Dong et al. (2006)
6.	(Oxiran-2-yl) methylpentanoate	*Cyptotrama asprata*	Larvicidal activity	Njogu et al. (2009)

4.2.1 Marine microbial biocompounds

Diverse endophytic actinomycetes have been discovered in plants that live in both aquatic and terrestrial habitats. Actinomycetes are known to generate active metabolites such as hydroxamate-type siderophores and catechols-type siderophores (Masand et al., 2015). Endophytic actinomycetes have been utilized successfully in the field as plant growth boosters and biological control agents against cucumber pythium disease to prevent seedling damping off and root and crown rots caused by *Pythium aphanidermatum*.

4.2.2 Bacterial bioactive molecules

4.2.2.1 Phytohormones

Microorganisms, particularly bacteria such as Bacillus, Pseudomonas, and Azospirillum, produce phytohormones such as cytokinins, ethylene, indole-3-acetic acid (IAA), and gibberellins. These hormones can be produced by both the plant and its associated microorganisms. The overall effect on the plant might be direct, promoting plant growth, or indirect, improving plant nutrition through increased root development, and distinguishing between the two is challenging. Table 12.6 summarizes microbial phytohormones and their effects on plants.

4.2.2.2 Volatile organic compounds

Microbial volatile organic compounds (VOCs) are a broad group of low-molecular-weight, lipophilic gaseous molecules produced by bacteria during both primary and secondary metabolism. VOCs can have a wide range of ecological effects, including cell-to-cell communication, plant growth stimulation, and the activation of systemic plant resistance in response

TABLE 12.6 Microbial phytohormones and their effect on plants.

S. No.	Microorganism	Phytohormone	Effect on plants	References
1.	*Azospirillum* spp.	Indole-3-acetic	Root initiation, cell division, and cell enlargement	Steenhoudt and Vanderleyden (2000)
2.	*Azospirillum*	Auxins	Stimulation of rooting	Steenhoudt and Vanderleyden (2000)
3.	*P. polymyxa*	Cytokinin	Shoot initiation	Cesa-Luna et al. (2020)
4.	*Azospirillum* spp.	Gibberlins	Stem elongation and germination	Steenhoudt and Vanderleyden (2000)
5.	*Burkholderia*	Ethylene	Enhanced basal resistance of the plant	Dobbelaere et al. (2003)

to biotic and abiotic stresses. Microbial VOCs usually have strong antibiotic properties, limiting bacterial growth and increasing the competitiveness of VOC producers (Wang et al., 2023). Plants can detect and respond to microbial VOCs in their surroundings, hence controlling plant development.

4.3 Biocontrol agents

Biological control is the use of beneficial organisms, their genes, and/or products, such as metabolites, to reduce the negative effects of plant diseases while promoting positive plant responses. Microorganisms produce bioactive substances that are employed as biocontrol agents in a wide range of industries, including agriculture, forestry, environmental management, and even public health. Bioactive chemicals used to manage plant diseases, pests, and pathogens include antibiotics, enzymes, and volatile organic compounds, which are more ecologically friendly than chemical-based pesticides and fungicides.

4.3.1 Agricultural disease and pest control

Bacillus spp. produces bioactive compounds such as lipopeptides, which have been found to successfully inhibit fungal infections. Lipopeptide antibiotics are among the most often generated by *B. subtilis*. They are amphiphilic surfactants with low molecular mass that can change the physical and/or chemical characteristics of surfaces. These peptide molecules have an important function in the attachment and detachment of microbes to and from plant surfaces, as well as boosting the bioavailability of hydrophobic substrates by increasing their apparent solubility. *Bacillus velezensis* is known to produce a variety of antimicrobial chemicals that inhibit plant diseases. The biosynthetic gene of *Bacillus velezensis* encode the biosynthetic enzymes, which employ variety of building block for the synthesis of variety of secondary metabolites for antibacterial activity with biocontrol potentiality against the pathogenic fungus (Fazle Rabbee & Baek, 2020).

4.3.2 Phytoremediation

Phytoremediation is the process by which plants remove or stabilize hazardous chemicals from their environment. Microbial bioactive compounds help break down environmental contaminants including heavy metals and pesticides, which improves soil health and reduces harmful accumulation. Plant growth-promoting bacteria (PGPB) contribute to phytoremediation by producing bioactive compounds (Gamalero & Glick, 2024). PGPB's most prominent indirect mechanisms include the synthesis of antibiotics and hydrogen cyanide; the synthesis of siderophores that can solubilize and sequester iron, preventing nearby phytopathogens from using iron; the ability to synthesize enzymes capable of digesting fungal cell walls; the synthesis of volatile organic compounds that can act as inhibitors of some phytopathogen genes; and the synthesis of quorum quenching molecules.

5. Food industry applications

Microbial bioactive molecules have significant applications in the food industry due to their natural origin, safety, and functional benefits. These molecules, produced by various microorganisms such as fungi, bacteria, and yeasts, include antimicrobial peptides, bacteriocins, enzymes, polysaccharides, and organic acids. They serve an important function in food preservation by limiting the growth of spoilage and harmful microbes, prolonging the shelf life of foods.

5.1 Natural preservative

Preservatives are a type of food additive that increases the shelf life of food by delaying or preventing the development of microorganisms as well as the physical changes in color, texture, and flavor that cause spoiling as shown in Fig. 12.5. They are classified into two types: natural and chemical/artificial preservatives. They can also work as antibacterial preservatives, inhibiting the growth of bacteria and fungus such as mold.

5.1.1 Marine microbial bioactive molecules

Ocean microbial life is regarded as one of the most dynamic aspects of the marine environment. These compounds include enzymes, antimicrobial peptides, polysaccharides, and bioactive lipids. They provide a variety of benefits, including natural preservation, improved food safety by blocking hazardous microorganisms, and extended shelf life without the need of chemical additives as shown in Fig. 12.6 (Senadheera et al., 2023). They may be included into the food manufacturing process at several phases, including processing and storage.

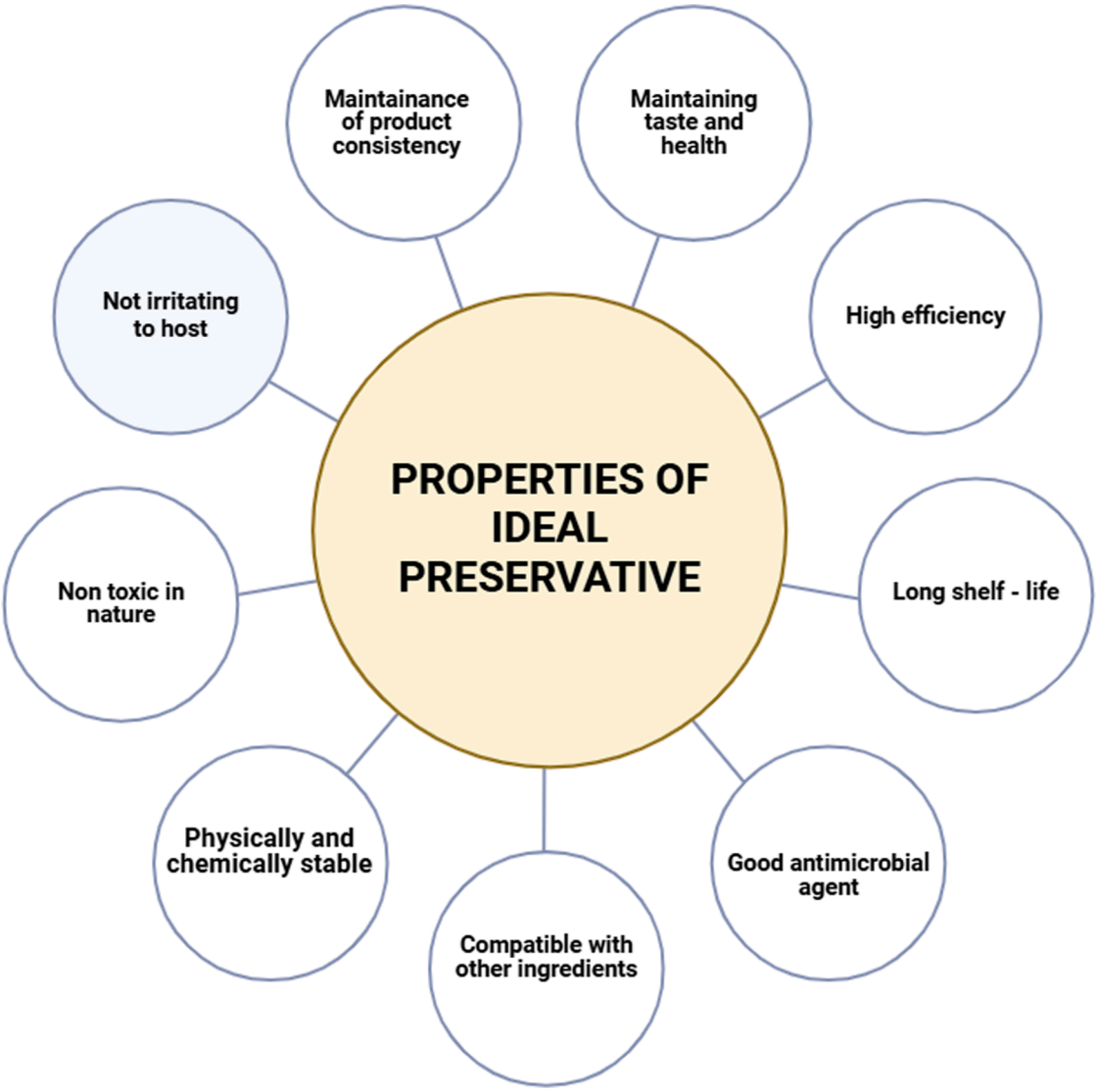

FIGURE 12.5 Properties of an ideal preservative.

5.1.2 Bacterial metabolites

Lactic acid bacteria are generally considered safe (GRAS) microorganisms and are commonly used as food additives to improve taste and shelf life while also limiting the growth of undesirable microflora. They are known to produce exopolysaccharides with a variety of compositions, structures, and molecular masses. Although high-molecular-weight polysaccharides are often utilized in the food industry as texturizers, stabilizers, viscosifiers, and emulsifiers, their potential as preservation agents has yet to be explored (Mishra et al., 2024). These bacteria are also known for generating organic acids. The majority of these organic acids' antibacterial activities come from their undissociated molecules (Castillo Martinez et al., 2013). Bacteriocins are chemicals generated by several bacterial species that extend the shelf life of food. Encapsulated nisin coupled with low temperatures has been used to treat pathogenic L. monocytogenes in milk (Kaur Sidhu & Nehra, 2021).

5.1.3 Yeast metabolites as natural preservative

Some yeast species, including *Saccharomyces cerevisiae* strains, produce antibacterial proteins called killer toxins or zymocins, which also inhibit pathogenic enzymes. Yeast cells attach to mold mycelium and produce β-glucanase, which destroys the cell wall (Younis et al., 2017). Yeasts isolated from diverse dietary categories have excellent antibacterial

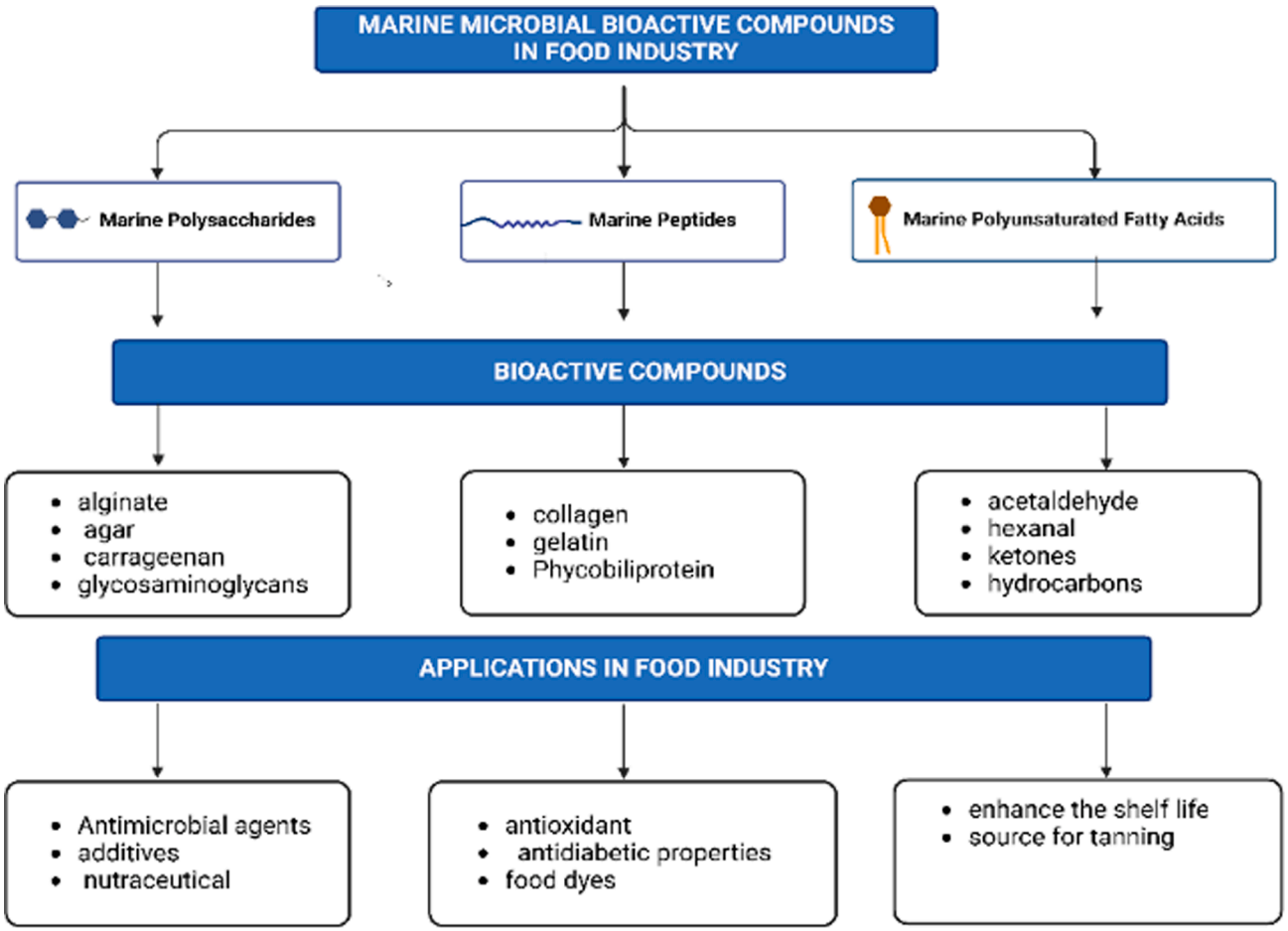

FIGURE 12.6 Marine microbial bioactive molecules and their application in food industry. *Created in BioRender.com.*

activity against *S. aureus* and *E. coli* but moderate activity against *Pseudomonas aeruginosa*. Some yeast species produce a range of colored pigments, including astaxanthin. Astaxanthin is a natural food colorant.

5.2 Flavor enhancers

Flavors and aromas play a major role in our everyday lives. These microorganisms generate flavor-enhancing substances during fermentation or other metabolic processes, including amino acids, peptides, nucleotides, and enzymes. Microbial bioactive molecules and their applications in food industry have provided in Table 12.7.

5.2.1 Microbial flavoring compounds

Microbial flavor enhancers are produced by microorganisms, such as bacteria, yeast, and fungi that intensify or improve the taste and aroma of food. Variety of bioactive molecules are produced by different microbial species, each contributing significantly to flavor and aroma profiles in food and related industries. These naturally occurring compounds, synthesized by microorganisms such as *Aspergillus niger*, lactic acid bacteria (LAB), *Hansenula anomala*, and Amycolatopsis spp., play key roles in flavor enhancement, simulating tastes ranging from fruity and dairy-like to buttery and distinctive aromas.

6. Environmental applications

Rich biological diversity of plants, animals, and microorganisms can be found in mangrove forests, which are found at the interface between terrestrial and marine environments. In addition to being an essential part of the mangrove ecosystem,

TABLE 12.7 Microbial bioactive molecules and their applications in food industry.

S. No.	Group	Bioactive molecule	Microbe	Activity	References
1.	Lactones	δ-Decalactone	Aspergillus niger	Dairy and fruit flavor	Kendirci et al. (2020)
2.	Carboxylate esters	Ethylacetate	Lactic acid bacteria (LAB)	aromas in fermented foods	Kumar Verma et al. (2022)
3.	Alcohol	2-phenylethanin	Hansenula anomala	Distinctive scent	Kim et al. (2014)
4.	Ketones	Diacetyl	Lactic acid bacteria (LAB)	Simulation of butter-like and other milky flavors	Wang et al. (2016)
5.	Aldehydes	ferulic acid	Amycolatopsis spp.	Bioflavor production	Tang and Hassan (2020)

microbes produce useful and significant products for biotechnology. They also play a vital role in the creation and maintenance of this biosphere. Microbes are crucial to the productivity of the mangrove ecosystem because they take part in the different stages of leaf litter decomposition and mineralization (Thatoi et al., 2013). They are capable of recycling nutrients, creating and consuming gases that impact the climate, eliminating pollutants, handling anthropogenic waste, and biologically controlling pests of both plants and animals (Thatoi et al., 2013).

Marine microorganisms are effective in the bioremediation of pollutants, including hydrocarbons, heavy metals, and pesticides, particularly in oil spill cleanups and wastewater treatment. Enzymes like proteases, lipases, and chitinases from marine bacteria and fungi contribute to breaking down complex pollutants and organic matter in contaminated ecosystems.

Antimicrobial bioactives produced by marine microorganisms and invertebrates can be employed to counterbiofouling on ships and marine structures, thereby lessening the environmental impact of antifouling chemicals. Eco-friendly coatings are being investigated to utilize these bioactives (Ghosh et al., 2022).

Marine-derived enzymes and bioactive peptides have potential uses in environmentally friendly detergents, green chemistry, and even the food and pharmaceutical sectors. For instance, microbial enzymes derived from extremophiles are used in industries with a high prevalence of harsh circumstances because they are more stable (Senadheera et al., 2023) Sustainable production methods and pollution management are two environmental issues that marine-derived bioactives may help with (Senadheera et al., 2023).

7. Biotechnology applications

7.1 Industrial enzymes

Microorganisms create a range of enzymes. Microorganisms are frequently employed in enzyme resource research due to their extensive variety and ease of usage in large-scale fermentation. Bacteria and fungi found in the terrestrial environment have emerged as the most major and well-studied sources of potential industrial enzymes and secondary metabolites in recent decades. Recent technical advances have made it easier to access marine resources. Enzymes are required for several economic, medical, and technological operations. The worldwide enzyme market is predicted to grow from $5.01 billion in 2016 to $6.32 billion by 2021, according to the Business Communication Company (BCC) Research. Market trends point to a rise in the manufacture of sophisticated enzymes, such as those used in the biodiesel, fabric, paper, and suede sectors (Dewan, 2014).

Alginate lyases have been identified and purified from a variety of marine organisms during the past few decades, including the marine fungus Saccharina, Laminaria (Pilgaard et al., 2019) marine algae, and marine bacteria Pseudomonas. Alginate lyases serve applications in the food, drug delivery, cosmetics, biomedical, and agricultural industries (Barzkar et al., 2022).

This enzyme chitinase degrades chitin, a polymer with several biotechnological advantages, including improved digestion, increased immunity, and toxin removal from the body. It is the second most common polysaccharide after cellulose, and its various applications include insecticide, fungicide, fertilizer, and antiparasitic. It breaks down into smaller molecules. Some producing marine bacteria are *Vibrio parahaemolyticus*, *Clostridium* sp., *Vibrio mimicus*, *Vibrio alginolyticus*, *Chromobacterium*, *Vibrio alginolyticus*, *Pseudomonas*, *Serratia*, *Listonella anguillarum*, and *V. harveyi* (Kamble & Vavilala, 2018).

Amylases are an enzyme used in the food, textile, and paper industries. They are glycosyl hydrolases, which break down starch and glycogen into sugars. They may generate around 30 responses and have 35 subfamilies. Marine microorganisms that generate these enzymes include *Aureobasidium pullulans*, *Rhodothermus marinus*, *Vibrio alginolyticus*, *Bacillus licheniformis*, *Halobacillus*, *Micrococcus* sp., and *Alteromonas haloplanktis* (Liu et al., 2012).

Sulfated polysaccharides, which make up about 80% of the food business, are broken down into smaller molecules called oligosaccharides by carrageenases, which have a variety of uses, including antiviral, anticoagulant, and anticancer properties. Pseudomonas, Cythopagia, *Alteromonas atlantica*, and *Alteromonas carrageenovora* are a few marine microbes that manufacture these enzymes (Zhang & Kim, 2010).

Proteases account for more than 60% of the enzyme market worldwide. In the dairy sector, the production of cheese is the primary use of proteases. *Rhizomucor miehei* culture media produce the enzyme mucorpepsin, which is most usually used in cheese-making. Lipase is generally employed to increase the flavor of cheese during maturation. Lactase is typically from Mucor miehei; as fungal species supply microbial lipase, it is used to convert lactose into glucose and galactose, increasing the solubility and sweetness of many dairy products (Hasan et al., 2006). The FDA has approved four recombinant proteases for cheese production.

7.2 Biopolymers

Polymers created naturally throughout an organism's growth cycle are referred to as biopolymers. They go by the label "natural polymers" as a result. They are created by intricate metabolic processes that occur within cells. The most intriguing materials for applications are starch and cellulose. More complicated hydrocarbon polymers made by fungus and bacteria are being studied, though, especially polysaccharides like xanthan, curdlan, pullulan, chitin, chitosan, and hyaluronic acid (HA). Bacteria can synthesize a wide variety of polymers that are used in an array of biological processes, including reserve materials, capsules for protection, and matrix elements for biofilms. Since many of these polymers are economically generated due to their desirable chemical and material qualities for industrial and medicinal applications, they offer a great supply of materials that are sustainable, biodegradable, and reusable. There are four types of bacterial polymers: polyesters, polyamides, polysaccharides, and inorganic polyanhydrides (Park et al., 2012).

Polyamides: The unique category of biopolymers known as nonribosomally produced polyamides is comprised of two extracellular polyamides, namely, the internal cyanophycin granule peptide (CGP) and only two extracellular polyamides: poly-γ-glutamate (PGA) and ε-poly-L-lysine (PL). It has been demonstrated that Pl possesses antimicrobial qualities. Therefore, environmentally friendly, nonhazardous, and disposable substitutes for polyacrylates may be found in bacterial polyamides.

Polysaccharides: The three significant biopolymers based on polysaccharides: chitosan, chitin, and cellulose. Certain bacterial species may also manufacture cellulose by fermentation, resulting in a very pure cellulose product with unique characteristics. The most popular applications for bacterial cellulose take use of its large surface area and ability for liquid absorption. As a result, relatively low quantities of bacterial cellulose may be used to create effective binding, thickening, and coating agents. Its thickening properties enable a variety of food-related applications.

Polyesters: Many investigations have been undertaken on polyhydroxyalkanoates (PHAs), which are biosynthesized from glucose and plant oils as carbon resources and accumulate in various bacteria to form biodegradable and biocompatible thermoplastic polymers. Experts classified PHAs into two classes based on the amount of carbons in the monomer: PHAs are classified into two types: medium-chain-length (MCL) PHAs (6-14 carbon atoms) and short-chain-length (SCL) PHAs (3–5 carbon atoms). Whereas MCLPHAs have elastic properties comparable to rubber, SCL-PHAs have thermoplastic properties similar to polypropylene.

7.3 Genetic engineering and synthetic biology

Metabolomics is a key component of the synthetic biology approach to the creation of secondary metabolites by a wide range of microorganisms, such as archaea, bacteria, and eukaryotes. The fundamental focus of metabolic engineering is to comprehend and design the metabolic network of a cell at the system level. To find new biosynthetic gene clusters and manufacture industrial producer strains, many metabolic engineering techniques have been developed recently and combined with other domains, such as synthetic biology and systems biology. Nonetheless, the majority of systems metabolic engineering methodologies have been executed utilizing a model organism such as *Saccharomyces cerevisiae* or *Escherichia coli*. It seeks to uncover and describe secondary metabolites and bioactive molecules in their metabolic contexts in natural or synthetic biosystems (Lee & Kim, 2015).

Actinobacteria, particularly the Streptomyces species, are known to be the principal producers of microbial bioactive natural products (NPs) such as immunosuppressants, antibiotics, chemotherapeutics, and antihelminthics, which are essential for both agricultural and medicinal applications. Specialized software (i.e., antiSMASH) has identified a plethora of hidden NP biosynthetic gene clusters (BGCs), which are expected to be an untapped treasure mine for the development of novel bioactive chemicals (Ziemert et al., 2016). This is due to significant advances in genome sequencing and mining techniques.

The reprogramming and rebuilding of regulatory systems in host organisms is a fundamental component of synthetic biology. The co-occurrence of genes encoding transcriptional regulatory proteins has been highlighted by genomics-based biocatalytic enzyme discoveries; this is not surprising, since many of these activities are essential to the basic metabolic processes of microbial cells. The ideal host organism's transcriptional, translational, and post-translational regulatory systems can be artificially manipulated since these processes can be programmed to be either repressed or activated. In microbial species, the LysR-type transcriptional regulator (LTTR) family is a crucial regulator of biocatalysis. Researchers previously explored the evolution of LTTR in the Pseudomonadaceae family, finding multiple clades of coevolved homologs (Reen et al., 2013). Understanding the roles of other transcriptional regulator families can help with better chassis design since they too contribute to the biocatalytic regulatory system within the cell. Other synthetic biology methods include modifying the host's ribosome, engineering elements of the translational machinery, supplying tRNAs and plasmid-encoded sigma elements that can identify uncommon codons, or creating artificially codon-adapted genes that can be expressed in a selected heterologous host (Bayer et al., 2009).

8. Healthcare and diagnostics applications

Microbial bioactive compounds have become crucial in healthcare and diagnostics due to their wide range of biological activities. These substances, generated by microorganisms including bacteria, fungus, and algae, are used as antibiotics, antifungals, immunosuppressants, and cancer treatments. For example, penicillin, generated from Penicillium fungus, transformed the treatment of bacterial infections, whereas doxorubicin, produced by Streptomyces species, is an important chemotherapeutic drug (Challinor & Bode, 2015). Furthermore, probiotics and their bioactive metabolites, known as postbiotics, help to modulate the immune system and keep the gut healthy.

8.1 Probiotics and gut health

The gut microbiome is important for human health, and supplementing the diet with probiotics, which are helpful microbes, can help maintain a healthy balance. Bioactive substances include short-chain fatty acids, antimicrobial peptides, and vitamins affect the immune system, limit pathogenic bacteria development, and improve nutrition absorption. Probiotics are known to create useful substances, demonstrate antagonist action against pathogenic bacteria, activate and control the immune response, and have a variety of other helpful effects, mostly due to their location in the gut. Probiotics can modify the immune response and strengthen the host's defense against external threats by colonizing the intestinal mucosa and interacting with the mucus layer (Saad, 2006). These bacteria create a variety of bioactive chemicals, including amino acids, bacteriocins, enzymes, exopolysaccharides, oligosaccharides, short-chain fatty acids, vitamins, and immunomodulators.

8.1.1 Applications of bioactive molecules produced by probiotic organisms

Probiotics can help with a wide range of acute and chronic infectious diseases. Many factors can impair the body's resistance, resulting in inflammatory, viral, neoplastic, and degenerative diseases. Other treatments, like as antibiotics, irradiation, and immunosuppressive medications, may alter the usual flora makeup of the stomach. As a result, probiotics play an important role in improving cellular health by accelerating the activation of cells' natural defense systems.

8.1.1.1 Cancer treatment

Cancer is a disease of great relevance in medicine. It is a condition caused by a lack of DNA repair or mutations formed during DNA replication, as well as environmental exposure, everyday living choices, and individual genetic heritage. Cancer is characterized by uncontrolled cell division and is often identified in its late stages. Once cancer cells spread, they require numerous stages of tumor formation to become malignant (Tegegne & Kebede, 2022). Cancer treatment is based on the administration of numerous medications and chemotherapy, which harm not only cancer cells but also healthy cells, resulting in resistance that may impair the patient's future treatments. Probiotic bacteria have been shown to play a key role in immune regulation and have anticancer properties.

8.1.1.2 Protective defense against pathogens

Bioactive compounds from probiotic organisms have an important function in changing gut microbiota temporarily. Pathogenic bacteria biofilms pose a significant risk to the medical community. Biofilm appears to be the major source of pathogenesis and treatment failure due to the antimicrobial resistance contained within the biofilm matrix. Teichoic acids extracted from Lactobacillus strains inhibited biofilm formation and deconstructed existing biofilms by enteric pathogens such as *Staphylococcus aureus*, Streptococcus mutans, and *Enterococcus faecalis*. Biosurfactants generated extracellularly or linked to cell walls are amphiphilic, which aids in the deconstruction of existing biofilms or inhibits biofilm development (Ma et al., 2023). These bioactive chemicals can also compete with pathogens for adhesion sites, resulting in their elimination. For example, lectins derived from or secreted by beneficial lactobacilli are potential bioactive components.

8.1.1.3 Immune system regulation

Probiotic bioactive chemicals have an important role in the gut–brain axis by regulating immune function. Exopolysaccharides (EPSs) have been found to modulate the immune system by increasing the proliferation of T/B lymphocytes and generating cytokines, hence improving the host's immunological response to infections (Da et al., 2024). EPS from *Lactiplantibacillus plantarum* MM89 isolated from human breast milk effectively improves the immunostimulatory activity of immune cells in an immunosuppressed animal model.

8.2 Microbial bioactive molecules as biomarkers in disease diagnosis

Biomarker discovery allows for a better understanding and exploration of possible biological pathways and processes that contribute to disease development or are controlled by medications. The identification of distinct metabolic abnormalities is critical for determining potential biomarkers and therapeutic targets. Biomarkers are characteristics that are assessed as an indication or indicator of physiological, biological, pathological, or pharmacological processes. Biomarkers have characteristics that can be quantified, analyzed, and linked to human phenotypes. They could be used for early disease detection, improving treatment outcomes and therapeutic strategy selection, reducing disease-related mortality, and identifying therapeutic targets (Hajjo et al., 2022).

8.2.1 Short-chain fatty acids

Colonic bacteria predominantly create SCFAs, which are then processed by enterocytes and the liver. They include acetate, propionate, butyrate, and so on. SCFAs with low molecular weight have a vital role in the physiology of several systems, both at the cellular and molecular levels. Short-chain fatty acids (SCFAs) have strong anti-inflammatory properties and are thought to be major preventative factors for IBD. Long-chain fatty acids contain both pro- and anti-inflammatory effects. SCFAs have a crucial role in colonic health. They contribute to the development of chronic diseases such as allergies, asthma, cancer, autoimmune and metabolic disorders, and, most significantly, neurologic difficulties. Serum SCFAs may act as biomarkers for multiple sclerosis and colorectal cancer (Farup et al., 2016).

8.2.2 Branched-chain amino acids

These are essential amino acids with branched carbon structures. BCAA supplementation promotes anabolic pathways and is critical for preventing muscle wasting (cachexia), reducing exercise-related tiredness, and stimulating insulin production. BCAAs are seen as possible indicators for insulin resistance, type 2 diabetes, and cardiovascular disease. BCAA levels in the blood may be able to predict populations at risk for cardiometabolic illness, type 2 diabetes, ischemic heart disease mortality, and significant depression (Batch et al., 2014).

8.2.3 Trimethylamine N-oxide

This amine oxide is produced by the gut's microbial metabolism of carnitine and choline. It accumulates in huge quantities in marine animal tissues and protects against urea's protein-destabilizing effects. TMAO is hypothesized to operate as a mediator in the progression of type 2 diabetes. TMAO's atherogenic effects are linked to alterations in cholesterol and bile acid metabolism, activation of inflammatory pathways, and enhanced foam cell generation. TMAO levels increase with decreasing renal function and are associated with mortality. It has the potential to serve as a novel biomarker for plaque rupture in ST-segment elevation myocardial infarction (STEMI).

8.2.4 Lipopolysaccharides

Lipooligosaccharides (LOSs) and endotoxins lipopolysaccharides (LPSs) are macromolecules that typically contain a hydrophobic domain, a nonrepeating oligosaccharide, and a distal polysaccharide. They are considered essential components of Gram-negative bacteria's outer membranes. Plasma LPS-binding protein (LBP) levels can be used to determine systemic exposure to bacterial endotoxins. Gram-negative bacterial overgrowth in the small intestine may raise insulin resistance, increase endogenous ethanol production, and produce choline deficiency, all of which have been associated to NAFLD and preeclampsia (Abu-Shanab & Quigley, 2010). Plasma LPS-binding protein levels can be used to determine systemic exposure to bacterial endotoxins.

9. Cosmetic applications

9.1 Antimicrobial agents in cosmetics

In recent years, the incorporation of bioactive compounds into cosmetic formulations has gained prominence due to their potential to enhance skin health and appearance. These compounds are often selected based on their ability to modulate specific biochemical pathways. For instance, antioxidants such as vitamin C and polyphenols are widely used for their capacity to neutralize free radicals and mitigate oxidative damage, which is a major contributor to skin aging. Peptides are utilized for their role in promoting collagen synthesis and improving skin elasticity. The efficacy of these compounds is often evaluated through rigorous clinical studies and in vitro assays to ensure their safety and performance in enhancing skin health (Oliveira & Dario, 2019, p. 1–23).

As the cosmetic industry continues to evolve, the integration of bioactive compounds is very promising for developing products that address various dermatological concerns while promoting overall skin wellness.

9.1.1 Types of antimicrobial agents

9.1.1.1 Preservatives

Preservatives are crucial in cosmetics to prevent microbial contamination. Some common preservatives include:

1. Parabens (e.g., methylparaben, propylparaben): Effective against a broad spectrum of bacteria and fungi, parabens work by disrupting microbial cell membranes and inhibiting enzymatic functions (Canavez et al., 2021). However, their use has raised concerns over potential endocrine-disrupting effects.
2. Phenoxyethanol: A widely used preservative that exhibits efficacy against Gram-negative bacteria and fungi. It acts by disrupting cell membranes and is often used in combination with other preservatives to enhance efficacy (Halla et al., 2018).
3. Sodium benzoate: Commonly used in acidic formulations, it is effective against yeast and molds. It works by inhibiting the enzymatic activity required for microbial metabolism (Costa & Santos, 2017).

9.1.1.2 Antimicrobial peptides

AMPs are naturally occurring compounds with broad-spectrum antimicrobial activity. They include:

1. Lactoferrin: Found in milk, lactoferrin possesses antibacterial, antifungal, and antiviral properties. It works by binding to bacterial iron, limiting its availability, and destabilizing bacterial membranes (Mazurkiewicz-Pisarek et al., 2023).
2. Lysozyme: An enzyme that breaks down bacterial cell walls, particularly effective against Gram-positive bacteria, making it suitable for formulations like facial cleansers (Joshi et al., 2011).

9.1.1.3 Essential oils

Essential oils are increasingly popular as natural preservatives due to their antimicrobial properties. Key examples include:

1. Tea tree oil (*Melaleuca alternifolia*): Known for its potent antimicrobial effects, particularly against *Staphylococcus aureus* and *Candida albicans*. The active component, terpinen-4-ol, disrupts microbial cell membranes (Joshi et al., 2011).
2. Lavender oil (*Lavandula angustifolia*): Exhibits activity against a range of bacteria and fungi, attributed to compounds like linalool and linalyl acetate. Its low toxicity profile makes it a favorable choice in cosmetics (Davidson et al., 2014).

9.2 Antiaging and skin care products

The integration of microbial actives into antiaging and skin care products has garnered significant attention in recent years. Probiotics and antimicrobial peptides are among the microbial derivatives being explored for their ability to enhance skin barrier function, modulate the skin microbiome, and promote overall skin resilience. As consumers increasingly seek formulations that harness the power of nature, the use of microbial actives represents a promising and innovative approach to skin care.

Marine bioactives have garnered significant attention in cosmetology and skincare due to their diverse beneficial properties for skin health. Algal extracts, rich in vitamins and antioxidants, are known to hydrate and protect the skin (Patel et al., 2020). Marine collagen, derived from fish sources, is utilized for its antiaging effects, enhancing skin elasticity and moisture retention (Resende et al., 2021). Seaweed, celebrated for its mineral-rich content, offers soothing and nourishing benefits, commonly incorporated into masks and scrubs (Pangestuti et al., 2021). Omega fatty acids from fish oils are recognized for maintaining skin barrier function and alleviating inflammation (Huang et al., 2018). Spirulina, a nutrient-dense blue-green algae, improves skin tone and texture (Ragusa et al., 2021).

9.2.1 Probiotic application in skin care

Probiotics, living bacteria that provide health benefits, are increasingly being used in skin care formulations because of their capacity to improve the skin microbiome.

Research suggests that specific strains of Lactobacillus and Bifidobacterium can improve skin barrier function, reduce inflammation, and modulate the immune response (Yu et al., 2020). A notable study demonstrated that topical application of *Lactobacillus plantarum* significantly reduced transepidermal water loss (TEWL) and improved skin hydration in individuals with atopic dermatitis (Prakoeswa et al., 2022).

9.2.2 Antimicrobial peptides

Antimicrobial peptides (AMPs) are key components of the skin's innate immune system. They have broad-spectrum antibacterial action against bacteria, viruses, and fungus, making them useful in antiaging compositions. AMPs such as defensins and cathelicidins have been shown in studies to suppress pathogen development while simultaneously stimulating wound healing and collagen production (Alencar-Silva et al., 2018).

9.2.3 Fermented ingredients

Fermented microbial products, such as those derived from *Saccharomyces cerevisiae* and Lactobacillus species, are gaining popularity in skin care due to their beneficial metabolites. Fermented ingredients are rich in antioxidants, vitamins, and organic acids, which promote skin cell turnover and enhance overall skin luminosity. For example, Saccharomyces fermentation extracts have demonstrated the ability to reduce fine lines and improve skin texture by promoting the production of hyaluronic acid (Pérez-Rivero & López-Gómez, 2023).

10. Case study and examples

10.1 Penicillin: A revolutionary antibiotic

Penicillin, discovered by Alexander Fleming in 1928, marked a pivotal moment in medical history. This β-lactam antibiotic, derived from the mold *Penicillium notatum*, was first used clinically in the early 1940s. Its ability to inhibit bacterial cell wall synthesis dramatically reduced morbidity and mortality from bacterial infections (Haider, 2023). Penicillin remains a cornerstone of modern medicine, with its mechanisms of action and clinical applications highlighting its significance as a therapeutic agent.

10.1.1 Clinical applications

Penicillin has been instrumental in treating various bacterial infections, including syphilis, *Streptococcal pharyngitis*, and pneumonia. Its broad-spectrum activity, especially against Streptococcus and Staphylococcus species, has made it a cornerstone in clinical settings (Finberg et al., 2004). The emergence of penicillin derivatives, such as amoxicillin and methicillin, has further expanded its clinical applications, allowing for targeted therapy against resistant strains.

10.1.2 Resistance issues

Despite its initial success, the widespread use of penicillin has led to the emergence of antibiotic resistance. Methicillin-resistant *Staphylococcus aureus* (MRSA) and penicillin-resistant Streptococcus pneumoniae exemplify the challenges posed by resistant pathogens (Gnanamani et al., 2017).

10.1.3 Synergistic effect with other microbial agents

Penicillin can also interact synergistically with other microbial bioactives. For instance, when combined with probiotics, their effects can be enhanced, leading to improved outcomes in both therapeutic and agricultural settings. This synergy may amplify the immune-modulating effects, fostering a more resilient microbial environment (Moghadam et al., 2018).

10.2 Cyclosporine: Organ transplantation and immunosuppression

Cyclosporine, a key immunosuppressive agent derived from the fungus *Tolypocladium inflatum*, has revolutionized organ transplantation by significantly reducing the incidence of acute rejection. Its clinical applications extend beyond transplantation, with emerging roles in treating autoimmune disorders. However, the drug's narrow therapeutic index necessitates careful monitoring to mitigate potential adverse effects, such as nephrotoxicity and hypertension.

10.2.1 Clinical applications in transplantations

Cyclosporine is predominantly used in solid organ transplant recipients, including kidney, liver, heart, and lung transplants. A pivotal study demonstrated that patients receiving cyclosporine experienced a marked reduction in acute rejection rates compared to those on nonimmunosuppressive regimens (Lindholm et al., 1993).

10.2.2 Adverse effects

While cyclosporine is effective in preventing transplant rejection, it is associated with a range of adverse effects. Nephrotoxicity is the most significant concern, often manifested as an increase in serum creatinine levels and reduced renal function (Remuzzi & Bertani, 1989). Other side effects include hypertension, hyperlipidemia, and increased risk of infections due to immunosuppression. Long-term use has also been associated with an increased risk of malignancies, particularly skin cancer (De Mattos et al., 2000).

10.2.3 Emerging applications and research directions

Recent research has explored the potential use of cyclosporine in treating autoimmune diseases and chronic inflammatory conditions. Studies have indicated its effectiveness in conditions such as psoriasis and rheumatoid arthritis, expanding its therapeutic applications beyond transplantation (Barrera et al., 2021). Additionally, novel formulations and delivery methods, including nanoparticles and microemulsions, are under investigation to enhance its bioavailability and reduce systemic toxicity (Agarwal & Rupenthal, 2016).

10.3 Statins: Cholesterol-lowering agents

Statins, a class of lipid-lowering agents, have been pivotal in the management of hyperlipidemia and the prevention of cardiovascular diseases. These compounds function primarily by inhibiting 3-hydroxy-3-methyl-glutaryl-coenzyme A (HMG-CoA) reductase, a key enzyme in the cholesterol biosynthetic pathway (Turner & Pirmohamed, 2020). Originally derived from microbial sources, statins exemplify the significant impact of microbial bioactive molecules on human health.

10.3.1 Clinical agents

Statins are commonly recommended for the treatment of dyslipidemia and the secondary prevention of cardiovascular events. Numerous clinical trials have proved their effectiveness in lowering cardiovascular morbidity and mortality (Mills et al., 2011). Statins have also been demonstrated to have pleiotropic effects, such as anti-inflammatory and antioxidant capabilities, which may contribute to their cardiovascular protection (Oesterle et al., 2017).

10.3.2 Adverse effects and emerging trends

While statins are generally well-tolerated, they are associated with a range of potential adverse effects. Myopathy, including rhabdomyolysis, is one of the most serious complications and is thought to occur due to alterations in muscle metabolism and mitochondrial function (Ray et al., 2014).

Some evidence suggests that statins may have an antitumor effect through the modulation of inflammatory pathways and the inhibition of cancer cell proliferation (Grabarek et al., 2021). Furthermore, ongoing research into the effects of statins on conditions such as Alzheimer's disease has yielded promising results, indicating that their neuroprotective properties may extend beyond lipid management (Crisby et al., 2002).

10.4 Erythromycin: A broad-spectrum antibiotic

Erythromycin, an antibiotic first isolated from *Saccharopolyspora erythraea*, exhibits broad-spectrum antibacterial activity. Since its discovery in the 1950s, erythromycin has played a significant role in the treatment of various infections, particularly in patients allergic to penicillin. Its unique mechanism of action, favorable pharmacokinetic properties, and clinical efficacy underscore its importance as a microbial bioactive compound.

10.4.1 Mechanism of action

Erythromycin's antibacterial actions are mostly due to its ability to impede bacterial protein production. It binds to the 50S ribosomal subunit, especially the peptidyl transferase center, preventing the translocation step during protein elongation (Jelić & Antolović, 2016). This binding inhibits the production of peptide bonds, resulting in the termination of protein synthesis and bacterial growth. Erythromycin's ability to impair ribosome activity renders it bacteriostatic at low doses and bactericidal at high ones (Zimmermann et al., 2018).

10.4.2 Adverse effects and drug interactions

Although generally well-tolerated, erythromycin is associated with a range of adverse effects. Gastrointestinal disturbances, including nausea, vomiting, and diarrhea, are among the most common (Rang, 2013, p. 3–18). Drug interactions are a significant concern, particularly with other medications metabolized by CYP3A4, which can result in increased plasma concentrations and heightened toxicity (Mellal et al., 2019).

11. Challenges and future direction

11.1 Drug resistance and its management

The emergence of drug resistance among microbial pathogens has become a critical global health issue threatening the efficacy of existing antimicrobial therapies. Microbial bioactives are pivotal in treating infectious diseases. However, the relentless evolution of resistance mechanisms undermines these treatments, leading to increased morbidity, mortality, and healthcare costs. Understanding the mechanisms of resistance and developing effective management strategies is essential for sustaining the efficacy of microbial bioactives.

11.1.1 Strategies for managing drug resistance

11.1.1.1 Antimicrobial stewardship programs

Implementing antimicrobial stewardship programs (ASPs) in healthcare settings is crucial for optimizing the use of microbial bioactives. ASPs promote the judicious use of antibiotics, reducing unnecessary prescriptions and ensuring appropriate drug selection, dosing, and duration (Roope et al., 2019). These programs have been shown to decrease antibiotic resistance rates and improve patient outcomes.

11.1.1.2 Combination therapy

Combination therapy involves using two or more antimicrobial agents to enhance efficacy and reduce the likelihood of resistance development. This strategy can provide synergistic effects, allowing for lower doses of each agent, which may minimize adverse effects and slow resistance emergence (Årdal et al., 2020).

11.1.1.3 Infection control measures

Stringent infection control practices are essential in preventing the spread of resistant pathogens. Measures include hand hygiene, environmental cleaning, and the use of personal protective equipment (PPE) in healthcare settings. Effective surveillance and outbreak management protocols also play a pivotal role in containing the spread of drug-resistant infections (Kollef et al., 2017).

11.1.1.4 Vaccination

Preventive strategies, including vaccination, can reduce the incidence of infections, thereby decreasing the need for antibiotics and minimizing the selection pressure that drives resistance. Vaccines targeting common bacterial pathogens, such as *Streptococcus pneumoniae* and *Haemophilus influenzae*, have demonstrated efficacy in reducing infection rates and subsequent antibiotic use (Jansen et al., 2018).

11.2 Sustainable production methods

The production of microbial bioactives, including antibiotics, enzymes, and other metabolites, is increasingly recognized for its potential in addressing global health and environmental challenges. Sustainable production methods are essential to ensure the long-term availability of these bioactive compounds while minimizing environmental impact.

11.2.1 Fermentation technology

Fermentation remains the cornerstone of microbial bioactive production. Traditional fermentation methods often rely on batch or fed-batch processes, which can be resource-intensive. Recent advances in continuous fermentation systems offer a more sustainable alternative, allowing for higher yields and reduced resource consumption (Terefe, 2021). Continuous processes enable the maintenance of optimal growth conditions, minimizing waste generation and improving the overall efficiency of bioactive production (Sadh et al., 2018).

Co-culturing different microbial species has been shown to increase the yield of specific metabolites, such as antimicrobial peptides and secondary metabolites, by leveraging the metabolic capabilities of diverse organisms (Guo et al., 2024).

11.2.1.1 Raw material sourcing

The choice of raw materials for fermentation significantly impacts the sustainability of microbial bioactive production. Utilizing agricultural by-products and waste materials as substrates is a promising strategy to reduce costs and environmental impact (Shahzadi et al., 2014). For instance, lignocellulosic biomass, which is abundant and underutilized, can serve as a carbon source for the fermentation of various microbial strains, leading to the production of valuable bioactive while promoting circular economy principles (Kumar et al., 2016). Moreover, the application of biotechnological innovations such as metabolic engineering and synthetic biology can optimize microbial strains for enhanced substrate utilization, improving both yield and sustainability (Mao et al., 2017).

11.2.1.2 Process optimization

The optimization of fermentation conditions is crucial for maximizing the production of microbial bioactive. Employing response surface methodology (RSM) and other statistical optimization techniques can help identify optimal conditions, leading to improved yields and reduced resource inputs (Yun et al., 2018). Furthermore, the implementation of bioprocess monitoring and control systems, such as real-time biosensors and automated feedback loops, enhances process efficiency (Schuler & Marison, 2012).

11.2.1.3 Green extraction methods

Organic solvents are usually used to extract microbial bioactives from fermentation broths, which can be harmful to the environment and human health. Sustainable extraction techniques, such as supercritical fluid extraction (SFE) and pressurized liquid extraction (PLE), provide cleaner alternatives. These approaches use environmentally friendly solvents and work under moderate circumstances, resulting in increased extraction efficiency and less solvent waste (Lemes et al., 2022).

Innovative approaches such as microwave-assisted extraction (MAE) and ultrasound-assisted extraction (UAE) have grown in favor due to their potential to improve bioactive chemical solubilization while reducing extraction time and solvent utilization.

11.2.1.4 Waste management and by-product valorization

Sustainable production of microbial bioactives also entails effective waste management strategies. By-products generated during fermentation can often be valorized for additional economic and environmental benefits. For example, residual biomass can be converted into bioenergy through anaerobic digestion or used as animal feed (Yaashikaa et al., 2022).

11.3 Regulatory and safety considerations

The increasing application of microbial bioactive molecules in pharmaceuticals, food, and agriculture necessitates rigorous regulatory and safety considerations. These bioactives require comprehensive assessment to ensure their efficacy and safety for human and environmental health.

11.3.1 Regulatory frameworks

11.3.1.1 Pharmaceutical regulation

In the pharmaceutical industry, regulatory organizations like as the United States Food and Drug Administration (FDA) and the European Medicines Agency (EMA) set strict requirements for approving microbial bioactives as medications. Preclinical investigations, clinical trials, and postmarketing surveillance are typical steps in the regulatory pipeline. Preclinical investigations evaluate pharmacodynamics, pharmacokinetics, and toxicity in appropriate animal models (Clinical trials guiding papers, 2021).

Clinical trials are categorized into phases, with phase I focusing on safety and dosage, phase II assessing efficacy, and phase III confirming effectiveness in larger populations (Guidelines for good clinical practice, 2016). Postmarketing surveillance, or phase IV studies, monitor long-term effects and rare adverse events once the product is on the market.

11.3.1.2 Food safety regulation

Microbial bioactives are also employed in food applications, where they must comply with food safety regulations. The Codex Alimentarius, established by the FAO and WHO, provides international food safety standards, including guidelines for the use of microbial additives (Fao/Who, 2021). In the US, the FDA oversees the Generally Recognised as Safe (GRAS) status, allowing certain bioactives to be used without extensive premarket approval, provided they are deemed safe based on existing scientific evidence (Fda, 2018).

11.3.1.3 Agricultural regulation

In agriculture, microbial bioactives are subject to regulation to ensure environmental safety and efficacy. The Environmental Protection Agency (EPA) in the US evaluates the safety and effectiveness of these products before they can be marketed. The assessment includes ecological risk evaluation, potential impacts on nontarget organisms, and the environmental fate of microbial formulations (Biopesticides, 2020).

11.3.2 Safety assessment methodologies

11.3.2.1 Toxicological evaluations

Safety assessments of microbial bioactive involve comprehensive toxicological evaluations. In vitro assays are often utilized as preliminary screenings to evaluate cytotoxicity and genotoxicity (Vilas-Boas et al., 2021). Following initial screenings, in vivo studies in relevant animal models provide further insights into the bioactive's safety profile.

11.3.2.2 Allergenicity testing

Given that some microbial bioactives may elicit allergic reactions, allergenicity testing is critical, particularly for food applications. Regulatory bodies recommend evaluating the protein structure of microbial bioactives to identify potential allergens (Guidelines for the assessment, 2013). Additionally, clinical studies may be required to assess the allergenic potential in susceptible populations.

11.3.2.3 Environmental risk assessment

For agricultural microbial bioactives, environmental risk assessments are imperative. These assessments evaluate the potential for adverse effects on ecosystems, including impacts on soil microbiota, water quality, and nontarget organisms. Ecotoxicological studies and modeling approaches are employed to predict the fate and effects of microbial bioactive in the environment (Grillo et al., 2021).

11.3.3 Challenges in regulation and safety

11.3.3.1 Complexity of microbial bioactives

The diverse nature of microbial bioactives poses challenges in regulatory and safety assessments. Unlike conventional chemical substances, microbial products can vary significantly based on production conditions, microbial strains, and extraction methods, complicating consistency in safety evaluations (Pham et al., 2019).

11.3.3.2 Rapid advances in biotechnology

The rapid development of biotechnological methods such as synthetic biology and genetic engineering has outpaced existing regulatory frameworks. This necessitates the adaptation of current guidelines to address novel bioactive compounds that may arise from engineered microorganisms (Wang & Zhang, 2019). Regulatory agencies are increasingly called upon to provide clear guidelines on the evaluation and approval of these innovative products.

11.3.3.3 Public perception and acceptance

Public perception of microbial bioactives, particularly in food and health applications, can significantly influence regulatory processes. Concerns about safety, environmental impact, and ethical considerations often shape public discourse. Transparent communication and stakeholder engagement are essential for fostering trust in regulatory decisions (Cordaillat-Simmons et al., 2020).

11.4 Innovations and emerging trends

The increasing resistance of pathogens to conventional antibiotics necessitates the exploration of novel microbial metabolites.

11.4.1 Advances in metagenomics and genome mining

Recent advancements in metagenomics have revolutionized the discovery of microbial bioactive molecules. High-throughput sequencing technologies enable researchers to access genetic material from environmental samples without the need for cultivation (Mahapatra et al., 2020). This approach facilitates the identification of biosynthetic gene clusters (BGCs) associated with bioactive compounds.

Furthermore, genomic mining strategies have been developed to enhance the yield of bioactive molecules. Techniques such as CRISPR-Cas9 gene editing allow for the targeted manipulation of microbial genomes to optimize the production of secondary metabolites (Bhagwat et al., 2022). This precision in genetic engineering is paving the way for the design of microbial strains with enhanced biosynthetic capabilities.

11.4.2 Synthetic biology and metabolic engineering

Synthetic biology plays a pivotal role in the engineering of microbial strains for the production of bioactive compounds. By employing modular genetic circuits and synthetic pathways, researchers can create microbial cell factories that produce complex natural products more efficiently (Liu et al., 2017). For instance, the reconstitution of entire biosynthetic pathways in heterologous hosts, such as *Escherichia coli* and yeast, has resulted in the successful production of valuable compounds, including antibiotics and antitumor agents (Park et al., 2020).

Moreover, the integration of machine learning algorithms into metabolic engineering allows for the prediction of optimal genetic modifications needed to enhance the biosynthetic potential of microorganisms (Kim et al., 2020).

11.4.3 Exploration of novel sources

The search for novel microbial sources of bioactive molecules has expanded beyond traditional environments. Extremophiles, microorganisms thriving in extreme conditions, have emerged as a rich source of unique bioactive compounds (Neifar et al., 2015).

The human microbiome is gaining attention as a reservoir of bioactive molecules. Studies have revealed that certain gut microbiota produce metabolites that modulate immune responses and gut health (Lin et al., 2014).

11.4.4 Natural product: Libraries and high-throughput screening

The construction of extensive natural product libraries is essential for the identification of new bioactive molecules. Advances in combinatorial chemistry and natural product synthesis enable the creation of diverse libraries that facilitate high-throughput screening (HTS) for biological activity (Ayon, 2023).

Innovative screening techniques, such as phenotypic screening and target-based assays, are being employed to uncover new antimicrobial agents. For instance, the integration of microfluidics in HTS enables the analysis of compound libraries in miniaturized formats, reducing reagent consumption and increasing throughput (Parihar & Pradeep Mehta, 2024).

12. Conclusion

Overall, microbial metabolites and extracts will play a more diversified and important role in human existence. Recombinant medicines are becoming increasingly popular as a result of the usage of innovative protein synthesis platforms and product development efforts. Microbial cells will continue to be excellent protein producers due to their versatility and low cost. Despite various challenges, bioengineering and recombinant DNA technology will allow for the increased synthesis of microbial natural products and recombinant proteins. More effort in natural product analog research will allow for the discovery of compounds with more biological activity than their natural counterparts. Modern scientific technology may be utilized to further the area of microbial natural products, which provide a consistent source of novel compounds for medication development.

12.1 Summary of key points

Microbial enzymes are extremely essential for the advancement of industrial biotechnology. Contemporary applications encompass pulp and paper, leather, detergents and textiles, medicines, chemicals, food and drinks, biofuels, animal feed, and personal healthcare. The majority of commercial enzymes are recombinant proteins generated by bacteria and fungus.

The utilization of natural nonribosomal peptide synthesis techniques is the foundation of contemporary biotechnologies for the creation and advancement of new antibiotics with medicinal usefulness (Mondol et al., 2013). Understanding the processes and possibilities of this kind of metabolite synthesis in marine and terrestrial bacteria is crucial from both a scientific and practical standpoint (Wang & Lei, 2018).

One of the most intriguing developments in modern biotechnology is the targeted control of biosynthesis mechanisms via metabolic engineering techniques to produce hybrid peptides or hybrid peptide synthetases by disrupting the target gene of nonribosomal synthesis in marine bacteria and their secondary metabolites. This route appears as one of the most promising paths for the development of novel drugs, as well as a potential target for controlling pathogenic bacteria's exocrine activity and, therefore, survival (Nguyen et al., 2019).

12.2 Future outlook

Microbial secondary metabolites have transformed the pharmaceutical business and been useful in treating human ailments for ages. Natural product drug development is about to enter an exciting new golden era, with a growing number of sequenced microbial genomes showing an abundance of novel biosynthetic genes. We are now much more aware of the abundance of unrealized biosynthetic potential due to data from the numerous freshly sequenced microorganisms and metagenomic libraries. These findings suggest that there are still many important natural products to be found and that, in terms of bioactive metabolite separation and identification, only the tip of the iceberg has been explored thus far. The approaches explored range from simple, low-tech, and inexpensive techniques like co-culturing and medium manipulation—which can be very successful—to more complex and targeted molecular biology techniques like bioengineering organisms to create a particular product. It should come as no surprise that no single strategy can be relied upon for opening every metabolic pathway. Novel natural products can be identified with greater ease, given recent developments in genome annotation tools, which is making it easier to anticipate natural products encoded in bacterial genomes. Nevertheless, flawless in silico prediction is limited to highly basic natural compounds. At now, biosynthetic cluster information is dispersed across the literature; however, in order to facilitate better sequence data mining and increased access ease, there is a necessity for the systematic deposition of data.

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Chapter 13

Biomaterials of marine organisms for industrial applications

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1. Introduction

Biomaterials are materials that are either extracted from natural sources or developed to have an interface with the biological system in medical, manufacturing or environmental use (Todros et al., 2021). They are critical in driving the advancement of technology as well as the enhancement of the standard of living through the creation of solutions within sectors such as health, bioengineering, and other industrial fields. Biomaterials include biopolymers, bioceramics, bioactive compounds, and composites each of which possesses certain properties ideal for certain functions (Detsch et al., 2018; Troy et al., 2021). The application of biomaterials consists of the fact that it is possible to recreate the properties of native tissues, which allows for achieving compatibility and functionality that cannot always be provided by synthetic analogs (Kim et al., 2021). These properties make them unreplaceable in tissue engineering and regenerative medicine, drug delivery, and biosensors (Sanchez Armengol et al., 2024). Furthermore, biomaterials derived from renewable sources and environmental conservation for other applicative purposes still support the global push toward green technology (Ramchuran et al., 2023).

Marine biomaterials are produced from marine organisms including algae, crustaceans, mollusks, sponges, and corals. Many of these organisms inhabit various and challenging environments, which grants the resulting biomaterials specific performance characteristics ideal for numerous industries (Wan et al., 2021). These living organisms are exposed to pressure, different temperatures, and new chemical compounds found in the marine ecosystem making the biomaterial have high mechanical properties, heat resistant and bioactive (Ghosh et al., 2022). For instance, chitin, which is extracted from the exoskeletons of crustaceans, and chitosan derived from it, display high biocompatibility, biodegradability and low toxicity as well as antimicrobial activity, thus have a high potential for use in medicine and pharmacology (Lagopati et al., 2022). In particular, marine sponges and fish scales-derived collagen are applied in wound dressing and tissue engineering because of their low antigenic properties and high biocompatibility. Marine bioceramics like calcium carbonate from corals and mollusk shells are used in bone grafting and dental implants because of their close structural redundancy to bone (Wan et al., 2021).

The characteristics of marine biomaterials also serve to improve their performance in certain functions and similarly provide potential for expansion in numerous sectors. The fact that many of them can act either as a replacement or a supplement to synthetic materials in various applications indicates their significance in the development of industrial processes and the support of the concept of sustainable growth (Bontempi et al., 2021). Marine biomaterials have great application prospects for changing different industries and their properties make them one of the most promising materials

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with environment-friendly properties. In the medical as well as healthcare applications, marine biomaterials are used for creating improved wound healing in dressing, tissue engineering scaffold and drug delivery field. Their origin and tendency to degrade through biological processes also minimize the potential for negative immune reactions and harm to the environment, which also makes them suitable for medical purposes (Ghosh et al., 2022).

Marine-derived bioactive has evolved to be one of the most popular therapeutic agents in the pharmaceutical industries in the treatment of different diseases such as cancer, infection among others and inflammation. Thus, influences from these compounds are appreciated for their rich chemical structures along with the mechanism of action resulting in fresh opportunities for drug designing and synthesis (Lagopati et al., 2022; Wan et al., 2021). The cosmetic industry takes advantage of marine biomaterials in that they provide active ingredients in treatment products and cosmetics. Some of the seawater-derived compounds which have commercial uses include collagen, alginate and fucoidan that has uses such as antiaging, moisturizing, and skin healing due to increased demand for natural and efficient cosmetics (Alves et al., 2020). Marine biomaterials also find application in the food industry through the formation of edible films and biodegradable packaging materials which are demanded due to the current concerns for packaging materials that can be recycled. These materials aid in the reduction of plastic use decently and also improve food storage, an approach to sustainability as embraced globally (Cheng et al., 2024; Mahmud et al., 2024).

Marine biomaterials can also be applied in environmental uses such as in the formulation of environmentally friendly products and waste disposal. Marine-derived biopolymers can be employed to manufacture sustainable materials with a tendency to biodegrade thereby lowering the impacts of industrialization on the environment (Bontempi et al., 2021). In the bioengineering and biotechnology field, marine biomaterials are used for the construction of cell culture, bioreactors and other hi-tech applications. Due to their characteristics, it is possible to create new applications that optimize biotechnological strategies (Detsch et al., 2018). This chapter therefore seeks to present a clear understanding of biomaterials from marine organisms; their characteristics, extraction and uses. Therefore, the present chapter has illustrated the extensive use of marine biomaterials in the contemporary industry regarding the various types of marine biomaterials together with their origin, extraction, and application procedures.

2. Types of marine biomaterials

Marine bio-resources of crude products such as crustaceans, fish, and algae are progressively important constituents, in medicine, biotechnology, and environmentalism. These materials include; polymers—chitin, chitosan, collagen; bioceramics (calcium carbonate, silica); and bio-active proteins—and enzymes. Marine biomaterials are characterized by their biocompatibility, biodegradability, and bioactivity which include applications in; wound healing, drug delivery systems, bone regeneration, and environmental remediation which confirms their applicability within a range of sectors.

2.1 Polymers (chitin, chitosan, and collagen)

Polymers derived from marine sources like chitin, chitosan, and collagen are particularly well-known because of their profound characteristics and uses. Chitin is thus a naturally occurring biopolymer and is extracted from crustacean's exterior body covering (e.g., crab, shrimp) and fungi cell walls. Its structure consists of long polysaccharide chains of N-acetylglucosamine which determine the high mechanical properties of the material (Elieh-Ali-Komi & Hamblin, 2016). The properties of chitin further include biocompatibilities and biodegradabilities and it has been used in wound healing where it may assist in forming the scaffold that supports tissue regeneration. Furthermore, it is used as a raw material for chitosan which has a wider application because of its solubility in aqueous acidic media (Ahmad Dar & Abd Al Galil, 2022).

Chitosan, a deacetylated product derived from chitin, has unique characteristics including antimicrobial, biocompatibility, and the capacity to form films, fibers, and hydrogels. Such characteristics have made it very useful in biomedical-related disciplines (Ahmad Dar & Abd Al Galil, 2022). For instance, chitosan-based hydrogels are effective in drug delivery systems because they can give a gradual release of a therapeutic substance. In agriculture, chitosan is used as a biodegradable pesticide that helps to stimulate the protective system of plants from pathogens (Elieh-Ali-Komi & Hamblin, 2016).

Another important marine polymer is collagen which is mainly produced from fish scales and skin. Connective tissues utilize it as a primary structural protein because of its high tensile strength and acceptable biocompatibility. Marine collagen has been well utilized in cosmetic products mainly because of its moisturization and antiaging activity. Furthermore, it finds its uses in medicated applications using it in tissue regeneration, and wound dressing, as it assists with the adhesion and proliferation of the cells hence faster healing processes (Lim et al., 2019).

2.2 Bioceramics (calcium carbonate and silica)

Marine bioceramics such as calcium carbonate and silica are extensively used in several applications owe to their excellent mechanical and chemical characteristics. Calcium carbonate is found in various marine living organisms including corals, mollusks and some algae. This forms polymorphic structures of calcites, aragonite, and vaterite each arising from different crystallography. Organic materials derived from corals and mollusk shells are best preferred because they are stronger than other forms of calcium carbonate and are biocompatible. In the biomedical field, calcium carbonate is used as bone graft material because of its osteoconductivity and its capacity to support bone growth. It is also used in products such as toothpaste and mouthwash as a mild abrasive, and in antacid preparations, its action being to neutralize stomach acid (Titsinides et al., 2019; Mahmoud et al., 2024).

One more important marine bioceramic is silica on which diatoms and sponges mainly rely. Thus, incidences of function loss are apt to be higher in diatoms, a group of microalgae, which have complex and robust siliceous cell walls called frustules. The marine sponges although soft-bodied multicellular animals develop silica spicules for mechanical support. Some of the properties of silica are characteristics of large surface area, biocompatibility and chemical resistance which make the material ideal for many uses including drug delivery, biosensors, and catalysts (Sardo et al., 2020). For instance, silica nanoparticles extracted from diatoms have been considered in the delivery of drugs through drug delivery systems. Specifically, their structure permits the encapsulation of drugs, and their biocompatibility with living tissues and cells is desirable for interaction with them. Moreover, the large surface area of silica also represents one of the key reasons for its potential use in adsorption and as a catalyst in the environmental sector including water treatment and pollutant elimination (Sardo et al., 2020; Min et al., 2024).

2.3 Proteins and enzymes

Marine proteins and enzymes are important biopolymers with high versatile utility in various industries owing to their bioactive and functional characteristics. Collagen and gelatin derived from fish and other marine organisms have been found to have several uses, particularly biomedical and cosmetic. As earlier noted, marine collagen is obtained from fish scales and the fish skin. Because of its biocompatibility and its support of cell adhesion and proliferation, it is ideal for wound healing, tissue engineering, or regenerative medicine. On the same note, marine collagen is applied in the body beauty industry since it contains efficacy qualities such as antiaging, skin moisturizing, and the capacity to help in the formation of skin with appropriate elasticity (Xu et al., 2021).

Marine gelatin, derived from fish skins and bones, is another important protein commonly used in food—particularly, as a pharmaceutical product. It has special gelling characteristics thus used in the production of food items like gummy bears and marshmallows. In pharmaceuticals, marine gelatin is used in the formulation of capsules, and as a stabilizer in vaccines or other formulations (Rather et al., 2022).

Marine enzymes have been found to possess distinctive catalytic activity and therefore hold much potential for usage in industries. For instance, proteases derived from marine bacteria and fungi are applied to a wide range of laundry products because they have properties of the effective degradation of protein stains under low-temperature conditions. Lipases that are isolated from marine sources are used in the synthesis of biodiesel and in food processing to strengthen the flavors and qualities (Singh & Bajaj, 2017). Marine enzymes are also used in the bioremediation process; in this they are used to break pollutants within the environment. For example, enzymes obtained from marine microorganisms are capable of degrading hydrocarbon in oil slicks thus helping in the environmental recovery process (Liu et al., 2023).

3. Sources of marine biomaterials

Marine biomaterials are derived from marine organisms inhabiting seas and oceans. These organisms have thus evolved with biochemical and structural properties that are fully functional within various industries (Wan et al., 2021). The sources of marine biomaterials which have been treated in this chapter comprise algae, crustaceans, mollusks, and sponges (Fig. 13.1).

3.1 Algae

Algae consist of larger seaweed and microalgae belonging to macro- and microorganisms which are highly diverse in genetic and morphological terms and find applications in numerous industries (Aransiola, Oyewole, et al., 2024). Some of the prominent biopolymers that it contains include alginate, carrageenan and agar each of which has its preferred qualities.

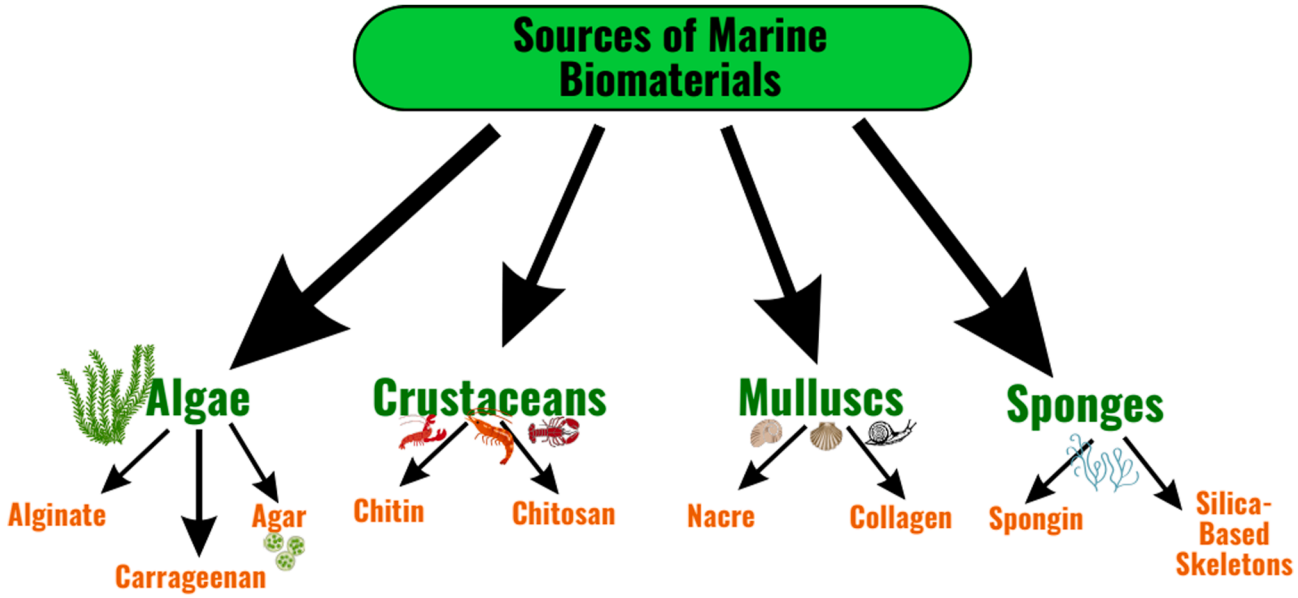

FIGURE 13.1 Sources of marine biomaterials.

One of the most widely used biopolymers in the food and pharmaceutical industry is alginate, which is primarily derived from brown algae. It is used as a gelling activator, stabilizer, and filler (Elkaliny et al., 2023; Aransiola, Bamisaye, et al., 2024). Carrageenan which is a polysaccharide extracted from red seaweed is utilized in the fabrication of dairy and meat products by providing gelling capacity; whereas Agar, which is also from red seaweed is important for microbiological uses as culture media. Besides the biopolymers, algae also produce other bioactive products crucial in nutraceuticals and skincare such as antioxidants, and antimicrobial and antiinflammatory substances. In addition, it contains omega-3 fatty acids, proteins, vitamins, and potential applications in functional foods and supplemental foods as well as biofuel (Menaa et al., 2021; Elkaliny et al., 2023).

3.2 Crustaceans

Crustaceans such as crabs, shrimps, and lobsters are of immense value for their exoskeletons, which are chitin-based and can be processed into chitosan. Chitosan is characterized by its biocompatibility, biodegradability, and natural antimicrobial properties which is unique and hence makes it suitable for use in fields of biomedicine, food, agriculture, and the environment. For instance, chitosan-based films are employed for edible food coatings reducing the spoilt age of foods due to bacterial growth. In pharmaceuticals, chitosan has applications in drug delivery systems, wound healing, and tissue engineering because of its natural property of adherence and stimulation of the uptake of cells (Elieh-Ali-Komi & Hamblin, 2016). In addition, crustaceans contain astaxanthin a red carotenoid utilized for nutraceuticals, supplements, cosmetics, and animal feed products. Astaxanthin has a great reputation in the current world in defending cells from oxidative stress which enhances skin well-being and health (Šimat et al., 2022).

3.3 Mollusks

Oysters and mussels are bivalve molluscs that possess complex biological components for use across different sectors. The formed shells are made of nacre, which is a kind of calcium carbonate with unique optical properties and a high strength-to-weight ratio, recently being used in medical applications of bioceramics for the repair and reconstruction of bone tissue (Marie et al., 2012). Owing to these characteristics, nacre is a promising material for creating orthopedic implants and dental restorations due to biocompatibility and osteoconductivity features. Furthermore, mollusk shells have proteins and polysaccharides with other uses in biomedical units and industries for example use in tissue engineering and natural additives of polymers (Yan et al., 2023). Marine collagen from the connective tissue of mollusks exhibits excellent skin regeneration and hydration properties for cosmetic use or as medical dressings and as scaffolding for tissue engineering (Lim et al., 2019; Xu et al., 2021).

3.4 Sponges

Marine sponges are a rich source of such bioactive and structural features that make them important in biomedical as well as industrial uses. These sea animals release siliceous spicules which are needle-like structures formed over silica; they have applications in nanotechnology and serve as a matrix supporting biomaterials fabrication knowledge (Mehbub et al., 2024). Sponges are also recognized for high collagen levels, which can be used in wound dressings, and skin substitutes and serve as a base for tissue engineering because it does not cause any harm when it comes into contact with human tissue. Furthermore, the bioactivity of natural origin, particularly of marine sponges, contains innumerable biologically active molecules, several of which are of potential pharmacopeia. For instance, substances from sponges have been established to possess antimicrobial, antiviral and anticancer activity hence research of new drugs from sponges. Chemical elements found in sponges have been of immense interest in the development of a new antibiotic and anticancer agent that proves that there is great medical potential in sponges (Mehbub et al., 2024; Varijakzhan et al., 2021).

4. Extraction and processing techniques

Some of the biomaterials are extracted and processed from marine resources, and the process methods must be carefully selected to obtain the desired purity, stability and bioactivity depending on the specific type of biomaterial and its application. These approaches include the traditional mechanical extraction, the chemical extraction method and the more sophisticated methods such as ultrasonic-assisted extraction that strive to achieve high yield and product quality while at the same time preserving the bio-functionality of marine sourced products. In this chapter, each method is described more closely with given examples and techniques utilized in the field.

4.1 Mechanical extraction

Mechanical extraction is perhaps the initial step in processing marine biomaterials whereby the use of tools such as a grinder, miller, and sieve are used. These processes are much easier and the effects on the environment are not very severe since these processes usually do not use solvents or other chemicals of high hazardous levels. For example, the shells of crustaceans such as crabs and shrimp must be subjected to mechanical pressure to initiate the process of chitin extraction from the polymer abundant in marine exoskeletons. Following grinding, different posttreatment methods are used to demineralize and de-matrix chitin and to separate the chitin from proteins and minerals through chemical or enzymatic procedures. Similarly, calcium carbonate derived from mollusk shells can be first ground and then milled into fine powder used in the preparation of bioceramics for use in bone and dental replacement (Kasongo et al., 2020).

4.2 Chemical extraction

Chemical extraction is an overall process of dissolving biomaterials from their source using selective reagents. This method is useful in identifying compounds that either strongly adhere to structural components within cells or need the exclusion of other unwanted particles. Chitin extraction, for instance, involves, the use of chemical reagents, the shrimp shells are treated with acid to remove proteins, and with base to remove minerals. Protein and mineral contents must be removed from within the shell: a process that usually employs hydrochloric acid for demineralization and sodium hydroxide for deproteinization; the end product remains chitin (Elieh-Ali-Komi & Hamblin, 2016).

Similarly, the purification of alginate from brown algae requires the treatment of algae with sodium carbonate to solubilize the alginate followed by the precipitation of the alginate with calcium chloride resulting in the formation of basement of gel-like material used commonly in foods, drugs and also in biotechnology (Bojorges et al., 2023). Chemical extraction is cost-effective, especially in large-scale processing but competent measures have to be adopted to curb the effects of the chemicals used in the processing on the environment (Mahmoud et al., 2024).

4.3 Enzymatic extraction

Enzymatic extraction is relatively mild in that cells and tissues are treated with specific enzymes which degrade their components. For instance, proteolytic enzymes to extract collagen from the skin of fish are used in its application. These enzymes degrade the noncollagenous protein and free the collagen in a process that is particularly favorable for applications involving high biocompatibility including wound healing and tissue engineering (Nagai & Suzuki, 2000). Although chemical methods have been developed and used in some cases enzymatic extraction is used because, this process does not harm the sensitive biomolecules and is considered eco-friendly (Fornari, 2021).

4.4 Fermentation and biotechnological methods

Fermentation and biotechnological methods involve the use of microorganisms to synthesize or recover biomaterials and are renewable solutions for obtaining valuable compounds from sea sources. For example, microalgae are being cultured under standard bioreactors and synthesize bioactive compounds such as polysaccharides and antioxidants. Commercial production of microalgae for biofuel and other products of pharmacological and nutraceutical value is growing due to the effectiveness of bioreactors in increasing production yields (Morais-Junior et al., 2020).

Fermentation of marine proteases and lipases is another practice, involving the bacterial or fungal engineering of a certain enzyme in large quantities. This method is suitable for industrial parts because the enzymes can be produced in large measures but in a controlled manner to have high purity and activity (Al-Maqtari et al., 2019). For example, proteases from marine sources are used in the detergent industry because they possess the enzyme activity of removing protein stains at low temperatures (Barzkar, 2020).

4.5 Ultrasonic and microwave-assisted extraction

Ultrasonic and microwave-assisted extraction techniques are some of the most modern methods devised to increase extraction yields, as well as shorten the extraction process. Sonication or ultrasonic extraction is the use of ultrasonic frequencies to produce cavitation which breaks cell walls and liberates intracellular products. This technique is more efficient when extracting bioactive compounds from marine algae and sponges since it increases their yields without needing high temperatures that decompose some compounds (Carreira-Casais et al., 2021).

Microwave-assisted extraction (MAE) applies microwave energy to heat the material making its cell walls rupture and thereby increasing the polarity and solubility of the bioactive compounds. This method has proved to be effective when extracting polysaccharides from algae because it takes a short time and uses fewer amounts of solvent hence environmentally friendly. MAE has also been used in extracting effective lipids and carotenoids from the microalgae which serve as the main ingredients of nutritional supplements (Nour et al., 2021).

4.6 Supercritical fluid extraction

Supercritical fluid extraction (SFE) is employed in the use of supercritical fluids especially carbon dioxide at high temperatures and pressure to extract bioactive compounds. Some gases when heated to certain conditions become a supercritical fluid and can dissolve compounds as well as any organic solvent but without the need for the solvent. SFE has been extensively employed for the extraction of heat-sensitive products such as carotenoids from algae where its efficiency enhances the product's bioactivity together with its quality. The given method is eco-friendly as it employs CO_2 which can be reused and has no use for hazardous solvents causing environmental pollution (Molino et al., 2020).

4.7 Electrophoresis and chromatography

Purification of biomaterials that involve the use of size and charge or their preferences is facilitated by the use of electrophoresis and chromatography. Polyacrylamide gel electrophoresis is utilized to prevent protein and enzyme-based samples depending on molecular weight to allow target probability and isolation of proteins. High-performance liquid chromatography (HPLC) is an exceptional method for the purification of bioactive compounds like peptides and small molecules derived from marine resources. For example, HPLC can be applied in the extraction of antioxidants from marine algae suitable for the pharmaceutical and nutraceutical market as a result of their antiinflammatory as well as anticancer features. Due to these factors, they provide highly pure biomolecules especially when used in laboratory and small-scale production due to their complexities and high costs (Queiroz et al., 2024).

5. Properties and advantages of marine biomaterials

Marine biomass derived from organisms including algae, crustaceans, mollusks, and sponges have been eyed due to unique attributes which include biocompatibility, biodegradability besides outstanding mechanical performance. These qualities place them well in biomedical, pharmaceutical, environmental, and even industrial applications and are distinctive features of many terrestrial biomaterials. This chapter discusses their characteristics and examines the benefits they have over terrestrial materials.

5.1 Unique properties of marine biomaterials

5.1.1 Biocompatibility

The property of biocompatibility is especially important for the biomaterials which are designed to be used in medical applications because such materials should be able to work in the presence of the human body without activating damaging immune responses. Chitin, chitosan and marine collagen which are obtained from sea organisms possess high compatibility for use in wound dressings, tissue scaffolds and drug delivery systems (Trucillo, 2023; Wang et al., 2024). Marine collagen derived from fish scales and skins is beneficial and can accelerate cell deposition and division vital in tissue repair and regenerative medicine (Morais-Junior et al., 2020). There is also low immunogenicity to avoid risks associated with immobilization, rejection and elimination. Chitosan which was obtained from crustacean exoskeletons also shown good biocompatibility for wound healing dressings where it can form a protective layer for the wound to avoid infection and at the same time encourage tissue regeneration (Ahmad Dar & Abd Al Galil, 2022). Furthermore, modified chitosan-based materials have been designed for a controlled-release drug delivery system that enhances the drug response and simultaneously decreases the side effects (Dutta et al., 2009).

5.1.2 Biodegradability

The biodegradability makes marine biomaterials more environmentally and medically attractive since they do not require local removal and only leave nontoxic residues. Chitin and chitosan are the most promising biodegradable materials since chitosan derived from chitin decomposes to biodegradable compounds such as N-acetylglucosamine which is further biodegradable in the body (Elieh-Ali-Komi & Hamblin, 2016). Further, marine polysaccharides like alginate and carrageenan extracted from different varieties of seaweeds are highly biodegradable and have already been used in application sectors including drug delivery and wound dressing. For example, alginate makes a biodegradable gel used in the construction of tissue scaffolds; it maintains the scaffold's stability while dissolving as cells return to the area (Bojorges et al., 2023).

5.1.3 Mechanical properties

Marine biomaterials possess tensile strength, compressive strength, and elastic modulus important for applications that involve materials that need to hold up under pressure and when under stress. Chitin and chitosan, because of their cellulose-like structure, have good tensile strength which enables them to be used in surgical sutures and wound dressings that must be subjected to manual stress and strain (Ahmad Dar & Abd Al Galil, 2022). While calcium carbonate from mollusk shells affords instances of the application of passive compressive strength, it has been used in orthopedically related surgeries involving the use of bone grafts. These shells made of calcium carbonate crystals deposited in the polymer matrix are extremely strong and lightweight, and this is due to the mineralized structure which has a strength-to-weight ratio in most synthetic materials (Elieh-Ali-Komi & Hamblin, 2016). The uses of marine sponges are another advantage because of their silica-based spicules, and apart from their flexibility, their hysteresis is equally strong; hence they can be very useful when bio-inspired materials for different applications, for example, lightweight, high-strength composites (Varijakzhan et al., 2021).

5.2 Comparative advantages of marine biomaterials to terrestrial biomaterials

Marine biomaterials are usually superior to terrestrial ones due to the specific strengthening and chemically induced processes that are created within marine conditions for improved functionality.

5.2.1 Structural complexity and versatility

Marine organisms live in high pressure, fluctuating temperatures, and salt-concentrated conditions which necessitate robust materials. As a result, there are other forms of biomaterials like the nacre, which is a mother of pearl found in mollusks show a hierarchical design that enhances the high toughness and durability of the mollusk (Meyers et al., 2007). The unique organization of the nacre derived from a mollusk shell, where the main material is coated with layers of organic and inorganic materials, can catch and dissipate energy more efficiently than many synthetic materials and terrestrial biomaterials and prevent the cracks from extending. Scientists are paying a lot of attention to mimicking certain structures of nacre to enhance the properties of the materials used in construction, aerospace and many other applications (Meyers et al., 2007).

5.2.2 Unique bioactive compounds

Marine biomaterials have bioactive molecules that are not present in other organisms from other environments because of their capacity to perform various tasks. For example, polysaccharides from seaweed comprising fucoidan and carrageenan are known to pose antiviral, antiinflammatory, and anticoagulant functionalities, which create new avenues for pharma (Pradhan et al., 2020). The latest research conducted regarding the brown seaweed product called Fucoidan has proved that it can slow down tumor cell growth and metastasis (Atashrazm et al., 2015). In addition to its use as a food thickening agent, carrageenan has been used in some antiviral research also, for instance, against herpes simplex and influenza viruses, showing that it has potential beyond the treatment of gastroenterological disorders (Campo et al., 2009).

5.2.3 Sustainability and renewability

Compared to biomaterials derived from terrestrial resources, many marine biomaterials have higher sustainability and renewability indexes due to the abundance of resources and minimally invasive technology for their extraction. For example, seaweed can be harvested frequently, does not need fresh water and can immobilize nutrients in the water; alginate derived from seaweed and carrageenan are sustainable sources of raw materials (Kraan, 2013). Seaweed farming does not take up arable land and also helps in capturing CO_2 from the atmosphere and expanding the environmental benefits. Also using fish skin and scale for collagen extraction not only minimizes the waste but also enhances the circular economy for both environmental and economic benefits (Nagai & Suzuki, 2000).

6. Industrial applications of marine biomaterials

Marine biomaterials use the properties originating from marine organisms such as algae, crustaceans and mollusks for industrial purposes. These materials, for example, chitin, chitosan and marine proteins play a significant role in most sectors including health, drug, beauty products, food containers, waste control, and biotechnology among others (Fig. 13.2). This section discusses their applicability across industries with a focus on sustainability and the made innovations.

6.1 Medical and healthcare

6.1.1 Tissue engineering

Marine biomaterials have found their way into tissue engineering in a big way because of their outstanding biocompatibility and cell functions such as growth and differentiation. Marine-derived fish skin is also another source of collagen; this is a protein which plays a role in the scaffolding of tissues in a body. This marine collagen is used to develop templates that help in the repair of many necessary tissues such as skin, bone as well as cartilage. These scaffolds have the elasticity of a 3D framework supporting cell adhesion and growth or establishing functional tissue which is key in efforts to repair damaged organs and tissues (Amirthalingam & Hwang, 2022; Kim et al., 2021). For example, chitosan hydrogel scaffolds extracted from the shells of crustaceans have recently received much attention in bone tissue engineering. Hydrogels prepared from chitosan satisfy the conditions for mimicking the natural extracellular matrix (ECM) required for the growth and proliferation of osteoblasts, which are responsible for bone regeneration (Bharathi et al., 2022; Kim et al., 2023). The use of these hydrogels has been found to enhance cell metabolism and proliferation thus bone repair and incorporation (Sanchez Armengol et al., 2024). Also, these marine biomaterials are biodegradable hence, as new tissue develops, the scaffold dissolves returning less demands on surgical removal and associated patient discomforts (Kim et al., 2021).

6.1.2 Wound dressings

Advanced wound dressings seaweed-based biomaterials like chitosan and alginates are used among marine-derived biomaterials. Because of their natural source, they possess high biocompatibility and because they are derived from the natural sources, their inherent ability to fight off infection in wounds is also high. Chitosan dressings have also been demonstrated to encourage clotting that stops bleeding when the material comes into contact with blood. This characteristic is especially advantageous in the case of acute and chronic wounds, where hemostasis requires a lot of attention (Kim et al., 2023).

Wound management would further benefit from alginates that are derived from polysaccharides found in brown seaweeds. On coming into contact with wound exudate, then it turns to a gel avoiding the formation of scab, which keeps

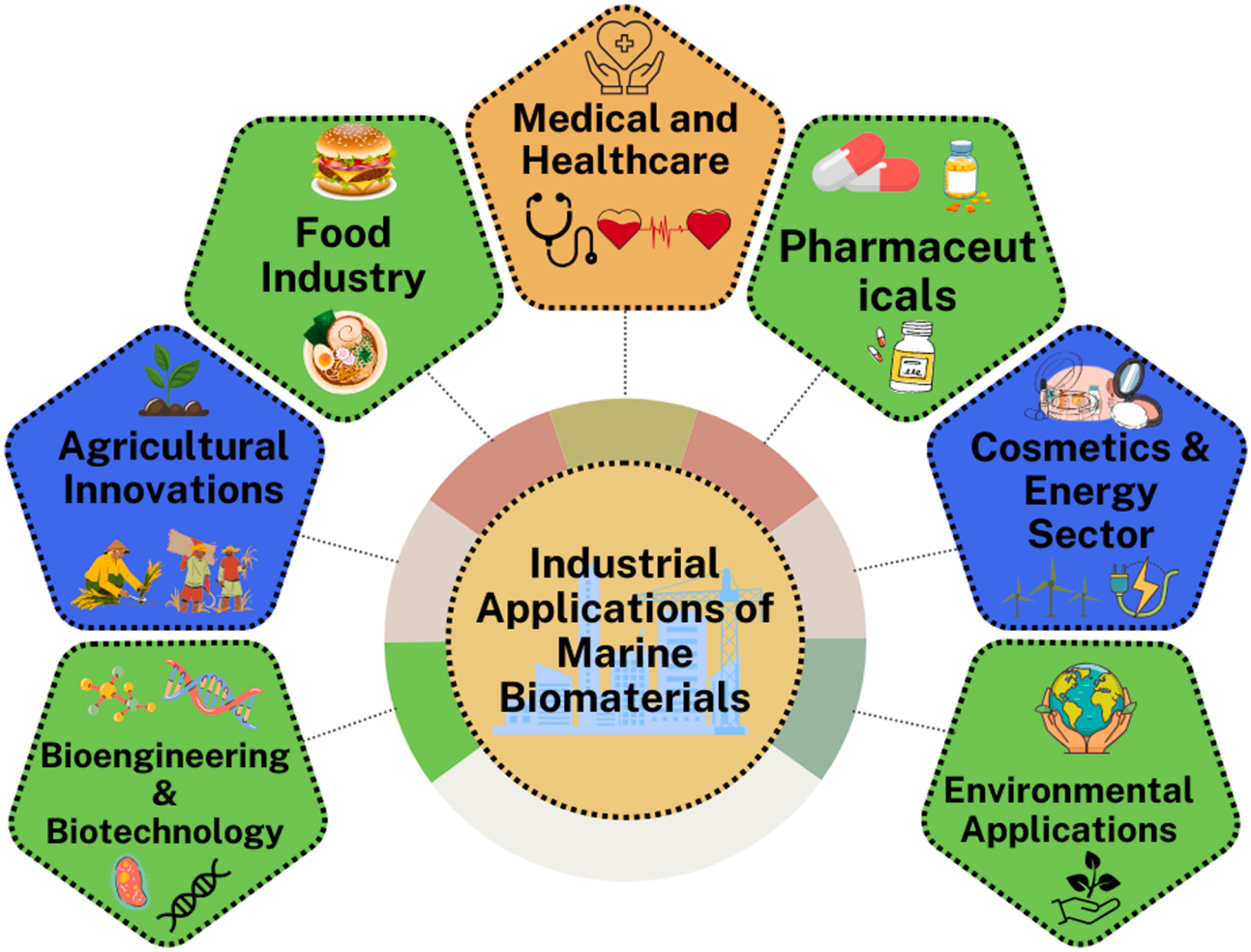

FIGURE 13.2 Industrial applications of marine biomaterials.

the wound moist, as it is appropriate. The warm and damp environment in these chambers enhances the healing process since the skin starts to epithelialize sooner because of the enhanced movements of kinase cells across the wound. In addition, alginate dressings are related to their biocompatibility and the property of taking up excessive amounts of fluid that can lead to maceration of a surrounding tissue. This particular property of alginates is well-suitable for the treatment of exuding wounds and ulcers (Kim et al., 2023; Sanchez Armengol et al., 2024).

6.1.3 Drug delivery systems

Marine biomaterials are also used to improve controlled release systems for therapeutic agents through the construction of drug delivery systems. There is a special emphasis on the cooperation between chitosan nanoparticles and drugs for the target delivery. These particles can be developed to be sensitive to particular physiological conditions including pH and temperature and therefore drugs will only be released to the intended site of action. Such targeting increases the effectiveness of the therapy while minimizing such drawbacks of systemic medication as adverse reactions (Trucillo, 2023).

Likewise, alginate beads have been used to maintain the integrity of diverse therapeutic agents or active pharmaceuticals. Beads also give gradual and predictable delivery of drugs in a specific period, which is very beneficial for drugs that need extended therapeutic impact. The flexibility of controlling the release rate of the encapsulated drugs improves patient compliance and overall treatment results. Besides, it is easily biodegradable, meaning once the drug has been released, the carrier material is entirely biodegradable in the body and cannot cause any harm (Bharathi et al., 2022).

6.2 Pharmaceuticals: Bioactive compounds for drug development

Marine production sources play an important role in offering a multitude of bioactive compounds of tremendous potential as drug leads. These compounds isolated from marine sources including algae, sponges and invertebrates show a myriad of biological activities that could be exploited for therapeutic uses (Ghosh et al., 2022; Lagopati et al., 2022). For example, fucoidan, a sulfated polysaccharide derived from brown algae, has exhibited considerable antiviral, antiinflammatory, and anticoagulant, activities for the treatment of viral diseases and cardiovascular diseases (Mensah et al., 2023; Pradhan et al., 2020). In the same way, carrageenan obtained from red algae has potential in applied medicine because of its immunomodulatory and antitumor effects (Liu et al., 2019).

In addition, marine sponges and also other invertebrates are capable of synthesizing novel secondary metabolites which exhibit different biological activities. One of them is trabectedin derived from the sea squirt *Ecteinascidia turbinata*. In oncology, trabectedin is a chemotherapeutic agent that has been derived from marine origin and is highly effective for soft tissue sarcoma and ovarian cancer (Lagopati et al., 2022; Wan et al., 2021). This supports the ongoing investigation of new marine bioactive and underlines the continued future potential for marine pharmacology. Such endeavors may result in, the discovery of new treatments and strengthen the current approaches toward combating multifaceted diseases (Ghosh et al., 2022).

6.3 Cosmetics: Ingredients for skincare and personal care products

Marine biomaterials have recently emerged into a promising field within the cosmetics industry and their gaining popularity is explained by employing several characteristics and advantages of the marine material influence on the skin. Marine collagen and elastin, which are derived from fish skin and scales, are the two most demanded active agents in antiaging cosmetic products. Premature wrinkles or any type of skin damage can severely decrease the skin's elasticity and its ability to retain moisture; these proteins are considered effective in reversing skin aging processes. Marine collagen research has revealed that it reduces fine lines and wrinkles on the skin hence its addition in many expensive products (Alves et al., 2020).

Further, algal extracts are been widely used in cosmetic formulations because they are packed with vitamins and minerals and have antioxidant properties. These extracts thus afford skin regeneration immunity to oxidative stress and environmental aggression through free radicals cancellation or neutralization. The two most popular types of seaweed—spirulina and kelp—included in cosmetic recipes are lauded for their nutritional values and skin-brightening ability to create a youthful look. These algal extracts can also stimulate keratinocyte proliferation and thus can be used as a skin repair factor, especially in sensitive and aging skin (Todros et al., 2021; Fonseca et al., 2023).

Chitosan, which is obtained from crustacean shells is another marine biopolymer employed extensively in the preparation of cosmetic products. With its bioadhesive and emollient properties, chitosan helps to stabilize and penetrate the substances the product contains and also influences the final product thickness. This property also adds a protective layer on the skin which assists in locking moisture hence the gel is highly suitable for use on creams or lotions (Fonseca et al., 2023). The inclusion of these marine extracts also enhances the features of skin care products while ensuring that they respond to the market demand for environmentally friendly and biocompatible products within the cosmetics industry today (Siahaan et al., 2022; Costa et al., 2023).

6.4 Food industry

The current food industry has shifted to using marine-derived biopolymers which include chitosan and alginate for food preservation and packaging. Some of the improvements include the realization of edible films and packaging materials to counter plastic products. They are composed of biopolymers which makes them bio-degradable thus will help to address the issue of plastic waste management and are better than plastics in terms of package (Al-Maqtari et al., 2019).

The chitosan polymer obtained from the crustacean shells is used predominantly due to its antimicrobial action that contributes significantly to the shelf life of food articles. When applied as an edible coating, films based on chitosan not only serve as a protective cover but also have antimicrobial activity that can prevent the growth of putrefactive microorganisms and thus prolong the shelf life of food products. This makes chitosan films very useful for fresh products such as meat, dairy products and baked foods (Cheng et al., 2024).

Equally, alginate used in the preparation of the coatings from brown algae is applied in fruit and vegetable processing. These alginate-based coatings decrease the water evaporation rate and consequently delay the postharvest aging process, enhancing the shelf life and marketability of the fruits and vegetables (Mahmud et al., 2024). The use of alginate coatings is most beneficial in the distribution of fresh produce since it keeps quality during transport and storage (Mahmud et al., 2024).

6.5 Environmental applications: Biodegradable materials for waste management

Recent awareness of environmental issues such as plastic pollution and general pollution has led to awareness of biodegradable materials particularly marine biomaterials which provide a sustainable means of waste disposal. Chitosan, a product of crustacean shell waste, is emerging as one of the significant players in the development of biodegradable packaging materials (Cheng et al., 2024). Chitin-based packaging films are different from conventional plastic packaging materials in a way that they disintegrate into natural constituents after a short period when treated with microbial activity. This characteristic alone reduces the pressure on the landfilling systems and plays a major role in reducing the environmental burdens of plastics (Wrońska et al., 2022).

In addition, different marine-derived bioactive biopolymers such as alginate and fucoidan are being used to prepare biofertilizers and soil amendants. They are environmentally friendly in that they can degrade while delivering relevant nutrients to the soil once they degenerate (Mensah et al., 2023). As an effective organic material, marine biomaterials develop soil fertility by recycling nutrients without pollution to degrade the environment. For instance, alginate can enhance the physical properties of soil such as structure, stability, and moisture-holding capacity, which directs to new growth of plants. Furthermore, the use of these biodegradable materials is aligned with the circular economy because products from marine sources are being reused instead of petroleum-based unsustainable products (Martínez-Cano et al., 2022).

6.6 Agricultural innovations

Marine biomaterials have a vast prospect for agricultural applications, with biofertilizer and soil-enhancing innovation being one of the most promising areas. Algae are known to have essential nutrients and growth-boosting substances and this makes them to be used in increasing plant growth and improvement of resistance to adverse weather conditions like drought and high salinity of soil. For instance, seaweed extracts, which earlier works demonstrated to enhance root growth and nutrient absorption, have been cited to enhance generation yields (Chen et al., 2021). Moreover, the ability of chitosan and other marine biopolymers used in the treatments facilitates microbial activity in the soil. The maximal use of these practices aids in the management of soil fertility and further eradicates the reliance on hazardous chemical fertilizers, making modern smaller-scale husbandry environmentally friendly approaches (Tennakoon et al., 2023; Wei et al., 2024).

6.7 Advanced material science

Biological materials have structural characteristics that could greatly impact scientific knowledge in the area of advanced materials. The layered arrangement of nacre, in mollusk shells has prompted imitative attempts by researchers to achieve the formation of composites with exclusive performance properties. Nacre is a natural material with a very high strength-to-weight ratio and it is quite ductile and therefore serves as an excellent model system for the engineering of advanced materials for performance-based applications. In this context, mimicking the nacre structure allows scientists to create novel lightweight but strong composite materials suitable for aerospace and the automotive industries which require parts that must endure severe conditions but should be as light as possible. These nanocomposite materials developed from marine biomaterials not only exhibit better durability performance but also make use of environmentally friendly and renewable resources (Naveen et al., 2021).

6.8 Energy sector

Marine biomaterials are useful for the energy potential of future biofuels and energy storage in the context of the energy sector. The algal biomass, especially the microalgae, for instance, can be transformed into bio-fuels to avail a renewable energy source as an option to the fossil energy sources. The utilization of algal biomass for the production of biodiesel or bioethanol is discussed today as a promising trend showing that algae can become an environmentally friendly fuel (Kraan, 2013). Additionally, marine-derived materials are considered for applications in energy storage devices, including supercapacitors and batteries because of their characteristics and large surface area. Such solutions are not only useful in solving energy issues but also assist in making an environmentally friendly solution as a byproduct of waste from the marine industries (Appiah et al., 2022).

6.9 Bioengineering and biotechnology

6.9.1 Scaffolds for cell culture

Marine biomaterials are enormously valuable for preparing cell culture scaffolds to offer structural support and encourage cell proliferation, differentiation as well as functionality. These scaffolds mimic the ECM of tissues and are more

appropriate for culturing cells when compared to simple two-dimensional cultures. Collagen and alginate hydrogels are especially preferred because of their biocompatibility and capacity to stimulate cell attachment. Most importantly, collagen acts as a matrix for different cell types such as fibroblast and stem cells with the capacity to multiply and differentiate in the presence of the protein (Amirthalingam & Hwang, 2022). Alginate has a particularly attractive characteristic for the process of tissue engineering: a balanced combination of good mechanical and biochemical characteristics can be obtained through the modification of the final product based on alginate, which is extracted from brown seaweed. These scaffolds help not only in analyzing cell behavior but also in the fabrication of functional tissue-engineered products including skin, cartilage and bone (Bharathi et al., 2022). The integration of marine biomaterials into the construction of cell culture scaffolds can help biomedical science move forward and promote innovative treatments for tissue interaction that will lead to the success of tissue engineering (Detsch et al., 2018; Kim et al., 2021).

6.9.2 Bioreactors

Marine biomaterials have also been used widely in the construction of bioreactors that are important tools used in microorganism or cell culturing for bio-based product synthesis. Alginate beads are widely employed in biotechnology where cells are trapped within bioreactors through immobilization hence suitable for fermentation and bioprocessing. Microbial cells are also retained with the help of alginate beads thereby increasing the metabolic process such as the synthesis of enzymes, production of biofuels, and manufacture of drugs and medicine (Soares et al., 2021; Berillo et al., 2024). Alginate's ability to gel in mild conditions makes it possible to encapsulate many types of cells and the released gel is biocompatible and allows for cell survival and functionality. In addition, aquatic biomaterials are biodegradable and nontoxic in contrast to the synthetic materials used in other bioprocesses (Wrońska et al., 2022). As a result of the properties of marine resources, it has been possible to engineer new solutions in the field of engineering, particularly in bioengineering and biotechnology, which pave the way to the development of more sustainable products and processes.

7. Future prospects of marine biomaterials

Marine biomaterials of the future lie in the innovative prospectus that would revolutionize technology and act as a springboard to sustainability in all its facets such as biomedical, environmental and industrial applications. The use of these materials can only be boosted by advances in extraction methods and interdisciplinary implementation. For instance, innovations in green extraction techniques, inclusive of supercritical fluid extraction, provide upgrade extraction techniques that are more environmentally friendly than mostly used conventional extraction methods, with efficiency in the extraction of bioactive compounds from marine sources, with the least effect on the environment (Molino et al., 2020). Moreover, there is progress regarding enzyme engineering toward improving the selectivity and effectiveness of these extraction procedures, where this desired product has a significantly higher purity and where less toxic chemicals need to be used. Furthermore, the nanotechnologies used in marine biomaterials introduce new drug delivery and improved medical implants, giving proof of the guided transformation of marine material in medical treatments. The emerging technology of bioprinting using marine-derived bioink could promote the development of the tissue architecture trilogy in various tissue engineering and regenerative medicine applications to create individualized treatments (Lam et al., 2023; Park et al., 2024).

Environmental concerns remain crucial in developing marine biomaterials because the raw materials and by-products remain scarce. For this reason, good practices that must be put in place to minimize possibilities of ecological disturbances and loss of biodiversity due to over-harvesting are; sustaining and diversifying aquaculture, particularly for seaweeds and shellfish, or other species that can provide a secure source of biomaterials, whilst supporting ecosystem health through integrated multi-trophic aquaculture systems (Ashkenazi et al., 2022). Moreover, the effectiveness of the concept of circular economy in managing waste and improving efficiency in using marine biomaterial can be explained by the idea of applying by-products of manufacturing in other industries, including the production of bioenergy. Supportive legal models also need to be set up as the core of the regulation of the efficient and nonharmful exploitation of marine resources, including the protection of beneficial environmental and equitable commercial uses. Last, increasing the knowledge about the prospects and problems of marine biomaterials in society can create a culture of sustainability and create a market for sustainable products and resources. Altogether, these development strategies will define the future trends in marine biomaterials while suggesting these materials as critical solutions to global problems.

8. Conclusion

Marine biomaterials possess certain benefits which cannot be provided by any other material making them significant across areas of application including; healthcare, pharmaceutical, packaging, and even environmental conservation. Their compatibility with biological systems enables them to perform well within excessively wet environments such as in the formation of medical implants and delivery systems for medicines. Also, more importantly, their biodegradability plays a perfect role in solving environmental problems that relate to waste and pollution. These materials further display good mechanical characteristics, they can be used in places with strength demands. As such, there is a need to strengthen future endeavors to extract materials efficiently, increase the durability of methods employed, and increase the feasibility of the process. New horizons of marine biomaterials may lie in technology enhancements embracing novel extraction methods as well as biotechnological performance. The interdisciplinary approach will also enhance the impact of these materials when combined with organizational and multidisciplinary collaboration to advance ideas and promote intervention in real-world sustainable development to address the problems affecting societies across the world. Marine biomaterials remain the next frontier for growth and they are expected to play a crucial role in the formation of a better tomorrow, environmentally friendly prosperous world.

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Chapter 14

Emerging pharmaceutical products from marine plants

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1. Introduction to marine plants and their pharmaceutical potential

1.1 An overview of marine plant diversity: Seaweeds, seagrasses, and mangroves

One of the fascinating things about the marine environment is that it contains various active compounds of biological value with promising prospects for novel drug development. Although not necessary for fundamental life functions, these secondary metabolites are useful for their medicinal properties. They might be vital in combating major disease conditions such as cancer, malaria, and aids (Gupta et al., 2023).

Seaweed is a good example of a marine plant with promising pharmaceutical prospects, as it contains some peculiar compounds with interesting medicinal properties. Brown seaweeds contain fucoidan and alginate, red seaweeds contain carrageenan and agar, and green seaweeds contain ulvan. Pereira (2018) stated that these essential polysaccharides are useful in the pharmaceutical industry due to their immunomodulatory effects and their ability to fight against inflammation, viral infection, tumors, etc. They also exhibit antithrombotic, anticoagulant, and antioxidant bioactivities. Also, it has been shown that making seaweed a part of one's daily diet improves digestive health, prevents chronic illnesses, as well as reduces the occurrence of certain diseases (Lomartire & Gonçalves, 2022). Green, red, and brown algae have been shown to have minerals, vitamins, and other compounds with interesting properties (Aransiola, Leh-Togi Zobeashia, et al., 2024; Aransiola, Oyewole, et al., 2024; Earp et al., 2018).

Apart from seaweeds, seagrasses contain bioactive compounds with promising pharmaceutical prospects (Xin et al., 2023). Seagrasses are underwater marine angiosperms found in proliferation in tidal and subtidal parts of all seas, apart from polar regions. They contain high amounts of chlorophylls and carotenoids, making them useful as vitamins and antioxidants. They are beneficial against diseases like diabetes and obesity and, hence are good options for functional foods and medications (Wagey et al., 2024). They have also been found to be strongly effective against malaria, skin diseases, muscle pains, stomach problems, and in wound healing and early stages of leprosy (Kim et al., 2021; Yuvaraj et al., 2011).

Mangroves refer to unique plant communities (salt tolerant ferns, large shrubs, or trees) normally found in estuarine and coastal habitats in tropical and subtropical regions, where they occur either within or adjacent to the intertidal region (Kim et al., 2021; Shelar et al., 2024). They occupy about 5% of the entire global forest areas and are categorized into two major classes, namely true mangrove species (plants seen only in tropical intertidal habitats) and mangrove associates (plants not constrained to these territories) (Thirumalaiselvan et al., 2020). Their ecosystem provides numerous benefits such as coastal protection, carbon storage, food for marine organisms, shelter and protection from predators for marine animals, etc. (Misiune et al., 2022). Most parts of these plants have been beneficial in treating various ailments such as diarrhea, stomachaches, diabetes, skin infections, conjunctivitis, toothaches, etc., and also useful as insecticides and pesticides (Heemsoth, 2020).

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Mangrove plants' hostile environment makes them biochemically unique and enables them to produce several natural compounds with unique bioactivity. Their bioactive metabolites contain peculiar chemical structures belonging to various chemical groups like alkaloids, phenol, steroids, terpenoids, and tannins. Furthermore, due to their extreme living conditions, they serve as a selective environment for the proliferation of endophyte microorganisms (Aransiola, Oyewole, et al., 2024; Aransiola, Leh-Togi Zobeashia, et al., 2024). These microorganisms give mangrove plants a significant pharmacological value because they secrete bioactive secondary metabolites of immense importance.

1.2 Historical uses of marine plants in traditional medicine

For centuries, marine plants have been valued for their medicinal properties. According to Narchi (2013), ancient civilizations recognized the therapeutic potentials of marine plants, with notable examples including Dioscorides' Materia Medica (65 CE), which highlighted the antiinflammatory effects of brown algae, and Galen's discussions on the medicinal uses of algae during the same period. The Islamic Classical Period saw scholars like al-Razi and al-Rasuli utilizing seaweed for therapeutic purposes. Avicenna's Canon of Medicine (al-Qanun fi al-Tibb) listed 23 diverse marine resources with medicinal applications. The Pen Tsao Kang Mu (1590 CE), a traditional Chinese medical text, featured numerous seaweed-based remedies.

According to the earliest works in China, *Laminaria japonica Aresch*. (Kelp extract), *Sargassum fusiforme, Porphyra* spp., and *Ulva* spp. have been medically beneficial in China for more than 20 centuries (Chengkui & Junfu, 1984). It can be seen that the medicinal use of seaweeds has extensive use in Asia. In Europe too, seaweeds were used by the ancient Romans to treat cuts and burns. Seaweeds signify a promising reserve of novel bioactive agents with a lot of health benefits that cannot be found in terrestrial plants (Chengkui & Junfu, 1984). Mangrove plants have been used in native medicines. Research has shown that marine plants and their extracts possess antimicrobial properties, effectively inhibiting the growth of several pathogens that affect humans, animals, and plants (Vinoth et al., 2019).

1.3 Importance of marine plants in modern pharmacology

The sea is thought to be the largest untapped reservoir of biomolecules with potential therapeutic activity, hence a tremendous store for new compounds (Gupta et al., 2023). Thus, it has become increasingly clear that marine bioresources are very important reservoirs of new biologically active substances as they hold therapeutic properties deficient in terrestrial plants (Déléris et al., 2016).

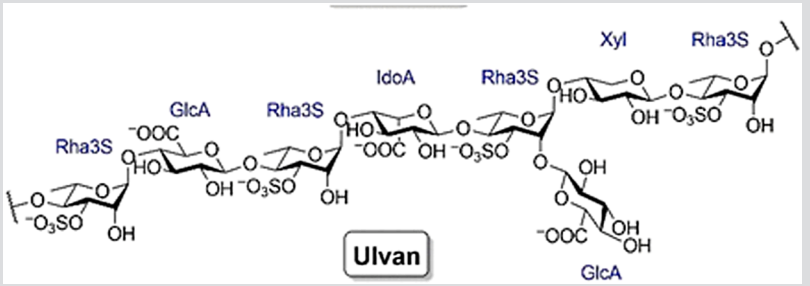
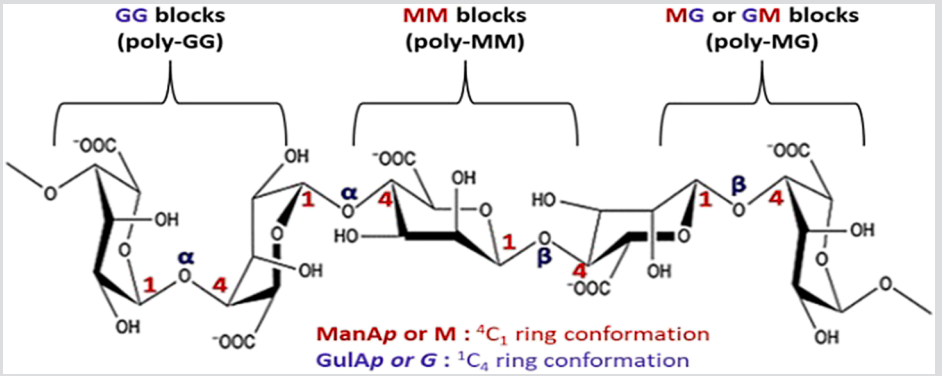
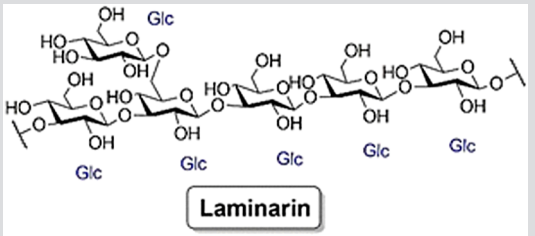
Marine plants are very crucial in modern pharmacology since they contain several secondary metabolites with medicinal properties such as antidiabetic, antineoplastic, antihypercholesterolemia, hypolipidemic, antioxidant, antiinflammatory, antiviral, antibacterial, and antifungal properties (Gupta et al., 2023). These plants provide unique natural resources that have generated special attention in drug development. Every day researchers are exploring the ocean for new compounds that may have potential medicinal benefits to man. All things considered, marine plants present a viable force to be reckoned with in the quest for new drugs with possible medicinal benefits (Musa et al., 2023).

2. Classification of bioactive metabolites; Polysaccharides, polyphenols, terpenoids, alkaloids, and others

2.1 Polysaccharides

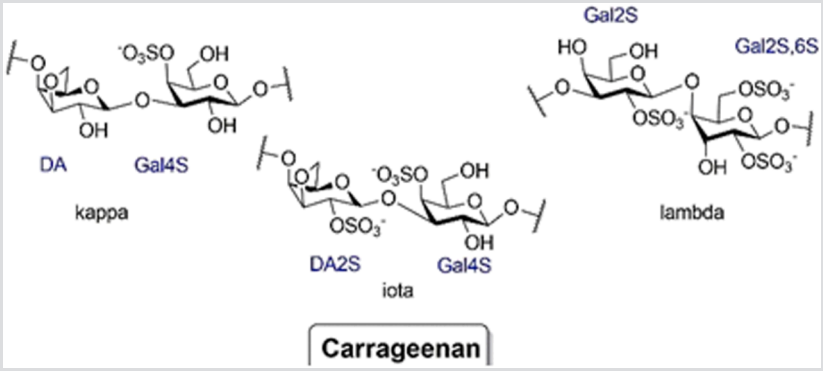
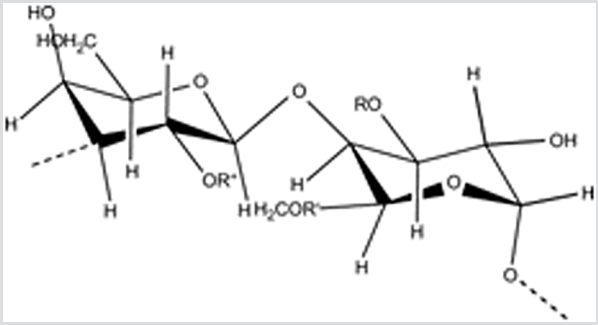
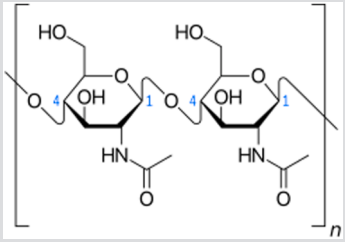
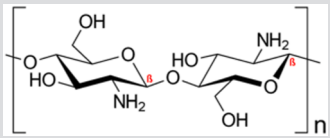
Polysaccharides are carbohydrate structures formed by long chains of sugar molecules, linked by glycosidic bonds. Their covalent structure allows them to adopt specific secondary shapes based on their primary sequences (Barbosa et al., 2019). Polysaccharides sourced from marine organisms are valuable biopolymers that exhibit a variety of chemical structures. They are abundant, affordable, biocompatible, biodegradable, and nontoxic, making them suitable for applications in nanotechnology, tissue regeneration, oncological treatment, lesion healing, and drug discovery. Current studies indicate that bioactive secondary metabolites and altered compounds derived from marine algae possess important pharmacological properties that help prevent and manage diverse diseases (Hao et al., 2023). These compounds can increase free radicals production and induce programmed cell death in colon cancer cells, demonstrating effective antitumor effects. Table 14.1 outlines the sources and structures of specific marine polysaccharides (Musa & Ikhajiagbe, 2023).

TABLE 14.1 Sources and structures of specific marine polysaccharide.

Name	Sources	Structure	References
Ulvan	Green algae		Bäumgen et al. (2021)
Alginate	Brown algae		Abka-khajouei et al. (2022)
Laminarin	Brown algae		Bäumgen et al. (2021)

Continued

TABLE 14.1 Sources and structures of specific marine polysaccharide.—cont'd

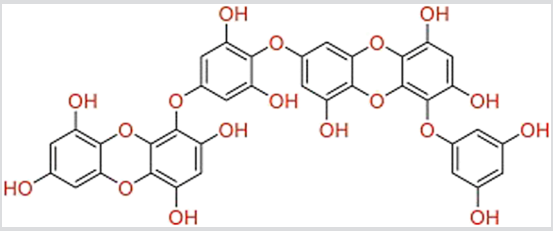
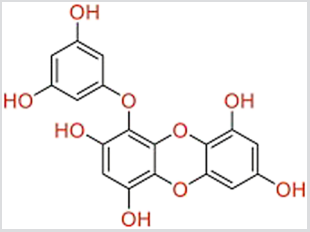
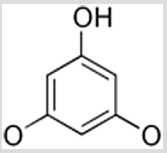
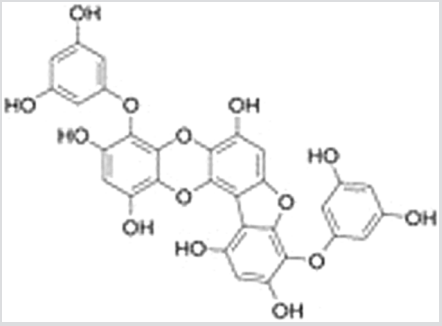
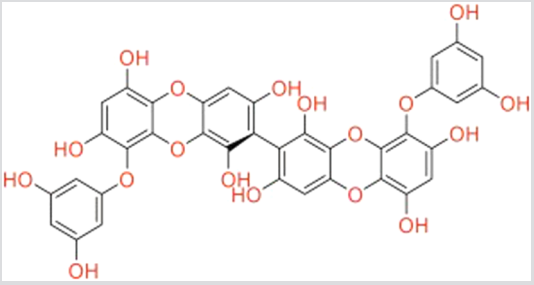
Name	Sources	Structure	References
Carrageenan	Red algae		Ficko-Blean et al. (2017)
Agarans	Red algae		Kumar et al. (2021)
Chitin	Crustaceans		Pighinelli (2019)
Chitosan	Crustaceans		Pighinelli (2019)

2.2 Polyphenols

Polyphenols are bioactive metabolites with hydroxylated aromatic structures that may be halogenated to enhance their biological effects (Freile-Pelegrın & Robledo, 2014). They range from simple phenolic acids to complex phlorotannins, primarily found in marine plants, especially brown algae. These compounds play a vital role in health due to their antioxidant properties, which can aid in lowering oxidative stress and preventing diseases such as cardiovascular issues, neurological disorders, and diabetes (Subbiah et al., 2023). Some polyphenols from brown algae may also aid in managing SARS-CoV-2 infections when used with antiviral treatments (Petit et al., 2021).

Polyphenols share characteristics that include the capacity to chelate metal ions and promote the precipitation of proteins and carbohydrates (Table 14.2). Various types, including phloroglucinol and dieckol, have been studied for their

TABLE 14.2 Polyphenolic antioxidants derived from marine algae.

Polyphenolic antioxidants	Chemical structure	References
Dieckol		Gentile et al. (2020)
Eckol		
Phloroglucinol		Petit et al. (2021)
Phlorofucofuroeckol A		Gentile et al. (2020)
8,8 Bieckol		

antioxidant potential (Kim & Wijesekara, 2017). Algal phlorotannins vary in molecular weight and structural diversity. Silico analyses suggest that dieckol effectively binds to the spike receptor–binding domain of SARS-CoV-2 (Aatif et al., 2021). Other phlorotannins have also been identified as potential interactors with the virus (Gentile et al., 2020). Overall, polyphenols are key dietary components, mainly sourced from macroalgae (Li et al., 2017).

2.3 Terpenoids

Terpenoids are a group of oxygen-containing terpenes characterized by a variety of functional groups and oxidized methyl groups (Perveen, 2018). They can be categorized into types such as alcohols, aldehydes, esters, ethers, epoxides, ketones, and phenols, with examples including carvacrol, citronellal, and menthol (Masyita et al., 2022). These compounds possess antimicrobial properties, effective against both antibiotic-sensitive and resistant strains of bacteria, by causing cell lysis and the inhibition of protein and DNA synthesis (Alvarez-Martínez et al., 2021). Terpenoids also show a variety of biological activities, including anticancer, antiallergic (Kobayashi et al., 2016), antibacterial (Guimarães et al., 2019), and antioxidant (Wang et al., 2019) effects. They are synthesized via the mevalonic acid and 2C-methyl-D-erythritol-4-phosphate (MEP) pathways, producing precursors like isopentenyl pyrophosphate (Stephane & Jules, 2020). Furthermore, the increased hydrophobicity and reduced flexibility of terpenoids may enhance their affinity for SARS-CoV-2 Mpro (Sepay et al., 2021). Compounds like dictyosphaeric acid A and excavatolide M have shown the potential to inhibit SARS-CoV-2 by interfering with the interaction of TMPRSS2 and SPPIs (Rahman et al., 2020).

2.4 Alkaloids

Marine alkaloids, sourced from marine organisms, include indole derivatives and halogenated alkaloids, with indole alkaloids mainly found in red algae and bromine- and chloride-containing alkaloids in green algae (Zahran et al., 2020). Marine algae contain 44 alkaloids, which include 1 phenylethylamine, 41 indole derivatives, and 1 naphthyridine derivative. Zahran et al. (2020) reported that alteramide A, a tetracyclic alkaloid originating in Pseudoalteromonas sp., exhibited high affinity to several SARS-CoV-2 proteins, such as RdRp, nsp16/10, Mpro, and the spike protein. A computational study by Khan et al. (2020) identified the alkaloids fistula in-3 (C31H30Br6N4O1) and chimyl alcohol (1-O-hexadecylglycerol) from *Desmapsamma anchorata* as having high binding affinities for Mpro. Additionally, Zahran et al. (2020) conducted molecular docking studies on 15 metabolites, including glycosides isotirandamycin B and tirandamycin A and B from *Streptomyces* sp., which displayed notable interaction with SARS-CoV-2 targets like methyltransferase, Mpro, and RdRp, suggesting their potential as inhibitors of the virus.

3. Methods of extraction and isolation of bioactive compounds

Extraction technologies for marine bioactive compounds are categorized based on their efficiency, cost-effectiveness, and sustainability. These methods can generally be categorized into two kinds: conventional solvent extraction and emerging techniques. Commonly employed methods primarily focus on liquid–solid extraction, utilizing heat and solvents with varying polarities. However, challenges persist in effectively extracting bioactive constituents from marine plants, influenced by variables such as the choice of solvent, extraction duration, particle size, temperature, and solid-to-solvent ratio (Ikhajiagbe et al., 2021; Rivas-Navia et al., 2023). Traditional extraction techniques often prove time-consuming and less efficient, which has prompted the implementation of newer technologies in the pharmaceutical, food, and medicinal sectors that use fewer solvents and shorten extraction time. In solid–liquid extraction, soluble components dissolve into the solvent, with mass transfer occurring along a concentration gradient until equilibrium is achieved (Fig. 14.1). Additionally, heating the solvent can improve mass transfer and solubility (Belwal et al., 2020).

3.1 Maceration

The maceration process is based on molecular diffusion, which can take considerable time and demands substantial energy and solvent. This method aids in dispersing concentrated solutions around the particle surfaces, allowing fresh solvents to facilitate further extraction (Kumar et al., 2023). In maceration, plant materials are soaked inside a sealed container with a solvent at room temperature for 2–3 days while stirring regularly to secure extracts. A sealed extractor prevents solvent evaporation. The objective is to tenderize and rupture plant cell walls, releasing soluble phytoconstituents. After the soaking period, the mixture is filtered or squeezed through filtration or decantation. Maceration remains one of the simplest and most commonly used extraction techniques. A variation known as digestion employs mild heat (35–40°C, not exceeding 50°C) during extraction (Kumar et al., 2023).

3.2 Soxhlet extraction

In this extraction method, ground marine plant samples are contained in a permeable bag constructed from sturdy filter paper and positioned in the Soxhlet apparatus (Gu et al., 2019). The extraction solvents are warmed in a round-bottom flask, vaporizing and entering the thimble, where they condense and drip back. The liquid is transferred back into the flask, and this cycle continues. However, this method requires a large amount of solvent and lacks the ability to stir the mixture. It is also unsuitable for thermolabile compounds, as prolonged heat exposure can cause degradation.

3.3 Hydrodistillation

Hydrodistillation is a method used to isolate volatile compounds, like fragrant oils, from aromatic and medicinal plants. The process involves heating the samples to break open their pores, allowing target compounds to be released at temperatures lower than their boiling point. This approach is effective for thermosensitive bioactive compounds and relies on isotropic distillation (Fotsing et al., 2022). The duration of the process varies depending on the plant material, with the samples being submerged in water and heated in an alembic under atmospheric pressure (Fotsing et al., 2022).

3.4 Enzyme-assisted extraction

Enzyme-assisted extraction (EAE) is effective at extracting a range of bioactive compounds from plants, resulting in fractions abundant in tiny, water-soluble compounds such as polyphenols and flavonoids (Tzanova et al., 2020). This technique uses specific hydrolyzing enzymes during extraction to enhance efficiency. Micelles formed from macromolecules in cell membranes and walls can impede extraction when proteins coagulate at high temperatures. EAE improves extraction by utilizing enzymatic hydrolysis to release natural products (Fotsing et al., 2022; Tzanova et al., 2020). Common enzymes used include cellulose and pectinase (Fotsing et al., 2022; Tzanova et al., 2020).

3.5 Microwave-assisted extraction

Microwave-assisted extraction (MAE) employs microwave energy ranging from 300 MHz to 300 GHz for rapid heating, reducing thermal gradients, and increasing volume through heat generation. This method enhances productivity by allowing smaller equipment sizes and more efficient processes (Fotsing et al., 2022). Microwaves, part of the electromagnetic spectrum consists of oscillating fields (1/cm to 1/m) that carry energy (Castro-Lopez et al., 2016). MAE is an environmentally friendly method, using water or alcohol at high temperatures and regulated pressures for extraction.

Numerous research have demonstrated that MAE offers higher extraction rates and is considerably quicker than traditional methods for extracting active compounds from plant materials (Castro-Lopez et al., 2016; Sing et al., 2020). It serves as a promising substitute for conventional solid-liquid extraction approach, with advantages such as reduced solvent use (only a few milliliters), shorter extraction times (15–20 minutes), improved yields, and suitability for thermolabile compounds. MAE can also extract trace amounts of heavy metals and pesticide residues from minimal plant material and enhances mass transfer through agitation during extraction (Castro-Lopez et al., 2016; Fotsing et al., 2022).

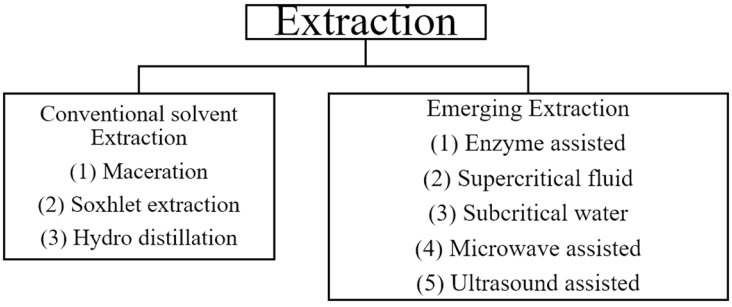


FIGURE 14.1 Workflow diagram illustrating the extraction of bioactive compounds from marine plants.

3.6 Ultrasound-assisted extraction

Ultrasound-assisted extraction employs ultrasound energy with solvents to isolate desired compounds from different plant materials (Kumar et al., 2021). Operating at frequencies of 20–2000 KHz (Fotsing et al., 2022), UAE can reach temperatures of 5000 K and pressures of 1000 atm. The process creates cavitation bubbles through cycles of compression and rarefaction, which then collapse, generating hot spots that accelerate biochemical reactions (Chemat, Rombaut, Sicaire, et al., 2017; Chemat, Rombaut, Meullemiestre, et al., 2017; Šic-Žlabur et al., 2015). Acoustic cavitation serves a vital function in UAE, as collapsing bubbles create shockwaves that fragment cellular structures, enhancing the solubilization of bioactive compounds by reducing particle size and increasing surface area (Roselló-Soto et al., 2015). Key factors affecting UAE efficiency include extraction time, power, solvent choice, liquid/solid (L/S) ratio, plant material type, frequency, amplitude, and intensity (Fotsing et al., 2022). Setyani et al. (2023) optimized UAE for *Moringa oleifera*, while Kurniasari et al. (2023) investigated the impact of solvent concentration on sappan wood extraction, determining that a 60% ethanol–water mixture yielded the best results (10.33% yield with an overall phenolic concentration of 2.63 mg GAE/g).

3.7 Supercritical fluid extraction

Supercritical fluid extraction (SFE) is a method that utilizes a fluid in a supercritical state, combining properties of both gas and liquid. This technique requires maintaining the fluid at a low boiling point (31°C) and a critical pressure (74 bar), with carbon dioxide (CO_2) commonly used as the supercritical fluid. These conditions enhance the fluid's solvating power, increase diffusivity, lower viscosity, and improve mass transfer. SFE is employed to separate components from their matrix by utilizing supercritical fluids as the extracting solvent.

The SFE method has several advantages, including low-temperature extraction that prevents damage to heat-sensitive materials and uses CO_2 as a safe, environmentally friendly solvent (Fotsing et al., 2022). However, it has notable drawbacks, such as high initial investment and operating costs due to the need for high pressures, leading to limited commercial use compared to more economical methods. The complex phase equilibrium of the solvent/solute system also complicates extraction condition design. Research by Conde-Hernández and colleagues showed that S–CO_2 extraction of rosemary essential oil yielded higher quantities and antioxidant activity than hydrodistillation and steam distillation (Conde-Hernández et al., 2017). Sharma et al. (2023) emphasized the coextraction of turmeric and dried coconut shreds through SFE, noting its promising anticancer activity in MCF7 and $CaCO_2$ cell lines. Additionally, Serdar (2024) applied SFE to extract compounds from pomegranate.

3.8 Subcritical water extraction

Subcritical water extraction (SWE) is an eco-friendly extraction technology that employs liquid water at temperatures and pressures below its critical point (temperature = 374.15°C, pressure = 22.1 MPa) (Cheng et al., 2021). Maintaining pressure above the vapor pressure is essential to maintain water in a liquid state. SWE provides the benefit of utilizing safe, nontoxic, and readily available water as a solvent, featuring adjustable selectivity and enhanced efficiency relative to traditional methods (Aćimović et al., 2021; Cheng et al., 2021). Its polarity can significantly decrease with temperature, allowing it to function similarly to methanol or ethanol, making it suitable for extracting various organic compounds (Cheng et al., 2021). Ko et al. (2020) confirmed the effectiveness of SWE in obtaining beneficial bioactive compounds from *Orostachys japonicus.*

4. Pharmacological properties of marine-derived compounds

4.1 Anticancer activity

Cell cancer has been linked to apoptosis failure (Shinkai et al., 1996). The ratio of cell growth to death is regulated by the physiological process of apoptosis, which involves the selective destruction of cells. Several studies have demonstrated that marine macroalgae have anticancer properties. An aqueous extract of *Codium fragile* inhibits CT-26 cell proliferation, activates caspase-3 and caspase-7, and reduces Bcl-xL production (Alabi et al., 2023; Kim et al., 2008).

By suppressing cellular FLICE-inhibitory protein, *Codium fragile* increases the sensitivity of tumor necrosis factor–related and caspase-inducing ligand (TRAIL) and c-caspase-8 and c-caspase-3 protein levels. Additionally, *Codium fragile* polysaccharides stimulate bone marrow–derived dendritic cells (DCs) in vitro and DCs in vivo, which in turn stimulate the natural killer cells (NKcs) of tumor-bearing mice (Park, Lim, et al., 2020). *C. fragile* polysaccharides have

been found to significantly inhibit the development of B16 tumors in animal models. *C. fragile* polysaccharides have also been shown to enhance anticancer immunity by inhibiting CT-26 cell proliferation with anti-PD-L1 antibodies. It was also found that *C. fragile* polysaccharides inhibited Lewis lung carcinoma cells from entering the lungs, with NK cells and CD8 T lymphocytes being essential for their antitumor growth effect (Wang et al., 2021). In another study (Park, Hwang, et al., 2020), *C. fragile* polysaccharides were found to prevent B16 and CT-26 cells from infiltrating the lungs and activate NK cells. Zhang et al. (2020) found that *C. fragile* polysaccharides also stimulate peripheral blood DCs, which activate T-helper cells and cytotoxic T lymphocytes, both of which fight cancer. A methanol extract of *C. fragile* was tested for its ability to stimulate human MDA-MB-231 cells (Dilshara et al., 2016). Nuclear factor-κB (NF-κB) activity is suppressed by *Codium fragile* methanol extract through the inhibition of matrix metalloproteinase-9, which in turn triggers the production of tumor necrosis factor.

In human melanoma cells, the activation of caspase-3 and caspase-9, the downregulation of Bcl-2, and the upregulation of BAX further demonstrated the cytotoxic effects of *Codium fragile* clerosterol (IC50 = 150 M) (Kim et al., 2013). When combined, *Codium fragile* produces chemicals that have a model. Proinflammatory mediators such as nitric oxide (NO) and prostaglandin E2 (PGE2), as well as proinflammatory proteins such as cyclooxygenase-2 (COX-2), inducible nitric oxide synthase (iNOS), and tumor necrosis factor-apha (TNF-α), which were activated by ultraviolet B (UVB) irradiation, also showed a decrease in activity in HaCaT cells following treatment with *C. fragile* extract. This finding also showed that the *C. fragile* extract decreased oxidative damage, including protein carbonylation and/or lipid peroxidation (Lee et al., 2013). This decrease could be attributed to an increase in antioxidant defense enzymes. Decreasing protein expression has therapeutic effects against cancer cells and can be utilized to improve anticancer immunity (Monmai et al., 2019).

Historically, seaweeds have been used in Chinese herbal medicine for treating cancer because they have biological properties, such as lowering plasma cholesterol, binding biliary steroids, preventing the growth of carcinogenic fecal flora, binding pollutants, boosting the immune system, and protecting beta-sitosterols (Yamamoto et al., 1984). According to Teas (1981), seaweed has been recommended as an anticarcinogen for breast cancer. The consumption of seaweed by the Japanese may be a major factor in the relatively low incidence of breast cancer in their nation. Studies using rat test systems have demonstrated that sulfated polysaccharides, such as carrageenans and fucoidans, can stop tumor metastasis by inhibiting the activity of heparanase made by tumor cells that are involved in membrane crossing (Coombe et al., 1987; Parish et al., 1987; Parish & Snowden, 1985). The proliferation of mouse S-180 tumors was inhibited by sulfated polysaccharides derived from *Sargassum kjellmanianum* (Nagumo et al., 1988). However, carrageenan substantially increased the effectiveness of mitomycin against leukemia-1210 ascites tumors in mice, despite being ineffective on its own (Matsumoto et al., 1988).

Furthermore, carrageenan has been shown to enhance the susceptibility of HEp-2 human Epipharynx carcinoma cells to lectin-dependent cell-mediated cytotoxicity (Perl et al., 1983). Red algae, *Porphyra yezoensis*, and *Eucheuma gelatinae*; green algae, *Enteromorpha prolifera*; and brown algae, *Laminaria japonica*, *Lessonia nigrescens*, and *Sargassum ringgoldianum*, have all been shown to have anticancer activity against Meth-A fibrosarcoma (Noda et al., 1990). Research has revealed the anticancer properties of fucoidan derived from *Sargassum thunbergii* and *S. kjellmanianum* (Itoh et al., 1995; Zhuang et al., 1995). Human colon cell line has demonstrated cytotoxicity toward Ulvan isolated from *Ulva lactuca* (Kaeffer et al., 1999). Human (HU) and murine (MU) cell lines are cytotoxically affected by the fucosterols found in *Turbinaria conoides* (Sheu et al., 1999). By preventing microtubule assembly and tubulin aggregation, the caulerpenyne of *Caulerpa taxifolia* has demonstrated anticancer efficacy in the treatment of Human neuroblastoma cell line (Barbier et al., 2001). Dihydroxysargaquinone, sargatriol, and diterpene from *Sargassum crispum* and *Sargassum tortile*, respectively, are known to be cytotoxic (Ayyad et al., 2001; Numata et al., 1991). China's Wuhan Center is linked to a type of bacteria called *Streptomyces fulvissimus* (ZZ40), which was recovered from the marine longitudinal seaweed *Haliplanella lineata*. It generates compounds known as streptomyces fulvissimus ketone and acid.

The substances, according to Zhejiang University, are potent antitumor agents that can be used to treat gliomas, the most common brain tumor that has a high death rate (Abirami & Kowsalya, 2013). According to studies conducted on human glioma U87MG cells (CytoC), these medications have a potent antiglioma effect by selectively targeting a variety of vital glioma glycolysis enzymes such as oxidative phosphorylase cytochrome C and the tricarboxylic acid cycle enzyme aconitase 2.

4.2 Antiviral activity

A viral infection is treated by targeting entry, replication, shedding, and latency (Kidgell et al., 2019). In a study, *Codium fragile* enzyme hydrolysates significantly inhibited Herpes simplex virus type 1 (HSV-1) with an EC50 of 36.5–41.3 g/mL

and a variety of infection (MOI) of 0.001 ID50/cell without cytotoxicity (1–200 g/mL). Furthermore, protease (P1) and carbohydrase (C3) extracts were effective without destroying cells at an MOI of 0.01 ID50. Beside HSV-1, *C. fragile* may also stop HSV-2 from replicating and increase the death rate of HSV-2-infected mice in vivo (Ohta et al., 2009). In another study, Siponaxanthin produced from *C. fragile* was shown to have antiviral activity (IC50 = 87.4 μM) against the SARS-CoV-2 pseudovirus in Human Embryonic Kidney 293 cells (Yim et al., 2021). A novel antiviral drug could be developed from *Codium fragile*, based on these results.

Seaweeds have been shown to have antiviral action due to sulfated polysaccharides (Hatch et al., 1979). The sulfated polysaccharides present in marine macroalgae inhibit HIV replication in vitro (Baba et al., 1988; De Clerq et al., 1988; Nakashima et al., 1987a; Neushul, 1990; Ueno & Kuno, 1987). HIV reverse transcriptase (RT) is inhibited in vitro by a sulfated polysaccharide derived from *Schizymenia pacifica* (Nakashima et al., 1987b).

Antiviral effects have been demonstrated by λ-carrageenan isolated from *Acanthophora spicifera* (Kamat et al., 1992). *Chondria atropurpurea* is the source of chondriome A, which has been demonstrated to have antiviral effects against HSV-2 (Palermo et al., 1992). The replication of influenza A and B, HSV-1, HSV-2, human cytomegalovirus (HCMV), respiratory syncytial virus (RSV), Junín and Tacaribe virus, and Simian immunodeficiency virus (SIV) was inhibited by sulfated xylomannan derived from *Nothogenia fastigiata* (Damonte et al., 1994). *Nothogenia fastigiata* and *Agardhiella tenera* have both produced galactan sulfate and xylomannan sulfate that have demonstrated efficacy against RSV, HSV-1 and HSV-2, and HIV (Damonte et al., 1994; Kolender et al., 1995; Witvrouw et al., 1994). Some HSV-1 and HSV-2 strains are susceptible to the antiviral properties of *Gigartina skottsbergii's* λ-carrageenan and partially cyclized μ/' i-carrageenan at the viral adsorption stage (Carlucci et al., 1997, 1999).

HSV-1 and HSV-2 proliferation in cell cultures was inhibited by the antiviral properties of *Gelidium spinosum* and *Polysiphonia denudata* (Serkedjieva et al., 2000). *Stenogramme interrupta* carrageenans have demonstrated antiherpetic properties (Caceres et al., 2000). Phase III clinical trials were conducted on Carraguard, a vaginal microbiocide based on carrageenan that has been demonstrated to prevent HIV and other STDs in vitro (Spieler, 2002; Zeitlin et al., 1997).

A Korean macroalgae has inhibitory activity against HIV-1, RT, and HIV-1 integrase (IN) (Ahn et al., 2002). HSV types I and II can be inhibited by agaroids derived from *Gracilaria corticata* (Mazumder et al., 2002), polysaccharide fractions from *Caulerpa* sp., *Padina arborescens*, *Corallina* sp., *Hypnea charoides*, *and Sargassum patens* (Zhu et al., 2003), fucoidans of *Adenocystis utricularis* (Ponce et al., 2003), sulfated polysaccharides from *Cryptonemia crenulata* and *Gymnogongrus griffithsiae* (Talarico et al., 2004), extracts of *Hydroclathrus clathratus* and *Lobophora variegata* (Hui et al., 2008), and sucrose sp. *Gymnogongrus griffithsiae* and *Cryptonemia crenulata* polysaccharides have been demonstrated to limit Dengue virus in Vero cells (Talarico et al., 2005), kahalalide A (Sayed et al., 2000) and F (Haefner, 2003; Hamann et al., 1996) of *Bryopsis* has demonstrated in vitro activity on *Mycobacterium tuberculosis*. Kahalalide F, which has anti-HIV properties, is derived from *Bryopsis* sp. (Haefner, 2003; Hamann et al., 1996). Seaweed fucoidan has strong antiviral effects on viruses such as HCMV (Feldman et al., 1999; Majczak et al., 2003; Ponce et al., 2003), HIV (Sugawara et al., 1989), RSV (Malhotra et al., 2003), and HSV types I and II. Human papillomavirus infection is inhibited by carrageenan, which is derived from red seaweed (Buck et al., 2006).

4.3 Antioxidant activities

The aqueous-soluble, unpolished polysaccharide (TCP) of *T. ornata* has antioxidant properties. The total antioxidant activity of TCP was assessed in vitro using tests for lipid peroxidation inhibition, 2,2′-azino-bis (3-ethylbenzothiazoline-6-sulfonic acid), 1,1-diphenyl-2-picrylhydrazyl, and nitric oxide scavenging. Polyphenols, proteins, and carbohydrates were found in TCP according to phytochemical analysis (Ananthi et al., 2010). Algae extracted from 37 samples showed complete antioxidant activity. Ferric reducing antioxidant power studies have been utilized to measure antioxidant activity. The *Turbinaria ornata* extract was found to be one of the most promising algae with potential medical applications (Kelman et al., 2012). Extracts of *Turbinaria ornata* in acetone have been shown to possess antiulcer, wound-healing, and hepatoprotective qualities. When compared to the standard medication on day 20, *T. ornata* extract demonstrated the least amount of reduction in the wound area at both doses (Senthil & Murugan, 2013). *Turbinaria* species have varying antioxidant properties based on location, season, salinity, and temperature. The total phenolic contents and antioxidant activities of *T. ornata* have been assessed in a variety of in vitro systems. *T. conoides* ethyl acetate extracts have a substantially higher phenolic content than *T. ornata* extracts (Chakraborty et al., 2013). Antioxidant activity was measured using DPPH free radical scavenging activity, total antioxidant capacity, and phenolic content. Good antioxidant qualities and a higher total phenolic content were found in the F5 fraction. Phlorotannin is the only phenolic compound found in the F5 fraction, according to spectrum analysis using UV-visible, thin layer chromatography, and Fourier transform infrared. It was discovered that the antioxidant action was due to the phenolic component (Girija et al., 2013). Ethanolic and

methanolic extracts from *Sargassum polycystum* and *T. ornata* were examined for their antioxidant and total phenolic content. Out of all the extracts, *T. ornata*'s methanol extract had the strongest antioxidant properties and the highest phenolic concentration (2.07 mg catechin/g).

This was revealed by the strong radical scavenging activity of DPPH and ABTS, which was connected to the reducing activity power of other extracts. In a red blood cell model, blood was collected from young, healthy, and vigorous helpers between the ages of 22 and 25 to determine antihemolysis and antiinflammatory properties. The results showed that *T. ornata* has a lot of bioactive substances. Methanol extracts of *T. ornata* (TOME) contain alkaloids, flavonoids, carbohydrates, saponins, phenolic compounds, steroids, coumarins, terpenoids, and tannins. At 100 μg concentrations, TOME exhibits 89.11% total antioxidant properties. The higher the TOME dosage, the higher the levels of nitric oxide, hydrogen peroxide, superoxide dismutase activity, and free radicals. At the recommended concentrations of 0.5, 0.75, and 1 mg/mL, TOME significantly reduces hemolysis by hydrogen peroxide. TOME concentrations have been shown to increase the stability of human RBC membranes, and the higher concentration level (500 mg/mL) indicates that about 81% of the antiinflammatory effects were significant when compared to diclofenac.

Thus, in the human RBC model, *T. ornata*, which contains strong biologically active compounds, exhibits strong antioxidant qualities that prevent hemolysis caused by hydrogen peroxide (Vijayraja & Jeyaprakash, 2017). The extract of *Turbinaria ornata* was reported to contain 43.72 mg GAE/g and to exhibit superior scavenging properties for DPPH, superoxide anion, and hydroxyl radicals (Vijayabaskar & Shiyamala, 2012).

HepG2 cell cycle arrest, apoptosis, and cytotoxicity were used to assess the antibacterial and antioxidant qualities of the *Turbinaria* species ethanolic extract as well as its potential to prevent cancer. The most effective antibacterial fraction was ethyl acetate, followed by aqueous, dichloromethane, and hexane. When compared to regular quercetin, the ethyl acetate fraction had cytotoxicity of 67% at 24 hours and 83% at 48 hours. Tumor cells were found to be significantly less common at the S phase and substantially more common in the G0/G1 proliferative stage (Ponnan et al., 2017).

Radiation and physiological waste products can also form free radicals, which are highly reactive molecules with an unpaired atom. Consequently, chain reactions are set off, which cause cell membranes and components like nucleic acids, proteins, and lipids to break down. Antioxidants lower oxidative stress levels, scavenge free radicals like hydrogen peroxide, lipid peroxyl, or peroxide, and delay or stop the onset of complications linked to diseases caused by oxidative stress (Wu & Hansen, 2008). Antioxidants found naturally in the body are not toxic or mutagenic, as are many synthetic antioxidants. Antioxidants found in seaweeds include ascorbate, glutathione, carotenoids, gallate, phlorotannins, eckol, tocopherols, ascorbic acid, as well as mycosporine-like amino acids and catechins (Alabi et al., 2024; Engel et al., 2002; Fisch et al., 2003; Formica & Regelson, 1995; Heo & Jeon, 2009; Shimizu, 2003; Yuan et al., 2005; Zubia et al., 2009).

The antioxidant properties of *Himanthalia elongata* and *Laminaria digitata* are similar to those of butylhydroxytoluene and vitamin E (Le Tutour, 1990; Le Tutour et al., 1998). *Additionally, reports of the* antioxidant activity from *Sargassum siliquastrum* (Cho et al., 2007; Lim et al., 2002; Yan et al., 1998), *Rhodomela confervoides* and *Symphyocladia latiuscula* (Huang & Wang, 2004), *Sargassum micracanthum* (Iwashima et al., 2005), *Kappaphycus alvarezii* (Fayaz et al., 2005; Kumar et al., 2008), *Gelidiella acerosa* (Devi et al., 2008), *Fucus vesiculosus* (Zaragoz et al., 2008), *Ishige okamurae* (Zou et al., 2008), *Undaria pinnatifida* (Young et al., 2009), *Sargassum pallidum* (Ye et al., 2009), *Capsosiphon fulvescens, Chaetomorpha moniligera*, *Enteromorpha compressa*, and *Ulva pertusa* (Cho et al., 2010), *Halimeda incrassata* (Novoa et al., 2011), *Alaria crassifolia*, *Cystoseira hakodatensis, Eisenia bicyclis*, *Kjellmaniella crassifolia*, and *Sargassum horneri* have been made (Airanthi et al., 2011). *The product of Haematococcus pluvialis, antioxidant astaxanthin, is available for purchase* (Life Extension, 1997).

4.4 Antifungal activity

Fungal pathogens can be killed or inhibited by antifungal agents, which work similarly to the mechanisms behind antibacterial agents. In a prior study, *Codium* extracts were found to have antifungal activity; *Codium bursa* was inhibited by *Fusarium* spp., *Penicillium expansum*, *Aspergillus flavus*, and *Rhizopus* spp. (Jerkovic et al., 2019); *Codium iyengarii* demonstrated strong antifungal activity against diverse pathogens, while *C. shameelii* showed weak antifungal activity (Rizvi & Shameel, 2004).

Dichloromethane extract from *T. ornata* may be a useful antifungal ingredient (Tye et al., 2016). Another *Turbinaria* species that has been found to possess antifungal properties is *Turbinaria conoides* (*T. conoides*). Some fungal strains have been tested against the solvent extracts, *including Aspergillus flavus, A. fumigatus, Candida albicans, C. parapsilosis, and Fusarium* sp. Strong inhibitory action against *Candida albicans* and *Candida parapsilosis* was shown by ethanolic, hexane, and chloroform extracts. Chloroform and ethanol extracts did not exhibit inhibitory activity on *Aspergillus fumigatus, Fusarium* sp*., and Aspergillus flavus* (Shibu & Dhanam, 2016).

The green algae *Penicillus capitatus* contains sulfate esters of triterpenes known as capisterones, which possess strong antifungal properties against the algal disease *Lindra thallasiae* (Kuniyoshi et al., 1985). Crude extracts from specific red algae species were used to test the antibiotic activity of some pathogenic fungi (Puglisi et al., 2004). Research has shown that marine macroalgae have exceptional fungicidal properties that help patients recover from recurrent asthma attacks. *L. paniculata*, in particular, has strong antifungal activity, making it a promising candidate for developing a new antifungal medication (Tariq, 1991).

4.5 Antibacterial activity

Halogenated compounds with antibacterial properties, such as bromophenols, have been found in a variety of seaweeds (Del Val et al., 2001; Ganesan et al., 2008; Plaza et al., 2009; Selvi et al., 2001; Yamada et al., 1985). Among the plants studied, *Bacillus subtilis, Staphylococcus epidermidis, and S. aureus were all susceptible to the antibacterial activity of Ulva fasciata, Caulerpa cupressoides, and Ulva lactuca* (Lima-Filho et al., 2002); *Sargassum fluitans, Ulva fasciata, and Ulva lactuca* inhibit the growth of *E. coli* and *S. aureus* (Oranday et al., 2004)*; P. fluorescens*, *Aeromonas hydrophila, Enterococcus tarda, and Vibrio alginolyticus* are all susceptible to the antibacterial properties of *Gracilaria corticata, Ulva fasciata,* and *Enteromorpha compressa* (Choudhury et al., 2005). *Ulva rigida, Enteromorpha linza, Padina pavonica, Dictyota linearis,* and *Dictyopteris membranacea* inhibited *Candida* sp.*, Enterococcus faecalis, Staphylococcus aureus, Staphylococcus epidermidis, Pseudomonas aureus,* and *Escherichia coli* (Tuney et al., 2006). *Pseudomonas aeruginosa, Salmonella typhi,* and *Micrococcus* sp. are inhibited by *Chaetomorpha aerea* (Maheswari et al., 2006)*; Shigella boydii, Micrococcus species,* and *Salmonella typhi* are effective against *Caulerpa scalpelliformis* (Thirumaran & Anantharaman, 2006); *Ulva lactuca, Sargassum* sp.*, Haliptilon virgatum, Corallina elongata, Ceramium indicum, Enteromorpha intestinalis, and Laurencia pediculata Padina gymnospora, Caulerpa racemosa, Caulerpa scalpelliformis, Gelidiopsis gracilis, Iyengaria stellata, Gelidium* sp., *Udotea indica, Gastroclonium iyengarii, Halimeda tuna, Gracilaria corticata, Heterosiphonia* has antibacterial activity against *B. cereus, M. flavus, K. pneumoniae, P. testosteroni,* and *C. freundii* (Kamenarska et al., 2009; Nair et al., 2007); *Cladostephus spongiosus, Cystoseira barbata, Dictyota dichotoma, Halopteris filicina, Ulva rigida,* as well as *F. verticillatus,* as defenses against *Staphylococcus aureus* (Taskin et al., 2007); *Enteromorpha compressa* has been reported to be effective against *Shigella sonnei* and *Mucor* sp. (Thirumaran & Anantharaman, 2008), *Haligra* sp. against *Staphylococcus aureus* (Devi et al., 2008), *Ulva lactuca, Padina gymnospora, Sargassum wightii,* and *Gracilaria edulis* inhibited *Staphylococcus aureus* (Vallinayagam et al., 2009)*; Ulva fasciata* is effective against *V. alginolyticus, Vibrio parahaemolyticus, and V. vulnificus* (Chakraborty et al., 2010)*;* and *Dictyota acutiloba* is effective against *A. niger, B. subtilis, C. albicans, Enterobacter* sp.*, methicillin-susceptible,* and *methicillin-resistant S. aureus, P. aeruginosa, S. typhi, and K. pneumonia* (Solomon & Santhi, 2008).

Methanolic extracts from brown seaweeds, including *Sargassum wightii* and *T. ornata*, were tested for their antibacterial properties. The antibacterial properties of both gram-positive and gram-negative humanoid pathogenic microorganisms were examined. Polyphenols are responsible for this action. These phenolic compounds, depending on their composition, influence the growth and metabolism of bacteria. The dosage results suggest using *T. ornata* methanol extracts as a good antimicrobial agent source (Vijayabaskar & Shiyamala, 2011). Additionally, they have discovered that *T. ornata* methanolic extracts exhibited scavenging behavior against a wide range of artificial and naturally occurring free radicals. *Aspergillus niger, Bacillus subtilis,* and *Salmonella enteritidis* did not grow in *T. ornata* methanol and ethanol extracts, but 500 mg/L extracts inhibited *Staphylococcus aureus* in an antibacterial susceptibility test (Rattaya et al., 2015).

In a different study, Kuniyoshi et al. (1985) showed that some microorganisms were susceptible to the antibacterial activity of Cladophora algae. The extract of *Cladophora fascicularis* was separated using chromatographic techniques to yield 2-(20, 40-dibromophenoxy)-4, 6-dibromoanisol47. Additionally, it inhibited the growth of *Staphylococcus aureus, Escherichia coli,* and *Bacillus subtilis* (Zhang et al., 2018). When tested for antibacterial activity, *T. ornata* extracts showed excellent suppression of the multidrug-resistant strain of *P. aeruginosa* at a dosage of 300 μg/mL. As a result, the current investigation revealed that marine *T. ornata* may serve as an antibacterial agent in both extracellular and intracellular lesions (Alharbi et al., 2020).

4.6 Antiinflammatory activity

Inflammation is the body's defensive response to stimuli, such as physical injury, precursor chemicals, microbial infection, and immunological reactions (Alabi et al., 2024; Medzhitov, 2008). Leukocyte and macrophage infiltration is a common inflammatory response. Lipopolysaccharide (LPS) upregulates the NF-κB pathway and MAPKs, including the

p38 subfamilies, c-Jun NH_2-terminal kinase (JNK), and extracellular signal-regulated kinase 1/2 (Sudirman et al., 2019). Consequently, in response to iNOS and COX-2, respectively, macrophages are quickly activated and encourage the release of proinflammatory cytokines, such as NO, and inflammatory mediators, such as PGE2 (Ah et al., 2017; Kang et al., 2012; Moon et al., 2018). Recently, alternative antiinflammatory medications have been found using marine macroalgae. By preventing peptidoglycan or NF-κB and MAPK phosphorylation, which inhibits the production of NO and PGE2 and lowers the levels of inflammatory cytokines in LPS-stimulated RAW 264.7 cells, the aqueous, ethanolic, and methanolic extracts of *C. fragile* have demonstrated antiinflammatory properties in vitro (Ah et al., 2017; Han et al., 2010; Kang et al., 2012; Yoon et al., 2011). Aqueous extract of *C. fragile* also decreased the thickness of rat paw edema caused by carrageenan by as much as 50% in vivo (Ah et al., 2017). Oleamide derived from *C. fragile* may inhibit the inflammatory response in LPS-induced RAW264.7 murine macrophages and carrageenan-induced inflammatory edema in the rat paw model (Moon et al., 2018). The activation of proinflammatory mediators, such as PGE2 and NO, and proinflammatory proteins, such as COX-2, iNOS, and TNF-α, that were induced by UVB irradiation in HaCaT cells also decreased following treatment with *C. fragile* extract. Additionally, this study showed that the *C. fragile* extract decreased oxidative damage by reducing protein carbonylation and/or lipid peroxidation, potentially increasing antioxidant defense enzymes (Lee et al., 2013).

The antiinflammatory qualities of *T. ornata* have not been well studied. Dexamethasone, a common antiinflammatory medication, was used to test the antiinflammatory properties of the aqueous *T. ornata* extract (ATO) in rats that had developed cotton granulomas. Hematological parameters, granuloma weight, and plasma markers (LDH, GPT, and CRP) were evaluated. The liver tissue has also been evaluated for oxidative stress and inflammatory markers, including GPx, GSH, SOD, nitrite, and LPO, as well as inflammatory markers like MPO and cathepsin D. The range of biochemical and inflammatory markers was significantly reduced in rats treated with the vehicle as opposed to those treated with the ATO (Subash et al., 2016). Concentrations of *T. ornata* methanolic extract enhanced the integrity of human red blood cell membranes; at 500 g/mL, the higher concentration level shows approximately 81% antiinflammatory activity, which is equivalent to regular diclofenac (Vijayraja & Jeyaprakash, 2017). Extracts from *T. ornata* were effective in treating chronic colitis in another in vitro study. There was an increase in Foxp3+ Treg cells and a release of the antiinflammatory cytokine IL-10. This effectively reduces the severity of colitis by inhibiting the production of proinflammatory cytokines and macrophages (Kim et al., 2020). Moreover, a polysaccharide that was extracted from the sea algae *T. ornata* was found to have antiinflammatory qualities (Bhardwaj et al., 2020).

Tissue damage can be caused by immunoregulation and mechanism abnormalities, as well as mutations in genes that arise from inflammation (Jones et al., 2006). The many side effects of antiinflammatory medications and antibiotic-resistant infections have led to the consideration of safe biological sources (Kaboli et al., 2001). Antiinflammatory chemicals have been found in seaweeds, according to earlier research (Bhakuni & Rawat, 2005, p. 103–124; Gamal, 2010; Jaswir & Monsur, 2011).

It has been established that *Sargassum hemiphyllum* inhibits the release of IL-8, PMA, and TNF-α from human mast cells (HMC-1) induced by A23187 (Na et al., 2005); It has been reported that *Sargassum micracanthum* inhibits LPS-induced RAW 264.7 macrophages (Yoon et al., 2009); research has demonstrated that *Petalonia binghamiae* inhibits ethyl acetate LPS-induced RAW 264.7 macrophages (Yang et al., 2010), while *Phorphyra dentata* inhibits LPS-induced RAW 264.7 macrophages (Kazlowska et al., 2010); *Sargassum thunbergii* and *Sargassum fulvellum* are valuable in treating erythema, blood flow, and ear edema brought on by *Phorbol myristate* acetate, while *Galaxaura marginata* has been confirmed to prevent mouse ear edema (Kang et al., 2008); *Ulva* and *Sargassum swartzii* reticulate against peritonitis in acute and chronic inflammatory models and against hind paw edema in rats produced by Carrageenan (Hong et al., 2011); *Turbinaria conoides* has been demonstrated to protect against carrageenan-induced hind paw edema (Boonchum et al., 2011), while *Dichotomaria obtusata* has been demonstrated to protect against TPA-induced water-ear edema and acetic acid-induced writhing (Vazquez et al., 2011).

5. Case studies of marine plant–derived pharmaceuticals

5.1 Success stories: Drugs currently in use derived from marine plants

Marine flora, including algae, seaweeds, and seagrasses, have proven to be rich in bioactive compounds, offering promising prospects for pharmaceutical applications. Some drugs derived from marine plants have successfully moved from research to clinical use, demonstrating the therapeutic potential of these natural resources.

One notable example is Halaven (eribulin mesylate), initially discovered in the marine sponge *Halichondria okadai,* though not a plant, it is often discussed in the context of marine-derived medicines. Halaven is used in the treatment of

metastatic breast cancer and liposarcoma by interfering with microtubule dynamics, thereby disrupting cancer cell cycles (Mayer et al., 2013).

Another important marine-derived drug is vidarabine (Ara-A), originally isolated from the Caribbean sponge *Tectitethya crypta* but now synthesized. Vidarabine is an antiviral medication commonly used to treat infections caused by the herpes simplex and varicella-zoster viruses. Its development paved the way for other nucleoside analog drugs (Blunt et al., 2015).

Within the realm of marine plants, sulfated polysaccharides from red algae have shown strong anticoagulant properties. Carrageenans, derived from various species of red seaweed, are widely used in pharmaceuticals for their antiviral and anticoagulant effects. These compounds inhibit viral replication, including that of the herpes simplex virus, and are used in topical applications due to their protective qualities (Kim & Karadeniz, 2011).

5.2 Ongoing clinical trials and promising compounds

Research into marine plant-based pharmaceuticals is active, with several compounds currently undergoing clinical trials to determine their efficacy and safety, potentially leading to new therapies for various diseases.

Fucoidan, a sulfated polysaccharide found in brown seaweed, shows promise due to its anticoagulant, antiviral, anticancer, and immunomodulatory properties. Clinical studies are investigating its potential in cancer treatment, with early results indicating that it enhances chemotherapy's effectiveness and inhibits tumor growth (Atashrazm et al., 2015).

Agar, a polysaccharide derived from the red algae *Gracilaria*, is known for its gel-forming abilities and holds potential in drug delivery systems. Current research is exploring its application in slow-release formulations and its ability to improve the bioavailability of certain drugs (Smit, 2004).

Phlorotannin, a polyphenolic compound from brown algae, is being studied for its strong antioxidant and antiinflammatory properties. Clinical trials are assessing its efficacy in treating chronic inflammatory diseases such as arthritis and inflammatory bowel disease (Pangestuti & Kim, 2011).

Caulerpin, extracted from green algae *Caulerpa*, is also under investigation for its potential antitumor effects. Preclinical studies have shown that it can induce apoptosis in cancer cells, and clinical trials are now evaluating its safety and effectiveness in cancer therapy (Blunt et al., 2015).

5.3 Comparative efficacy of marine plant-derived drugs versus terrestrial plant-derived drugs

Comparing the efficacy of drugs derived from marine plants to those from terrestrial plants is an area of growing interest, highlighting both the advantages and challenges of using marine bioresources in drug development.

Marine plant–derived compounds often have unique structural features not commonly found in terrestrial plants. For example, polysaccharides like carrageenans and fucoidans from marine sources have distinctive sulfation patterns that contribute to their potent antiviral and anticoagulant activities. These structural differences may lead to novel mechanisms of action and superior efficacy in specific therapeutic areas (Kim & Karadeniz, 2011).

In cancer treatment, marine-derived compounds such as halichondrin B, the precursor to Halaven, have demonstrated strong activity against various cancer cell types, sometimes outperforming agents derived from terrestrial plants. Similarly, the unique polyphenolic structures of phlorotannins from brown algae could offer stronger antioxidant and anti-inflammatory effects than terrestrial polyphenols, potentially providing more effective treatments for inflammatory diseases (Pangestuti & Kim, 2011).

However, marine-derived drugs present certain challenges, such as the difficulty in sourcing and sustainability concerns. Terrestrial plants are generally easier to cultivate and harvest, which simplifies production. Additionally, harvesting marine plants must be done carefully to avoid overexploitation and damage to ecosystems (Smit, 2004).

In summary, while both marine and terrestrial plant-derived drugs offer valuable therapeutic potential, the chemical diversity of marine plants makes them a rich source for new pharmaceuticals. Continued research and clinical trials will help further uncover their benefits and develop sustainable ways to utilize them.

6. Recent advances in marine pharmacognocy

6.1 Recent advances in marine pharmacognosy

The marine environment that was once considered sterile due to its high salinity and limited nutrient availability has emerged as a vital source of innovative biological compounds that hold great potential pharmacological applications such

as combating infections resulting from multidrug-resistant pathogens and several other diseases, thus making it an exciting frontier in the pursuit for novel therapeutic compounds (Karthikeyan et al., 2022).

6.2 Biotechnological tools for the study and utilization of marine plants

Marine plants have long been identified for their ability to provide valuable compounds for pharmaceutical development (National Research Council, 1999). Emerging research in biotechnology has revolutionized the field of pharmacognosy, enabling the effective discovery and production of biologically active materials from marine plants (Ana et al., 2012). Recent developments in marine metagenomics are revolutionizing marine research at the molecular level. Metagenomic studies of organisms in the aquatic environment provide fresh perceptions of deep-sea biological diversity and ecosystem functioning, enabling the exploration of ecological interrelationships at the gene level. A pioneering study by the J. Craig Venter Institute surveyed diversity in aquatic organisms, finding thousands of fresh species with loads of new genes, and protein families (Venter et al., 2004). This work demonstrated the power of environmental metagenomic shotgun approaches, identifying 1800 genomic species of microbial origin and 1.2 million unknown genes from just 200 L of surface water from the Sargasso Sea. Subsequent studies, reviewed by Gilbert and Dupont (2011), have further highlighted the potential of massive sequencing to uncover extraordinary microbial biodiversity and elucidate key components of phosphorus, sulfur, and nitrogen cycling pathways. The integration of "omics" tools, such as genomics, proteomics, and metabolomics, has enabled a comprehensive "study it all" method to discover diversity in the oceans.

6.3 Advances in genomics, proteomics, and metabolomics

6.3.1 Genomics

Genomics has brought a lot of transformation in biological, biomedical, and pharmaceutical research by shifting from individual gene studies to a holistic approach. This involves simultaneously investigating multiple components and their environmental interactions, from pathways and cells to whole organisms and ecosystems (Ritchie et al., 2017). New genomic approaches, such as DNA bar-coding, offer a rapid and robust way to describe and catalog marine biodiversity. This involves analyzing standardized gene sections (e.g., COI, 16S, 18S, and ITS) to delimit species borders and discover new species (Carvalho et al., 2010, p. 1–32). Molecular tools can identify functional capacity and provide a comprehensive understanding of marine ecosystems, complementing traditional identification methods. The idea of DNA barcoding is a novel approach to species identification that addresses the limitations of old taxonomy was introduced by Hebert et al. This barcode provides a standardized means for robust species identification. The system is based on the "matching hypothesis," which states that each known species can be uniquely matched with its corresponding DNA barcode by comparing the same DNA regions.

6.3.2 Metabolomics

Metabolomics, a key "omics" technology, has enhanced our understanding of marine organisms' interactions with their habitat at a metabolic level, leading to the detection of novel metabolites that are beneficial to the health of humans (Bayona et al., 2022). Marine chemical ecology has greatly benefited from metabolomics, enabling researchers to decipher complex interactions between organisms of marine origin facilitated by chemical signals (Hay, 2009). There have been significant advancements in this field in the last 2 decades, uncovering the diverse roles of active compounds synthesized by various aquatic species (Brown et al., 2019; Hay, 2014; Leão et al., 2012; Mascuch & Kubanek, 2019).

As research continues, metabolomics is expected to reveal further understandings of the metabolic responses of aquatic organisms, elucidating the functions of specific metabolites during interactions (Kuhlisch & Pohnert, 2015). The marine habitat has been demonstrated to be a treasure trove of novel compounds, amounting to an annual discovery rate of over 1200 compounds from various phyla (Blunt et al., 2016; Carroll et al., 2020). Many isolated compounds exhibit remarkable biological activities, including their ability to fight against cancer and bacterial, antifungal, and viral infections. This underscores the potential of marine natural agents as valuable reserves of fresh therapeutics and warrants further investigation into their modes of action (Gerwick & Moore, 2012; Molinski et al., 2009; Stuart et al., 2020).

6.3.3 Proteomics

Marine proteomics is a powerful tool for understanding marine biotechnology (Slattery et al., 2012). It reveals the proteome, a crucial interface between genotypic and phenotypic variability, making it an ideal biomarker for ecophysiological responses and adaptations (Slattery et al., 2012). Proteomics informs biosynthetic pathways and mechanisms of

novel marine natural products, which have driven pharmaceutical discovery and development (Newman & Cragg, 2012). Proteomic profiling can identify expressed enzymes, revealing pathways of novel pharmacological compounds (Amoutzias et al., 2016).

6.4 Innovative extraction and purification techniques

Conventional extraction methods, including soaking maceration, pressurized hot water, and Soxhlet solvent extraction, rely on carbon-based solvents such as hexane and chloroform which are carcinogenic; they alter the bioactive compounds thus making them toxic for human consumption. These methods face limitations due to high solvent usage, low extraction rates, prolonged extraction times, energy intensity, and potential thermal degradation of thermolabile compounds (Calinescu et al., 2021). All these drawbacks and limitations of the traditional methods made researchers develop cutting-edge extraction techniques that prioritize sustainability, safety, and compound quality, enabling the effective yield of bioactive constituents (Calinescu et al., 2021). According to the literature microwave extraction, SFE, EAE, and ultrasonic-assisted extraction (UAE) have been reported as novel and green nonthermal methodologies employed in extracting bioactive ingredients from marine vegetation (Calinescu et al., 2021; Getachew et al., 2020).

6.5 Supercritical fluid extraction

This method extracts biologically active components from marine plants using high-pressure carbon dioxide. Arumugham et al. (2021) reported supercritical fluid CO_2 extraction as an emerging and safe technology over traditional extraction methods for several uses, particularly for the extraction of bioactive materials and the elimination of ecological pollutants. Molino et al. (2019) used supercritical carbon dioxide to extract valuable compounds like β-carotene and fatty acids (FAs) from microalgae *Dunaliella salina.* Since the microalgae are marine plant and survive in saline habitats, they can withstand salinity concentrations of up to 4 M NaCl (García-González et al., 2005). *D. salina* can accrue an improved quantity of β-carotene compared to traditional methods (Lamers et al., 2010; Pisal & Lele, 2005). In addition, extracts from *D. salina* are rich in other carotenoids such as lutein and zeaxanthin, which possess numerous antioxidant properties and thus are potential pharmaceutical agents (Dufossé et al., 2005).

6.5.1 Ultrasonic-assisted extraction

UAE harnesses ultrasonic energy to enhance the process of extraction, thus reducing the need for organic solvents and minimizing environmental impact (Shen et al., 2023). This technique exploits thermal, mechanical, and cavitation properties to extract the active constituents. Ultrasonic treatment disrupts cell walls and hence facilitates the release and diffusion of cellular components. Researchers have proposed various mechanisms for the UAE, including fragmentation, erosion, and sonoporation (Chemat, Rombaut, Sicaire, et al., 2017; Chemat, Rombaut, Meullemiestre, et al., 2017; Khadhraoui et al., 2018; Vinatoru et al., 2017). This method is specifically advantageous in upscaling the yield of active constituents and can influence their physicochemical properties. For example, UAE can affect the configuration and function of proteins, polyphenols, and complex carbohydrates (Shen et al., 2023).

6.6 Microwave-assisted extraction

Microwave-assisted extraction is an extensively used method in extracting active substances, such as phenolic compounds, from various seaweed species (Abdelhamid et al., 2019; Dang et al., 2018; Garcia-Vaquero et al., 2020; Luo et al., 2010). MAE utilizes microwave heating, produced by dipole rotation of polar solvents and ionic conditions, to rapidly rupture cells and release compounds into the solvent (Getachew et al., 2020). Yuan et al. (2018) compared MAE with orthodox extraction procedures for phenolic compounds from four brown seaweed species and found that MAE was more efficient than conventional agitation at 25°C. Similarly, Manusson et al. reported a 70% rise in polyphenol yield by MAE compared to solid–liquid extraction. This improvement is attributed to MAE's ability to access up to 40% of polyphenols trapped in the cell wall, which is impossible with conventional methods (Mangusson et al., 2017). However, excessive microwave power can lead to excessive heating and the breakdown of heat-labile components like polyphenols (Getachew et al., 2020).

6.7 Enzyme-assisted extraction

Enzyme-assisted extraction is an emerging technique for recovering biologically active constituents from marine plants, driven by ongoing research in extraction process optimization and the discovery of robust enzymes (Getachew et al., 2020). Phenolic compounds in marine plants exist in several forms, including soluble and insoluble complexes with macromolecules like proteins and carbohydrates (Gligor et al., 2019). Often, these compounds are trapped within thick cell walls or bound to proteins, making extraction challenging (Getachew et al., 2020). However, some of these compounds are readily extracted when in the external cell walls, such as in physodes (Deniaud-Bouët et al., 2014; Jacobsen et al., 2019). The discovery of enzymes that can degrade the cell wall, like alginate-lyases, glucuronan-lyases, carrageenases, laminarinases, and agarases, has revolutionized EAE (Michel & Czjzek, 2013). These enzymes break down polysaccharides, releasing phenolic compounds into the extraction medium, thereby increasing yield (Getachew et al., 2020). For example, phlorotannins, abundant in brown seaweeds, form covalent bonds with proteins, requiring enzymes capable of hydrolyzing these bonds for extraction (Gligor et al., 2019). Recent discoveries of novel enzymes from marine organisms have expanded the possibilities for EAE, offering promising avenues for efficient phenolic compound extraction.

6.8 High-performance liquid chromatography

Purifying marine products involves refining and separating impurities from the desired compounds to obtain active compounds with higher levels of purity. High-performance liquid chromatography (HPLC) is an analytical method that characterizes bioactive compounds in crude samples (Cannell, 1998, p. 165–208). In marine pharmacognosy, HPLC is pivotal in purifying and analyzing bioactive compounds derived from marine plants. HPLC enables the purification of target compounds by distinguishing them from structurally similar substances. Each compound exhibits a unique retention time and peak profile under specific chromatographic conditions (Sasidharan et al., 2011).

7. Ecological and environmental considerations

7.1 Sustainable harvesting of marine plants

Conservation strategies are essential in conjunction with a sustainable system for harvesting medicinal plants from marine ecosystems. Unsustainable and unplanned harvesting of resources, especially marine plants, is one of the most significant threats that humans can pose to the environment and, consequently, to biodiversity. In addition to the usual factors that reduce biodiversity, such as global population growth, industrialization, freshwater scarcity, uncontrolled deforestation, emissions and finally global climate change, unscientific and business exploitation of marine plants, reduces the biodiversity of these valuable resources (Musa et al., 2024).

Sustainable harvesting of marine plants is crucial for keeping our oceans healthy and for ensuring the continued availability of these valuable resources. Many species depend on marine plants like seaweed and seagrass for food and habitat, making them vital to the marine ecology. They also help to filter pollutants from the water and produce oxygen. Through following the principles of sustainable harvesting of marine plants, the long-term preservation of marine plants and healthy marine ecosystem can be achieved (Comfort et al., 2024, p. 145).

Seaweed beds have been damaged in some areas due to overharvesting for commercial purposes (Buschmann et al., 2014). This has raised concerns regarding overexploitation of these resources. To protect these valuable resources, we need management strategies and accountability. It is important to develop and use management tools to maintain the health and integrity of these resources. A rigorous management system can help preserve these natural resources for the long term. Resource exploitation necessitates careful consideration and economic evaluation to ensure the sustainability of these crucial but vulnerable resources. To ensure the long-term sustained and availability of these critical but fragile resources, a proactive approach to sustainable management is essential for resource scientists, managers, conservationists, governments, and others (Mac Monagail et al., 2017).

7.2 Conservation strategies for marine ecosystems

Marine ecosystems and their associated biodiversity are fundamental to sustaining life on Earth. Human activities have caused significant changes to marine ecosystems and biodiversity. These ecosystems are being damaged quickly due to unsustainable practices and a changing climate. Conservation strategies are important for ensuring the health and vitality of marine ecosystems and the well-being of countless species. Marine protected areas serve as crucial instruments for

preserving the biodiversity of marine ecosystems, acting as refuges for harvested species and reducing the detrimental effects of human activities within marine ecosystems.

The cumulative effects of human activities in coastal and marine areas endanger ocean health and ecosystem functioning. Climate change, with its rising sea levels, ocean acidification, and altered temperature regimes, exacerbates these challenges. The sustained viability of numerous marine species is increasingly imperiled by the combined pressures of exploitation and climate change. In addition to the effects of exploitation, the increasing consequences of climate change also endanger the long-term survival of many marine species.

Marine protected areas (MPAs) are a prevalent method for conserving marine ecosystems, which serve to protect ecosystems by isolating them from human interference and restricting exploitative and harmful processes. MPAs are regarded as powerful tools for reducing the human effects on marine biodiversity by restricting resource utilization and exploitation within MPA boundaries and promoting ecosystem resilience. Marine protected areas act as underwater sanctuaries, safeguarding marine life from human pressures and help conserve the variety of species marine ecosystems (Xuereb et al., 2020, p. 423–446).

7.3 Effects of climate change on marine plant bioresources

Climate models predict substantial changes to the oceans over the next century. These changes will have significant effects throughout the Earth, impacting marine biodiversity and human well-being. Various studies have concluded that climate change and rising temperatures have detrimental effects on marine ecosystems and their biodiversity. On a global scale, marine and coastal ecosystems like coral reefs, kelp forests, mangrove forests, salt marshes, and seagrass beds are some of the most vulnerable to climate change.

Climate change can impact marine ecosystems, including changes in species distribution and population collapse (Moreno-Marín et al., 2018). Climate change is a major driver of the global distribution and abundance of seaweed species. This poses an increasing threat to fisheries worldwide (Mac Monagail et al., 2017).

Temperature is a crucial factor determining the distribution of marine species and can impact biological processes at various levels, from genetic to ecosystems. When temperatures exceed optimal levels, plants can suffer from reduced enzyme activity, increased protein damage, and instability of cellular membranes, including those involved in photosynthetic apparatus (Moreno-Marín et al., 2018).

The most noticeable impacts of recent climate change have been on coral reefs, where rising sea temperatures are closely linked to regional-scale bleaching of scleractinian corals. Climate change–induced coral bleaching has severely damaged coral-reef ecosystems and is likely to become more frequent and intense in the future (Pratchett et al., 2008). The trend of climatic change is expected to intensify in the future, posing a significant risk to the survival of coral reefs, particularly in the Caribbean, and the valuable ecosystem services they offer (Buddemeier et al., 2011).

Increased mortality, decreased larvae survivorship, and slower healing times were frequently noted when temperatures were 1–1.5°C higher than the maximum monthly sea surface temperature. Many studies have shown that thermal stress negatively impacts coral reproduction. These impacts include decreased larval survival and settlement rates, increased mortality after settlement, and a loss of genetic diversity. The combination of slow growth and poor recruitment makes coral *Cladocora caespitosa* a vulnerable species, especially in the face of extreme events like warming-related mortality events (Tregarot et al., 2024).

Warming has been observed to adversely affect seagrass *Posidonia oceanica* through increased mortality, diminished growth rate, restricted dispersion, and heightened grazing pressure. Seagrass's spatial distribution has been adversely affected by warming, particularly in relation to acute and chronic heat stress (Tregarot et al., 2024). Warming negatively affects the density, abundance, photosynthesis, habitat structure, and distribution of Zostera marina. It can also decrease carbohydrate reserves in seagrass roots and leaves, increase heat-shock-protein up-regulation, and allow more toxic sulfide to enter the seagrass. However, warming can decrease the prevalence of a pathogen *Labyrinthula zosterae* in *Z. marina* tissues. Temperatures above 25°C can harm the survival of Zostera *marina* (Moreno-Marín et al., 2018).

8. Emerging pharmaceutical products from marine plants

8.1 Regulatory and economic challenges

Oceans are home to a diversity of species that vary greatly in their physiology, characteristics, and, thus, in the secondary metabolites they may create (Debbab et al., 2010). Microalgae produce a variety of compounds, including vitamins and proteins that contain essential amino acids, polysaccharides, FAs, sterols, pigments, fibers, and enzymes. Many of these

compounds exhibit superior chemical structures and activities compared to their synthetic alternatives (Martins et al., 2014).

One of the most often utilized organisms in this field is microalgae. Due to their ability to photosynthesize, microalgae can also be grown effectively in open ponds and outdoor photobioreactors. Air pollutants can be reduced and a large amount of biomass can be produced using solar energy and greenhouse gases (Andrade et al., 2018).

The actinobacteria, a Gram-positive bacteria thought to be a gold mine of secondary metabolites, are of special interest. These bacteria are thought to have produced around one-third of the 3000 compounds with antibiotic action that have been identified from microbes thus far. The Streptomyces genus, which is prevalent in both marine and terrestrial environments, is the source of the majority of these bioactive compounds (Hassan & Shaikh, 2017).

Similarly, some diverse Gram-negative Proteobacteria have attracted a lot of scientific attention due to the large variety of secondary metabolites they produce and their unique structural distinctions from actinobacteria as well as their terrestrial counterparts. The sulfur-containing heterocycles, halogenation, nonribosomal peptides, and polyketides with a particular structure that are found in a greater variety of activities, many of which are not found in other species, are characteristics that set these compounds apart (Timmermans et al., 2017).

Using marine species to produce high-value chemicals and biofuels requires consideration of the delicate nature of marine ecosystems. In actuality, the amounts directly produced by marine species are insufficient to meet both the more constrained requirements of the drug development process and industrial requirements. Therefore, it is rarely sustainable to directly harvest bioactive chemicals and other compounds of industrial interest. Considering that many of these species are endangered and that overexploitation could upset the delicate ecosystem's equilibrium, this is especially true.

Consequently, there is a growing need for alternative solutions. Currently, the majority of conventional chemical and microbiological methods have involved the chemical synthesis or semisynthesis of a substance that is comparable to the natural product. However, the use of hazardous solvents and the volume of waste generated by these processes have a negative impact on the environment. Therefore, by creating more environmentally friendly technologies, researchers and businesses involved in marine biotechnology can get around this restriction (Murray et al., 2013). Because aquaculture and other alternative techniques for growing marine organisms, such as corals and sponges, do not require toxic compounds and raw materials can be supplied without endangering fragile marine ecosystems, they unquestionably constitute a sustainable production method (Sayari et al., 2016).

The conventional downstream methods that are employed to extract the product from marine organisms also harm the environment. The traditional method of producing microalgae is not only energy-intensive and produces organic waste, but it is also frequently prohibitively expensive, making up to 80% of the total process cost. Marine biotechnology has the potential to address the pressing need for the development of alternate downstream processes once more (Andrade et al., 2018). Using fishing industry trash to produce highly valuable compounds is another aspect of sustainable production. The waste generated by the by-catch and the fish processing businesses together amounts to more than dozens of tons of millions of tons annually and prompts several questions regarding potential disposal options and the impact on the environment. Nonetheless, because of this waste's extraordinary chemical richness, biotechnological techniques can transform it into very valuable goods like collagen or protein hydrolysates with antioxidant qualities. Thus, this procedure offers a potential substitute for the direct collection of bioactive materials while also providing a means of disposing of waste originating from the fish supply chain (Sayari et al., 2016).

Obtaining pharmaceuticals from marine sources presents several significant obstacles. The same organism may produce a different metabolite each time due to the fluctuating environmental variables. One of the most significant issues that arise from time to time is that the microbes that reside within the marine animals are the ones that produce the bioactive chemicals, not the invertebrate hosts (Martins et al., 2014). Maintaining a sustainable supply of identified and isolated lead compounds can occasionally be challenging due to the lead compound's low presence or the technical challenges of isolating it (Molinski et al., 2009). The amount required can range from a few grams for preclinical drug development and safety studies conducted in various setups to the kilogram quantities needed for multiple clinical study rounds and hundreds of tons of cosmetics, depending on the molecule's intended use (drug, cosmetic, etc.) (Martins et al., 2014). One of the main concerns might be the amount of readily available lead compounds.

A summary of the factors limiting the development of marine drugs has been provided. Research and development of some extremely powerful marine new compounds has occasionally been impeded by the absence of a sustainable supply of the candidate molecule. Attempts have been made to circumvent this issue by either making a simpler, easier-to-make pharmacophore or by producing more derivatives of synthetic or semisynthetic analogs with specific, desired properties (Radjasa et al., 2011). When identifying a synthetic or semisynthesized bioactive chemical, it is crucial to use the biologically derived compound as a reference. The structural complexity and low yield of the isolated compound, which are typical for marine compounds, can lead to errors in the assignment of one or more stereo centers, intramolecular bond

configuration, entire configuration, real constitution (planar connectivity), and chemical formula (Maier, 2009). The issue of a steady supply can be solved by controlling the use of natural resources to support the growth of marine species in their natural habitat through farming, or "mariculture" (Gerwick & Moore, 2012). Culturing marine species in artificial environments is an additional choice.

Martins et al. (2014) have provided a comprehensive explanation of the relevant and often overlooked commercial and market concerns that arise during the development of new natural products. One of the constraints associated with the development of marine drugs is the need for universal expression systems for high-yield biosynthesis of small molecules, the development of genetic tools for accessing the in vivo potential of cultured marine microorganisms, and the reactivation of dormant biosynthesis pathways (Gerwick & Moore, 2012).

In the development of drugs, safety, and effectiveness are assessed in vivo in animal models, the mechanism and site of action are identified, structure–activity relationships are developed, and pharmaceutical properties and pharmacokinetic parameters are formulated and characterized, including enhancements through medicinal chemistry (Gerwick & Moore, 2012).

Spirulina and *chlorella* dominate the microalgae market. The first is a green microalga belonging to the phylum Chlorophyta, which includes macro- and microalgae. Due to its antiinflammatory, antibacterial, and anticancer properties, it is widely used in food, cosmetics, and pharmaceutical products. However, spirulina, a photosynthetic microorganism, is a blue–green algae that belongs to the phylum Cyanobacteria and is great for cuisine due to its high protein content. These microalgae's unique cellular systems allow them to grow quickly and be easily adapted to changing environmental circumstances (Zahra et al., 2020). Furthermore, bacteria and fungi are great sources of bioactive compounds due to their distinct characteristics. Moreover, bacteria and fungi have developed distinctive traits that are reflected in the metabolites they generate as a result of the harsh environments in which they live. These microorganisms usually live symbiotically with invertebrate organisms, whose defense depends solely on the chemicals these microorganisms produce (Debbab et al., 2010).

The collection of metabolites from the most easily collected species has accounted for most of the early work in marine natural product chemistry (Ayer & Kadambi, 2011). Analytical and biological assessments are complicated by minor metabolites that are present in extremely small amounts. For a better understanding of the natural structure of these small drug candidates, silico screening programs could be useful. Technology advancements like NMR microcryogenic and capillary flow probes, biological assays in smaller volumes, like 384- and 1534-well plates, and improvements to mass spectrometry methods, informatics, and logistics are helping researchers better access minor metabolites (Gerwick & Moore, 2012). Another aspect of marine drug discovery programs that require improvement is the use of biological assay techniques for extracts, fractions, and pure compounds. The process of identifying different classes of natural products in the environment may be greatly improved by automating assay-based isolation design for marine natural products (Gerwick & Moore, 2012).

Many research institutes in India and around the world focus on research and training in marine pharmacology due to its vast potential and opportunities. The majority of research institutes seek to discover potential new compounds, extract and isolate them, evaluate their safety and effectiveness, and produce them on a large scale.

A consumer product's large-scale manufacturing is inextricably linked to its marketing. Many promising compounds that are tested in the laboratory never make it to market because their production costs are too high when compared to alternatives that are synthesized, derived from fossil fuels, or extracted from other organisms.

It is essential to establish processes that produce biomass aligned with market demand, ensuring high yields and enhancing competitiveness to fully leverage the potential of marine resources (Ale et al., 2014). In light of this, new genetic and metabolic engineering methods are being developed at an increasing rate, with a focus on microalgae (Tork et al., 2017). Optimizing the culture conditions for the organism affects the extraction process, biomass production, and the types and quantities of secondary metabolites (Zhou et al., 2014). Bioreactor structures can replicate the marine environment, enhancing organism productivity. Technological advancements have significantly increased the scalability of these systems. System designs that utilize modules deposited on the seafloor to allow for the sustainable exploitation of marine resources or systems that can derive energy from microbial metabolism are particularly innovative (Zhang et al., 2011).

In certain situations, the natural product's qualities need to be enhanced to increase its activity in the case of a medication or to give it characteristics that will appeal to more consumers. For example, the microalgae spirulina has a high nutritional value and excellent therapeutic properties, but it cannot be used as a food supplement due to its limited protein availability and unpleasant odor. Techniques for extraction and fermentation based on ethanol have been developed to solve this problem. These can improve the availability of nutrients and produce goods with a more appealing taste and scent for the consumer (Bao et al., 2018).

9. Future prospects and directions

Indeed, marine organic substances have proven very effective in pharmaceutical fields; however, it comes with various challenges which gives room for future prospect and direction. One of such challenges is the environmental condition of the marine organism, leading to the production of different metabolite from the same organism. Based on this and many other challenges, the future prospect of marine organisms in drug and pharmaceutical industries should focus on culturing the marine organisms under artificial conditions by the process called aquaculture. This would help in obtaining same metabolite from the marine organism and in same and required complexes and quantity (Maier, 2009).

Martins et al. (2014) explained some business issues that are very important in understanding the use of marine plants for pharmaceutical product development. In their study, they identify some of the important points that should be looked in the developmental stages of marine plants in pharmaceutical industries. These are (i) what are the potential industrial uses of the marine product, and why is it needed in the market? (ii) What is the final price per kg for the last compound from the marine plant? and (iii) What is the desired formulation and preferred means of administration of the bioactive compound?

The subsequent levels in drug development have to do with the in vivo evaluations of the level of safety and then understanding the efficiency of the marine plant when tested with animal models. It is also important to keep in mind the mechanism of action, the structure–activity relationships, characterization of the pharmacokinetics parameters, and pharmaceutical properties including improvements through the use of medicinal chemistry (Bergmann & Stempien, 1957). Considering the enormous potential of this marine plants, some institutes in India as well as all over the world, have now shifted their concentration to the marine pharmacology field. Researchers are now trying to discover novel marine plant compounds, extract them, and then isolate them, also, consider their biosafety and large-scale commercialization. Some of the institutes doing research and universities imparting training on marine pharmacology in and outside India are mentioned in respectively.

9.1 Emerging trends in marine plant pharmacology

Since a large diversity of plant is found in the ocean. The photosynthetic green plants alone comprise over 12 plant divisions. With the inclusion of the known unique adaptations of some plants to high-salt environments and high hydrostatic pressure, the immense diversity of the plants in marine habitats becomes apparent. However, the pharmaceutical industries have not taken advantage of this enormous resource. The reason rests with the tendency of researchers to explore familiar and more readily accessible plants. Plants in the marine habitat are easily cultivable. The green plant diversity of the marine environment has thus become available for scientific study, and new programs are emerging worldwide. In the United States and Japan, intense focus on coastal sediments and organisms associated with marine invertebrates has resulted in a growing number of papers documenting the production of novel, bioactive metabolites. Both green plants and fungi are now the targets of biomedical study, and fascinating reports of novel metabolites are becoming more and more common. Even green algae samples from coastal sediments, when grown under saline conditions, have yielded new antibiotics, antitumor, and antiinflammatory compounds (Trischman et al., 1994). Similarly, when the surfaces of marine plants and the internal tissues of invertebrates have been sampled, bacteria, and fungi have been discovered that also produce bioactive compounds with pharmaceutical potential.

9.2 Vision for the future: Integrating marine bioresources into mainstream pharmaceuticals

Looking at the massive potential of marine pharmacology, there are several organizations all over the world which are concentrating on research in this domain of drug development. For example, some details of this have been tabulated in Table 14.3. Another use of the compounds from marine plant is their importance as probes in molecules (Musa et al., 2024). Molecules broadly defined as nondrug substances, which can be used to probe the foundations of important biochemical events. The functions and overall structures of the membrane channels which facilitate nerve transmission. Knowledge of the function of these neurotoxins has allowed drugs to be designed and targeted to those sites of nerve transmission.

It is now clear that the development of drugs from marine plants involves a well-planned stage. In addition, the field also faces a lot of challenges in this development, and therefore many companies are working closely with research institutions to bridge these challenges. Recent report shows very encouraging outcomes in the fields. Certain inhibitors of the signal transduction pathways involved in cancer development have been obtained from marine organisms, and further studies are under process to attain evidence on their efficacy in cancer therapy. There is hope to find drugs of marine origin for targeted cancer therapy that is difficult currently with other available sources (Table 14.4).

TABLE 14.3 Comparative study of bioactive compounds in different marine plants.

Name of marine plant	Major bioactive compounds	Extraction methods	Biomedical application	References
Seagrass (Zosteraceae, Hydrocharitaceae, Posidoniaceae, Cymodoceaceae, and Ruppiaceae)	Flavonoids, tannins, and phenolics	Microwave-assisted extraction (MAE), ultrasound-assisted extraction (UAE)	Antioxidant activity	Susilo et al. (2023)
Kelp (*Macrocystis pyrifera*)	Protein, lipid, polysaccharides	Enzyme-assisted extraction	Antibacterial, antiviral, antifungal properties	Hold and Kraan (2011)
Red algae (Rhodophyta)	Proteins (phycobiliproteins), polysaccharides (carrageenan, agar), lipids (docosahexaenoic acid, eicosapentaenoic acid)	Solid-liquid extraction	Anticoagulant, antiviral, immune-modulating properties	Carpena et al. (2023)
Phytoplankton (cyanobacteria, diatoms, dinoflagellates, and green algae)	Fatty acids, fucoidans, fucoxanthin, laminarin, mannitol	Enzyme-assisted extraction, supercritical-fluid extraction	Antidiabetic, antioxidants, antimalarial, antiviral	Menon et al. (2023)
Sargassum (brown seaweed, gulfweed)	Fucoidans, sterols, phlorotannins, meroterpenoids, glycolipids	Solid-liquid extraction	Antiinflammatory, anticancer, antimicrobial, antiviral, antioxidant, liver protection properties	Luna-Pérez et al. (2023)

TABLE 14.4 Marine natural products under pipeline.

S/N	Example	Treatment	Approval date
1.	Trabectedin found in Tunicate	Ovarian cancer	October 23, 2015
2.	Bryostatin 1 found in *Bugula neritina*	Alzheimer's disease	January 20, 2018
3.	Tetrodotoxin found in algae and bacteria	Analgesics	October 10, 2019

10. Conclusion

The exploration of marine plants for pharmaceutical applications has unveiled a treasure trove of bioactive compounds with immense therapeutic potential. As the world grapples with those challenges of infectious diseases, cancer and other health crisis, the marine environment offers a promising solution. The emergence of pharmaceutical products from marine plants heralds a new era in drug discovery and development. As research continues to unravel the secrets of the marine environment, we can expect innovative treatments to address pressing healthcare challenges. By embracing sustainable practices, cutting-edge technologies, and collaborative efforts, we can unlock the full potential of marine plants to improve human health and well-being.

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Chapter 15

Development of marine organisms as models for studying human diseases

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1. Introduction

The quest to understand and treat human diseases has been a driving force in biomedical research for centuries. In this pursuit, model organisms have played a pivotal role, serving as surrogates to unravel the complexities of biological processes and pathological mechanisms that underlie human health and disease. Our understanding of fundamental biological processes and the causes of illnesses has improved greatly, thanks in large part to model organisms. They are vital tools for biomedical research, providing important information about the fundamental mechanisms underlying human diseases (Vashishat et al., 2024). These organisms, which range from simple bacteria to complex mammals, are chosen based on their genetic, physiological, and biochemical similarities to humans. They offer a controlled environment for studying disease pathology, genetic mutations, and the effects of potential treatments, thereby accelerating the pace of scientific discovery and medical advancements (Niu et al., 2023; Shorbaji et al., 2024). Despite the historical dominance of conventional model organisms such as fruit flies, nematodes, and mice in biomedical research, there has been a notable change in recent decades. Marine life has become a powerful and innovative model for studying many aspects of human biology and illness (Li, Yu et al., 2024; Settivari et al., 2024; Townsend, 2023). The vast and largely unexplored biodiversity of marine ecosystems offers a treasure trove of unique organisms with characteristics that make them particularly suitable for studying specific aspects of human biology and disease. From the simplest unicellular organisms to complex vertebrates, marine life encompasses a wide range of biological complexity, providing researchers with an unparalleled array of model systems to choose from Appanna (2023) and Sommer (2024). This diversity not only allows for the study of conserved biological processes but also offers insights into unique adaptations that can inform our understanding of human physiology and potential therapeutic strategies.

Marine organisms present several advantages as model systems. One of the primary advantages of marine organisms as model systems is their surprising degree of genetic and physiological similarity to humans, despite their apparent morphological differences. This evolutionary conservation, rooted in the common ancestry of all life on Earth, allows researchers to investigate fundamental biological processes that are directly relevant to human health (Bornbusch et al., 2024; Nanglu et al., 2023). For instance, the basic mechanisms of cell division, signal transduction, and gene regulation are often remarkably similar between marine organisms and humans, making these models invaluable for studying processes such as embryonic development, tissue regeneration, and cancer biology. Moreover, many marine species possess unique adaptations or specialized tissues that can serve as excellent models for specific human organs or systems. The regenerative capabilities of some marine invertebrates, such as sponges, sea stars, planarians and zebrafish, offer unprecedented insights into tissue repair and regeneration in humans (Levanoni et al., 2024; Lv et al., 2024). Similarly, the electroreceptive organs of sharks and rays provide a unique platform for studying sensory systems and neurological

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disorders (Chin et al., 2024, pp. 306–319; Graham et al., 2022). Another significant advantage of many marine organisms is their transparent embryos or larvae, which facilitate real-time observation of developmental processes and disease progression. This characteristic, combined with their often-rapid development and high fecundity, makes them ideal for high-throughput screening of genetic mutations and potential therapeutic compounds (Bauer et al., 2021; Das & Patel, 2020). For example, zebrafish embryos, with their optical clarity and rapid development, have become a favored model for studying cardiovascular diseases (CVD), cancer, and neurodevelopmental disorders (Bauer et al., 2021).

The use of marine organisms in biomedical research has led to significant breakthroughs in our understanding of various human diseases. Studies on sea urchins, for instance, have provided valuable insights into the cell cycle and cancer biology, leading to the discovery of cyclins and cyclin-dependent kinases (CDKs), which are crucial regulators of cell division (Yang, Yu et al., 2021; Tjeerdema et al., 2024). Research on the California purple sea urchin (*Strongylocentrotus purpuratus*) has also contributed to our understanding of the innate immune system, revealing ancient defense mechanisms that are conserved in humans (Tjeerdema et al., 2024). Similarly, the study of marine organisms has advanced our knowledge of neurodegenerative diseases. The giant axon of the squid, famously used by Hodgkin and Huxley in their Nobel Prize-winning work on action potentials, continues to be a valuable model for studying neuronal function and dysfunction (Curtis, 2024; Wingate, 2023). The sea slug, *Aplysia californica*, has emerged as a crucial model for memory and learning studies in recent years. It provides important new information on the molecular mechanisms behind neurological diseases like Alzheimer's (Akter et al., 2024). In the realm of developmental biology, marine organisms have been instrumental in elucidating key pathways and mechanisms. The ascidian *Ciona intestinalis*, a sea squirt, has helped researchers understand the evolution of the chordate body plan and the development of the notochord, a structure crucial in human embryonic development (Beyer et al., 2023; Lovejoy, 2023). Similarly, studies on the cnidarian *Nematostella vectensis* have shed light on the evolution of body axes and the ancient origins of many human genes involved in development and disease (Krueger et al., 2024; Sheloukhova & Watanabe, 2023).

This chapter examines how marine life informs biomedical research through an evolutionary lens. We will introduce important marine model organisms and their roles in studying human health. The discussion will cover how these models enhance our knowledge of various conditions, including cancer and cardiovascular disorders to neurodegenerative diseases and developmental abnormalities. Furthermore, we will examine the cutting-edge technologies and techniques that have propelled this field forward, including advanced imaging methods, genome editing tools like CRISPR-Cas9, and high-throughput screening platforms. These technological advancements have greatly enhanced our ability to manipulate and study marine organisms, further cementing their place in biomedical research. We will also consider the translational potential of findings derived from marine model organisms. While the path from marine biology to human therapeutics may seem long, history has shown that fundamental discoveries in these seemingly exotic creatures can lead to groundbreaking medical applications. Green fluorescent protein (GFP), discovered by the Nobel Prize-winning jellyfish, *Aequorea victoria*, has revolutionized biomedical imaging and research, demonstrating the enormous potential of marine species to improve human health (Hamdoun et al., 2023, pp. 181–201; Zimmer, 2023). As we face global challenges such as climate change and habitat destruction, the study of marine organisms takes on added significance. Not only do these creatures offer valuable insights into human biology and disease, but they also serve as sentinels of ecosystem health. Understanding the impact of environmental changes on marine life can provide crucial information about potential threats to human health and well-being (Hamdoun et al., 2023, pp. 181–201). The development of marine organisms as models for studying human diseases represents a frontier in biomedical research that promises to yield valuable insights and potential therapies. By harnessing the unique attributes of marine life, researchers are opening new avenues for understanding and potentially treating a wide array of human diseases. This chapter intends to offer a thorough overview of this dynamic field, highlighting its current applications, recent breakthroughs, and future possibilities for enhancing human health and medicine.

2. Evolutionary perspective

Marine organisms, with their evolutionary diversity and unique biological traits, serve as invaluable models for understanding fundamental biological processes. The use of marine organisms as models for studying human diseases is deeply rooted in the principles of evolutionary biology. Marine organisms' hundreds of millions of years of evolutionary history provide important insights into the emergence of complex biological systems and the early stages of multicellular life (Bozdag et al., 2024). This perspective provides a crucial framework for understanding why organisms that may seem vastly different from humans can offer valuable insights into our own biology and pathology. Studying these organisms helps researchers understand the fundamental processes that shaped animal development and function across different environments. It also helps guide researchers in selecting appropriate organisms and interpreting results in the context of

human health. The two main ideas of the evolutionary method to implementing marine species as models for human illness research are homology, or similarities resulting from a common ancestor, and analogy, or similarities that have developed separately. The homology includes common ancestry and conserved molecular mechanisms, gene conservation and homology, evolutionary developmental biology (Evo-Devo), while the analogy includes convergent evolution and analogous systems and evolutionary innovations and unique adaptations (Medina et al., 2023; Pollen et al., 2023).

2.1 Common ancestry and conserved molecular mechanisms

All life on Earth shares a common ancestor, a fact that underpins the utility of diverse organisms in biomedical research. This shared evolutionary history is reflected in the conservation of many fundamental biological processes across species, spanning from unicellular organisms to complex multicellular life forms. The last common ancestor of humans and many marine organisms existed hundreds of millions of years ago. For instance, the split between vertebrates and urochordates (which include sea squirts) occurred approximately 550 million years ago (Li, Boldt et al., 2024). Numerous cellular and molecular processes have been very well conserved in spite of the great evolutionary gap. The basic molecular functions of transcription, translation, and DNA replication are extremely conserved in all living organisms. The genetic code itself is nearly universal, with only minor variations in some organisms. Numerous proteins involved in these processes are included in this conservation. The enzymes that aid in DNA replication, known as DNA polymerases, for example, share structural and functional characteristics with bacteria and humans alike (Picarazzi & Mori, 2024, pp. 9–22). Key cellular processes such as cell division, apoptosis, and signal transduction also share many common features between humans and marine organisms. A conserved class of proteins, which includes cyclins and CDKs, controls the cell cycle. Since their discovery in sea urchin eggs, these proteins have come to be understood for their crucial functions in cancer biology and human cell division (Zhou et al., 2024).

The conservation of signaling pathways is particularly relevant to disease research. The fundamental elements of pathways like Notch, Wnt, and Hedgehog are substantially conserved throughout metazoans and are essential for both development and illness. For example, the Notch signaling system, which is crucial for determining cell destiny and has been connected to a number of human malignancies, has been thoroughly studied in the sea slug *Aplysia californica*, providing insight into its basic processes and evolutionary history (Kumari et al., 2024).

- **Wnt signaling pathway:** Numerous facets of cell biology, such as cancer, tissue maintenance, cell differentiation, and embryonic development, depend on this highly conserved cell signaling pathway (Hayat et al., 2022). It was originally discovered in *Drosophila* and mice; it is critical across a wide range of species, from invertebrates to vertebrates, including humans (Hayat et al., 2022). The pathway is named after the *Wg* (Wingless) gene in *Drosophila* and the *Int* (Integration site) oncogene, whose homologs in vertebrates were later grouped as Wnt proteins (Hayat et al., 2022). Embryonic development, stem cell maintenance, and disorders like cancer are all impacted by dysregulated Wnt signaling. The canonical (β-catenin dependent) pathway, the noncanonical planar cell polarity (PCP) pathway (also known as β-catenin-independent), and the Wnt/Ca^{2+} pathway are the three primary branches of the Wnt pathway (Liu, Xiao et al., 2022). The family of secreted glycoproteins known as Wnt proteins, which attach to cell surface receptor complexes, activates each pathway. Different biological effects result from the convergence of these pathways on distinct cellular targets. The specificity of Wnt signaling is influenced by the cell's developmental stage, type, and context, with precise regulation being crucial for normal physiology. The canonical (or β-catenin-dependent) pathway and the noncanonical (or β-catenin-independent) pathway are its two primary branches (Liu et al., 2022). Each branch uses distinct signaling components and controls various cellular functions.
- **Canonical Wnt signaling pathway:** The stability and translocation of β-catenin to the nucleus, where it affects gene expression, are what defines the Wnt/β-catenin pathway. This pathway is involved in many developmental and pathological processes and are essential for controlling decisions about cell fate. The process starts when a series of secreted glycoproteins called Wnt ligands (e.g., Wnt1, Wnt3a) attach to Frizzled (Fzd) receptors (as shown in Fig. 15.1B) on target cell surfaces (Koni et al., 2020). A co-receptor called low-density lipoprotein receptor-related protein (LRP) 5/6 is enlisted when Wnt binds to Frizzled (Davidson, 2021). Disheveled (Dvl), an essential protein that functions as a signal transducer, is activated by the conformational shift that this receptor-ligand combination causes (Aghabozorgi et al., 2020). When Wnt signaling is not present (as shown in Fig. 15.1A), glycogen synthase kinase 3 (GSK3) constantly phosphorylates β-catenin, a crucial pathway component, directing a destruction complex consisting of proteins such as Axin, adenomatous polyposis coli, and GSK3 to ubiquitinated and degrade it. Disheveled (Dsh) is recruited when Wnt binds to Frizzled and LRP5/6, which inhibits this degradation complex (Aghabozorgi et al., 2020). Because of this inhibition, β-catenin is unable to degrade, which causes it to accumulate in the cytoplasm

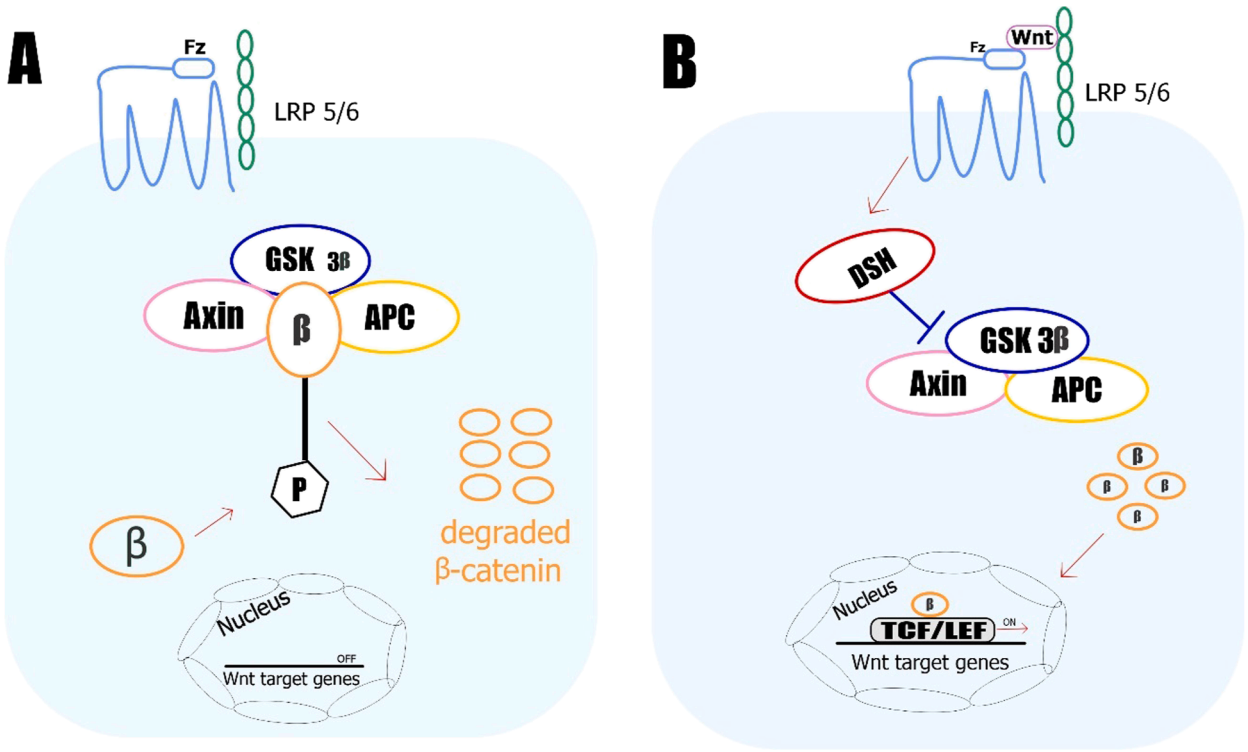

FIGURE 15.1 The simplified canonical Wnt signaling pathway. (A) In the absence of a Wnt signal, β-catenin (β) is phosphorylated by a complex containing APC, GSK 3β, and Axin. The phosphorylated β-catenin is rapidly degraded. (B) Wnt ligand binds to Frizzled (Fz) and LRP 5/6, Dsh then inactivates the phosphorylation complex. As a consequence, degradation of β is inhibited and it is accumulated in the cytoplasm. β-catenin translocate to the nucleus and binds TCF/LEF which leads to transcription of a number of Wnt target genes.

and eventually go to the nucleus. Stabilized β-catenin builds up in the cytoplasm before moving into the nucleus, where it combines with transcription factors called T-cell factor/lymphoid enhancer factor to trigger the production of target genes such as cyclin D1 and c-Myc (Aghabozorgi et al., 2020). This system is essential for organ development and tissue repair because it controls genes involved in cell proliferation, stem cell renewal, and differentiation (Davidson, 2021).

- **Noncanonical PCP pathway:** It involves many signaling cascades that control things like cell migration and polarity and operates independently of β-catenin. Cell polarity and mobility are precisely controlled by the PCP pathway. Frizzled and receptor tyrosine kinases (such ROR2 or Ryk) are among the receptors that are activated by Wnt proteins, such as Wnt5a and Wnt11. Small GTPases like Rho and Rac are activated as a result of this signaling cascade, modifying the cytoskeleton and directing cell migration (Guo & Xing, 2022). This pathway is crucial for coordinating cell movements during processes like embryonic development and tissue regeneration (Qin et al., 2024). PCP signaling governs processes like neural tube closure and inner ear development, ensuring correct tissue structure and cellular orientation
- **Wnt/Ca^{2+} pathway:** Another noncanonical branch, the Wnt/Ca^{2+} pathway, regulates intracellular calcium signaling. Phospholipase C (PLC) is activated when Wnt attaches to Frizzled receptors, raising intracellular Ca^{2+} levels. Protein kinase C and calmodulin-dependent protein kinase, more especially calcium/calmodulin-dependent protein kinase II, are activated by the increased Ca^{2+}, which affects cellular functions including contraction and migration (Qin et al., 2024). This pathway modulates processes such as cell adhesion, migration, and inflammatory responses. It also interacts with other signaling pathways, including PCP signaling, to ensure proper coordination of cellular behavior during development (Yu et al., 2021).
- **Notch signaling pathway:** Numerous developmental processes, including cell fate determination, differentiation, proliferation, apoptosis, and tissue homeostasis, depend on this highly conserved cell signaling pathway (Kumari et al., 2024). Notch signaling was first identified in *Drosophila melanogaster* and has since been identified as a crucial regulator of several biological processes in a variety of animals, including humans. It operates by means of direct connections between cells. Studies on the marine chordate, *Ciona intestinalis*, have revealed the ancient origins and

conserved functions of Notch signaling in development and tissue homeostasis (Di Gregorio, 2020; Lv et al., 2024). There are two main ligand families in mammals: Delta-like (DLL1, DLL3, DLL4) and Jagged (Jagged1 and Jagged2), and there are four Notch receptors (Notch1, Notch2, Notch3, and Notch4) (Moldovan et al., 2021). According to Hussan et al. (2024), notch receptors are single-pass transmembrane proteins that interact with ligands produced on neighboring cells through extracellular EGF-like repeats. The pathway is activated when Notch ligands attach to Notch receptors, setting off a series of events. A metalloprotease called ADAM10 or ADAM17 cleaves the Notch extracellular domain following the first contact between the ligand and receptor, exposing the Notch intracellular domain (NICD) (Hozumi, 2020). The γ-secretase complex, which is made up of presenilin, nicastrin, APH-1, and PEN-2, subsequently cleaves this NICD a second time, releasing it from the membrane (Hozumi, 2020). After being released, the NICD moves into the nucleus, where it regulates gene expression by interacting with the CSL transcription factor (CBF1/RBP-Jκ, Su(H), Lag-1) (Moldovan et al., 2021). The NICD combines with CSL and coactivators such as mastermind-like proteins to create a complex in the nucleus. Target genes like *Hes* and *Hey*, which are involved in cell division, proliferation, and apoptosis, are activated by this complex, which changes CSL from a repressor (Anand et al., 2024). Feedback mechanisms control the Notch pathway to guarantee proper signaling length and intensity. Notch signaling is influenced by several elements, including the presence and arrangement of Notch ligands on the cell surface, as well as the endocytosis and recycling of these ligands. The strength and specificity of signaling are modulated by ligand differential expression and their capacity to interact with Notch receptors (Parambath et al., 2024).

The Notch pathway is highly conserved and is active in a variety of developmental processes, such as neurogenesis, somitogenesis, vascular development, and hematopoiesis (McIntyre et al., 2020). During neurogenesis, for example, Notch signaling ensures the balance between neural progenitors and differentiated neurons. It suppresses premature differentiation, maintaining a pool of stem cells while promoting the timely differentiation of others into functional neurons (de Morree & Rando, 2023). This fine-tuned regulation is essential for the proper formation and patterning of the nervous system. Similarly, in vascular development, Notch signaling regulates arterial-venous specification, with Notch activation promoting arterial identity, while its absence leads to venous fate.

- **Hedgehog signaling pathway:** Numerous developmental processes, including cell differentiation, tissue patterning, and organogenesis, are regulated by this essential signaling system (Sigafoos et al., 2021). It is called after the Hedgehog gene in *Drosophila melanogaster*, whose mutations produce characteristic spiky, or "hedgehog-like," body segments. The pathway is conserved across many species, from flies to mammals, and its dysregulation can result in various diseases, including cancers and congenital disorders. It is essential for cell proliferation, differentiation, and embryonic patterning. Three Hedgehog ligands are found in vertebrates: Desert Hedgehog (Dhh), Indian Hedgehog (Ihh), and Sonic Hedgehog (Shh) (Ohba, 2020). The activation of the Hh signaling pathway depends on whether Hh ligands are present or not. A transmembrane protein called Patched1 (Ptch1) suppresses the activation of another receptor protein called Smoothened (SMO) when the Hedgehog signal is not present (as shown in Fig. 15.2A) (Zhang & Beachy, 2023). By blocking SMO's migration to the main cilium, an organelle essential to vertebrate Hedgehog signaling, Ptch1 functions as a negative regulator (Gigante & Caspary, 2020). A cytoplasmic complex including the Gli transcription factors (Gli1, Gli2, and Gli3) and suppressor of fused (SUFU) is still active in this "off" state. Inhibiting the expression of Hedgehog target genes, this complex aids in the cleavage and degradation of Gli proteins into repressor forms (Chai et al., 2021).

When a Hedgehog ligand binds to PTCH1 (Fig. 15.2B), the inhibition on SMO is relieved, allowing SMO to accumulate in the primary cilium and this interaction triggers a series of intracellular events that lead to the dissociation of the SUFU–Gli complex and activation of the Gli transcription factors (Paradise et al., 2023). When SMO is activated, intracellular signaling proteins including SuFu are involved in a series of events. The full-length Gli proteins can enter the nucleus and trigger target gene expression when activated SMO prevents the conversion of Gli proteins (Gli1, Gli2, and Gli3) into their repressor forms (Sigafoos et al., 2021). The route can drive the developmental processes necessary for appropriate embryogenesis and tissue creation when it is in this "on" state (Sonnen & Janda, 2021). SuFu binds to Gli proteins and prevents their activation, acting as a negative regulator of the Hedgehog pathway. Hedgehog signaling influences the stability and activity of Gli proteins via modulating the interaction between SuFu and Gli proteins (Paradise et al., 2023). The Hedgehog pathway is regulated by feedback mechanisms to ensure balanced signaling.

- **TGF-β signaling pathway:** The transforming growth factor beta (TGF-β) signaling pathway is a fundamental signaling cascade that regulates a variety of cellular processes, including cell growth, differentiation, apoptosis, embryogenesis, tissue homeostasis, and disease progression, and extracellular matrix (ECM) production (Tzavlaki

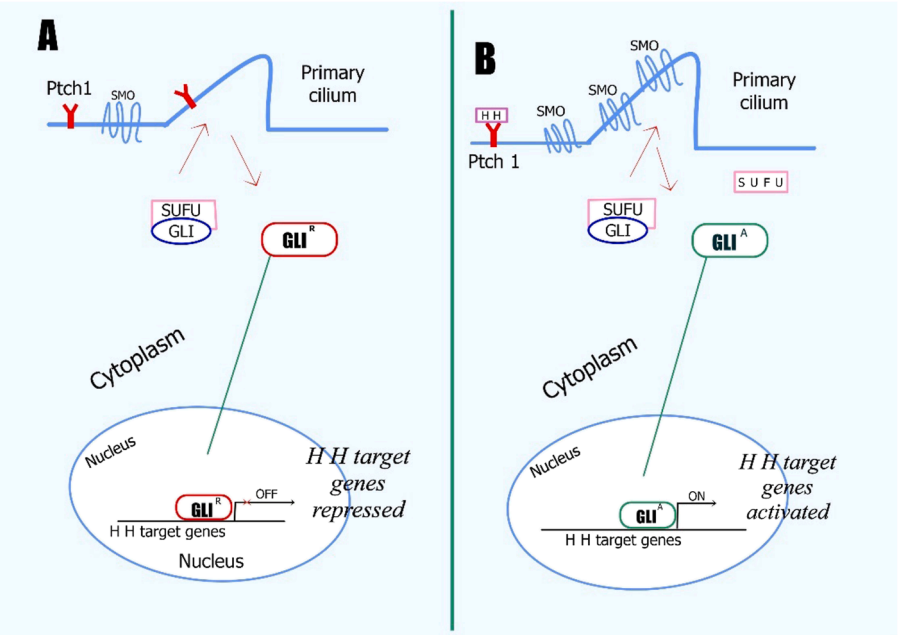

FIGURE 15.2 The simplified hedgehog signaling pathway. (A) In the absence of hedgehog ligand, (HH), a transmembrane protein, patched1 (ptch1), inhibits SMO and prevents its translocation to the primary cilium. In the absence of SMO, GLI transcription factors are processed into their repressor form (GLI^R) and thus acts to negatively regulate HH gene expression. (B) In the presence of HH ligands, the inhibition of SMO by ptch1 is relieved, thus, allowing SMO to translocate to the primary cilium. Activated SMO allows the enzymatic processing of GLI transcription factors into their active form (GLI^A), hence, activating the HH gene expression.

& Moustakas, 2020). It is highly conserved across species, and its dysregulation is implicated in numerous pathological conditions, including fibrosis, cancer, and developmental disorders. The dysregulation of TGF-β signaling has been implicated in various pathological conditions, including cancer progression, fibrosis, and immune disorders. The TGF-β superfamily consists of a wide range of ligands, including TGF-βs, bone morphogenetic proteins (BMPs), activins, inhibins, and growth differentiation factors (Tzavlaki & Moustakas, 2020). These ligands initiate signaling by binding to serine/threonine kinase receptors on the cell surface. In mammals, there are three main isoforms of TGF-β: TGF-β1, TGF-β2, and TGF-β3, although they share similar signaling mechanisms, these isoforms have distinct roles in development and physiology (Tzavlaki & Moustakas, 2020).

The canonical TGF-β signaling pathway begins when a TGF-β ligand binds to a type II receptor on the cell surface (W (C.S. et al., 2024). Upon ligand binding, the type II receptor recruits and phosphorylates a type I receptor (TβRI), activating its kinase domain (Duan et al., 2021). The activated TβRI then phosphorylates receptor-regulated Smad proteins, primarily Smad2 and Smad3. These phosphorylated Smads associate with a co-Smad, Smad4, and the complex translocates into the nucleus, where it binds to DNA and interacts with other transcription factors to regulate the expression of target genes (Runa et al., 2024). The genes controlled by TGF-β signaling regulate key processes such as cell cycle arrest, epithelial-mesenchymal transition (EMT), and immune regulation. According to Morgos et al. (2024), TGF-β also activates noncanonical pathways, often referred to as Smad-independent pathways. These include the activation of mitogen-activated protein kinases (MAPKs), such as ERK, JNK, and p38, as well as the PI3K-Akt and Rho-GTPase signaling cascades (Kciuk et al., 2022). These noncanonical pathways contribute to the diverse cellular outcomes elicited by TGF-β signaling and provide additional layers of regulatory control (Kciuk et al., 2022).

- **Bone morphogenetic protein (BMP) signaling pathway:** It is one of the most crucial developmental signaling systems in marine organisms, playing fundamental roles in embryonic development, tissue homeostasis, and regeneration (Krishnapati & Ghaskadbi, 2024). They are part of the TGF-β superfamily, which regulates diverse biological processes and are initially identified for their role in bone and cartilage formation in vertebrates, BMPs are now recognized as key regulators of embryogenesis, tissue patterning, cell differentiation, and organ development (Krishnapati & Ghaskadbi, 2024). This pathway has been highly conserved throughout evolution, making it an important area of study in developmental biology and regenerative medicine. It functions through a complex interplay of extracellular ligands, cell-surface receptors, intracellular mediators, and transcriptional regulators (Krishnapati & Ghaskadbi, 2024). Its precise regulation is essential for the proper development of tissues and organs, while dysregulation can lead to developmental abnormalities, cancer, and fibrosis. In marine organisms, the BMP pathway consists of highly

conserved components that closely resemble their mammalian counterparts, and it begins with the binding of BMP ligands to a receptor complex composed of type I and type II serine/threonine kinase receptors on the surface of a target cell (Gipson et al., 2020; Koosha & Eames, 2022). Upon ligand binding, the type II receptor phosphorylates the type I receptor, initiating a cascade of intracellular signaling events. The activation of these receptors leads to the phosphorylation of intracellular proteins known as Smads, which serve as critical mediators of BMP signaling (Sanchez-Duffhues et al., 2020). Once activated, Smad proteins form complexes that translocate into the nucleus, where they regulate the transcription of specific target genes involved in development, cell growth, and tissue differentiation (Gipson et al., 2020). In addition to canonical Smad-dependent signaling, BMPs can also activate noncanonical pathways involving MAP kinases and other molecules, further expanding their range of biological effects (Gipson et al., 2020).

- **Fibroblast growth factor (FGF) pathway:** It is a crucial signaling network that regulates a wide range of biological processes, including embryonic development, cell growth, tissue repair, angiogenesis, metabolism, and homeostasis (Farooq et al., 2021). FGFs constitute a family of structurally related proteins, which interact with fibroblast growth factor receptors (FGFRs) on the surface of target cells to trigger intracellular signaling cascades (Farooq et al., 2021). The FGF pathway has been evolutionarily conserved across vertebrates and invertebrates, underscoring its fundamental role in orchestrating complex physiological events. Dysregulation of this pathway is implicated in various developmental disorders, cancers, and metabolic diseases, highlighting its significance in both health and disease. The FGF family consists of at least 22 members, which can be grouped into paracrine, endocrine, and intracellular FGFs based on their modes of action (Phan et al., 2021). Paracrine FGFs, such as FGF2 and FGF8, act locally by binding to receptors on neighboring cells, while endocrine FGFs, including FGF19, FGF21, and FGF23, function as hormones that circulate in the bloodstream to exert systemic effects on distant organs (Phan et al., 2021). Intracellular FGFs, which lack a signal peptide for secretion, play roles in modulating intracellular functions. Despite these differences in action, the fundamental mechanism of FGF signaling begins with the binding of an FGF ligand to an FGFR. This interaction is stabilized by the presence of heparan sulfate, a glycosaminoglycan cofactor that enhances ligand–receptor affinity and specificity (Liu, Ni et al., 2023). Upon ligand binding, FGFRs, which are transmembrane tyrosine kinase receptors, undergo dimerization and autophosphorylation. This activates the receptor's intracellular kinase domain, leading to the recruitment of signaling molecules and the initiation of downstream signaling cascades (Phan et al., 2021). The most prominent pathways activated by FGFRs include the Ras-MAPK pathway, the PI3K-Akt pathway, and the phospholipase C-gamma (PLCγ) pathway (Liu, Huang et al., 2023). Each of these pathways plays distinct roles in regulating cellular responses. The Ras-MAPK pathway is primarily involved in promoting cell proliferation and differentiation, while the PI3K-Akt pathway controls cell survival, metabolism, and growth. The PLCγ pathway contributes to calcium signaling and the regulation of gene expression (Farooq et al., 2021). The integration of these signaling pathways allows FGFs to coordinate complex biological outcomes, such as tissue formation and homeostasis.
- **mTOR (mechanistic target of rapamycin) pathway:** It is a central regulatory system that controls cellular metabolism, growth, proliferation, and survival in response to environmental cues such as nutrient availability, energy levels, growth factors, and stress conditions (Wu & Storey, 2021). As a serine/threonine kinase, mTOR integrates these signals to maintain cellular homeostasis, facilitating anabolic processes like protein, lipid, and nucleotide synthesis while inhibiting catabolic processes such as autophagy (Liu, Guo et al., 2024). This pathway is evolutionarily conserved from yeast to humans, underscoring its importance in organismal development and physiology (Huang, Long et al., 2020). Dysregulation of the mTOR pathway is implicated in various diseases, including cancer, diabetes, neurodegenerative disorders, and aging-related conditions. The mTOR pathway is organized around two distinct multiprotein complexes: mTOR complex 1 (mTORC1) and mTOR complex 2 (mTORC2) (Werlen et al., 2021). These complexes differ in their protein composition, upstream activators, downstream targets, and biological functions. mTORC1 contains the protein Raptor (regulatory-associated protein of mTOR), which confers sensitivity to nutrient levels and energy status (Yang et al., 2022). It primarily controls cell growth and metabolism by promoting protein synthesis and inhibiting autophagy. On the other hand, mTORC2 contains rapamycin-insensitive companion of mTOR, which regulates cytoskeletal organization, cell survival, and metabolism. Unlike mTORC1, mTORC2 is less sensitive to nutrient levels and is activated mainly by growth factors such as insulin and IGF-1 (Liu, Guo et al., 2024).

The upstream regulation of mTORC1 involves multiple signaling pathways. One of the key regulators is the tuberous sclerosis complex (TSC1/TSC2), which acts as a negative regulator by inhibiting the small GTPase Rheb. Under favorable conditions, growth factors such as insulin activate the PI3K-Akt pathway, leading to the phosphorylation and inactivation

of TSC2, thereby relieving its inhibition on Rheb (Wu & Storey, 2021). Active Rheb then binds to and activates mTORC1. Nutrient availability also plays a crucial role in mTORC1 activation, for example, amino acids, particularly leucine and arginine, activate mTORC1 by recruiting it to lysosomes, where it interacts with Rheb. Energy levels are monitored through AMP-activated protein kinase, which inhibits mTORC1 under conditions of low energy by phosphorylating TSC2 and mTOR directly (Wu & Storey, 2021). Hypoxia, another environmental stressor, suppresses mTORC1 via the REDD1 protein, which promotes TSC2 activation (Werlen et al., 2021). Once activated, mTORC1 promotes anabolic processes, with a significant focus on protein synthesis. It phosphorylates downstream targets such as ribosomal protein S6 kinase (S6K1) and eukaryotic initiation factor 4E-binding protein 1 (4E-BP1) (Werlen et al., 2021). Phosphorylation of S6K1 enhances ribosome biogenesis and translation, while phosphorylation of 4E-BP1 releases the translation initiation factor eIF4E, facilitating the translation of mRNAs involved in cell growth (Yang et al., 2022). mTORC1 also stimulates lipid synthesis by activating sterol regulatory element–binding proteins, which regulate the expression of enzymes required for cholesterol and fatty acid synthesis. At the same time, mTORC1 inhibits autophagy by phosphorylating and suppressing ULK1, a key initiator of autophagy, thus preventing cellular degradation processes under nutrient-rich conditions.

The role of mTORC2 is more closely related to cell survival, metabolism, and cytoskeletal organization Table 15.1. Upon activation by growth factors, mTORC2 phosphorylates and activates proteins in the Akt pathway, including Akt itself, which promotes cell survival and inhibits apoptosis (Werlen et al., 2021). mTORC2 also influences glucose metabolism by modulating insulin signaling and is involved in the regulation of lipid metabolism. In addition, it phosphorylates protein kinases such as SGK1 and PKC, which are crucial for cytoskeletal rearrangement and cell migration (Yang et al., 2022). These functions of mTORC2 are particularly important in immune cells, where it contributes to immune responses and inflammation.

2.2 Gene conservation and homology

One of the key advantages of using marine organisms as models in biomedical research is the conservation of genetic and molecular pathways across species. Many fundamental biological processes, such as cell division, differentiation, and apoptosis, are regulated by highly conserved genes and signaling pathways. For example, the Wnt signaling pathway, which plays a critical role in embryonic development and cancer, is conserved from sea urchins to humans (Liu, Xiao et al., 2022). Zebrafish (*Danio rerio*), a teleost fish, share a significant proportion of their genome with humans, making them a valuable model for studying vertebrate development and disease. The conservation of genetic pathways involved in heart development and function has made zebrafish an important model for cardiovascular research (Bowley et al., 2022; Yushko et al., 2024). Similarly, the conserved nature of the circadian clock genes between the marine dinoflagellate *Gonyaulax polyedra* and humans has provided insights into the genetic and molecular basis of circadian rhythms (Jones et al., 2024).

Genomic studies have revealed a surprising degree of genetic similarity between humans and various marine organisms. This conservation is evident not only in the presence of homologous genes but also in the preservation of gene order and synteny in some cases. The sea anemone *Nematostella vectensis*, a cnidarian that diverged from the human lineage over 700 million years ago, shares about 80% of its genes with humans (Krueger et al., 2024). This includes genes involved in complex processes such as neural function and immunity, challenging the notion that these systems evolved solely in more complex organisms. In marine vertebrates, the genetic similarity to humans is even more pronounced. Zebrafish (*Danio rerio*), a popular model organism, share approximately 70% of their genes with humans. Moreover, 84% of genes known to be associated with human diseases have a zebrafish counterpart (Yushko et al., 2024). This extensive homology makes zebrafish an excellent model for studying a wide range of human disorders, from rare genetic diseases to complex conditions like cancer and heart disease. Many genes implicated in human diseases have homologs in marine organisms. The tumor suppressor gene p53, crucial in cancer biology, has been identified in organisms ranging from sea anemones to mammals, with conserved functions in DNA damage response and apoptosis (Roy et al., 2024). The study of p53 in marine organisms has provided insights into its evolutionary history and core functions, informing our understanding of its role in human cancers. Similarly, genes involved in neurodegenerative diseases like Alzheimer's and Parkinson's often have functional homologs in marine invertebrates. For instance, the presenilin genes, which are linked to early-onset Alzheimer's disease in humans, have homologs in the sea slug *Aplysia californica*. Studies in Aplysia have elucidated the role of presenilins in synaptic plasticity and memory formation, providing valuable insights into the fundamental functions of these proteins (Akter et al., 2024).

TABLE 15.1 Key pathways and their biomedical relevance.

Signaling pathway	Biological role and mechanism	Relevance to human health	References
Wnt/β-catenin pathway	Regulates embryogenesis, cell fate, tissue homeostasis, and cancer progression through β-catenin accumulation and target gene activation.	Dysregulation is linked to colorectal cancer, liver disease, and neural disorders.	Davidson (2021)
Noncanonical Wnt pathway	Regulates cell polarity and migration independently of β-catenin.	Relevant to tissue regeneration and cancer metastasis.	Guo and Xing (2022)
Wnt/Ca^{2+} pathway	Regulates intracellular calcium signaling.	Modulates processes such as cell adhesion, migration, and inflammatory responses	Qin et al. (2024) and Yu et al. (2021)
Notch pathway	Controls cell fate, tissue development, and apoptosis through receptor-ligand interaction and nuclear translocation of the notch intracellular domain.	Associated with leukemia, neurodevelopmental disorders, and cancers.	Kumari et al. (2024) and McIntyre et al. (2020)
Hedgehog pathway	Governs cell differentiation and organogenesis by activating smoothened (Smo) and GLI transcription factors.	Dysregulation leads to congenital defects and cancers like basal cell carcinoma.	Sigafoos et al. (2021) and Sonnen and Janda (2021)
TGF-β pathway	Regulates cell growth, differentiation, immune responses, and extracellular matrix production through SMAD and non-SMAD pathways.	Implicated in fibrosis, cancer metastasis, and immune dysfunctions.	Tzavlaki and Moustakas (2020)
Bone morphogenetic protein (BMP) pathway	Involved in bone and cartilage formation, embryonic development, and tissue repair through SMAD signaling.	Dysregulation is linked to skeletal disorders, cardiovascular disease, and cancer.	Gipson et al. (2020) and Krishnapati and Ghaskadbi (2024)
Fibroblast growth factor (FGF) pathway	Controls embryonic development, cell proliferation, angiogenesis, and wound healing by activating receptor tyrosine kinases.	Dysregulation is associated with developmental defects, metabolic disorders, and cancer.	Farooq et al. (2021)
mTOR pathway	Regulates cell growth, protein synthesis, and metabolism by sensing nutrients and energy levels.	Dysfunction is linked to cancers, neurodegenerative diseases, and metabolic disorders.	Wu and Storey (2021) and Yang et al. (2022)
PI3K/Akt pathway	Promotes survival, metabolism, and angiogenesis through phosphorylation cascades.	Implicated in diabetes, cardiovascular diseases, and cancer progression.	Farooq et al. (2021)
Ras-MAPK pathway	Promotes cell proliferation and differentiation.	Tissue formation and homeostasis	Farooq et al. (2021)
PLCγ pathway	Contribute to calcium signaling and the regulation of gene expression	Tissue formation and homeostasis	Farooq et al. (2021)

2.3 Evolutionary developmental biology (Evo-Devo)

The field of evolutionary developmental biology, or "evo-devo," has been particularly influential in leveraging marine organisms to understand human development and disease. By comparing developmental processes across diverse marine species, researchers can identify conserved "toolkit" genes that play crucial roles in body plan formation and organ development (Love, 2024). Sea urchins have been instrumental in evo-devo research, particularly in understanding the gene regulatory networks governing early development. The sea urchin embryo, with its relatively simple and transparent structure, allows for detailed observation of developmental processes. Studies on sea urchins have elucidated the gene regulatory networks controlling the specification of germ layers and the development of the skeleton, providing a framework for understanding similar processes in more complex organisms, including humans (Zhou et al., 2024). Research on the ascidian *Ciona intestinalis* has revealed conserved gene regulatory networks involved in heart development. Despite their simple body plan, ascidians possess a heart-like organ that shares developmental origins with the vertebrate heart. Studies in Ciona have identified key transcription factors and signaling molecules involved in heart development, many of which have human homologs implicated in congenital heart defects (Huang et al., 2023). The study of cnidarians, such as the sea anemone *Nematostella vectensis*, has provided insights into the evolution of body axes and the ancient origins of many human genes involved in development and disease (Smith et al., 2023). Despite their radially symmetric adult form, cnidarians exhibit molecular asymmetries during development that are governed by conserved genes also involved in vertebrate axial patterning. This research has implications for understanding birth defects and developmental disorders in humans (Love, 2024).

2.4 Evolutionary innovations and unique adaptations

While conservation is a key aspect, evolutionary innovations in marine organisms also provide valuable models for studying human biology and disease. Some marine species have evolved unique adaptations that make them particularly suited for studying specific biological processes or diseases. The remarkable regenerative abilities of some marine organisms offer a prime example of how evolutionary innovations can inform human medicine. Planarians, for instance, can regenerate entire body parts, including their brain, from small tissue fragments. This ability is due to a population of adult stem cells called neoblasts, which are distributed throughout their body. Studying planarian regeneration has led to the identification of key genes and signaling pathways involved in stem cell regulation and tissue repair, some of which are conserved but inactive in humans (Morkotinis, 2023; Rajagopalan et al., 2024). Zebrafish also possess significant regenerative capabilities, particularly in their heart and fins. Unlike humans, adult zebrafish can regenerate heart tissue after injury, making them an excellent model for studying cardiac regeneration. Research in zebrafish has identified factors that promote heart regeneration, such as the protein neuregulin 1, which has potential therapeutic applications in treating human heart disease (Bowley et al., 2022).

The study of marine organisms that have evolved resistance to cancer, such as sharks and whales, may provide insights into novel tumor suppression mechanisms. These animals, which have long lifespans and large body sizes, theoretically should have a higher risk of cancer due to increased cell divisions and potential mutations. However, they exhibit remarkably low cancer rates, a phenomenon known as Peto's paradox (Plutynski, 2023). Research has revealed that these animals have evolved enhanced DNA repair mechanisms and additional copies of tumor suppressor genes. For example, elephants, while not marine animals, provide a terrestrial example of this phenomenon with multiple copies of the p53 gene, offering insights that could be applied to marine mammals (Trivedi et al., 2023). Some marine organisms have evolved unique sensory systems that can serve as models for studying human sensory biology and related disorders. The electroreceptive organs of sharks and rays, for instance, provide a unique platform for studying sensory systems and neurological disorders. These organs, which detect weak electrical fields in the water, involve ion channels and sensory neurons that share similarities with human sensory systems. Studying these specialized organs has provided insights into the evolution and function of ion channels, which are implicated in various human neurological disorders (Hassani, 2023).

2.5 Convergent evolution and analogous systems

In some cases, marine organisms have evolved similar traits or mechanisms to humans through convergent evolution. While not directly homologous, these analogous systems can still provide valuable insights into human biology and disease. The complex eyes of cephalopods like octopuses and squids evolved independently from vertebrate eyes, yet both share similar structures and functions. This convergent evolution of camera-type eyes offers a unique opportunity to study the genetic and developmental mechanisms underlying complex organ formation. Research on cephalopod vision has

provided insights into the evolution of light-sensing proteins (opsins) and the development of complex neural circuits for visual processing. These studies have implications for understanding human eye diseases and the evolution of sensory systems (Brodrick & Jékely, 2023). Another example of convergent evolution is the presence of complex social behaviors in some marine organisms. The social structures of dolphins and whales, for instance, share similarities with human social organizations. Studying these analogous social systems can provide insights into the evolution of social behavior and cognitive abilities, with potential implications for understanding social cognitive disorders in humans (Kheloui et al., 2023; Slavich et al., 2023).

2.6 Application of evolutionary perspective

- **Implications for drug discovery and therapeutics:** The evolutionary perspective also has important implications for drug discovery and development. Many bioactive compounds produced by marine organisms have evolved to interact with conserved molecular targets, making them potential sources of new therapeutics for human diseases (Rigogliuso et al., 2023). Marine natural products have been a rich source of drug leads. For example, the discovery of spisulosine, a compound derived from the sea mollusk *Spisula polynyma*, led to the development of ES-285, a drug candidate for treating various cancers (Patra et al., 2020; Ngandjui et al., 2024). The evolutionary conservation of the compound's target between mollusks and humans made this discovery possible. Another example is the development of ziconotide (Prialt), a pain medication derived from the venom of cone snails (Trevisan & Oliveira, 2022). This drug targets voltage-gated calcium channels, which are highly conserved across species. The study of cone snail venom peptides has not only led to new therapeutics but also provided insights into the structure and function of ion channels implicated in various human neurological disorders (Caliskan & Corzo, 2023). The study of extremophile marine organisms, such as those living in deep-sea hydrothermal vents, has led to the discovery of enzymes with unique properties. These enzymes, adapted to extreme conditions, have found applications in biotechnology and have the potential to inform the development of more stable and efficient protein-based therapeutics for human use (Caliskan & Corzo, 2023).
- **Evolutionary medicine and human health:** The evolutionary perspective in studying marine organisms extends to the broader field of evolutionary medicine, which applies evolutionary principles to understanding human health and disease. This approach considers how our evolutionary history, including adaptations to past environments, influences our susceptibility to modern diseases. For instance, studying the dietary adaptations of marine mammals can provide insights into human metabolic disorders (Yuan et al., 2021). The evolution of blubber in marine mammals involves adaptations in lipid metabolism that could inform our understanding of obesity and related conditions in humans (Blawas et al., 2024). Similarly, the study of marine organisms' immune systems can shed light on the evolution of immunity and inform our approach to treating immune-related disorders. The discovery of a simpler yet effective adaptive immune system in lampreys and hagfish, for example, has provided insights into the evolution of vertebrate immunity and suggested new approaches to immunotherapy (Blawas et al., 2024).

The evolutionary perspective provides a strong theoretical foundation for the use of marine organisms as models for studying human diseases. It justifies the relevance of these models, guides the selection of appropriate organisms for specific research questions, and informs the interpretation of findings in the context of human health. By understanding the evolutionary relationships and conservation of biological processes between marine life and humans, researchers can leverage the vast biodiversity of the oceans to advance our understanding of human biology and disease. This approach not only enhances our fundamental knowledge but also opens new avenues for therapeutic interventions and drug discovery, potentially revolutionizing the field of medicine.

3. Selection criteria for marine model organisms

The careful selection of marine organisms for biomedical research is essential to ensure relevance, reproducibility, and translatability of findings to human diseases. Marine organisms provide unique advantages due to their biological diversity, evolutionary proximity to vertebrates, and specific traits that allow exploration of complex biological processes (Rabosky, 2022). The primary criteria used to select marine model organisms for biomedical studies include genomic and evolutionary relevance to humans, accessibility and breeding capacity, unique biological features, molecular and genomic tools, relevance to disease models, ethical and conservative considerations, reproductive and lifespan, and finally, the omics technologies and system biology (Fig. 15.3) (Faktorová et al., 2020; Freires et al., 2023).

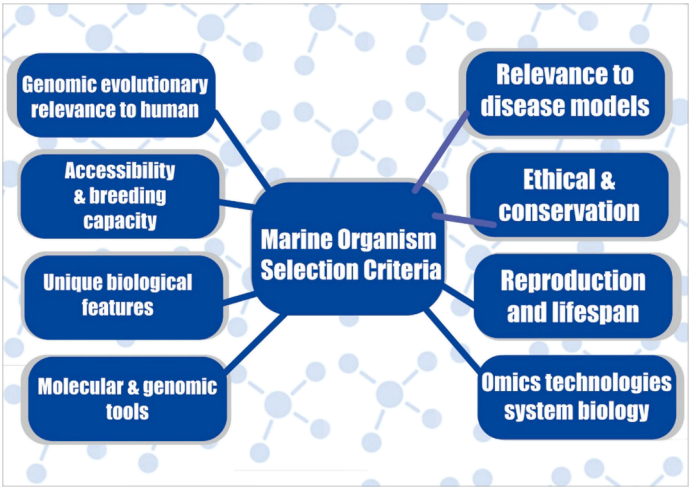

FIGURE 15.3 Marine organism selection criteria.

3.1 Genomic and evolutionary relevance to humans

A model marine organism should share significant genetic homology with humans, enabling the study of conserved biological processes (Guryanova & Ovchinnikova, 2022). Comparative genomics helps identify which marine organisms can provide insights into human physiology and pathology. Marine species that share significant portions of their genomes with humans allow scientists to investigate basic pathways involved in development, immune responses, and disease mechanisms (Balbi et al., 2021; Montuori et al., 2022). The sea urchins (*Strongylocentrotus purpuratus*) share over 7000 genes with humans, including those involved in immune functions and neurological processes (Kang et al., 2020; Stöhr, 2021). These organisms have contributed to understanding immune system evolution and disease susceptibility. Similarly, tunicates, like *Ciona intestinalis*, which belong to the phylum Chordata (making them evolutionarily closer to vertebrates), exhibit conserved gene networks and embryological pathways involved in organogenesis, allowing researchers to explore human developmental processes and regeneration (Buono et al., 2024; Zhang et al., 2020). The genetic homology between these organisms and humans makes them valuable for studying conserved signaling pathways like Wnt, Hedgehog, and Notch, which play crucial roles in both normal development and disease states (Arizza et al., 2020).

3.2 Experimental accessibility and breeding capacity

Marine model organisms are selected based on their ease of handling, breeding, and experimental manipulation. Organisms like zebrafish (*Danio rerio*) and African clawed frog (*Xenopus tropicalis*) are widely used due to their rapid development, external fertilization, and transparent embryos (Blahova et al., 2021). These features allow for real-time observation of embryonic development and facilitate experimental interventions and genetic studies (Medina-Cuadra & Monsoro-Burq, 2021). Katoch and Patial (2021) reported that zebrafish are especially valuable in drug screening and genetic studies, and with a short generation time and large clutch sizes, they support high-throughput experiments and genetic manipulation through CRISPR/Cas9. Sea urchins and ascidians are also popular because they can be maintained under laboratory conditions, have predictable developmental stages, and provide access to early-stage embryos for cell lineage tracing (Eliso et al., 2020). The ability to manipulate these organisms at various developmental stages has significantly contributed to research in developmental biology and disease modeling (Hamdoun et al., 2023, pp. 181–201; Johnstone et al., 2022).

3.3 Unique biological features of marine species

Marine organisms possess distinct biological features that provide unique insights into regenerative processes and disease mechanisms. Planarians are known for their remarkable regenerative abilities, making them an ideal model for studying stem cells and tissue regeneration. These flatworms can regenerate entire organs and body parts, offering a model to understand pluripotency and stem cell behavior (Ge et al., 2022). Echinoderms, such as sea cucumbers and sea stars, have an innate immune system that lacks adaptive components (Wu et al., 2020; Pespeni & Lloyd, 2023). These species allow

the study of ancient immune strategies, which offer new perspectives on immune-related diseases (Pespeni & Lloyd, 2023; Wu et al., 2020). These unique traits provide researchers with tools to study phenomena like regeneration, immune responses, and aging that are not easily observed in traditional vertebrate models (Wu et al., 2020).

3.4 Availability of molecular and genomic tools

The usefulness of a marine model depends on the availability of genetic, molecular, and biochemical tools. Technologies such as CRISPR/Cas9, RNA interference, transgenesis, and single-cell RNA sequencing (scRNA-Seq) are crucial for functional genomics and enhance the utility of marine organisms in studying gene function and disease pathways (Black et al., 2024; Robinson et al., 2023). Zebrafish are favored for their genetic tractability, with multiple transgenic lines available for research on cancer, CVDs, and neurodegenerative disorders (Doyle & Croll, 2022). *Xenopus tropicalis* is an essential model for studying vertebrate development and has benefited from CRISPR/Cas9 technologies, enabling gene knockouts and functional genomics (Willsey et al., 2024). Sea urchins have become a useful model for epigenetic research, with tools available for genome-wide association studies and transcriptomics (Liu, Zeng et al., 2023; Wang et al., 2022). The accessibility of these molecular tools allows for targeted research, particularly on conserved developmental pathways and disease models.

3.5 Ethical and conservation considerations

The use of marine species in research must align with conservation efforts and ethical guidelines, and species with sustainable populations and low ecological impact are preferred. Marine organisms such as sea urchins and tunicates, which can be easily bred in captivity, are often selected for studies to avoid depleting wild populations (Das & Patel, 2020). Sea urchins are widely used for developmental studies due to their availability and minimal ecological impact and their ability to spawn large numbers of gametes ensures sustainable research practices (Adonin et al., 2021). Zebrafish breeding programs allow for large-scale studies without environmental concerns, given their well-established care guidelines and high fecundity (Kent et al., 2020; Kohale, 2021, pp. 277–311). Marine research also aligns with ethical guidelines that emphasize minimizing harm and using species sustainably, ensuring compliance with environmental and research ethics protocols (Buchan et al., 2023).

3.6 Relevance to disease models

Marine organisms are selected based on their relevance to specific human diseases. Their unique physiology and genetic makeup enable disease modeling in areas such as cancer, neurodegeneration, and cardiovascular disorders. Studies have shown that zebrafish are extensively used to study cancer, as tumors induced in zebrafish models display behaviors like human malignancies, including metastasis (Astell & Sieger, 2020). Sea urchins have been employed to investigate oxidative stress and neurodegenerative diseases, contributing to research on Alzheimer's disease (Khotimchenko et al., 2022). Ascidians aid in the understanding of cardiovascular biology and regenerative medicine, as they exhibit heart regeneration capabilities, which have implications for treating heart diseases (Rizzo-Valente et al., 2022). These models allow researchers to develop a deeper understanding of disease mechanisms and evaluate therapeutic interventions.

3.7 High reproductive capacity and lifespan considerations

Marine organisms with high fecundity and short generation times are preferred for research to enable fast experimental cycles (Kohale, 2021, pp. 277–311). Species like zebrafish, which produce many offspring in a short period, allow for large-scale studies and genetic screening (Dubey et al., 2022). Furthermore, marine organisms with predictable developmental stages (e.g., sea urchins) are ideal for studying developmental biology and toxicology (Pontheaux et al., 2021).

3.8 Omics technologies and systems biology approaches

The integration of omics technologies has revolutionized the use of marine models in biomedical research. The sequencing of marine species, like sea urchins and tunicates, has provided comprehensive insights into their gene networks and evolutionary history. Single-cell RNA-seq in planarians has identified molecular signatures of pluripotent stem cells, contributing to advancements in regenerative medicine (Maynard et al., 2024). These approaches in marine organisms have helped identify disease biomarkers and metabolic pathways relevant to human health (Ferrario et al., 2020).

Omics technologies allow researchers to explore complex biological systems holistically, bridging gaps between marine biology and human medicine.

4. Model marine organisms

Marine organisms have become indispensable in research due to their unique characteristics, evolutionary conservation, and potential to model human biological processes. These species offer insights into development, regeneration, genetics, and disease mechanisms.

4.1 Zebrafish (*Danio rerio*)

Zebrafish also known as *Danio rerio* is a freshwater fish that belongs to the Cyprinidae family. Though it is both a tropical and subtropical animal, it is often called a tropical fish. It is one of the best leading models used to study developmental biology, cancer, toxicology, molecular genetics, and drug discovery due to their high genetic similarity to humans and their ease of maintenance (Larijani et al., 2021). Approximately 70% of human genes have zebrafish counterparts (Tal et al., 2020). It is also remarkable for its regenerative abilities and has been modified by researchers to produce many transgenic strains (Weinberger et al., 2024). They are asynchronous spawners, which under favorable conditions such as water parameters and food availability, can spawn daily (Maqsood et al., 2024). For ovulation and fertilization to occur, the male and female zebrafish must be present. The female zebrafish can lay eggs in hundreds every 2–3 days facilitating high-throughput studies. The eggs afterward start to form an embryo which stops in the absence of sperm after the prior cell divisions. The appearance of the fertilized egg becomes transparent following fertilization. Their embryo goes through a fast development in which the precursor cells responsible for organ development will appear in 36 hours postfertilization. First, it starts as a yolk with one big cell at the top, and then it divides into 2 and continues to divide until there is presence of many cells. These cells will then move along the sides of the yolk and start forming a head and tail. Likewise, the tail will get elongated and detaches from the body. With time, the yolk will reduce since the fish will use it for nutrition in the earlier days. With many months passing, the adult fish reaches reproductive maturity (Ghate et al., 2023).

The high level of similarity in the genome structure of zebrafish and humans makes it more suitable to be used as a model organism in the study of human genetic disease. Zebrafish produce hundreds of embryos in a single clutch, which are fast, relatively large, optically clear, and can develop independently of their mother (Hajam et al., 2021; Maqsood et al., 2024). This allows for live imaging of the organism during studies. Zebrafish models have enabled the study of tumor growth and metastasis, helping researchers identify oncogenes and screen anticancer drugs. Their hearts regenerate efficiently after injury, making them ideal models for studying heart diseases and potential therapies for myocardial infarction. Their larvae are useful in drug screening and toxicology tests due to their small size and transparency. They have been used as a model organism to study several human diseases such as mental disorders and metabolic diseases (Choi et al., 2021). Its application has also been effective in the study of human neurodegenerative disorders such as Parkinson's, epilepsy, and autism (Yushko et al., 2023). Brain functions such as sleep, memory, and learning can be analyzed through behavioral assays.

4.2 Sea urchins (*Strongylocentrotus purpuratus*)

Sea urchins have long been essential models for developmental biology due to their simple yet representative embryonic stages. Their evolutionary proximity to vertebrates makes them useful for studying conserved biological pathways. Sea urchins are aquatic organisms utilized over the years in developmental and biological research. They are spiny animals belonging to the Echinoidea class and have served a crucial role in understanding cellular physiologies, developmental biology, processes of evolution, and disease modeling. As model organisms, sea urchins possess spectacular characteristics that make them scientifically adequate studies. These characteristics consist of its embryonic development and its large egg tendencies, which are visually clear (Molla & Aljahdali, 2023). They are dioecious organisms, possessing separate male and female sexes with each of the reproductive organs producing either male-or-female gametes. However, differentiating them by their physical morphology is quite difficult. The adult sea urchins can be male or female, having normal sex ratio of 1:1; both sexes go through spawning and produce their gametes (egg or sperm) into the sea water where mixing and fertilization of the eggs occur, forming a blastula embryo within 12 hours. Their fertilization is external which enhances easy access to gametes, and they also undergo rapid embryogenesis which facilitates time-lapse observation of development. The blastula in turn transforms into a cone-shaped echinopluteus larva. In most species,

this larva possesses 12 long-arms lined with bands of cilia that assist in capturing of food particles and sending the food particles to the mouth for feeding (Costantini et al., 2024).

Usually, it requires the larva many months to complete its maturity. In early development of sea urchins, its embryo goes through 10 cycles of cell division resulting in a single epithelial layer enveloping the blastocoel (Molla & Aljahdali, 2023). After that, the embryo begins the process of gastrulation, which rearranges the structure of the embryo to produce the three germ layers, involving an EMT; primary mesenchyme cells move into the blastocoel and become mesoderm (Molla & Aljahdali, 2023). A peculiar feature of a sea urchin development is the replacement of the larva's bilateral symmetry by the adult's broadly five-fold symmetry. Mesoderm and small micromeres are specified during cleavage. Coelomic pouches are formed by the cells of these two types at the end of gastrulation. In the larval states, the adult rudiment grows to become the adult. The oral–aboral axis feature is specified early in cleavage, and the left–right axis appears at the late gastrula stage (Costantini et al., 2024).

As deuterostomes, sea urchins share similarities in development with vertebrates, such as the formation of the embryonic gut (blastopore) and signaling pathways (McClay et al., 2020). Some important features of sea urchins that make it relevant to disease modeling are their embryonic development, which is like that of humans than other invertebrates. The sea urchin immune system contains numerous innate immune receptors like those in humans, making them useful models for studying immunity (Guryanova & Ovchinnikova, 2022). Because sea urchins are sensitive to environmental stressors, they serve as valuable indicators for ecological health and oceanic pollution. Also, their large, optically clear eggs and embryos allow for easy manipulation of the cells, thus making them an idea organism for studying the mechanisms of fertilization, gene expression, and early embryonic development. Recently, the embryo of a sea urchin plays a role as a model to study some diseases of humans such as in the study of neurodegenerative disorders that can cause dementia and memory loss (Li, Boldt et al., 2024, Li, Yu et al., 2024; Lin et al., 2023). This study is made possible due to what happens during gastrulation; a larval nervous system arises within the ectoderm of the embryo. Some of the neurodegenerative disorders studied includes Parkinson's, Alzheimer's, and Huntington's diseases (Ascanelli et al., 2024).

4.3 Marine sponges

Marine sponges are invertebrate organisms that belong to the phylum Porifera. They are found in temperate, tropical, and polar regions. They are filter feeders; they thrive with potentially hazardous particles by producing neutralizing bioactive compounds making them valuable for pharmacology. Sponges synthesize these bioactive compounds and are major contributors of bioactive compounds discovered in and extracted from the marine environment (Varijakzhan et al., 2021). They are believed to be some of the most basal animals alive till date and are possibly the first to branch off the evolutionary tree from the last common ancestor of all animals, which would make them the sister group of all other animals (Rossi, 2024). The compounds obtained from these sponges are known to exhibit various bioactivities, such as antimicrobial, antitumor, and general cytotoxicity. Marine-sponges like *Theonella swinhoei* for instance have exhibited various bioactivities, such as antiviral, antifungal, and antibacterial activities (Varijakzhan et al., 2021).

Sponges lack true tissues and organs but exhibit complex cell communication and immune responses. The lifecycle of the aquatic sponges involves sexual and asexual reproduction. The majority of the sponges reproducing by sexual means are hermaphrodites releasing eggs and sperm at diverse times. They often disperse sperms into the water space and these sperms are further captured by the female-sponges of similar species. Once the sperm gets into the female sponges, they will be sent to the eggs by unique or specific cells termed "archaeocytes," and fertilization occurs in the mesenchyme. Sponges in temperate regions live for at most a few years, but some tropical and deep-ocean species may live for 200 years or more. The synthesis of bioactive compounds by marine sponges makes it a good model for studying some human disease conditions. Just recently, it was shown that most genes linked to human diseases, such as cancer genes, evolved in two major evolutionary transitions—the emergency of unicellular organisms and the transition of multicellularity (Niculescu, 2022). It has been established that human diseases can be studied by analyzing genes and proteins that cause the disease using model organisms that belong to the evolutionary level at which these genes have emerged. Sponges are an ideal model organism for such studies, having a wild variety of genes known to be engaged in complex processes and signaling pathways associated with higher animals (Rossi, 2024). Human diseases such as cancer, bacterial, viral, fungal, malarial, and inflammations have been studied using bioactive compounds from marine sponges as a model organism (Varijakzhan et al., 2021).

4.4 Ascidians (Tunicates, *Ciona intestinalis*)

The ascidian *Ciona intestinalis*, also known as sea squirt, belongs to the phylum Chordata, Class Ascidiacea, and plays a pivotal role in understanding the evolutionary transition from invertebrates to vertebrates. It is a filter feeder and has

emerged as a significant model for studying embryology due to its straightforward representation of chordate development. It features a compact genome, a larval stage capable of free swimming, and embryogenesis characterized by precise cell division patterns (Yaguchi & Wada, 2022). The adult sea squirts are simple, sessile filter feeders. The embryos and larvae exhibit distinct chordate characteristics, such as a well-defined notochord (a precursor to the vertebrate spinal cord) and a dorsal, hollow neural tube. *Ciona* embryos have relatively few cells, which makes it possible to trace every cell division from a fertilized egg to a fully formed larva. Embryos at the tail-bud stage and mature swimming tadpoles are composed of approximately 1000 and 2600 cells, respectively, and have comprehensive lineage information (Stracke & Hejnol, 2023). The embryos are transparent, allowing real-time observation of developmental processes such as cell division and tissue morphogenesis. Ascidians help researchers explore the origins and evolution of vertebrates. Some tunicates possess remarkable regenerative abilities, providing insights into tissue regeneration and repair mechanisms. Sea squirts have been used in the study of human neurodegenerative disorders such as Alzheimer's disease and Parkinson's disease (Choi et al., 2021).

4.5 Octopus and other cephalopods

Cephalopods, particularly octopuses, have emerged as fascinating model organisms in biomedical research due to their remarkable biological features and sophisticated nervous systems. Octopuses possess an extraordinarily complex nervous system, comprising approximately 500 million neurons, with two-thirds distributed throughout their arms (Nesher et al., 2020). This unique neural architecture provides an excellent model for studying nervous system organization and function. Their nervous system exhibits remarkable similarities to vertebrate neural circuits, despite evolving independently. Pungor and Niell (2023) reported that the presence of a sophisticated camera-like eye, strikingly similar to human eyes, makes them excellent models for vision research and eye development studies. The adaptive camouflage abilities of cephalopods, achieved through specialized skin cells called chromatophores, offer insights into cellular communication and control mechanisms. Their ability to rapidly change both color and texture has implications for understanding complex cellular responses and signal transduction pathways (Deravi, 2021). Moreover, their extraordinary regenerative capabilities, particularly in octopus' arms, present opportunities for studying tissue regeneration and wound healing mechanisms (Pérez-Polo et al., 2024). The reproduction of the octopus presents unique features that make them valuable for developmental biology studies. Female octopuses typically lay thousands of eggs, which they tend meticulously until hatching. The embryonic development occurs within transparent eggs, allowing direct observation of developmental processes. This transparency enables researchers to study organogenesis, neural development, and genetic expression patterns in real time (Bauer et al., 2021). The reproductive cycle of octopuses is particularly interesting from a research perspective. After mating, female octopuses undergo significant physiological changes, including cessation of feeding and eventual death after their eggs hatch. This programmed senescence provides insights into aging processes and end-of-life mechanisms. The short lifespan of most cephalopods (1–2 years) allows for rapid generational studies and aging research (Pierce et al., 2024).

They serve as excellent models for various biomedical research areas. Their sophisticated nervous system makes them valuable for studying neurodegenerative diseases and neural regeneration. The similarity between octopus and human eyes provides opportunities for research into retinal diseases and visual processing disorders (Buckley et al., 2022). Studies have shown that their unique immune system, which differs significantly from vertebrates while maintaining effective pathogen defense, offers insights into alternative immune mechanisms and potential therapeutic approaches (Gerdol et al., 2020; Imran et al., 2023). The study of their venom components has led to discoveries of novel bioactive compounds with potential pharmaceutical applications (Romano et al., 2022). Behavioral studies with octopuses have contributed to our understanding of learning, memory, and cognitive processes (Schnell et al., 2021). The problem-solving abilities and capacity of the cephalopods for both short- and long-term memory make them excellent models for studying the biological basis of intelligence and learning (Earl, 2023; Schnell et al., 2021).

4.6 Planarians

Planarians have emerged as a valuable model organism in scientific research due to their extraordinary regenerative capabilities, simple body plan, and evolutionary significance (Kangale et al., 2021). They belong to the phylum Platyhelminthes and are free-living flatworms, commonly found in freshwater environments, although some species also inhabit marine and terrestrial ecosystems. A study by Chen and Lei (2023) has provided key insights into fundamental biological processes such as regeneration, stem cell biology, and tissue patterning, making them an important tool for understanding complex biological phenomena in higher organisms. These organisms can regenerate a complete body from

a small fragment, making them ideal for studying cellular differentiation and tissue renewal. Regeneration in planarians is driven by pluripotent stem cells called neoblasts, which are distributed throughout the body (Golfeshan et al., 2022). Neoblasts are capable of differentiating into any cell type required for rebuilding lost tissues, including muscle, nervous tissue, and epithelial cells. Some research on planarians has significantly advanced the understanding of stem cell behavior, tissue polarity, and the genetic mechanisms underlying regeneration, offering potential applications in medicine, particularly in regenerative therapies and tissue engineering (Molina Jiménez & Cebrià Sánchez, 2021). The morphology of planarians is relatively simple, yet it showcases features that are shared with more complex organisms. Their body is soft and dorsoventrally flattened, which facilitates gas exchange directly through the skin, as they lack specialized respiratory or circulatory systems. The anterior part of the body contains a pair of simple eyespots, which allow planarians to detect light, though not to form images. They also possess a basic centralized nervous system, comprising two cerebral ganglia connected by longitudinal nerve cords. This arrangement provides insights into the evolution of the nervous system and serves as a model for understanding neuronal function and regeneration (Kuznetsov et al., 2024).

Reproduction in planarians can occur through both sexual and asexual means, demonstrating the versatility of their life cycle. In sexual reproduction, most planarians are hermaphroditic, meaning that each individual contains both male and female reproductive organs. They typically engage in reciprocal copulation, where two individuals exchange sperm to fertilize eggs. Fertilized eggs are deposited in protective cocoons, which hatch into juvenile planarians. Sexual reproduction contributes to genetic diversity, which is essential for adaptation to changing environments (Guo et al., 2022). Asexual reproduction occurs through fission, a process where the planarian splits its body into two or more parts. Each fragment regenerates the missing tissues, resulting in genetically identical offspring. This form of reproduction relies heavily on the activity of neoblasts to rebuild the entire organism. Asexual reproduction allows planarians to quickly increase their population size under favorable conditions and has made them an invaluable model for studying cellular mechanisms of regeneration and stem cell proliferation. The simplicity and regenerative potential of planarians have made them a cornerstone of developmental biology research (Golfeshan et al., 2022). Their ability to regenerate entire organs and body structures after injury provides a unique system for examining molecular pathways involved in tissue repair and organogenesis (Pérez-Polo et al., 2024). Furthermore, research on planarians has helped elucidate signaling pathways such as Wnt, Hedgehog, and BMP, which are also conserved in vertebrates and play crucial roles in development and disease (Gao, Fan et al., 2021). Planarians have also contributed to studies on aging, behavior, and toxicology. Their simple nervous system, combined with their ability to regenerate neurons, has made them an attractive model for studying neurodegeneration and neuroplasticity. Gao et al. (2022) reported that the effects of environmental toxins and pollutants can be easily observed in planarians, as exposure to harmful substances impacts their regeneration ability and overall health.

4.7 Hydra

Hydra, a genus of freshwater cnidarians, has become an essential model organism in developmental biology, regenerative research, and evolutionary studies. Belonging to the phylum Cnidaria, these organisms possess a simple body structure but demonstrate complex biological processes that offer insights into cellular regeneration, aging, and morphogenesis. They have gained prominence in research due to their ability to regenerate from small tissue fragments or even dissociated cells, its continuous stem cell proliferation, and its simplicity as a biological model (Zullo et al., 2020). Their study provides significant insights into fundamental biological processes, some of which are conserved in higher organisms, including humans. A key feature of hydra is its tubular, radially symmetric body, which is composed of two distinct cell layers: the outer ectoderm and the inner endoderm, separated by a gelatinous ECM called the mesoglea (Gooshvar et al., 2023). The body is organized with a basal disc at one end, used for attachment to substrates, and a mouth opening surrounded by tentacles at the opposite end. These tentacles are equipped with specialized cells called cnidocytes, which contain nematocysts capable of delivering toxins to immobilize prey (Das & Patel, 2020). Its simple structure, combined with its ability to respond to environmental stimuli, has made it a valuable system for investigating cellular differentiation and the evolution of nervous systems. Hydra's ability to regenerate entire organisms from small fragments has placed it at the forefront of stem cell research. Regeneration in hydra is made possible by three main stem cell lineages: ectodermal, endodermal, and interstitial cells (Ghaskadbi, 2020). These stem cells continuously undergo self-renewal, enabling hydra to replace aged or damaged cells throughout its life (Schenkelaars et al., 2020). This feature allows researchers to study the molecular mechanisms that regulate cell fate, tissue remodeling, and pattern formation. Notably, research on Hydra has contributed to understanding the roles of key signaling pathways, such as Wnt and Notch, which also play essential roles in vertebrate development and disease (Ghaskadbi, 2020).

Reproduction in hydra occurs both sexually and asexually, reflecting the organism's ability to adapt to changing environmental conditions. In favorable conditions, they primarily reproduce asexually by budding. In this process, a small outgrowth, or bud, forms on the parent's body and develops into a genetically identical clone. Once fully formed, the bud detaches from the parent, becoming an independent individual (Holstein, 2024). Asexual reproduction allows hydra to rapidly increase its population, making it an ideal system for experiments that require large sample sizes. Sexual reproduction in hydra occurs when environmental stress triggers the formation of reproductive organs. Some hydra species are hermaphroditic, while others have separate sexes. During sexual reproduction, testes or ovaries develop on the body, producing sperm and eggs, respectively. Fertilization results in a zygote that develops into a resistant cyst, which can survive harsh conditions until favorable environments return. The cyst eventually hatches into a new hydra, contributing to genetic diversity (Lechable et al., 2020). Sexual reproduction in hydra offers insights into developmental plasticity, germline formation, and the evolutionary dynamics of cnidarian reproduction. One of the most intriguing aspects of hydra is its apparent biological immortality. Unlike most organisms, hydra shows no signs of aging, and its cells do not exhibit replicative senescence. Continuous stem cell activity allows it to maintain tissue integrity indefinitely, making hydra an exceptional model for studying the biology of aging and mechanisms that prevent cellular deterioration (Lathe & St. Clair, 2023). Understanding how hydra maintains its cellular health may provide clues for developing therapies to combat age-related diseases in humans.

Hydra's relatively simple nervous system, known as a nerve net, is another important area of study. The nerve net consists of interconnected neurons distributed throughout the body, without a centralized brain. This arrangement provides valuable insights into the evolution of nervous systems and neural plasticity. Notably, Hydra's neurons can regenerate following injury, making it an important model for investigating neurogenesis and nervous system repair. Studies on synaptic connections in Hydra have also advanced understanding of how primitive neural circuits function, offering a comparative framework for research on vertebrate nervous systems (Moroz & Romanova, 2022). In addition to their roles in regeneration and neural studies, hydra has been utilized in toxicology research to assess environmental pollutants and their effects on living organisms. Hydra's sensitivity to chemical changes in its environment makes it an effective bioindicator for water quality. Toxicological studies often use hydra to observe changes in morphology, feeding behavior, and regeneration capacity in response to pollutants, helping scientists understand the environmental impact of various contaminants (Vimalkumar et al., 2022).

4.8 Corals

Corals, belonging to the phylum Cnidaria and the class Anthozoa, have emerged as important model organisms in various fields, including evolutionary biology, ecology, climate science, and symbiosis research. They exist as colonies of genetically identical polyps, form reef ecosystems that host diverse marine life, making them critical to marine biodiversity and ecosystem services (Donovan et al., 2023). The study of corals is crucial for understanding not only the biology of these marine organisms but also the broader implications of climate change on marine ecosystems. One of the defining features of corals is their symbiotic relationship with photosynthetic dinoflagellates of the genus *Symbiodinium*, commonly referred to as zooxanthellae (Curran & Barnard, 2021). This mutualistic relationship is fundamental to coral physiology and the productivity of coral reefs. The algae reside within the tissues of corals, providing the host with essential nutrients through photosynthesis, while the corals, in turn, offer protection and access to sunlight (Shah & Shah, 2021). This symbiosis exemplifies complex interspecies interactions, and research on corals has significantly advanced the understanding of mutualistic relationships, nutrient cycling, and cellular communication (Rädecker et al., 2021).

The morphology of corals varies widely, ranging from massive boulder-like forms to branching structures. Individual coral polyps have a cylindrical shape, with a mouth surrounded by tentacles that are equipped with cnidocytes—specialized cells containing stinging organelles called nematocysts. These nematocysts allow corals to capture small plankton and other prey, supplementing the nutrition provided by their symbionts (Rädecker et al., 2021). Levy and Mass (2022) reported that they secrete calcium carbonate exoskeletons, which accumulate over time to form coral reefs. This process, known as biomineralization, has become a focal point of research, as it sheds light on how marine organisms interact with their physical environment and respond to changing oceanic conditions, such as ocean acidification. Reproduction in corals is highly diverse, with both sexual and asexual modes contributing to their population dynamics. Asexual reproduction occurs through budding and fragmentation. In budding, new polyps form from existing ones, leading to the growth of the coral colony. Fragmentation, on the other hand, occurs when parts of the colony break off, often due to physical disturbances, and establish new colonies elsewhere. Asexual reproduction plays a vital role in the maintenance and expansion of coral reefs, especially in stable environments (Caruso et al., 2021).

Sexual reproduction in corals typically involves mass spawning events, where corals release gametes—eggs and sperm—into the water column simultaneously. These synchronized spawning events, often regulated by lunar cycles and water temperature, increase the likelihood of cross-fertilization. The fertilized eggs develop into free-swimming larvae called planulae, which eventually settle on suitable substrates and metamorphose into new polyps. Sexual reproduction enhances genetic diversity, enabling corals to adapt to environmental changes (Voolstra et al., 2021).

One of the most pressing areas of research involving corals is their response to environmental stress, particularly in the context of climate change. Coral bleaching, a phenomenon where corals expel their symbiotic algae due to stress from elevated sea temperatures, has become a major focus of study. Bleaching leaves corals vulnerable to disease and mortality, disrupting reef ecosystems. Studies have been exploring the molecular mechanisms underlying bleaching, with the goal of identifying genetic or environmental factors that could enhance coral resilience to warming oceans (Suggett & Smith, 2020; van Woesik et al., 2022). Corals also offer a unique perspective on the evolution of immune systems and symbiosis. Unlike vertebrates, corals rely on innate immunity to recognize and manage symbiotic relationships with algae and to defend against pathogens. Research on coral immunity has revealed molecular pathways involved in host-symbiont recognition, immune modulation, and stress response, many of which are conserved across different species, including vertebrates (Jacobovitz et al., 2023; Zhang, Huang et al., 2024). These studies have broadened our understanding of immune system evolution and the mechanisms underlying successful symbiosis. In addition to their biological importance, corals play a vital ecological role as the foundation of reef ecosystems. Coral reefs provide habitat and food for a wide array of marine organisms, including fish, crustaceans, and mollusks. They also serve as natural barriers, protecting coastlines from erosion and storm surges (Joy & Gopinath, 2021). The ecological complexity of coral reefs has made them ideal systems for studying community dynamics, ecosystem functioning, and species interactions. However, the growing threats posed by ocean warming, acidification, and pollution have heightened the need for conservation research to preserve these ecosystems.

4.9 Electric eel (*Electrophorus electricus*)

The electric eel is a fascinating model organism that offers significant insights into neurobiology, bioelectricity, and evolutionary adaptation. Although commonly referred to as an eel, it is actually a knifefish and belongs to the family Gymnotidae. Found primarily in the freshwater rivers and swamps of the Amazon and Orinoco basins in South America, the electric eel is renowned for its remarkable ability to generate electric fields, which it utilizes for navigation, communication, and predation. One of the most striking features of the electric eel is its capacity to produce electric discharges, and this ability is facilitated by specialized cells known as electrocytes, which are modified muscle cells that can generate voltage when activated (Xiao et al., 2024). The electric eel can produce three types of electrical discharges: low-voltage pulses for navigation and communication, high-voltage bursts for stunning prey or deterring predators, and continuous low-voltage signals for electro-location (Zhou et al., 2024). The electric organ, located along the length of the body, consists of thousands of electrocytes arranged in series (Xiao et al., 2024). This unique arrangement allows the electric eel to generate significant voltage, with some individuals capable of producing discharges exceeding 600 V (Yang, Sencadas et al., 2021). The study of these electric discharges has provided insights into the mechanisms of bioelectricity and has implications for understanding electrical signaling in other biological systems. In addition to their electric capabilities, electric eels possess several morphological adaptations that enhance their predatory efficiency and survival (Yang, Sencadas et al., 2021). They have a long, cylindrical body that can reach lengths of up to 3 m, allowing for agile movement in their aquatic environment. Their dorsal and anal fins are elongated and fused, facilitating swift swimming and maneuvering in complex habitats. Electric eels also possess a unique respiratory system, comprising highly vascularized mouth tissues that allow them to extract oxygen from the water. This adaptation is crucial, as electric eels often inhabit oxygen-poor waters, and they are capable of supplementing their gill respiration with aerial respiration by rising to the surface to gulp air every 15–20 minutes (Kibenge & Strange, 2021, pp. 1–111).

The reproductive behavior of electric eels is equally intriguing and has been the subject of various studies. Electric eels are known to exhibit a form of parental care, a rarity among fish. During the breeding season, males and females come together in shallow waters to spawn. The male electric eel engages in a courtship display that involves intricate swimming patterns and the use of electric signals to attract a female. Following courtship, the female lays up to 17,000 eggs, which the male fertilizes externally, and the eggs are adhesive and stick to submerged vegetation (Xiao et al., 2024). After spawning, the male guards the nest, protecting the eggs from potential threats until they hatch into free-swimming larvae after approximately 2–3 weeks (Bastos et al., 2021). This parental care behavior provides a unique opportunity for researchers to investigate social interactions, mating systems, and the evolutionary significance of parental investment in aquatic environments. Their electric discharges serve multiple purposes, including navigation in murky waters,

communication with conspecifics, and hunting prey. The ability to emit electric fields enables electric eels to detect the presence of objects and other organisms in their environment, even in low visibility conditions. They utilize both passive and active electro-location techniques, allowing them to assess the size, shape, and distance of nearby objects (Yang, Sencadas et al., 2021). This capability has made electric eels a model organism for studying sensory systems and the evolution of bioelectrogenesis, providing insights into how organisms adapt to their ecological niches. The mechanisms underlying the generation of electric fields have inspired the development of bio-inspired technologies, including new energy storage systems and sensors. Moreover, the study of electric discharges and their physiological effects on the nervous system has opened avenues for investigating neuromuscular disorders and developing potential therapeutic strategies (Xiao et al., 2024).

4.10 Seahorse (*Hippocampus* spp.)

Seahorses, belonging to the family Syngnathidae, are intriguing marine organisms known for their unique morphology, reproductive behaviors, and ecological roles. They are found in shallow coastal waters, often inhabiting seagrass beds, coral reefs, and mangroves, predominantly in tropical and subtropical regions worldwide. Seahorses exhibit distinctive physical characteristics, including a horselike head, elongated body, and prehensile tail, which enable them to anchor themselves to vegetation and other substrates in their environment (Whittington & Friesen, 2020). Their bodies are covered in bony plates instead of scales, contributing to their unusual appearance and offering protection from predators. One of the most remarkable aspects of seahorses is their reproductive strategy, which is highly atypical for the animal kingdom. Seahorses are known for their unique form of reproduction known as male pregnancy (Holt et al., 2022). During courtship, which often involves intricate displays of color changes and synchronized swimming, the female deposits her eggs into the male's brood pouch located on his abdomen. This pouch serves as a safe environment where the fertilized eggs develop. The male then fertilizes the eggs internally and carries them in his pouch for a gestation period that can last from 10 days to 6 weeks, depending on the species and environmental conditions (Parker et al., 2023). The brood pouch provides oxygen and nutrients to the developing embryos, protecting them from predators and environmental stresses. Once the young seahorses are fully developed, the male undergoes contractions to release them into the water, where they are independent from birth and must quickly evade predation.

Seahorses exhibit a variety of adaptations that contribute to their survival and reproductive success. Their elongated bodies allow for efficient swimming, while their prehensile tails enable them to grasp onto seagrass, coral, or other structures, reducing energy expenditure in strong currents. The ability to change color not only aids in camouflage from predators but also plays a role in communication during mating rituals. This ability to alter pigmentation is influenced by environmental factors, mood, and social interactions (Jerez-Cepa & Ruiz-Jarabo, 2021). Their unique reproductive strategies provide valuable insights into the evolution of parental care and sex roles in animals. Research into their mating systems and the ecological implications of male pregnancy can enhance understanding of evolutionary pressures shaping reproductive strategies across different taxa (Whittington & Friesen, 2020). Additionally, seahorses have become a focus for studies on genetic diversity and population dynamics due to their sensitivity to environmental changes and habitat degradation. Conservation efforts are critical for seahorse populations, as they face numerous threats, including habitat loss, overfishing, and the aquarium trade. Seahorses are often used as bioindicators of marine ecosystem health, reflecting the overall state of their habitats. Their reliance on specific environments, such as seagrass beds and coral reefs, makes them susceptible to ecological disturbances. Therefore, studying seahorses contributes to broader conservation strategies aimed at protecting marine biodiversity and ensuring the sustainability of marine ecosystems (Ternes et al., 2023).

4.11 Blue tilapia (*Oreochromis aureus*)

Blue tilapia is a freshwater fish species widely recognized as a model organism in aquatic research and aquaculture. Native to Africa, particularly the Nile River system, blue tilapia has been introduced to various regions around the world, including parts of Asia, the Americas, and Europe, due to its adaptability and significant role in aquaculture and fisheries (Geletu & Zhao, 2023). This species is characterized by its distinctive blue coloration, particularly prominent in males, and its deep, laterally compressed body, which allows it to navigate efficiently through various aquatic environments. One of the key features that make blue tilapia an ideal model organism is its rapid growth rate and tolerance to a range of environmental conditions, including varying salinity and temperature (Yu(C.S. et al., 2024). This adaptability allows researchers to study the effects of different environmental factors on growth, behavior, and physiology. It is particularly significant in aquaculture because of its ability to thrive in a variety of habitats, from freshwater lakes and rivers to brackish waters (Geletu & Zhao, 2023). As a result, it has become a valuable species for food production in many

countries, contributing to both local economies and food security. They are mouthbrooders, which means that females carry fertilized eggs in their mouths until they hatch. The breeding process begins with courtship displays by males, characterized by vibrant colors and fin displays to attract females (Webster & Lim, 2024). After successful courtship, the female lays her eggs in a nest that the male has prepared on the substrate. The male fertilizes the eggs immediately after they are laid, and the female collects the eggs in her mouth to incubate them. This mouthbrooding behavior provides protection for the eggs and larvae from potential predators, enhancing their survival rates (Bessa et al., 2022). The incubation period lasts about 7–10 days, after which the female releases the fry into the surrounding environment while still providing protection by allowing them to return to her mouth if they feel threatened (Webster & Lim, 2024).

The reproductive cycle of blue tilapia is influenced by environmental conditions, including temperature and photoperiod, which play a significant role in triggering spawning behaviors. This sensitivity to environmental cues makes blue tilapia an excellent model for studying the effects of climate change and habitat alteration on reproductive strategies in fish. Additionally, the species has a relatively short generation time, making it suitable for experiments in evolutionary biology and genetics (Yue et al., 2024). In terms of physiological features, blue tilapia possesses a well-developed sensory system, particularly in relation to vision and olfaction, which is crucial for locating food and navigating their environments. Their diet primarily consists of algae, detritus, and small invertebrates, and they play an essential role in their ecosystems as herbivores and detritivores. Their ability to adapt to varying diets also provides an excellent opportunity for research into nutrition, metabolism, and growth performance in aquaculture settings. The blue tilapia serves as a valuable model organism not only for ecological and environmental studies but also for research in developmental biology and genetics (Geletu & Zhao, 2023). The transparent embryos of blue tilapia allow for real-time observation of developmental processes, enabling scientists to study key events such as organogenesis and the effects of environmental stressors on early development. Genetic studies using blue tilapia have also contributed to our understanding of fish physiology, behavior, and adaptation mechanisms, with implications for improving aquaculture practices and enhancing sustainable fish production (Geletu & Zhao, 2023).

5. Case studies

Studies of marine organisms offer deep insights into many fundamental biological pertinent to human health, paving way for significant advancements in biomedical research. Presented below are typical examples of the contributions of these marine organisms.

5.1 Zebrafish in cardiovascular research

Currently, the zebrafish has emerged as an appealing model for studying the effects of genetic variants identified in patients with cardiovascular abnormalities through candidate gene or whole-genome-association studies. There are also research involving unbiased and whole-genome forward genetic screens, which have progressed to the identification of novel genes required for cardiovascular development and disease (Angom & Nakka, 2024). The zebrafish, *Danio rerio* (previously *Brachydanio rerio*) is a small tropical freshwater fish originating in the Ganges River and its tributaries in northern India (Ghate et al., 2023) and typically found near the bottom of the water where they it stays to avoid predator attacks. The Zebrafish was introduced as an animal model for use in genetic investigations by George Streisinger and colleagues at the University of Oregon, who subsequently launched the modern era for zebrafish in the field of biomedical research (Alves-Pimenta et al., 2024; Shimizu et al., 2023). Zebrafish since their introduction have become popular animal models because they offer various advantages over other species, most especially, their fully sequenced genome, facile genome manipulation, high fecundity, a short generation time (approximately 3 months), rapid embryonic development (24 hours), and external fertilization (Javaid et al., 2022). Zebrafish is a generally remarkable animal model for understanding the human etiology of metabolic illnesses and developing potential therapeutic alternatives (Angom & Nakka, 2024).

Zebrafish embryos are specifically well suited for investigating gene function during cardiovascular development because they are not completely dependent on a functional cardiovascular system for their development (Ali et al., 2024; Weinberger et al., 2024). Due to the small size of the zebrafish embryo, oxygen may enter and reach all tissues in zebrafish embryos without blood circulation. This characteristic allows embryos to survive the earliest period of embryonic development and enables the investigation of embryos with severe circulatory abnormalities (Coppola et al., 2023). This contrasts with avian and mammalian embryos, which die rapidly in the absence of a functioning cardiovascular system. Aside from making it easier to detect and study genetic mutations, the optical transparency of zebrafish embryos has provided new insights into different cellular components of cardiovascular development (Angom & Nakka, 2024;

Coppola et al., 2023). Similarities have been observed between the elements of the cardiovascular system such as the heart, a vascular network composed of arteries, veins, and capillaries, and the lymphatic system in the zebrafish and that of any vertebrate (González-Rosa, 2022).

The use of new transgenic technologies to induce tissue-specific expression of fluorescent proteins, as well as sophisticated imaging technologies such as live imaging with single- or multiphoton confocal microscopy and single-plane illumination microscopy, has gradually increased interest in the zebrafish embryo for the investigation of cardiovascular development and disease (Faraj et al., 2022; Liu, 2021). In a report, researchers created CRISPR-Cas9-mediated dnah10 mutants in zebrafish that exhibited similar cardiac abnormalities as seen in heterotaxy syndrome, providing the first in vivo and functional evidence for dnah10 in left/right patterning (Asif et al., 2024; Liang et al., 2020). During their study, they also increased the number of causal gene candidates for this condition by discovering RNF115 deletion mutations with CRISPR-Cas9. Zebrafish with a linear heart tube that fails to loop, which mimics developmental problems in human Holt-Oram syndrome, were studied by Gauvrit et al. (2022). In a report by Quintanilla and Ho (2020), a comparative RNA-seq investigation conducted in zebrafish embryos revealed that knocking down the TBX5 paralogs alters gene expression in a variety of organs, resulting in alterations in somite size, vasculature progenitor differentiation, and trunk blood vessel patterning.

5.2 Sea urchins in cancer research

Sea urchins are bottom-dwelling aquatic invertebrates that belong to the class Echinoidea and phylum, Echinodermata (Molla & Aljahdali, 2023). They are nonchordate deuterostomes (echinoderms) with long history of serving as research models for studies advancing the knowledge of gene-regulatory networks of development, the function of chromosomes in inheritance, and cell-cycle regulation (Cormier et al., 2023; Polinski et al., 2024). Sea urchins have been identified for their extraordinary longevity while maintaining tissue homeostasis and physiological function and avoiding degenerative and neoplastic diseases associated with aging. Sea urchins share a close genetic relationship with vertebrates, especially humans, making them excellent models for the study of molecular, cellular, and systemic mechanisms that underlie longevity and good aging (Costantini et al., 2024). Modern cancer research was first conducted in the early 20th century by a German Biologist, Boveri on the sea urchin where improper fertilization of an egg by two sperm cells led to chromosomal abnormalities and subsequent failure of proper embryonic development (Kiermaier et al., 2024). In toxicological and environmental health scientific studies, sea urchins are commonly used as experimental models because they facilitate accurate estimates of cancer risk, even without epidemiologic evidence (Verma et al., 2024). Other reports also suggest the use of early embryonic stage of sea urchins as models for cancer research certain since their morphogenetic signaling pathways could be abnormally activated during tumorigenesis (Ascanelli et al., 2024; Lin et al., 2023; Liu, Sun et al., 2024). Furthermore, the capacity of sea urchins to grow and regenerate continuously while being resistant to cancer (Adonin et al., 2021) and their ability to regenerate damaged tissues with age Carnevali et al. (2024) and Ali et al. (2024) present significant potential strategies for natural pathways of cancer prevention. Studies suggest that coelomocytes (circulating cells) in sea urchins can elicit strong DNA repair response, possess characteristic high resistance to substances capable of damaging the DNA, and effectively repair damaged DNA (Coscia et al., 2023; Davies, 2024). These genetic traits contribute to their ability to maintain genomic stability and tissue function and resist diseases, including cancer. In a study on sea urchins, Grant et al. (2024) characterized the expression of Myc gene and the single combo gene—p53/p63/p73, which are known to synergistically function as oncogene and tumor suppressors in mammals. Myc and p53 are transcription factors involved in cell apoptosis and cell proliferation, which when overexpressed and/or mutated play significant roles in tumor development (Trejo-Solís et al., 2024; Marei et al., 2021; Ayaz et al., 2022). An understanding of the roles of these and other genes, and the effects of their overexpression and mutations in relation to the development of tumors create clearer insights into the pathogenesis and progression of human cancers and identifying novel targets for cancer therapy.

5.3 Marine sponges in antibiotic discovery

The increasing threat posed by multiplying drug resistant infectious diseases has encouraged the search for new antimicrobial compounds, and having extensively studied and investigated terrestrial sources, the present emphasis on marine sources of antimicrobials is appropriate (Terreni et al., 2021). The ocean provides a wide range of living organisms inhabiting diverse microflora that have the capacity to adapt to all kinds of marine environments. This capacity to adapt involves the production of bioactive molecules and the development of chemical protection strategies employed in their highly competitive predator–prey environment which mechanism may be useful to humans in several ways (Cushnie

et al., 2024; Rathinam et al., 2024). Marine sponges are examples of marine organisms that have evolved to develop chemical defenses against predators (Mehbub et al., 2024). Sponges (phylum Porifera) are sessile vertebrates that possess wide range of species, shapes, consistencies, and colors, show relatively little tissue differentiation and coordination, and dwell in various marine and freshwater ecosystem in most regions of the world (Giere & Schratzberger, 2023; Leys & Hejnol, 2021). They are important components of the bottom dwelling otherwise, known as benthic communities in the ocean (González-Murcia et al., 2023).

Sponges originated approximately 600 million years ago, and their effective survival in many severe settings is attributed to their extensive defenses and evolutionary adaptations, as well as the functions of associated microorganisms (Kotsyurbenko et al., 2024). Sponge-associated microorganisms may be symbiotic or pathogenic. Sponges adsorb several microorganisms (which they recognize either as food bacterial or bacterial symbionts) within them either extracellularly or intracellularly (Devaprakash et al., 2024). These microorganisms which include cyanobacteria, heterotrophic bacteria, and fungi contribute to 35%–60% of the sponge biomass (Alhaddad et al., 2024). The association between the sponges and their associated microorganisms, as seen in other marine species, has led to the production of marine natural products including secondary metabolites that are used in the production of pharmaceutical agents like antimicrobials, antiinflammatory, analgesics, etc. (Mehbub et al., 2024; Wang, Li et al., 2024). The discovery of the nucleosides—spongouridine and spongothymidine (that eventually formed the basis for production of ara-C and ara-A, the first marine-derived anticancer agent and antiviral drug, respectively) in the marine sponge *Cryptotethya crypta*, sparked pharmaceutical research in marine sponges in the early 1950s (Haque et al., 2022; Kumar & Swarnalatha, 2024, pp. 85–100). Presently, more than 5300 distinct pharmaceutical compounds have been identified from marine sponges (Santhanam et al., 2024), and more are found every year. With almost 200 new metabolites published annually, sponges are the most prolific marine makers of novel compounds (Mehbub et al., 2024). In addition, more compounds originating from sponges than from any other marine phylum are being tested in clinical and preclinical settings (e.g., as anticancer or anti-inflammatory medicines) (Ghallab et al., 2024; Tan, 2023).

Several authors have reported the production of effective bioactive secondary metabolites with antibacterial potency from several species of sponges—bromotyrosine derivatives from sponges of the genus Suberea (El-Demerdash et al., 2019), diterpene alkaloids from the sponge, *Agelas mauritiana* (Nasser Alahmari et al., 2022) and aaptamine, 9-demethylaaptamine, 4-N-methylaaptamine, and 9- methoxyaaptamine, from the sponge *Aaptos aaptos* (Kasanah et al., 2022). In addition, antibacterial potent extracts have been obtained from different sponges by different researchers. For instance, methanolic extracts of sponges of the phylum, Porifera—*Aaptos suberitoides*, *Neopetrosia exigua*, *Cinachyrella australiensis*, *Clathria basilana*, *Xestospongia testudinaria*, *Pachastrella* sp., *Clathria reinwardti* and *Stylissa carteri* demonstrated strong bacterial activity against MDR *P. aeruginosa* and methicillin-resistant *Staphylococcus aureus* (MRSA) (Anteneh et al., 2021). Kamaruding et al. (2020) reported the potency of diethyl ether and butanol extracts of *Xestospongia exigua*, *Iotrochota baculifera* and *Xestospongia muta* against *Escherichia coli*, *Micrococcus luteus*, *Salmonella typhimurium,* and *Staphylococcus aureus*. In another study, Piron et al. (2022) demonstrated the antibacterial activity of ethanol and aqueous extracts of the sponges—*Verongula rigida*, *Desmapsamma anchorata,* and *Agelas clathrodes* against *Staphylococcus aureus*, *Staphylococcus saprophyticus*, *Escherichia coli*, *Pseudomonas aeruginosa,* and *Bacillus cereus*.

5.4 Sea squirts in neurodegenerative disease research

Neurodegenerative diseases are a diverse group of late-onset pathological conditions caused by slow progressive malfunction and death of neurons and synapses in selected areas of the nervous system, resulting in a series of cognitive and motor disorders (Catanesi et al., 2021; Sanghai & Tranmer, 2023). While there is presently no cure for neurodegenerative diseases, some of the symptoms may be reduced by various treatment regimens, slowing down the diseases' progression (Mawe et al., 2022). These diseases in humans range from Alzheimer's disease and Parkinson's disease to psychiatric conditions such as anxiety-related disorders and depression. The development of successful great promise for discovering naturally occurring cancer prevention mechanisms management of these conditions relies heavily on advanced knowledge of the molecular mechanisms observed in neuronal dysfunction (Lu et al., 2023).

Ascidians commonly referred to as sea squirts or sea tunicates are sessile and highly diversified invertebrates of the phylum chordata and sub-phylum Tunicata known to consist of about 3000 species present in every marine region, from shallow water to the deep sea (Öztürk, 2020). Species of sea tunicates such as *Botryllus schlosseri* (Anselmi et al., 2022) and *Ciona intestinalis* (Ruiqi et al., 2024) have been used to study neurodegenerative conditions. Šimat et al. (2024) opined that human genes associated with neurodegeneration are analogous to those found in *Botryllus* species. Anselmi

et al. (2022) suggested that *B. schlosseri* offers an innovative and essential platform for the study of neurogenesis, neurodegeneration, and evolving neurological science. This quality is alluded to in its many unique features, including a transparent body and vas Vaughan culture, assayable life cycle, ability to enhance and transplant adult tissue-specific stem cells, morphological variations associated with colony age, and previously sequenced genome. Anselmi et al. (2022), in their study, discovered 428 putatively homologous genes in *B. schlosseri* that were expressed in its central nervous system (CNS), which are linked to human neurodegenerative diseases such as Alzheimer, Parkinson, frontotemporal dementia, and Huntington. The study sequenced and analyzed transcriptomes of dissected neural complexes in both young and old colonies of *B. schlosseri* to evaluate gene expressions as well as identify molecular signatures potentially linked with development and degeneration phenotypes in the brain tissue. Increase in age has been linked with increasing incidence of neurodegenerative diseases, making it the main factor in the neurodegenerative processes. This was corroborated by the report of Anselmi et al. (2022), which stated that older colonies of *B. schlosseri* contained significantly fewer neurons and exhibited reduced behavioral response and reduced activity, alongside changes in the expression of 148 such genes when compared to younger colonies. The increased number of neurons observed in the brains of younger colonies is probably a reflection of robust cell division and stem cell activity in these colonies, which authors suggest are connected to the role of the immune system in neurodegenerative diseases (Kraus et al., 2021; Pluvinage & Wyss-Coray, 2020). Key features of neurodegenerative diseases include the excessive production of ROS and inflammation, which disrupt the homeostasis of the central nervous system (Teleanu et al., 2022). Others include histopathological damage, mitochondrial malfunctions, DNA damage, lipid peroxidation, altered dendritic growth, neuronal apoptosis, etc. (Iqubal et al., 2020). Sea squirts are also potential sources of bioactive natural chemicals, several of which have been identified and utilized for therapeutic uses (Qurashi, 2024; Sibiya et al., 2021).

6. Developmental processes and disease modeling

Marine organisms have been very useful in the areas of developmental biology, providing researchers with an opportunity of obtaining biological knowledge (Yaguchi & Wada, 2022). Basic biological processes can be studied through the use of aquatic biota, which includes fish and other invertebrates from both freshwater and marine habitats, which serve as valuable bioindicators (Okwuosa et al., 2019). The body patterns and developmental processes of marine invertebrates vary greatly (Lv et al., 2019). The utilization of model marine organisms, including zebrafish, alongside newly discovered nonmodel organisms, such as marine nematodes, ciliates, amphioxus, and ascidian, have been extensively used in research to investigate evolutionary developmental biological processes, study regulatory signals, and environmental adaptation in order to expand our understanding beyond conventional model species (Zhao et al., 2021). The process of morphogenesis describes how the bodies and tissues of living organisms acquire and take on their forms through migration, rearrangement, and changes in shape brought about by cell division and death (Lv et al., 2019). Among the several intriguing morphogenetic examples observed in marine invertebrates are the extraordinary morphological structures of mollusk shells and the intricate germline morphogenesis of polychaetes (Lv et al., 2019). Marine invertebrates have a variety of developmental processes; with certain species undergoing direct development without a feeding larval stage, whereas others undergo indirect development, which includes a feeding larval phase (Johnson et al., 2019). More recent advances in research have allowed for a deeper comprehension of the morphogenesis of marine invertebrates involving the molecular, cellular, and tissue and organ-system developmental level through live imaging methods, genetic perturbation, and quantitative analysis (Lv et al., 2019). The cells receive instructions on what actions to do through a signaling cascade that begins with morphogens, establishing the patterning of a particular tissue (Lv et al., 2019).

Echinoderms are closely related to chordates and therefore are of substantial research importance in understanding the cellular and molecular regulation of development, allowing evolutionary comparisons to be drawn between other deuterostomes, including vertebrates (Perillo et al., 2024). Sea urchins, sea cucumbers, and sea stars, belonging to the phylum echinoderm, offer a great model for studying gene regulatory systems and developmental gene expression (Gildor et al., 2019). The release of genome sequence of the sea urchin has gained popularity as a model organism for developmental biology research (Lv et al., 2019). Sea cucumbers (holothuroids), which are benthic during their adult stage, develop through free-swimming planktonic larvae (Perillo et al., 2024). Sea cucumbers, unlike most echinoderms, have been used to study anterior–posterior patterning. They retain bilateral traits in adulthood and show sequential *Hox* gene expression in early embryonic stages, making them a key model for studying axis development and *Hox* gene evolution in echinoderms. These *Hox* genes are well-known for being essential for the patterning of the body (Perillo et al., 2024). The phylum Cnidaria includes sea anemones, which are made up of two germ layers: the inner endoderm, or gastrodermis, which lines the gut cavity, and the outside ectoderm. Thus, the starlet sea anemone is a perfect model for research on the evolution of the mesoderm and bilaterians because of its notable characteristic (Lv et al., 2019). Sea squirts, often referred to as

ascidians, have been the subject of numerous studies that have shed light on the development of notochords and important vertebrate tissues and organs, such as the neural crest (Lv et al., 2019). Marine genomics aids in studying developmental processes like cell signaling, gene regulation, and patterning, offering insights into evolutionary conservation and diversification, potentially benefiting research on human diseases (Yaguchi & Wada, 2022). Research, primarily focused on marine urchins and sea stars, has uncovered conserved neuronal subtypes and gene regulatory networks that control the development of neurons. With significant distinctions from other echinoderms, such as the lack of ectodermal projections and changes in serotonergic neuron location, sea cucumber larvae exhibit a growing complexity in their nervous system that may indicate evolutionary adaptations (Perillo et al., 2024).

Studies of marine animals using big data, particularly deoxyribonucleic acid (DNA) sequencing results, provides a comprehensive picture of the history of life on earth, since development occurs from primary life forms originating in the ocean and marine metazoans are present in nearly all major clades of the phylogenic tree (Stracke & Hejnol, 2023; Yaguchi & Wada, 2022). Therefore, the integration of modern technologies and big data can significantly advance research in biological fields, including developmental, cell, and evolutionary biology, by employing nonmodel marine creatures in addition to model organisms (Yaguchi & Wada, 2022). The central nervous system of echinoderm larvae is represented by the ciliary band neurons, which are the peripheral nervous system, and the apical organ, which serves as the central nervous system. Mesodermal precursors in echinoderms form various larval cell types, including muscles, immune cells, and the skeleton (Perillo et al., 2024). In holothurians, immune cells are involved in defense, and immune genes are expressed early in development. The hydrocele, unique to echinoderm larvae, aids in establishing pentaradial symmetry and forms the water vascular system (Udagawa et al., 2022). In sea cucumbers, their development differs from other echinoderms, with early morphogenesis still unclear. Primordial germ cell (PGC) development in sea cucumbers is also poorly defined, with gene markers like vasa and nanos suggesting further research is needed to clarify PGC precursors and their specification (Perillo et al., 2024). Moreover, genome sequencing has proven to be very helpful in the research of epigenetic alterations; *Apostichopus japonicus*, in particular, has been used to analyze DNA methylation and acetylation in response to various experimental settings (Perillo et al., 2024).

Marine species, especially fish, have numerous bioactive compounds with great potential for use in various applications of human health (Vidhya et al., 2024). Neuroscience studies with sea slugs have demonstrated the complex brain network involved in memory retention (Yaguchi & Wada, 2022). Although marine species have made significant contributions to "traditional" sciences, their use in molecular biological and/or genetic procedures has not made these animals as popular in "modern" biology. This is because most of these species lack internal breeding systems and genomic information. However, recent tremendous developments in DNA sequencing and bioinformatics technologies have been able to overcome the drawbacks of using marine organisms as biological models (Yaguchi & Wada, 2022). Various bioactive compounds broadly categorized into peptides, polysaccharides, proteins, and fatty acids derived from marine fishes' exhibit interactions with a broad range of molecular targets and biological pathways within the human body, exerting their effects through a variety of mechanisms, such as immune function modulation and inflammatory process regulation (Vidhya et al., 2024). Polysaccharides such as fucoidan have been shown to have the potential to modify immunological responses by stimulating immune cells and encouraging the synthesis of cytokines that are important for immune regulation (Vidhya et al., 2024). The synthesis of proinflammatory mediators and signaling molecules can be strongly inhibited by peptides and omega-3 fatty acids (Vidhya et al., 2024). A number of proteins and peptides that are obtained from marine fish have antiviral and antibacterial properties, which suggests that these compounds can be developed into novel antimicrobial drugs. These substances have the ability to compromise the integrity of microbial cell membranes, impede the development and reproduction of bacteria and viruses, and strengthen the body's defenses against infections (Vidhya et al., 2024). Studies to determine the impact of different bioactive chemicals involve in vitro testing of the compounds on cultured cells or tissues to determine how they influence specific biological processes such as inflammation, apoptosis, and cell proliferation (Vidhya et al., 2024). The modes of action of various marine bioactive substances and their interactions with particular molecular targets or signaling pathways involved in disease pathogenesis are investigated through molecular and cellular studies. Processes such as gene expression analysis, proteomics, and metabolomics provide a comprehensive understanding about the molecular mechanisms underlying the therapeutic effects of these compounds (Vidhya et al., 2024).

6.1 Importance of marine models and evo developmental processes in human diseases

Marine organisms possess the ability to biosynthesize substances with unique chemical structures, range of biological activities, and diverse mode of actions which allows them to be easily utilized in research studies for development of therapeutic agents against human diseases (Silva et al., 2023). Marine models, particularly zebrafish, have gained

prominence in recent years for investigating human diseases due to the transparency and rapid development of their embryos. Over 72% of human genes have at least one unique homologous gene within the zebrafish genome, and orthologs for more than 82% of genes implicated in human diseases have also been identified in zebrafish (Zhao et al., 2021). Globally, there are numerous initiatives devoted to drug research and development that are focused on deriving bioactive substances from natural sources. Nine of the 14 commercially available medications derived from marine sources are currently used to treat cancer, while numerous more are undergoing clinical trials (Montuori et al., 2022). Bioactive compounds produced by marine fishes have diverse chemical structures and exhibit a range of biological activities, which makes them very useful for biomedical research (Vidhya et al., 2024). Cellular and molecular processes that occur during cardiac regeneration have been demonstrated and studied using zebrafish, blind cavefish, giant danio, gray bichir, and goldfish to explore the intrinsic and extrinsic factors of the natural cardiac regeneration processes in order to develop a strategy for in vivo reactivation or enhancement of the regenerative capacity of the human heart following myocardial infarction in most cases of CVDs (Zhao et al., 2021). Approximately 7.6%–9.4% of people worldwide suffer from immune system-related illnesses (Montuori et al., 2022). Bioactive chemicals derived from marine fishes have the potential to treat various health conditions by targeting important processes related to immunological response, inflammation, microbial defense, and oxidative stress (Vidhya et al., 2024). β-D-glucan YCP, a polysaccharide purified from the mycelium of the marine fungi *Phoma herbarum* YS4108, shows significant immunomodulatory functions and regulation of T-lymphocytes and dendritic cells in vivo, and activates macrophages and increased phagocytic activity (Liu et al., 2020). It is also of great importance in relieving symptoms of acute colitis in mice, restoring intestinal immune homeostasis, and aiding tissue regeneration. Irish deep-sea organism extracts derived from filamentous fungi have been shown to have the ability to induce human mesenchymal stem cell (hMSC) differentiation (Montuori et al., 2022).

Studies on fish-derived bioactive compounds have demonstrated its significance in the prevention and treatment of human disorders as a result of the activities of these chemical compounds. Piscidins are a family of antimicrobial peptides that are present in fish species like hybrid and striped bass, which have demonstrated strong antimicrobial activity against a range of diseases. Bioactive peptides derived from fish proteins have additionally shown encouraging promise in the management and prevention of cardiovascular disorders, including hypertension and atherosclerosis (Vidhya et al., 2024). Comprehensive studies have been undertaken about the advantageous effects of long-chain polyunsaturated omega-3 fatty acids, including eicosapentaenoic acid (EPA) and docosahexaenoic acid (DHA), present in marine fish, on human health. These effects include reduced inflammation, improved cardiovascular function, and support for cognitive function (Vidhya et al., 2024). Fucoidan, extracted from brown seaweeds consumed by some fish species, exhibits several biological properties, including immunomodulatory, anticancer, anticoagulant, and antiinflammatory effects (Vidhya et al., 2024). Oxidative stress is linked to the pathogenesis of various chronic diseases, including cancer, diabetes, and neurological disorders. Strong antioxidant qualities found in marine fish bioactive substances such astaxanthin and certain peptides aid in scavenging free radicals and lessening oxidative damage to tissues and cells, which aid in preventing oxidative damage and shield against age-related illnesses (Vidhya et al., 2024).

6.2 Advantages of using marine organisms for modeling specific diseases

The primary form of life can be traced as far back to its origin in the ocean, with most marine species possessing anatomical characteristics and features that can be traced back to the earliest forms of almost every essential animal organ system, including the nervous system, muscles, digestive systems, reproductive organs, and excretory organs (Stracke & Hejnol, 2023). Marine organisms have been shown to produce numerous chemicals that play defense and communicative roles in the natural environment, as well as possible health benefits for humans (Montuori et al., 2022). The knowledge derived by utilizing marine organisms as models in evolutionary development facilitates the understanding of the evolution of nonmarine species and the increasing complexity and diversity of their organ systems (Stracke & Hejnol, 2023). This can be very useful in understanding the progression of many diseases. Throughout the recent decades, compounds derived from marine species have shown significant biological activity, including anticancer, antibacterial, antifungal, antiviral, and anti-inflammatory effects (Silva et al., 2023). Future preclinical research could benefit from the neuroprotective potential of marine-derived compounds, which target inflammatory pathways, mitochondrial dysfunction, oxidative stress, and α-synuclein aggregation in Parkinson's disease (Silva et al., 2023). By studying marine species, researchers can infer traits from the last common ancestors at deep phylogenetic nodes, leading to the identification of novel physiological and cellular processes useful in understanding the pathways of pathogenic organisms in various disease processes (Stracke & Hejnol, 2023). Biologically active compounds used in the treatment and prevention of various immune system disorders, cancer, and other diseases can be found in marine species. Commercially marine-derived compounds have been shown to target and modulate the immune system for the treatment of various tumors.

For instance, a B-receptor-containing antibody–drug conjugate, polatuzumab vedotin (DCDS-4501A), which was isolated from cyanobacteria and mollusks, and is CD79b-directed is indicated in cases of relapsed or refractory diffuse large B-cell lymphoma among adult patients (Montuori et al., 2022). Large-scale explorative of cardiac regeneration using zebrafish and African killifish allows for comparative analyses between vertebrate species and gives a better understanding of the evolutionary context through extensive comparative investigations, providing insight into the development of treatment approaches for cardiovascular disorders (Zhao et al., 2021). Marine fungi produce compounds with immunomodulatory and antiinflammatory effects, such as semi-vioxanthin, which exhibits immunomodulatory activity, and azonazine, which shows antiinflammatory activity (Montuori et al., 2022). The embryo of the zebrafish has the ability to develop externally, which facilitates the characterization of organogenesis deficits for the purpose of imitating ciliopathies in humans. For instance, in ciliary mutants and morphants, cystic kidneys regularly form in the glomeruli and the proximal tubules area (Zhao et al., 2021). Compounds derived from marine organisms such as piloquinones A and B, mannosylglycerate, and secalonic acid A exhibit neuroprotective activities, which make it beneficial for treating neurodegenerative illnesses such as Parkinson's disease.

6.3 Limitations of using marine organisms for modeling specific diseases

Accessibility of marine biodiversity: One of the primary challenges in marine biomedical research is obtaining access to a variety of marine environments and its inhabitants. Generalizing findings across multiple taxa is challenging since successful gene disruption may require techniques for each marine species (Mohajer et al., 2024). Marine organisms that require extremely specific or highly specialized environmental conditions may not be culturable (Stracke & Hejnol, 2023). Researchers' capacity to gather samples and study marine organisms in their native habitats may be hampered by limited access to isolated or protected locations, logistical challenges, and regulatory obstacles (Vidhya et al., 2024). The limited usage of marine species in the past has been mostly caused by technological constraints, such as the incapacity to obtain enough tissue because of their small body size (millimeter to a range of centimeters) (Stracke & Hejnol, 2023). Because of the intricacy and robustness of adult tissues, functional studies on adult marine invertebrates are much more difficult than those on larval or juvenile stages (Mohajer et al., 2024). Furthermore, researchers have financial difficulties due to the high cost of marine expeditions and sample collection activities, especially those operating in environments with limited resources (Vidhya et al., 2024).

Exploration and evaluation of bioactive compounds: Finding new bioactive substances in marine species is a difficult and drawn-out process that calls for multidisciplinary cooperation and sophisticated analytical methods. The existence of multiple structurally identical molecules and pollutants makes it difficult for researchers to isolate, purify, and characterize bioactive chemicals from complex marine extracts. The identification and characterization process are further complicated by the absence of reference databases and standardized protocols for marine natural products (Vidhya et al., 2024).

Preclinical and clinical research: In marine biomedical research, another major limitation is the process of transitioning from the discovery phase to preclinical and clinical development. More markers are required when carrying out research on marine invertebrate stem cells to differentiate between the different stages of cell development in various species (Mohajer et al., 2024). Preclinical research involving in vitro and in vivo experiments is necessary to evaluate the safety, efficacy, and mechanism of action of medications derived from marine sources as models for the treatment of human disorders before carrying out human clinical trials. However, obstacles to advancement in this field may include a lack of recognized preclinical models for drugs originating from marine sources, regulatory obstacles, and restricted funding (Vidhya et al., 2024). Detailed functional investigations are limited in many marine invertebrates due to a lack of comprehensive genetic tools (Mohajer et al., 2024). More difficulties for researchers arise from the need for significant infrastructure, funding, and regulatory approval for performing clinical studies to evaluate the medicinal potential of substances produced from marine environments (Vidhya et al., 2024).

Trademarks and commercialization: The commercialization of marine-derived compounds and the acquisition of intellectual property rights pose significant challenges for researchers and industry partners. Natural products face difficulties in protecting their intellectual property due to issues with novelty, patentability, and prior art. Additionally, the lengthy and expensive process of developing new drugs, combined with the uncertain regulatory pathway for marine-derived therapeutics, can discourage investment from venture capitalists and pharmaceutical companies. Consequently, many promising marine-derived compounds remain in the research stage, which limits their potential impact on human health (Vidhya et al., 2024).

7. Emerging technologies and techniques

In recent years, the field of marine organism research for human disease modeling has undergone a revolutionary transformation, driven by cutting-edge technologies and techniques. These advancements have significantly improved our ability to manipulate, observe, and analyze marine model organisms, resulting in unprecedented insights into human biology and disease mechanisms. The application of advanced methodologies has not only revolutionized the study of marine organisms but also deepened our understanding of their biology and facilitated their use as models for human diseases (Hahn & Sadler, 2020; Li, Zheng et al., 2021). These technological advances have enabled researchers to explore genetic, molecular, and cellular processes, shedding light on the mechanisms underlying development and disease. Some of the advanced technologies contributing to this progress include genetic manipulation technologies, genomic and transcriptomic technologies, imaging and analysis technologies, high-throughput technologies, multiomics approach, and 3D culture systems (Dai & Shen, 2022; Dar et al., 2023; Veenstra, 2021).

7.1 Genomic manipulation technologies

7.1.1 CRISPR-Cas9 and genome editing

- Gene knockout and knock-in

The advent of CRISPR-Cas9 genome editing has revolutionized functional genomics in marine organisms. This technology allows for precise manipulation of genes, enabling the creation of knockout and knock-in models to study gene function and disease mechanisms (Kanakarajan et al., 2024; Laurent et al., 2024). It also allows researchers to make specific changes to DNA sequences with unprecedented accuracy and efficiency, enabling the creation of disease models and the study of gene function in a wide range of marine species. Ye et al. (2024) and Leal et al. (2024) developed a method for CRISPR-mediated knock-in in zebrafish embryos, allowing for precise genomic modifications in specific cell types during development. This approach enables the generation of complex disease models and reporter lines with unprecedented speed and precision. CRISPR-Cas9 has been successfully applied in zebrafish to model human diseases such as cancer and cardiovascular disorders (Dong et al., 2022; González-Rosa, 2022; Rubbini et al., 2020). In zebrafish, CRISPR-Cas9 has been extensively used to create models of human genetic disorders. Raby et al. (2020) demonstrated the efficacy of this system in zebrafish, achieving mutation rates of up to 59% in target genes. While Tesoriero et al. (2023) used CRISPR-Cas9 to disrupt the dystrophin gene in zebrafish, mimicking the genetic defect seen in human patients with Duchenne muscular dystrophy (Zhang, Qin, et al., 2021; Weiss et al., 2022) employed CRISPR-Cas9 to create zebrafish models of leukemia, melanoma, and other cancers by targeting specific oncogenes and tumor suppressor genes. The technology has been used to model human cardiac disorders by targeting genes involved in heart development and function (Liu & Olson, 2022; Seok et al., 2021).

In marine invertebrates, CRISPR-Cas9 has opened new avenues for research into evolutionary developmental biology and the origins of human disease–related genes. In the sea anemone *N. vectensis*, CRISPR-Cas9 has been used to study the evolution of developmental processes relevant to human embryogenesis (Röttinger, 2021). Researchers have targeted genes involved in axis formation and germ layer specification, providing insights into the ancestral functions of these genes (Paix et al., 2023; Tang, 2023. In the amphioxus *Branchiostoma lanceolatum*, a close invertebrate relative of vertebrates, CRISPR-Cas9 has been employed to study the evolution of the nervous system and other vertebrate innovations (D'Aniello & Bertrand, 2021; Hajirnis & Mishra, 2021). The CRISPR-Cas9 system has several advantages over other genome editing techniques, which include higher efficiency and precision compared to earlier methods, ability to target multiple genes simultaneously (multiplexing), relatively simple design and implementation, and applicability to a wide range of organisms (Laurent et al., 2024; Ye et al., 2024).

- TALENs and ZFNs

While CRISPR-Cas9 has become the dominant genome editing tool, transcription activator-like effector nucleases (TALENs) and zinc finger nucleases (ZFNs) continue to play important roles, especially in organisms where CRISPR efficiency is lower or where more precise editing is required. In zebrafish, TALENs have been used to create models of human CVDs (Larijani et al., 2021). For example, Sam et al. (2020) used TALENs to disrupt the gata5 gene, creating a model of human congenital heart defects. In the sea urchin *S. purpuratus*, ZFNs have been employed to study the gene regulatory networks governing early development, providing insights into the evolution of developmental processes relevant to human embryogenesis (Zueva & Hinman, 2023). In the ascidian *C. intestinalis*, TALENs have been used to study the development of the notochord, a structure crucial for vertebrate development (Olivo et al., 2021; Sasakura &

Horie, 2023). Advantages of TALENs and ZFNs include high specificity, potentially reducing off-target effects, ability to target a wider range of sequences compared to early CRISPR systems, and established track record in some marine organisms (Roy et al., 2022). However, these techniques are generally more time-consuming and expensive to design and implement compared to CRISPR-Cas9.

- Base editing and prime editing

Newer genome editing technologies, such as base editing and prime editing, are beginning to be applied to marine organisms. These techniques offer even more precise genetic modifications with potentially fewer off-target effects. Base editing allows for the direct conversion of one DNA base to another without causing double-strand breaks. Reddy et al. (2020) demonstrated the use of base editors in zebrafish, achieving high efficiency in creating point mutations. This technique is particularly useful for modeling human genetic diseases caused by single nucleotide polymorphisms (SNPs) (Karapurkar et al., 2021; Sieliwonczyk et al., 2023). Prime editing, which offers even greater precision and versatility than base editing, has also been successfully applied in zebrafish Li, Jia et al. (2021) reported efficient prime editing in zebrafish embryos, opening up new possibilities for modeling complex human genetic disorders.

- Gene regulation studies

CRISPR interference and CRISPR activation technologies enable the modulation of gene expression without altering the DNA sequence. These methods have been used to study gene regulatory networks in marine organisms, providing insights into the genetic basis of development and disease (Ghavami & Pandi, 2021).

7.1.2 Genomic and transcriptomic technologies

Whole-genome sequencing has been instrumental in uncovering the genetic makeup of various marine organisms. The sequencing of genomes, such as those of the sea urchin (*S. purpuratus*), zebrafish (*D. rerio*), and sea anemone (*N. vectensis*), has provided comprehensive datasets that facilitate comparative genomics and the identification of conserved genes and pathways relevant to human health (Eide et al., 2021; Pankov et al., 2021; Suraweera et al., 2022). Another genomic technology is the RNA sequencing (RNA-Seq), which allows for the detailed analysis of gene expression profiles in marine organisms. This method has enabled researchers to study the dynamic changes in gene expression during development, disease progression, and response to environmental stressors. For example, RNA-Seq has been used to investigate the molecular mechanisms of regeneration in planarians and the immune responses in sea urchins (Medina-Feliciano & García-Arrarás, 2021; Parey et al., 2024).

7.1.3 Single-cell technologies

- Single-cell RNA Sequencing (scRNA-Seq)

scRNA-Seq allows for the analysis of gene expression at the single-cell level, providing insights into cellular heterogeneity and the identification of distinct cell populations. This technology has been applied to marine organisms to study developmental trajectories and cellular responses to environmental changes (Chang et al., 2024; Santra & Tseng, 2020) and has been transformative in understanding the complexity of tissues and organs in marine organisms. In zebrafish, scRNA-seq has been used to create comprehensive cell atlases and study developmental processes (Farnsworth et al., 2020). Truong (2022) used this technique to create a single-cell transcriptome atlas of zebrafish embryogenesis. They profiled over 92,000 cells from 12 stages of embryonic development, revealing new insights into cell fate decisions and lineage specification. This work provided a valuable resource for understanding vertebrate development and has implications for studying human developmental disorders. Tomasso et al. (2023) applied scRNA-seq to study heart regeneration in zebrafish. They profiled over 45,000 cardiac cells at various timepoints following heart injury, revealing the cellular dynamics and gene expression changes during regeneration. This work provided insights into the regenerative capacity of the heart, which could inform regenerative medicine approaches for human heart disease. In marine invertebrates, scRNA-seq has been used to study evolutionary developmental biology (Liu, Li et al., 2022). Bump and Lubeck (2023) and Moroz and Romanova (2022) used scRNA-seq to compare the cell type repertoires of diverse animal phyla, including cnidarians, ctenophores, and sponges. This work provided insights into the evolution of animal cell types and the origins of complex tissues, which is relevant to understanding human tissue organization and disease.

- Single-cell ATAC-Seq

Single-cell ATAC-Seq (Assay for Transposase-Accessible Chromatin using sequencing) enables the analysis of chromatin accessibility and regulatory elements at the single-cell level, providing insights into gene regulation and epigenetic states. This method has been used to investigate the epigenetic regulation of gene expression in marine organisms, shedding light on the mechanisms of development and disease and to study developmental processes and cell fate decisions (Almeida et al., 2021; Calderon et al., 2022; Sun et al., 2024; Vogt, 2022, pp. 35–108). Sun et al. (2024) applied this technique to zebrafish embryos, profiling chromatin accessibility in over 100,000 single cells across multiple developmental stages. This work revealed the dynamics of regulatory element usage during development and provided insights into the mechanisms of cell fate specification. In sea urchin embryos, single-cell ATAC-seq has been used to study the gene regulatory networks governing early development. Davidson et al. (2022) and Voronov et al. (2024) combined single-cell ATAC-seq with scRNA-seq to map the regulatory landscape of sea urchin embryogenesis. This integrative approach revealed the complex interplay between chromatin accessibility and gene expression during development, providing insights into the mechanisms of developmental gene regulation that are relevant to understanding human embryogenesis and congenital disorders.

- Spatial transcriptomics

Spatial transcriptomics techniques, which allow for the mapping of gene expression in the context of tissue architecture, are beginning to be applied to marine organisms. These methods provide crucial information about the spatial organization of cell types and gene expression patterns. In zebrafish, spatial transcriptomics has been used to study organ development and disease processes. Zhou et al. (2023) and Sampath Kumar et al. (2023) reportedly used Slide-seq, a high-resolution spatial transcriptomics method, to map gene expression in the developing zebrafish heart. This work revealed the spatial organization of different cell types during heart development and provided insights into the mechanisms of congenital heart defects. In marine invertebrates, spatial transcriptomics has been used to study regeneration and body plan organization. Some researchers have reportedly used a spatial gene expression mapping approach in planarians to study the organization of the nervous system during regeneration (Cui et al., 2023; Ge et al., 2022; Paré et al., 2023). This work provided insights into the mechanisms of neural regeneration, which could inform regenerative medicine approaches for nervous system injuries in humans.

7.1.4 Imaging and analysis technologies

7.1.4.1 Live-cell analysis and imaging

Live-cell imaging technologies enable the real-time observation of cellular and molecular processes in living organisms. In marine models like zebrafish and sea urchins, live-cell imaging has been used to study cell migration, cell division, and morphogenetic movements during development and disease (Zocchi et al., 2023). The development of advanced microscopy techniques, such as light sheet fluorescence microscopy (LSFM), correlative light and electron microscopy (CLEM), confocal microscopy, two-photon microscopy, adaptive optics, and superresolution microscopy, has enhanced the visualization of cellular and subcellular structures in marine organisms (Guo et al., 2021). These techniques allow for high-resolution imaging of developmental processes, cellular dynamics, and tissue architecture, providing detailed insights into biological mechanisms (Cuny et al., 2022; Shroff et al., 2024).

- **Light sheet fluorescence microscopy (LSFM):** LSFM has revolutionized in vivo imaging in marine organisms. This technique allows for high-speed, high-resolution, and long-term imaging of live specimens with minimal phototoxicity, making it ideal for studying developmental processes and disease progression in real-time. In zebrafish, LSFM has been used to observe embryonic development and disease processes in unprecedented detail (Bernardello et al., 2021; Turrini et al., 2023). Raiola et al. (2023) used LSFM to create a 4D digital atlas of zebrafish embryonic development, capturing cell movements and divisions across the entire embryo with subcellular resolution. This provides a comprehensive view of vertebrate morphogenesis and sets a new standard for developmental imaging. LSFM has also been applied to study specific disease processes. Bouchalova and Bouchal (2022) used LSFM to visualize tumor cell dissemination in a zebrafish model of melanoma. They were able to track individual tumor cells in real-time as they invaded surrounding tissues, providing new insights into the early stages of metastasis. In marine invertebrates, LSFM has been used to study regeneration and wound healing. Röttinger (2021) used LSFM to visualize the regeneration process in *N. vectensis* following amputation. He was able to track cell movements and proliferation during regeneration, providing insights into tissue repair mechanisms that could be relevant to regenerative medicine in humans.

- **Super-resolution microscopy:** Techniques like stimulated emission depletion microscopy (STED), photoactivated localization microscopy (PALM), and stochastic optical reconstruction microscopy (STORM) have broken the diffraction limit, allowing for nanoscale imaging of cellular structures. These techniques have been applied to marine models to study processes relevant to human diseases. Iyer et al. (2021) used superresolution microscopy to study the dynamics of cell division in sea urchin embryos. They were able to visualize the organization of microtubules during cell division with unprecedented detail, providing insights into the mechanics of cell division that are relevant to understanding cancer biology. In zebrafish, superresolution microscopy has been used to study synaptic structures in the developing brain. Gallagher and Zhao (2021) and Gong et al. (2023) used STORM to image synaptic proteins in zebrafish larvae, revealing the nanoscale organization of synapses in vivo. These works have implications for understanding neurodevelopmental disorders and synaptic dysfunction in human neurological diseases.
- **Correlative light and electron microscopy (CLEM):** CLEM combines the specificity of fluorescence microscopy with the ultrastructural detail of electron microscopy. This technique has been particularly useful in studying cellular processes in marine organisms. In zebrafish, CLEM has been used to study the ultrastructure of synapses in vivo. Markert (2023) used CLEM to correlate the activity of individual neurons with their synaptic structure in the zebrafish visual system. This approach provided insights into the relationship between neuronal function and structure, which is relevant to understanding neurodevelopmental disorders and synaptic plasticity in humans. CLEM has also been applied to marine invertebrates to study subcellular structures. Morris and Vacquier (2019) used CLEM to study the structure and function of cilia in sea urchin embryos. They were able to correlate ciliary beating patterns with the ultrastructure of individual cilia, providing insights into ciliary disorders that affect humans.
- **Adaptive optics:** Adaptive optics, originally developed for astronomy, is increasingly being applied to biological imaging to correct optical aberrations in thick specimens. This technique has relevance for imaging deep into the tissues of marine organisms. In zebrafish, adaptive optics have been used to improve imaging depth and resolution in the brain. Sahu and Mazumder (2020) used adaptive optics two-photon microscopy to image deep into the zebrafish brain with cellular resolution. This technique allows for the study of neural circuits in intact, behaving animals, providing insights into brain function relevant to human neuroscience.

7.1.4.2 High-throughput screening technologies

- **Automated behavioral analysis** Advanced tracking systems and machine learning algorithms have enabled high-throughput behavioral analysis in marine organisms, particularly in zebrafish larvae (Wang, Dong et al., 2024). Zhang, Liang et al. (2021) developed a high-throughput platform for analyzing zebrafish behavior in response to small molecules. They screened thousands of compounds and identified several that altered neural signaling and behavior. This approach has implications for identifying neuroactive drugs and studying the neural basis of behavior. More recently, Geng et al. (2023) developed a system for high-throughput analysis of social behavior in adult zebrafish. Using computer vision and machine learning, they were able to automatically quantify complex social behaviors in groups of fish. This system has applications for studying social behavior deficits associated with human psychiatric disorders. In marine invertebrates, automated behavioral analysis has been used to study the effects of environmental stressors. Limer et al. (2024) developed an automated system for tracking the behavior of coral larvae in response to different settlement cues. This approach has implications for understanding coral reef ecology and the impacts of climate change, which indirectly affect human health through ecosystem disruption.
- **Microfluidic devices:** Microfluidic technologies have enabled precise manipulation and analysis of marine embryos and larvae, facilitating high-throughput experiments and precise control of the microenvironment. Chen et al. (2022) developed a microfluidic chip for high-throughput analysis of zebrafish embryos. This device allowed for automated imaging and analysis of multiple embryos simultaneously, facilitating rapid assessment of drug effects and toxicity. Such systems have applications in drug discovery and toxicology studies relevant to human health. In marine invertebrates, microfluidic devices have been used to study cellular behavior and development. Berendsen et al. (2020) developed a microfluidic device to study chemotaxis in sea urchin sperm. This system allowed for precise control of chemical gradients and high-resolution imaging of sperm behavior, providing insights into fertilization processes that are relevant to understanding human reproductive biology (Berendsen et al., 2020; Penny et al., 2022; Wu et al., 2024).
- **Organs-on-chips:** While primarily developed for mammalian systems, organs-on-chips technologies are beginning to be applied to marine organisms. These devices aim to recapitulate the complex 3D structure and function of organs in vitro. Zhu et al. (2021) developed a "heart-on-a-chip" using zebrafish cardiac cells. This system allowed for the study of cardiac function and drug responses in a controlled in vitro environment. Such platforms have potential applications

in drug screening and studying cardiac diseases. In marine invertebrates, similar approaches are being developed to study organ function and development. Roger et al. (2021) developed a microfluidic device to culture tentacles from the sea anemone *N. vectensis*. This system allowed for long-term culture and manipulation of tentacles, providing a platform for studying regeneration and tissue homeostasis.

7.1.6 Multiomics approach

7.1.6.1 "Omics" technologies

- **Proteomics:** Advanced proteomic techniques, including mass spectrometry (MS)-based approaches, have enabled comprehensive analysis of protein expression and modification in marine organisms. In zebrafish, proteomics has been used to study various aspects of development and disease. Linscheid et al. (2021) used quantitative proteomics to study protein expression changes during zebrafish heart regeneration. They identified several proteins and pathways involved in the regenerative response, providing potential targets for regenerative therapies in humans. In marine invertebrates, proteomics has been used to study evolutionary adaptations and stress responses. For instance, Kong et al. (2022) used proteomic analysis to study the response of mussels to heat stress. This work provided insights into the molecular mechanisms of thermal tolerance, which is relevant to understanding the impacts of climate change on marine ecosystems and, indirectly, on human health.
- **Metabolomics:** Metabolomic profiling has allowed researchers to study the small molecule composition of marine organisms, providing insights into metabolic processes and potential bioactive compounds (Bayona et al., 2022; Bouyahya et al., 2024; Lahiri et al., 2023). In zebrafish, metabolomics has been used to study various physiological processes and responses to environmental stressors (Mashabela et al., 2023). Ding and Wang (2024) used metabolomic analysis to study the effects of bisphenol A (BPA) exposure on zebrafish embryos. They identified several metabolic pathways affected by BPA exposure, providing insights into the potential health effects of this common environmental contaminant on humans. In marine invertebrates, metabolomics has been used to discover novel bioactive compounds with potential pharmaceutical applications. Tan (2023) used metabolomic profiling to study the chemical defenses of soft corals. They identified several novel compounds with potential anti-inflammatory and anticancer properties, highlighting the potential of marine organisms as sources of new drugs.
- **Epigenomics:** Epigenomic studies, including DNA methylation analysis and histone modification profiling, provide insights into gene regulation and cellular memory in marine organisms, with implications for understanding human development and disease. In zebrafish, epigenomic studies have revealed important insights into developmental programming and disease susceptibility. Mayne et al. (2020) and Liu, Zeng, et al. (2023) used whole-genome bisulfite sequencing to map DNA methylation changes during zebrafish development. They identified dynamic methylation patterns associated with key developmental transitions, providing insights into the epigenetic regulation of vertebrate development that are relevant to understanding human developmental disorders. Huang, Zheng et al. (2020) studied the transgenerational effects of BPA exposure in zebrafish using epigenomic approaches. They found that BPA exposure induced changes in DNA methylation patterns that persisted across generations, highlighting the potential long-term impacts of environmental exposures on epigenetic regulation. This work has implications for understanding the epigenetic basis of human diseases and the potential transgenerational effects of environmental toxins. In marine invertebrates, epigenomic studies have provided insights into evolutionary adaptations and phenotypic plasticity. Hackerott et al. (2023) used epigenomic profiling to study coral responses to ocean acidification. They found that corals can rapidly adjust their gene expression through changes in DNA methylation, providing a mechanism for acclimation to environmental stress. This work has broader implications for understanding epigenetic adaptations to environmental changes, which could inform strategies for managing human health in the face of climate change.
- **Optogenetics and chemogenetics:** These techniques allow for precise control of neural activity in living organisms, providing powerful tools for studying neural circuits and behavior. In zebrafish, optogenetics has been used to study various aspects of neural function and behavior. Sugioka et al. (2023) used optogenetics to map the neural circuits controlling locomotion in zebrafish larvae. By selectively activating specific neurons, they were able to induce swimming behaviors, providing insights into spinal cord function relevant to human motor disorders. More recently, Zhu and Goodhill (2023) used optogenetics in combination with whole-brain imaging to map the neural circuits underlying visual perception in zebrafish. They were able to manipulate specific visual pathways and observe the resulting neural activity across the entire brain, providing a comprehensive view of visual processing in a vertebrate system. In marine invertebrates, optogenetics is beginning to be applied to study nervous system function. Tang (2023) developed optogenetic tools for the sea anemone *N. vectensis,* and this work opened up new possibilities for studying the evolution of

neural circuits and behaviors in early branching animals, which could provide insights into the fundamental principles of nervous system function relevant to human neurobiology.

Chemogenetic approaches, which use engineered receptors activated by specific drugs, are also being applied to marine organisms. These techniques offer the advantage of noninvasive manipulation of neural activity over longer time scales. In zebrafish, Zhu et al. (2024) developed a chemogenetic approach using engineered TRPV1 channels to manipulate the activity of specific neurons. This system allowed for temporally precise control of neuronal activity in freely swimming zebrafish, providing a powerful tool for studying neural circuit function and behavior.

7.1.7 3D culture systems

7.1.7.1 Organoid technologies

While primarily developed for mammalian systems, organoid technologies are beginning to be applied to marine organisms, allowing for the creation of 3D tissue cultures that better mimic in vivo conditions.

- **Fish organoids:** Researchers have developed various types of organoids from fish cells, providing new models for studying organ development and disease. For instance, Li, Gong et al. (2022) developed retinal organoids from zebrafish cells. These fish organoids recapitulated key aspects of retinal development and organization, providing a new model for studying eye development and diseases (Aasen & Vergara, 2020; Zhang, Xu et al., 2021. Pawolski and Schmidt (2020) developed intestinal organoids from zebrafish, which they used to study interactions between the gut epithelium and enteric nervous system. This model provides opportunities for studying gastrointestinal disorders and host–microbe interactions in a system that is amenable to high-throughput screening.
- **Invertebrate organoids:** Organoid technologies are also being adapted for marine invertebrates. For example, Hewaidy (2023) developed methods for generating organ-like structures from disaggregated cells of the sea anemone *N. vectensis*. These "neomorphs" recapitulated aspects of normal development and regeneration, providing a new platform for studying the mechanisms of regeneration and body plan formation in a basal metazoan.

8. Translational application

Translational research aims to produce meaningful, applicable results that are advantageous to human health (Papon et al., 2022). The objective of translational research is to move primary science findings more swiftly and efficiently into practice (Papon et al., 2022). In other words, translational research entails moving scientific discoveries from laboratory (basic research) to clinical application, with the objectives of enhancing patient care or developing emergent therapies through stringent clinical trials, refining techniques, the safety, and test efficacy of new treatments before implementation (Jafari Porzani & Nowruzi, 2023, pp. 316–354).

8.1 Potential applications of discoveries made using marine model organisms in developing new diagnostics, therapeutics, and personalized medicine approaches

Generally, chronic or acute infections are greatly associated with CVDs and other noncommunicable diseases such as diabetes, cancer, renal infections, and other illnesses (Supriya et al., 2022). However, personalized medicine propelled by marine models possesses numerous health advantages such as antiinfection, antioxidant, and antidiabetic amongst other discoveries toward the production and development of medications (Papon et al., 2022). Therefore, making their application necessary for the control and prevention of both CVD and noncommunicable diseases. Specific examples drawn from different species are discussed below.

8.1.1 Invertebrate marine model organisms

8.1.1.1 Phylum: Marine Porifera (marine sponges)

Marine sponges from the Porifera phylum have evolved through adaptative measures to become the most fertile marine bioactive compounds in the pharmaceutics industry with over 9000 species classified into four classes; Calcarea, Demospongiae, Hexactinellida, and Homoscleromorpha (Mannelli et al., 2021). Currently, there are over 5300 renowned natural compound derivatives from isolations and associated bacteria (Nasser Alahmari et al., 2022). In similitude with other marine sessile, sponges have developed biological adaptation measures responsible for developing metabolites (used in reacting in their natural habitats) for protection from predators, pathogens, and rivalries (Kamaruding et al., 2020).

These metabolites contain properties that are anticancer cells, antiviral, and anti-inflammatory characterization (Mannelli et al., 2021). The following are some organisms' examples under the marine sponges used for treatment purposes:

- **Eribulin (Halichondrin B analog):** Eribulin mesylate is the synthetic analogue of halichondrin b isolated from the marine sponge *Halichondria okadai* belonging to the demospongiae class and known for the production of okadaic acid (Facey, 2024). Eribulin functions by obstructing microtubule dynamics, requisite components of cell division, thereby preventing the widespread of cancer cells within the patient (Wang, Li et al., 2024). The synthetic production of halichondrin b obtained different analogs, including eribulin mesylate formed by the right-handed lactone ring of macrolides, but with the absence of a side chain substituted by primary amine (Das et al., 2022). Based on the phase 111 clinical trial designated as embrace, the molecules show a 55% survival advantage when administered compared to conventional treatments. Consequently, in 2010 and 2011, the FDA in the USA and the European medicines agency sanctioned its usage in the management of metastatic breast cancer and liposarcoma after two previous anthracycline- and taxane-based therapies (Haque et al., 2022).
- **Discodermolide:** Discodermolide extracted from the sponge *Discodermia dissoluta* is renowned for its microtubule-stabilizing properties with impact on cancer cells (Montuori et al., 2022). Its compounds are known for their efficacy in distorting cancer cell development by promoting tubulin polymerization, similar to the widely used chemotherapy drug Taxol (Lu et al., 2021). Additionally, discodermolide has been employed in the treatment of diverse cancer strains especially in the formation of exoskeleton in glass sponges (Hexactinellida) (Romano et al., 2022). The basilica silica structure primarily comprises an axial filament made of actin thereby enhancing mineralization and osteogenesis in vitro by fostering tissue mineralization (Iskandar et al., 2023). Thus, it has been used in numerous biological applications especially in tissue engineering and bone replacement research, due to its ability to facilitate hydroxyapatite production, especially the demosponge *Suberites domuncula* species (Iskandar et al., 2023).

8.1.1.2 Phylum: marine tunicate

Marine tunicates commonly known as sea squirts are classified in the subphylum tunicate of the phylum Chordata revealing a closer relationship to vertebrates than invertebrates (Bakal & Lewbart, 2022). Marine tunicate generates different secondary metabolites ranging from alkaloids, polyketides, and terpenes, with the Ascidiacea encompassing 3000 renowned species, whereas taxonomists estimate about 1500 unclassified species (Avhad & Bhangale, 2023). The following are some medicinal extracts from tunicate species:

- **Trabectedin (Ecteinascidin-743):** Trabectedin is a primary compound derivative of the phylum Chordata of the sea squirt Ecteinascidia *turbinata*, recognized amongst the abundant structural alkaloids (Avhad & Bhangale, 2023). Trabectedin is a structurally complicated alkaloid that is seldom derived from marine creatures with its structure consisting of two tetrahydroisoquinoline rings combined by a lactone bridge (Avhad & Bhangale, 2023). Trabectedin uses a distinct mechanism toward binding with the guanine residues to the minor groove of the double helix DNA acting as an alkylator leading to sequencing that causes the bending of strands away from the alkylation (Mannarino, 2021), thereby interfering with the cancer cells by inducing apoptosis that stops the processes of RNA polymerase ii and stops the transcription of DNA (Mills & Gago, 2021). Trabectedin's efficacy toward the disruption of the DNA repair procedure for cancer cells renders it potent in locating tumors that have developed standard treatment resistance (Begum & Hemalatha, 2022). Hence, trabectedin is approved and utilized in the treatment of soft tissue sarcoma and ovarian cancer.
- **Plitidepsin (Aplidine):** Plitidepsin is a cyclic peptide derived from the marine tunicate *Aplidium albicans*, reveals immense anticancer potency by limiting the eukaryotic elongation factor 1A2 (eEF1A2), which onset oxidative stress, leading to swift activation of c-Jun N-terminal kinase (JNK) and p38/MAPK, and invariably causing apoptosis (Antunes et al., 2023; Sukmarini, 2022), a protein implicated in the widespread and survival of cancer cells. Plitidepsin has been experimented with in clinical trials for multiple myeloma and other malignancies even COVID-19 (Sukmarini, 2022) and exhibited anti-SARS-CoV-2 sequences, with an IC90 value of 0.88 nM, higher than remdesivir in the human cell line hACE2-293T by a factor of 27.5, with limited toxicity revealing potency as a possible therapeutic alternative, particularly for diseases resistant to traditional therapies (Sukmarini, 2022).

8.1.1.3 Phylum: marine molluscs

Marine molluscs, especially cone snails, are renowned for their bioactive properties with their venom containing millions of peptides (conotoxins), with the ability to affect the nervous systems (Dhiman et al., 2021). Marine molluscs have been identified for neurological studies due to their precision in targeting ion channels and receptors (Zhang, Feng et al., 2024).

The approximate number of marine Mollusca species exceeds 50,000, whereas cyanobacteria include about 1600 species, with predictive studies suggesting a total exceeding 6000 (Gao, Fan et al., 2021). Examples of marine mollusc usage include:

- **Lignarenones** are classified under aryl octanoids produced by polyketide synthase-like enzymes (Romano et al., 2022). The studies of fluorescence and electron microscope tissue revealed that the development of aromatic polyketides happens in the cytoplasm of Blochmann's glands, situated along the mantle's boundary (Romano et al., 2022). Recent studies revealed that lignarenone B possesses the possibility of decreasing GSK3 activity, presumably via both ATP-competitive and noncompetitive allosteric mechanisms (Llorach-Pares et al., 2020). These compounds are responsible for improving neurites in the primary cortical neuron cells without inducing neurotoxicity (Llorach-Pares et al., 2020), therefore, serving as a primary basis for the development of therapeutic drugs in the treatment of neurodegenerative disorders such as Alzheimer's disease.
- **Ziconotide (Prialt):** Ziconotide is a synthetic derived from the venom of the cone-shaped snail *Conus magus* as an alternative to peptide. Ziconotide stimulates N-type calcium channel blockers in the central nervous system, which are the primary pain signals (Choudhary et al., 2023). Ziconotide perform by inhibiting Cav 2.2 channels and possess high potency and specificity therefore used in the treatment of chronic pain especially for patients who are nonresistant to other therapies (Gao, Yao et al., 2021). Additionally, unlike opioids with tendencies of addiction, tolerance build-up in the immune system or misuse, ziconotide do have such effect, making them an alternative in pain management, although it is administered intrathecally (Ilias, 2020).

8.1.1.4 Phylum: marine echinodermata

Echinoderms are deuterostome invertebrates possessing phylogenetic characteristics associated with chordates and hemichordates (Ezhova & Malakhov, 2022). The phylum has approximately 7000 extant species ranging from sea urchins to sea cucumbers and over 13,000 extinct species (Ezhova & Malakhov, 2022). A classic example is:

- **Sea urchin:** The sea urchin possesses 400 genotypic expressions with 65 ATP-binding cassette transporter including ions, lipids, peptides, and steroids that regulate homeostasis cell and sequence conservation (Adonin et al., 2021). The mutation process of the genes results in human health issues such as cystic fibrosis, cholesterol transport abnormalities, anemia, and retinal degeneration, among others (Adonin et al., 2021). Furthermore, the sea urchin embryos are used toward cellular molecular pathways examining neurodegenerative ailments that result in dementia and memory impairment (Fogliano et al., 2024). Hence, the sea urchin is continuously utilized in the health science realm resulting in a concise investigation of cancer threats before epidemiological information (Molla & Aljahdali, 2023).

8.1.2 Vertebrate marine model organisms

8.1.2.1 Phylum chordata

- **Zebrafish:** *Danio rerio* (Zebrafish) have expressions, such as a transparent body, egg, in vitro fertilization, in vitro development, and high homology, with human genes and tissues making them suitable species toward their usage as marine models (Konno et al., 2020). Zebrafish are small vertebrate tropical marine fishes that are exemplified for their cost-efficient maintenance and overexploited as model marine fish for reverse and forward genetic works (Monteiro et al., .2021). The works of Bergen et al. (2022) discovered 604 genes linked with the process of formation, mineralization and regrowth of the scale, which reveals that bone remanence can be achieved through these structures. Additionally, the mutation of zebrafish structures in humans can be used in the treatment of bone mineralization (Bergen et al., 2022). This proposes that zebrafish structures are used as an efficient model for studying the pathogenesis of skeletal ailments, clarification, and formation (Li, Boldt et al., 2024). Furthermore, beyond 80% of acknowledged human disease genes, oncogenes and tumor suppressor genes comprise orthologs in zebrafish, with numerous pathways such as carcinogenesis (Russo et al., 2022). The above characteristics have improved the use of zebrafish as a marine model toward explaining human genetic imbalances such as cancer and elucidated greater potential for in vivo screening of novel therapies, especially in the notion of personalized medicine (Russo et al., 2022).
- **Lamprey eel:** Lamprey eels is a jawless fish (predator family), utilized as a model organism in spinal cord research. The Adult Lamprey (LIP) bodies possess cytocidal activity against human MCF-7 and K562 cells with selectivity for the target cells (Supriya et al., 2022). LIPs showcase potent cytocidal impact on tumor cells in both vitro and vivo settings. Supriya et al. (2022) reported silver nanoparticles are utilized for their antimicrobial characteristic, and their cytotoxic impact was examined in the heart and gill cell lines of Indian carps revealing tremendous improvement in spinal cord research (Supriya et al., 2022).

8.1.2.2 Challenges and considerations in translating findings from marine models to human clinical settings

Anatomical and genetic variations: The physiological composition of marine organisms differs from that of humans regardless of genetic similarities with humans. For example, although zebrafish are utilized for cardiovascular and cancer research resultant of their similitudes with humans (70% of human genes have at least one zebrafish ortholog), their ecosystems, immunology, and thermostatics vary from human physiology, thereby potentially affecting drug absorptions, metabolism and reactivity (Bhatia et al., 2024). Similarly, although models can mimic genetic mutations or disease phenotypic, the intricacies of human multiple genes and disease environmental factors infringe on the direct application of research findings since numerous pathways or disease mechanisms between both organisms and humans may not function identically (Bhatia et al., 2024). Thus, this difference can result in translating research findings inhibiting the predictive value of marine models to specific conditions.

Ethical considerations: Ethical and environmental considerations in the overexploitation, endangerment of sentient species and fear of biodiversity-ecosystem disruptions have continually raised concerns (Sigwart et al., 2021). The increase in human population is proportional to the need for harvesting more species toward disease treatments resulting in overexploitation of organisms for biomedical research threatening and distorting the biodiversity ecosystems' (Bhatia et al., 2024). Therefore, the use of endangered, sentient, or rare species for their properties will eventually lead to the extinction of marine organisms since artificial reproduction measures are 100% attainable in confined situations for most marine species (Sigwart et al., 2021).

Complexity of compounds: Marine organisms' compounds, although structurally unique and promising for drug creation, frequently present scalability and reproductive capability (Pound & Ram, 2020). These organisms possess complex compounds in small quantities and are usually complex structures, collecting them becomes impractical or often biodiversity damaging. Furthermore, these organisms are extremely variable (inferring the production of their properties fluctuates) based on factors such as their ecosystems, further complicating scientific measures to standardize and mass-produce their compounds for clinical usage (Pound & Ram, 2020).

Regulatory complexities: The translation of research findings using marine organisms' transverse through different stringent regulatory measures for the safety and well-being of humans (Kenny, 2019). Marine-based compounds undergo different preclinical trial measures starting from nonhuman models before being approved for human trials. This preclinical process can extend for years thereby slowing down clinical procedures and being costly especially when translation to human models is not in alignment (Kenny, 2019). Furthermore, promising marine models' compounds can alter in the advanced phase of drug testing resulting in wastage of resources and time in the drug development processes (Papon et al., 2022).

9. Future directions and emerging areas of research involving marine model organisms in disease modeling

Marine organisms are critically emerging and utilized in biomedical research to understand human diseases at a molecular level in order to showcase their potential as valuable models for studying various health conditions (Bosnar et al., 2020). There are several marine organisms that could aid in understanding human disease modeling. Oysters and zebrafish, which serve as models for studying the transmission of pathogens via microplastics, aid in understanding disease dynamics in both marine ecosystems and potentially human health (Bowley et al., 2021). Research on the genome of the Chinese white dolphin (*Sousa chinensis*) provides insights into the molecular mechanisms for adaptation and the potential development of marine peptide–based drugs for treating CVDs (Jia et al., 2019). The microbial peptides and genome sequencing of lined seahorse (*Hippocampus erectus*) and giant grouper (*Epinephelus lanceolatus*) have been identified to support antimicrobial resistance and aid the development of AMP-based fish food and human drugs in combating external pathogens (Wang et al., 2019). The study by Chen et al. (2019) reveals that the genomic studies of Japanese eel (*Anguilla japonica*) could be used in the evolutionary development of marine drugs. Moreover, several unique organisms such as sponges, seaweeds, corals, sea cucumber, and octopus are rich in biodiversity and produce several compounds that have potential applications in medicine, including anticancer, antiviral, antiinflammatory agents, and antimicrobial properties (Blunt & Carroll, 2019; Raghavendra & Reddy, 2020; Kwan & Hsiao, 2021).

Various approaches to emerging research directions involving marine organisms in human disease modeling involve advanced surveillance, molecular techniques, developing new therapeutic strategies, and enhancing our understanding of host–pathogen interactions (Kanellopoulos et al., 2024, p. 171). These marine organisms, which include bacteria, fungi, and macroalgae, are rich in bioactive compounds and have shown significant anticancer properties (Khalifa et al., 2019).

These bioactive compounds belong to unique chemical classes that are found only in marine organisms, which aid drug development. For example, marine-derived drugs, such as cytarabine and trabectedin, have been approved for cancer treatment, demonstrating their therapeutic potential (Barreca et al., 2020). In this context, similar to their anticancer properties, these marine organisms help researchers discover new biomarkers and study how tumors grow, develop, and metastasize, aiding them in developing novel pathways for finding new treatments (EMBRC, 2024).

Additionally, the extraordinary potential of the increased focus on genomic and transcriptomic studies brings about an advancement in sequencing technologies that will enable comprehensive genomic and transcriptomic analysis of marine organisms. Hence, facilitating the identification of novel gene pathways involved in disease progression enhances the understanding of disease mechanisms and potential therapeutic targets. Moreso, the application of CRISPR/Cas9 gene-editing technology in marine model organisms enables researchers to create precise genetic modifications, helping them study gene function and paving the way for targeted therapies (Nymark et al., 2016). Understanding the microbiomes of marine organisms and the influence of their microbial communities on the immune system of the host leads to novel therapeutic strategies for understanding the role of the microbiome in health and disease (Uniacke-Lowe et al., 2024). Research has shown that marine organisms are known for the discovery of diverse natural products. In this context, they are a rich source of bioactive compounds with a wide range of applications, which include pharmaceuticals, biotechnology, agriculture, material science, and nutraceuticals (Stien, 2020); hence, the increased need for research in the characterization of these natural products and exploring their potential uses in treating human disease (Avhad & Bhangale, 2023).

Rotter and colleagues reported that the integration of genomics, proteomics, metabolomics, and other omics contributes to an advanced study on the biology of marine organisms and their responses to diseases (Rotter et al., 2020). Additionally, Zheng (2024) reported that the integration of multiomics advances the understanding of biological systems by combining data from genomics, transcriptomics, proteomics, metabolomics, and epigenomics (Zheng, 2024). These comprehensive approaches uncover complex interactions and pathways involved in human disease progression, allowing researchers to study gene functions in mixed microbial communities (Rotter et al., 2020; Zheng, 2024). Next-generation sequencing, MS, and microarray are high technologies that enable the generation of these multiomics datasets (Cao et al., 2022). These approaches provide in-depth information about microbial communities, linking genes to proteins and metabolites, which is crucial to understanding their function and interactions in the environment (Wu et al., 2024). Additionally, integrating these multiomics data enhances precision medicine by enabling scientists to identify molecular signatures and biomarkers that are critical for disease diagnosis, prognosis, and treatment response. Moreover, this brings about the development of more precise medical interventions and improved patient outcomes in cancer, neurodegenerative disorders, and metabolic syndromes (Ahmed, 2020).

Genomic integration involves using genomic data from marine organisms and their genetic diversity and adaptations to improve human health research (Bosnar et al., 2020). This approach enabled researchers to investigate the physiology and developmental processes of various marine organisms such as microbes, plants, invertebrates, and vertebrates (Li, Wang et al., 2022; Oleksiak & Rajora, 2019). In comparison, the integration of proteomics focuses on the protein level in human health, and the aim of nutritional proteomics is to advance human health by providing a clear relationship between diet, protein levels, and health outcomes (Katsarou et al., 2021; Sonbol, 2024), while metabolomics utilizes the metabolic profiles of marine organisms to elevate potential health benefits and therapeutic applications. In this context, there is an increased focus for researchers to identify bioactive compounds in the biochemical process within marine organisms. This focus can lead to the discovery of novel drugs and therapeutic properties for human health (Bayona et al., 2022). However, the use of metabolomics facilitates the interactions between marine organisms and their environments. These ecological interactions are crucial for identifying the source of the marine-derived metabolites that can be utilized in studying human diseases (Bayona et al., 2022). In light of Zheng and colleagues' study, Kuperstein and colleagues reported that computational modeling facilitates the analysis of diverse multiomics datasets, enabling researchers to uncover complex interactions and regulatory mechanisms within cells and organisms (Kuperstein et al., 2015). Several computational methodologies, such as statistical modeling, machine learning, and network analysis, help manage the complexity of multiomics data. Machine learning algorithms such as random forests and neutral networks are essential for data integration, dimensionality reduction, and predictive modeling (Yagin, 2023, pp. 23–38). Moreso, single-cell omics and spatial omics technologies provide information in areas of cellular heterogeneity and tissue microenvironments. In light of this, it is crucial to integrate computational approaches for these high-resolution datasets, which help map cellular states and understand tissue-specific molecular interactions (Vandereyken et al., 2023). This approach integrates multiomics datasets, which demonstrates a great potential for considering marine organisms at different levels in the advancement of human health. Additionally, the description also indicates the challenges in these integrations, which require addressing

data heterogeneity and standardization, scalability, interoperability, technical biases, and ethical considerations related to data privacy and security.

10. Conclusion

The discovery of marine model organisms over the years has been a ground-breaking modality for biomedical researchers in better understanding and critically analyzing the mechanisms of human disease due to the complexity of these marine organisms which share similar biochemical, genetic, and physiological properties to humans when compared to other life forms including invertebrates and mammalian vertebrates. The use of marine organisms in studying human diseases encourages biomedical research and allows for new innovations and interdisciplinary approaches, which allows for collaborations resulting in development of novel models for the treatment of various human diseases. The study of the diversity of marine organisms in understanding various biological and cell processes will facilitate the advancement of marine organisms' culture methods, increasing the available alternatives to the use of animals in research, which will further promote our understanding of complex human diseases. The complexity and applications of marine model organisms vary. While zebrafish (*Danio rerio*) and fruit flies (*Drosophila melanogaster*) are excellent models for studying genetics and the development of diseases, small, simple animals like yeast are often employed to investigate gene alterations in human cancers. In order to better understand how diseases progress and how new treatments are developed, mouse models are also often employed in biomedical research. The development of marine species as models for human diseases is one area of biomedical research that looks promising for useful insights and possible treatments of various diseases. Researchers are creating new pathways for the understanding and maybe treatment of a wide range of human ailments by utilizing the special qualities of marine life including the ability of marine organisms to produce mutants for the purpose of studying specific features or diseases, their short generation cycles, and ease of maintenance and reproduction in a laboratory setting. The evolutionary development of marine model organisms provides valuable insights into various biological systems and their functions at the cellular, tissue, organ, and system level. It is very likely that prospects for the creation of novel tools for the diagnosis, treatment, and prevention of various diseases will arise from ongoing and future research in this area.

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Chapter 16

Biotechnological applications of marine biomolecules and bio-nutraceuticals

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1. Introduction

Marine biomolecules are enzymatic polymers obtained from a variety of sources such as red and brown algae, sea anemones, corals, sponges, fish, and marine bacteria. These bio-molecules are polysaccharides, peptides, lipids, proteins, polyphenols, alkaloids, and enzymes having structural and functional diversities. Bioactive molecules derived from marine organisms have been reported to exhibit a variety of biological activities that include antimicrobial, antioxidant, antiinflammatory, and anticancer properties. All these compounds have received much interest of late due to their prospect in enriched sources of new therapeutic products and functional food components (Ghosh et al., 2022). Marine bio-nutraceuticals can be described as those bio-molecules belonging to marine resources and are used for their health-promoting properties. These bio-nutraceuticals come in the forms of food supplements, functional foods and even cosmetics which people take or apply in their bodies as a way of improving their general health. Some specific marine bionutraceuticals include the omega-3 polyunsaturated fatty acids (PUFA) from fish oils, the fucoidans and alginates obtained from seaweed, and collagen peptides originating from fish and marine invertebrates (Senadheera et al., 2023). These bio-molecules are advisable for use in replacement of terrestrial bio-molecules because of the prolific, more unspecified biological diversity found in marine environments and the rising utilization of bio-based products. Marine bioactive compounds and biofunctional foods and nutrients remain sought after in the pharmaceutical, food industry, and cosmetic industries (Alhajj et al., 2020).

As a result, marine biomolecules and bio-nutraceuticals are key technologies in biotechnology that identify the unique functionality of medications, proposed functional foods, and viable bio-processing technology. These types of compounds contain unique chemical structures that are discordant with the bulk of land-canopied species, making them useful for the development of new therapies. Marine bio-molecules exhibit considerable potential biological activities such as anticancer, antimicrobial, antioxidant, and antiinflammatory activity, thus making them ideal for disease management including cancer, cardiovascular disease and neurodegenerative disease (Aransiola et al., 2024; Kabir et al., 2022). Besides their effectiveness in Medical fields, Marine bio nutrition has been sought for their functionality in the promotion of health. For instance, omega-3 PUFAs found in marine fish oil have been studied for ant cardiovascular disease including hypertension, reduced cholesterol and improved endothelial function.

Likewise, polyphenols and carotenoids isolated from marine algae possess acceptable antioxidant potential to overcome the anxiety of oxidative stress and disorders (Pradhan et al., 2020). Marine bio-molecules also find their use in environmental biotechnology as part of biotechnological applications. For example, some enzymes isolated from marine

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environments are being applied in waste treatment, biodegradation, and biotransformation. These enzymes have tolerance and productivity in conditions like high salinity, and low temperature and hence can be viewed as important candidates for industrial use (Thapa et al., 2019). Therefore, not only does it have a bright future for being a potential source for human health improvement but also it has a bright potential for the future development of marine bio-molecules and bio-nutraceuticals for sustainable biotechnological applications where there is a need for addressing global health and environmental issues.

2. Marine bio-molecules: Sources and classification

2.1 Types of marine bio-molecules

Marine bio-molecules encompass a broad range of compounds with diverse chemical structures and biological activities. These molecules are derived from various marine organisms, and their applications span across biotechnology, medicine, and food industries. The major types of marine bio-molecules include:

- **Polysaccharides** Polysaccharides are macromolecules which are made up of long chains of monosaccharides. Marine polysaccharides are mainly obtained from red seaweeds and marine algae they include; agar, carrageenan and alginate. These polysaccharides possess gelling, thickening, and stabilizing properties thus finding great uses in the food industry, pharmaceuticals, and cosmetics. However, they are also employed in drug delivery systems because of their compatibility and degradation profiles (Ha & Gardella, 2005). Some polysaccharides contain important bioactivity of fucoidans and laminarins as anticancer and antiviral agents (Geetha & Tuvikene, 2021).
- **Peptides and Proteins** Marine peptides and proteins, often derived from marine invertebrates and fish, possess a wide range of bioactivities. Marine collagen, derived from fish and other marine animals, is a notable example, widely used in the cosmetic and pharmaceutical industries for its antiaging and skin-healing properties (Rahman et al., 2024). Moreso, bioactive peptides such as antimicrobial peptides (AMPs) and antioxidant peptides isolated from marine organisms have shown therapeutic potential in treating infections and oxidative stress-related diseases (Chakniramol et al., 2022).
- **Lipids** Marine lipids, particularly omega-3 fatty acids (e.g., EPA and DHA), are primarily sourced from marine fish oils, krill, and algae. These PUFAs have proven cardiovascular, antiinflammatory, and neuroprotective effects (Giacobbe et al., 2020). Marine phospholipids, such as those found in fish and krill oils, are also crucial in membrane structure and function and are used in the development of functional foods and dietary supplements (Rahman et al., 2024).
- **Alkaloids** Alkaloids are nitrogen-containing compounds that have been found to have widely disparate activity profiles on the body such as analgesic, antimicrobial and anticancer activity. Marine alkaloids are natural products isolated from sponges, corals, and mollusks and they have attracted significant interest owing to their unique structural features and conspicuous biological properties. For instance, the marine alkaloid latrunculin derived from marine life has demonstrated immunosuppressive and anticancer potential (Luparello et al., 2020).
- **Polyphenols** The three polyphenolic compounds characterized to occur in marine algae are Flavonoids, phenolic acids and tannins mainly in brown algae. These compounds display remarkable antioxidant, antiinflammatory, and anticancer activities, and thus the authors Silva and his team consider marine bio-nutraceuticals prospects healthier. Marine polyphenols have also attracted increased interest regarding their roles in oxidative stress and metabolism (Méndez & Medina, 2021).
- **Enzymes** Proteases, lipases, and cellulases of marine origin find immense potential in biotechnological applications because of their ability to work at high pressure and in fluctuating temperatures and pH ranges. Currently, enzymes isolated from marine sources and their application can be found in further fields including; food processing, bioremediation, and biotechnology (Barone et al., 2019).

2.2 Sources: Marine flora and fauna

Marine bio-molecules are sourced from both marine flora (algae and seaweeds) and fauna (marine animals). These sources provide a rich diversity of bioactive compounds with significant applications in various industries.

a. **Marine Flora** Marine algae and seaweeds are among the richest sources of bioactive molecules. There are three primary groups of marine algae: "Chlorophyceae, Phaeophyceae, and Rhodophyceae." Each group produces different types of bioactive compounds:

- **Green Algae (Chlorophyta):** Green algae, such as *Chlorella* and *Ulva*, are rich in polysaccharides like ulvan, which possess antiviral and immunomodulatory activities. They are also sources of bioactive peptides and fatty acids with antimicrobial properties (Reynolds et al., 2021).
- **Brown Algae (Phaeophyta):** Members of the Phaeophyta division including Laminaria and Fucus bear polysaccharides alginates and fucoidans that exhibit antioxidant, anticoagulant, and anticancer properties (Li et al., 2021). Fucoidan, a sulfated polysaccharide derived from brown seaweed, has gained much interest due to its cancer- and cardiovascular-disease-fighting properties.
- **Red Algae (Rhodophyta):** Members of Rhodophyta have been recognized to produce carrageenans and agar which are used extensively as gelling agents. More specifically, the antioxidant and antiinflammatory polyphenols of red algae (Aziz et al., 2021).

b. Marine Fauna Invertebrates such as sponges, mollusk and corals, and vertebrates: fish and marine mammals are other important sources of bioactive compounds.

- **Fish and Marine Mammals**: Fish resources are very rich in omega-3 PUFA, EPA, and DHA vital for cardiopulmonary health (Tocher et al., 2019). Fish collagen and marine elastin are also used for cosmetic and medicinal purposes (Makgobole et al., 2024).
- **Marine Invertebrates**: Many marine invertebrates synthesize numerous types of bioactive compounds such as peptides, alkaloids and enzymes within sponges, corals, and mollusks. For instance, marine sponges contain AMPs and new alkaloids with anticancer potentialities (Elissawy et al., 2021). Pectineous shellfish such as oysters and clams also contain protein and mineral bioactive with immunomodulatory and antiinflammatory properties.

A marine environment full of diverse species continues to be an essential source of identifying new products and bioactive compounds with biotechnological potential in pharmaceuticals, the food industry, and technology. Fig. 16.1 above provides an example of a complex marine ecosystem including corals, sponges, algae, and diverse organisms including extremophiles in which they can be found such as the hydrothermal vent and the abyssopelagic zone. The deepest habitat, the deep sea, derives resources from the foundational habitat, coral reefs while extending its bioactive compounds to other coral reef members. Sponges play an essential role as filtration feeders for the corals; the algae and seaweed play the role of primary producers as well as carbon fixists. Deep sea and abyssal organisms, thus, exhibit special adaptations to such severe environments as proved by the complexity and stability of the sea ecosystems. This interconnected system showcases the ecological relationships, resource sharing, and specialized adaptations that sustain marine life in diverse and sometimes harsh environments.

3. Extraction and characterization of marine bio-molecules

3.1 Techniques for isolation and purification

The techniques of isolation and purification of ocean bio-molecules are by far some of the most important processes of obtaining bioactive compounds in order to offer them to firms in the biotechnological, pharmaceutical and nutraceutical sectors. The extraction techniques must enable one to purify the target bio-molecule in a cost-effective, fast and selective process without compromising the biological activity and in the process avoid contamination by other unwanted compounds.

- **Solvent Extraction**

One of the most effective methods for extracting bioactive compounds from marine organisms is conventional extraction. It can be the extraction of bioactive molecules with a solvent (ethanol, methanol, acetone, water, etc) from the marine matrix. The decision on the particular solvent is determined by the solubility of the wanted target molecules. For example, ethanol is an organic solvent that needs an organic phase for the extraction of lipophilic compounds like omega-3 fatty acid while for the extraction of hydrophilic compounds like polysaccharides an aqueous solvent would suffice such as water (Martínez et al., 2022). Further optimization of a solvent extraction process can be chosen using ultrasonic-assisted extraction or microwave-assisted extraction as both of them apply mechanical energy and heat successively to the gaining process (Shen et al., 2023).

- **Pressurized Liquid Extraction (PLE)**

PLE is one of the most complex extraction techniques that uses high pressure solvents in order to extract bioactive compounds. In as much as this it allows extraction of the compounds at a higher degree of temperature and pressure than offered by the standard or conventional means of extraction while at the same time improving the extraction rate. These PLE techniques are particularly applicable in the extraction of bioactive lipids and polyphenols from the marine source

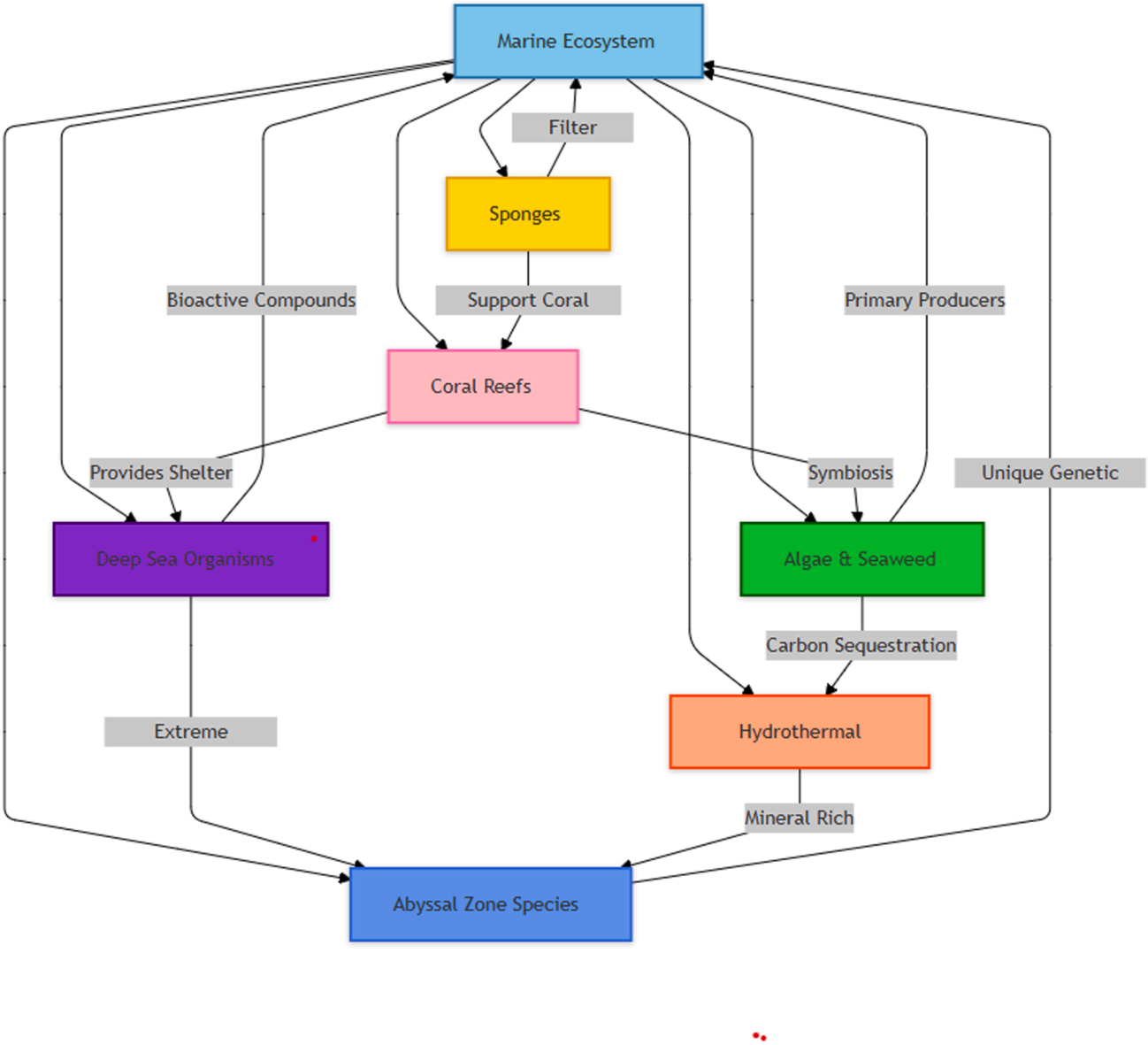

FIGURE 16.1 Diverse marine ecosystem with extreme environment adaptations.

microalgal cells due to the following advantages; low solvent usage, shorter extraction time, and high recovery yield (Quitério et al., 2022).

- **Supercritical Fluid Extraction (SFE)**

SFE's use of supercritical CO_2 as extracting solvent had been established to have a very efficient extraction profile: having a low viscosity and a very high diffusion coefficient. This method is especially desirable for the isolation of compounds of low solubility in water and high solubility in organic solvents such as essential oils, omega-3 fatty acids and other bioactive lipids from marine life (Uwineza & Waśkiewicz, 2020). SFE is more environmentally friendly than other conventional extraction methods since it offers advantages for instance selectivity, low thermal stress effects as well as solvent residues.

- **Enzyme-assisted Extraction**

Enzyme-assisted extraction (EAE) is defined as the process where a specific enzyme capable of degrading the plant cell wall or membrane is applied in order of the best release of one or many bioactive compounds. It is especially useful in

the extraction of polysaccharides and proteins from marine macroalgae and lowly formed invertebrate marine organisms. Depending on the target compounds, cellulase, pectinase, and proteases can well be used in this preparation (Yosri et al., 2021). The benefits include, that EAE is not destructive to the bioactivity of sensitive compounds and EAE offers a high yield that makes it suitable for producing high-quality extracts, which could be useful in nutraceutical or pharmaceutical applications.

- **Membrane Filtration and Chromatography**

In most cases, it is followed by purification steps, which involve the separation of bioactive compounds since most plants consist of several components. The techniques of membrane filtration, for instance, microfiltration and ultrafiltration; aim at removing form larger fruit suspensions and debris while retaining smaller bioactive compounds. HPLC and LC-MS are used to separate compounds that have specific charges and gel filtration chromatography to separate compounds according to the nature of their interaction with the stationary phase. These techniques are crucial in order to obtain bioassay-confirmed pure bioactive compounds with different chemical profiles (Castro-Muñoz et al., 2021).

Fig. 16.2 below is a complex process, which includes several steps that should help to select and extract useful chemical compounds from sea organisms. Marine biomass collection is the first procedure in which a range of sea organisms, for instance, algae, corals or sponges, are collected. This is then succeeded by an extraction process that can be carried out employing; solvent extraction, supercritical extraction or EAE. The step that is next to the raw bio-molecule mixture extraction is the purification & separation where techniques like chromatography and membrane filtration help in bio-molecule extraction. The final step involves characterization techniques, where advanced methods like mass spectrometry, NMR analysis, and FTIR spectroscopy are used to identify and characterize the molecular structures of the extracted bio-molecules. This process is essential for developing marine-derived bioactive compounds for applications in pharmaceuticals, nutraceuticals, and other biotechnological industries.

3.2 Analytical methods for characterization

The chemical nature as well as the superiority of marine biomolecules necessitates characterization to unlocking of potential uses. Different chromatographic techniques are used in the determination of the molecular composition and biological activity of the extracted compounds.

a. **Spectroscopic Techniques**
   Spectroscopic techniques are widely used in the identification and determination of bioactive compounds isolated from marine sources. Some widely used techniques include:
   - **UV-Vis Spectroscopy**: This technique is often used to determine the concentration of certain bioactive compounds such as polyphenols, carotenoids and proteins, based on their absorption of ultraviolet or visible light of specific wavelength (Lozada-Ramírez et al., 2021). UV-Vis spectra can also used to predict the functional groups that are present in a given compound.
   - **Fourier Transform Infrared Spectroscopy (FTIR)**: FTIR spectroscopy provides data regarding the characteristics of functional groups in bioactive molecules by examining how much of it is absorbed in the infrared light. It is also used broadly for the identification of the molecular composition of polysaccharides, proteins and lipids extracted from marine products (Johnson et al., 2023).
   - **Nuclear Magnetic Resonance (NMR) Spectroscopy**: NMR is one of the most extensively applied and versatile methods in the elucidation of structures of organic molecules. It offers valuable information on the molecular neighborhood, connectivity of atoms in the molecule of interest, and general construction of bioactive structures particularly suitable for the deciphering of intricate molecules like marine alkaloids, peptides, and polyphenols (Marcarino et al., 2020).

b. **Mass Spectrometry (MS)**

MS is applied to identify molecular mass, chemical composition or structure of biologically active substances, as well as to analyze their fragmentation properties. Sometimes the technique is used together with Liquid Chromatography in MS form or Gas Chromatography in MS form for better separation and analysis. Among them, LC-MS is widely applied for the identification of the reasonable and quantitative analysis of complicated marine extracts, which could identify and quantify trace components like peptides, polyphenols, lipids, etc. of marine resources (Stavrianidi, 2020). Mass spectrometry is especially useful in identifying novel bioactive molecules in marine organisms that have yet to be extensively studied.

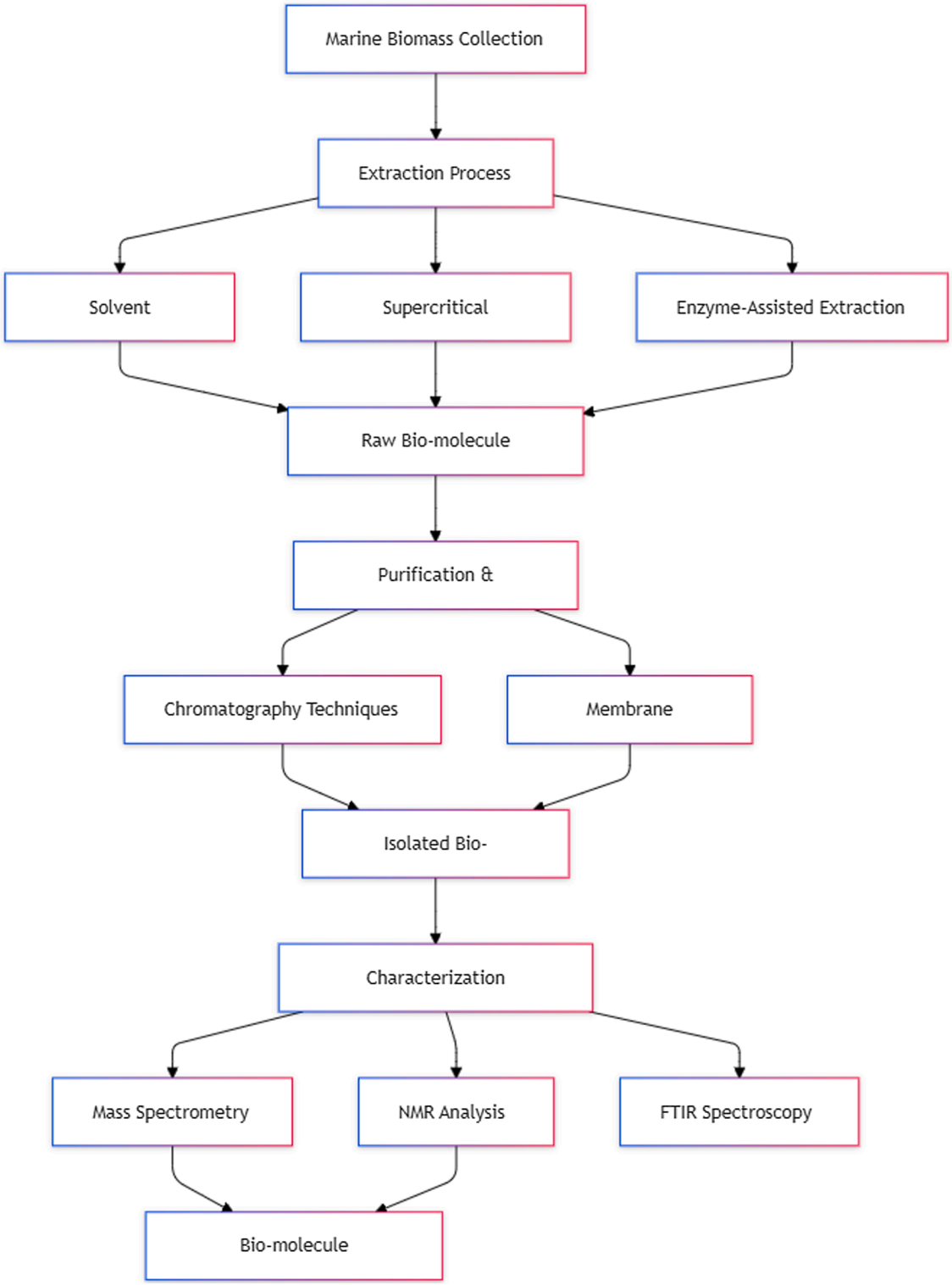

FIGURE 16.2 Extraction and characterization of marine bio-molecules: A step-by-step process.

c. High-Performance Liquid Chromatography (HPLC)

HPLC is a significant technique of analysis, separation and determination of the bioactive constituents in the bio-molecules of marine origin. It may be used in the analytical as well as preparing states. HPLC is widely used in the separation of bioactive peptides, polyphenol compounds and polysaccharides from marine origin. The process occurs through partitioning by size, charge, and the ability of the compound to interact with the stationary phase (Šimat et al., 2024). When connected to detectors such as UV, or MS, HPLC can give more information as to what makes up marine extracts.

d. Bioassay for Biological Activity

Another aspect of the characterization of marine bio-molecules is a biological activity assessment, which is an important stage in the creation of functional ingredients. Some of the most frequently performed bioassays include the use of antimicrobial, antioxidant as well as antiinflammatory assays. For instance, DPPH (2, 2-diphenyl-1-picrylhydrazyl) is tested for antioxidant activity, and the disc diffusion method for antimicrobial activity (Indrayanto et al., 2021). These assays proved useful in the evaluation of the therapeutic efficacy of marine biomolecules.

e. X-ray Crystallography

For highly pure compounds, especially proteins and peptides, X-ray crystallography can yield detailed structural determinacy at the atomic level. These techniques are applied to study the functional aspects of various marine bio-molecules at the molecular level useful in designing drugs or functional foods. It is especially the bioactive proteins or enzymes obtained from marine organisms (Spiliopoulou et al., 2020).

4. Biotechnological applications of marine bio-molecules

Marine organisms are a source of bioactive compounds that exhibit one-of-a-kind biological activities making it an important aspect in biotechnological applications. Such bio-molecules result from marine sources such as proteins, lipids, polysaccharides, peptides, and secondary metabolites with uses in pharmaceuticals, cosmetics, and food industries among others in various biotechnology sectors. In the following section, the focus is placed on several main fields of using marine biomolecules.

4.1 Pharmaceutical applications

Marine natural products have been of interest to drug discovery scientists for years because of their substantial biological activities and unique modes of action. The condition in which marine organisms dwell makes them produce substances that are not produced by other living organisms from the land and may hold promise for the development of new drugs.

- **Antimicrobial and Antiviral Agents**

Bioactive compounds isolated from marine organisms especially, marine microorganisms, algae, and invertebrates exhibit enormous potential as antimicrobial, antifungal and antiviral agents. For instance, substances such as sulfated polysaccharides from sea plants and brominated compounds from sea sponges inhibit various pathogens, and antibiotic-resistant bacteria and viruses (Karthikeyan et al., 2022). Parasins and defensins derived from organisms of marine environment also possess wide-spectrum antimicrobial substances opening doors for new modes of development of antimicrobial agents to combat the rising problem of antibiotic resistance (Arbulu et al., 2022).

- **Anticancer Agents**

Marine organisms synthesize several bioactive metabolites that possess highly effective anticancer properties and thus can act as promising sources for new anticancer agents. For instance, marine alkaloids, including dolastatins available in marine sponges, have shown strong antiproliferative and metastatic cancer cell activity (Patra et al., 2020). Other compounds have also been studied; terpenoids, and lipids from marine algae; that have demonstrated abilities to suppress cancer cell proliferation and trigger apoptosis possibly as a suitable carrier for chemotherapy (Alabi et al., 2023; Carneiro & El-Deiry, 2020).

- **Antiinflammatory and Immunomodulatory Agents**

Currently, marine bio-molecules used for antimicrobial and anticancer purposes are also increasingly explored for antiinflammatory and immunomodulatory activities. Marine-derived fatty acids including omega-3 PUFA found in fish

oils for instance, have shown great potential for antiinflammatory activity and are already employed to address some health conditions such as rheumatoid arthritis and cardiovascular diseases (Saheed et al., 2023). Likewise, the polysaccharides isolated from sulfated marine algae also exhibit immunological effects that prompt immune reactions and inflammation, which would be useful for autoimmune and inflammation chronic conditions (Alabi et al., 2024; Feng et al., 2023).

- **Vaccine Development**

Marine bio-molecules are also of interest for therapeutic vaccine applications. For instance, lipopolysaccharides from marine bacteria are used to stimulate more reactions in the body of a vaccinated person. Moreover, bioactive peptides derived from the marine source have emerged in the discussion concerning the potential applied to the prevention boosting effect of vaccines by altering some signaling ways in the immune system.

4.2 Cosmetic and personal care industries

Marine bio-molecules are increasingly being utilized in the cosmetic and personal care industries due to their antioxidant, antiaging, moisturizing, and skin-protective properties. These compounds offer natural alternatives to synthetic chemicals, aligning with the growing demand for sustainable and eco-friendly products.

- **Antiaging and Skin Rejuvenation**

Marine-derived peptides, proteins, and polysaccharide have also demonstrated significant effects such as antiaging effects, *collagen synthesis* promotion, and skin-firming and antiwrinkle effects. For instance, collagen peptides derived from fish skin and scales holding cosmeceutical potential for enhancing skin hydration and elasticity have been widely used (Aguirre-Cruz et al., 2020). Furthermore, the polyphenols and flavonoids present in seaweed extracts are used to remove free radicals which bring about skin aging and are a recommended source of food for skin health (El-Beltagi et al., 2022).

- **Hydration and Moisturization**

Marine bio-molecules such as *hyaluronic acid* and *polysaccharides* from marine algae are widely used in moisturizers and serums for their ability to retain water in the skin, promoting hydration and enhancing the skin's barrier function. These compounds are highly valued in skincare formulations for their ability to attract moisture to the skin, keeping it plump and hydrated (Morganti, 2023).

- **Sun Protection and Antipollution Properties**

Marine natural products are also present in sun protection lotions and antipollution skin treatments. Some marine algae have been proven to synthesize substances that have in their nature, the ability to filter UV rays that can harm the skin. For example, researchers discovered that phlorotannins in brown algae have UV protection ability which can be used in sunscreen gels (Livinus et al., 2024a). Furthermore, marine bio-molecules have demonstrated the ability to counter skin damage resulting from pollutants, making marine bioactive molecular pollution protection a natural addition to skincare compositions.

- **Antioxidant Properties**

The antioxidant potential of marine bio-molecules shows that polyphenols, carotenoids and flavonoids, sourced from marine plants and algae are the most potent. These compounds quench free radicals and shield individual skin cells from oxidative damage, a process that is responsible for skin aging and other skin conditions (Papaccio et al., 2022). Marine antioxidants are often used in antiaging creams, serums, and lotions to protect the skin from the effects of environmental damage.

4.3 Food and beverage applications

The food and beverage industry has also benefited from the use of marine bio-molecules, which offer a wide range of functional properties that contribute to the nutritional value, preservation, and enhancement of food products. The use of marine bioactive compounds in food applications is not only driven by their health benefits but also by consumer demand for more natural, sustainable, and innovative food ingredients.

- **Functional Foods and Nutraceuticals**

Marine bio-located molecules like omega-3 PUFA in fish oils and polysaccharides in different types of sea vegetables are frequently used in functional food and nutraceuticals. For instance, Omega-3 fatty acids are rich in cardiovascular and cognitive health and are frequently incorporated in milk products, beverages and supplements (Camfield et al., 2011). The important nutrient-rich extracts such as seaweed fiber, vitamins, and minerals are used as functional ingredients in snack foods, soups and salads instead of normal food additives.

- **Antioxidant-Rich Additives**

Marine bio-molecules are endowed with high antioxidant compounds and are hence widely used in the food industry for preserving their quality and enhancing their taste. For instance, astaxanthin, one of the carotenoids sourced from marine algae and shrimp, is a more powerful oxidant than vitamin E used in the beverage and dietary supplement industries to alleviate oxidative stress and promote health (Dang et al., 2024). Likewise, bioactive polyphenolics derived from marine plants like brown algae are now incorporated into food commodities to boost their quality and longevity (Afonso et al., 2019).

- **Food Preservation**

Seaweed bio-active compounds especially the polysaccharides such as agar and carrageenan are employed as gelling agents and stabilizers in many food systems. These natural polymers are widely used for their desire to make alterations in texture and stability along with products such as jams and jellies, dairy and processed food. Besides, their antimicrobial perspective helps in the preservation of perishable foods since they have a short shelf life (Ahmed et al., 2024).

- **Bioactive Beverages**

Complex marine bio-molecules find their use in functional food applications like marinated collagen drinks, marine tea made from seaweed and probiotic beverages. These drinks have health effects that can benefit the consumer such as good skin, proper digestion and a strong immune system. For instance, marine collagen peptides are taken in drinks and supplements to improve skin flexibility, joint information and hair regrowth (Cuvas-Limon et al., 2021).

5. Marine bio-molecules in bio-nutraceuticals

Marine bio-molecules are now appreciated more as sources for bio-nutraceuticals, which are products containing features of both food and drugs. These bioactive compounds obtained from marine organisms are being incorporated into functional foods, nutraceuticals and other food products that relate to health. Marine bio-molecules including PUFAs, polysaccharides, peptides, and antioxidants including succinate are well explored for their health benefits and are used therapeutically and preventatively.

5.1 Role in functional foods and dietary supplements

- **Incorporation in Functional Foods**

Functional food is any food that has some specific positive effect on health other than merely supplying the number of nutrients that are needed to support the body's basic functions. Based on these health issues, marine biomolecules are incorporated into functional foods to amplify their solutions. Omega-3 PUFAs, predominantly composed of fish oils, are major ingredients often incorporated into functional foods like dairy products, bakery products, and beverages. These are eicosapentaenoic acid and docosahexaenoic acid which are important for brain and heart health, and enable support against inflammation (Siriwardhana et al., 2012). In addition, carrageenan and agar–agar that belong to seaweed polysaccharides are employed as active ingredients in almost all food products because they contain dietary fibers and are very nutritious for digestion issues (Liao et al., 2021).

- **Dietary Supplements**

Marine bioactive compounds are also incorporated into dietary supplements, offering convenient ways to enhance daily nutrient intake. For example, marine collagen supplements, derived from fish skin and scales, have become increasingly popular for improving skin elasticity, and joint health, and reducing signs of aging (Geahchan et al., 2022). Marine algae, rich in essential vitamins and minerals such as iodine, calcium, and magnesium, are utilized in supplements to support metabolic health and strengthen immune functions (Siddiqu et al., 2024). Further, natural antioxidant ingredients from the sea include astaxanthin derived from algae and shrimp which is incorporated in supplements targeting the possible aspect of oxidative stress and health benefits (Dang et al., 2024).

- **Support for Cognitive Function and Mental Health**

Marine bio-molecules are also used in dietary supplements targeting brain health. The presence of omega-3 PUFAs in fish oils has been linked to improved cognitive function and mental health. Studies show that regular consumption of omega-3 fatty acids may help prevent cognitive decline and reduce symptoms of depression and anxiety (Parolini, 2024). Polyphenols from marine algae, such as *phlorotannins*, have shown strong antioxidant properties, which help prevent cellular damage caused by free radicals and protect against diseases like cancer and neurodegeneration (Ahmmed et al., 2020).

- **Gut Health and Immune Support**

Marine-sourced bio-molecules are active in functional foods and vitamins that deal with gut health and the immune system. Marine algae polysaccharides including *fucoidan* and *laminarin* have been reported to display prebiotic functionality and enhance the growth of probiotics enhancing digestion health (Corino et al., 2021). Moreso, marine-derived compounds such as astaxanthin and omega-3 fatty acids have demonstrated immune-modulating properties, contributing to better overall immune defense and resistance to infections (Siddiqu et al., 2024).

5.2 Antioxidant, antiinflammatory, and antimicrobial properties

- **Antioxidant Properties**

The most investigated function of marine bio-molecules is their antioxidant activity. In nature, antioxidants are compounds, which possess the ability to eliminate free radicals in the body and avoid subsequent adverse effects, such as oxidative stress and damage to cells attributed to chronic diseases, aging, and inflammation. Marine-derived antioxidants include *astaxanthin*, polyphenols, and carotenoids belonging to the group of compounds including those derived from algae, fish, and crustaceans. *Astaxanthin*, a carotenoid derived from microalgae, is a powerful antioxidant classified as one of the most effective ones; it is effective for the skin and for preventing oxidation thereby stopping various problems like heart diseases (Dang et al., 2024). Phlorotannins, a kind of polyphenols existent in marine algae, have a high antioxidant capacity to inhibit the cellular damage of radicals and diseases including cancer and neurodegenerative diseases (Ahmmed et al., 2020).

- **Antiinflammatory Properties**

Most of the diseases rooted in chronic inflammation have been found to be connected to cardiovascular diseases, cancers, and neurodegenerative diseases. These include omega-3 fatty acids and polysaccharides of which more than half of the marine food bio-molecules show strong antiinflammatory activity. Omega-3 PUFAs, found in fish oils, have the potential to influence cytokines and eicosanoids—the inflammatory mediators. Omega-3 fatty acids have been found to reduce the degree of inflammation signs, CRP and risk of inflammation diseases such as rheumatoid arthritis, and inflammatory bowel disease (Feng et al., 2023). Moreover, polysaccharides such as fucoidan and laminarin extracted from the marine macroalgae also appear to have reported antiinflammatory properties, useful in the treatment of diseases characterized by excessive inflammation as *asthma*, *ulcerative colitis*, *osteoarthritis* and so on (Murphy et al., 2023).

- **Antimicrobial Properties**

Marine bio-molecules, including peptides, polysaccharides, and secondary metabolites, possess antimicrobial properties that make them valuable in combating infections caused by bacteria, fungi, and viruses. Marine-derived peptides, such as *defensins* and *parasins*, have demonstrated broad-spectrum antimicrobial activity against pathogens, including antibiotic-resistant bacteria (Liu et al., 2020). In addition, the brominated compounds of the marine sponge and the sulfated polysaccharides from seaweeds possess the antimicrobial properties of such materials offering great prospects for the creation of new antiresistant drugs to combat contemporary infections, such as MRSA (Mandrekar et al., 2019). These bioactive molecules can be utilized in the development of natural antimicrobial agents for formulations in pharmaceuticals, personal care products and food preservation.

- **Combination of Bioactive Effects**

Bio-molecules derived from marine resources usually possess antioxidant, antiinflammatory, and antimicrobial activities making the marine bio-molecules so valuable in bio-nutraceuticals. For instance, marine peptides containing antimicrobial properties interact also with antioxidants and antiinflammatory effects meaning that such peptides can be applied in products designed for protection against various diseases including infections, and chronic diseases associated with oxidation and inflammation (Vladkova et al., 2022). This feature is one of the possible explanations why marine-derived compounds are highly appreciated in the nutraceutical market because they provide so many health benefits in one product.

6. Challenges and opportunities in marine biotechnology

Marine biotechnology, which explores the potential of marine organisms for various biotechnological applications, offers substantial opportunities, particularly in the development of novel bioactive compounds. However, several challenges need to be addressed to fully capitalize on the vast and underexplored resources of the ocean. These challenges include environmental concerns, sustainable harvesting practices, and technological barriers that hinder large-scale production. Despite these obstacles, marine biotechnology presents vast opportunities for innovation in medicine, agriculture, and environmental management.

6.1 Sustainable harvesting and environmental concerns

- **Overexploitation of Marine Resources**

Some of the major issues that face the field of marine biotechnology include the continued exploitation of marine creatures; especially marine plants and animals. Marine resources, including algae, sea cucumbers and sponges, are sources of bioactive compounds but the irrational utilization of these resources threatens their sustainability. If all wildlife is exploited beyond its acceptable limit, disturbance of the marine ecosystems endangering of particular species and lowering of the general stock of biological diversity is possible. They noted that wild collection of algae, for instance, entails detrimental impacts on the marine ecosystems as poses threats to species' populations and destruction of their habitats (Livinus et al., 2024b). One issue is that most of the target species in marine fishing experience slow growth rates and long generation times and hence are very vulnerable to fishing pressures and environmental impacts if not well managed.

- **Environmental Impact of Harvesting Techniques**

The techniques applied for the collection of marine species can otherwise also pose a significant influence on the environment. Grazing and destructive methods, including pulling by suction, or blowing, can harm complex sea environments that are critical for many species like coral reefs and seagrass beds (Wilkinson & Salvat, 2021). In addition, wild collection of marine bio-molecules can at times lead to some level of habitat degradation, making these resources nonrenewable. To mitigate these impacts, it is crucial to adopt sustainable and environmentally friendly harvesting practices, such as selective harvesting and regulated collection methods, as well as the cultivation of marine organisms in controlled environments like seaweed farms or marine aquaculture (Abdulsalam et al., 2024a).

- **Aquaculture and Marine Biotechnology**

One of the effective solutions to meet the sustainability challenge is the future generation of marine aquaculture and seaweed farming. Such approaches enable raising marine organisms in a controlled manner and can be used in order to channel the pressure off the wild resource and provide even more efficient sources of bio-active molecules. For example, large-scale farming of seaweed as a source of food and other uses discourages wild harvesting thus preserving the ecosystems (Mac Monagail et al., 2017). In a more specific sense, the rearing of fish and shellfish for aquaculture products can adjust their feed and rearing methodologies to enhance the production of beneficial ingredients; occasion includes Omega 3 PUFA and marine collagen without causing harm to the environment (Feng et al., 2023). New developments in integrated multitrophic aquaculture concerning growing various species in the same farm pens will help to address the problems of inefficiency and wastage affecting the sustainability of marine biotechnology.

- **Regulation and Conservation Efforts**

For better realization of proper usage of marine resources and the conservation of sea life, there should be more institutes and guarantees from the side of the state and international organizations. On the basis of international law and regional agreements and treaties like the United Nations Convention on the Law of the Sea and the Convention on Biological Diversity there are regulations for the management of marine resources. In addition, over 15% of the world's waters are protected by MPA's and it is essential to use ecosystem, based management approaches and thus exploit existing marine bioresources in a sustainable way (Matz, 2002).

6.2 Technological barriers in mass production

- **Challenges in Cultivating Marine Organisms**

A significant challenge in marine biotechnology is the difficulty in cultivating marine organisms at a commercial scale. Some marine organisms for example algae corals and invertebrates have particular environmental conditions that have to be met before they can be easily grown in mass. For example, some marine algae need light, temperature and salinity to specific levels to grow; conditions which are a challenge to replicate due to large-scale controlled farming environment (Gupta et al., 2018). Furthermore, cloning valuable attributes within marine organisms like high content of bioactive compounds is relatively easy given that most of them reproduce slowly and have many sensitive biological cycles to reproduce.

- **High Costs of Production**

The manufacturing of marine bio-molecules sometimes proves to be very expensive and hence can only produce large quantities of these molecules such that they are marketed competitively in the marketplace. The bioactive compounds of marine organisms use high-energy and expensive processes like solvent extraction, supercritical fluid extraction enzymatic treatments, etc. These methods may be costly because substantial amounts of raw materials are usually required, and the compounds being isolated are usually rather intricate (Abdulsalam et al., 2022). Further, it may also include the cost incurred in establishing controlled environments and for growing marine organisms like algae and marine invertebrates, which also forms part of the high production costs.

- **Lack of Standardization and Quality Control**

One of the main technological challenges in marine biotechnology is the absence of unified techniques in many respects in the production and extraction of bio-molecules from the marine environment. Factors such as the grade of starting materials, the extraction techniques and the final product may influence the standard deviation of bioactive compounds. This lacks some level of standardization and hampers the quality and reproducibility of the products especially in the pharmaceutical and nutraceutical industry where the safety and efficacy of products must meet important requirements (Musa et al., 2024a). Marine bio-molecules should therefore be cultivated, extracted, purified and controlled in ways that achieve the highest level of standardization.

- **Bioreactor Systems and Process Optimization**

One of the technological advancements needed to overcome the barriers to the mass production of marine bio-molecules is the development of efficient bioreactor systems. Marine microorganisms and algae suitable for dieters can be grown in bioreactors for large-scale production, but achieving the best conditions that will give the greatest yields of the bioactive compounds has always been a problem. Environmental variables like light intensity, aeration/mixing, nutrients and other rich supplies need the best and most accurate control to yield high quality and productivity. Moreover, the translation of bioreactor systems from laboratory to industrial scale is another difficulty in achieving consistency and efficiency in manufacturing strategies (Hemmerich et al., 2018). The application of automated monitoring and control technologies will help overcome the existing technological limitations of the bioreactor.

- **Innovation in Extraction Technologies**

New extraction technology is also required in the production of marine bio-molecules with enhanced low cost and least harm to the environment. There are difficulties associated with solvent costs, extraction time, and energy consumption, as well as more traditional obstacles associated with general economic considerations. Microwave extraction, ultrasonics extraction and enzyme extraction methods are current approaches which can possibly bring a solution to the issues that are related to the extraction step. Any of these methods may help in minimizing the number of toxic solvents and energy and lowering the cost of production while at the same time enhancing the yield and purity of bioactive compounds (Saheed et al., 2024).

- **Genetic Engineering and Synthetic Biology**

New technologies such as genetic engineering or synthetic biology can therefore present solutions to the problems concerning large-scale production. A selective breeding modification of marine organisms like microalgae will make it easy to improve their efficiency in producing the aforementioned bioactive compounds. By manipulating the metabolic pathways of marine microorganisms, it is possible to increase the yield of target compounds, such as PUFAs or

antioxidants, and tailor them to specific industrial needs (Abdulsalam et al., 2024b). Moreso, synthetic biology could be used to create engineered microorganisms capable of synthesizing marine-derived bioactive molecules on demand, potentially bypassing the need for wild harvesting or cultivation.

7. Emerging trends and future directions

Marine biotechnology is rapidly advancing, with new applications emerging across pharmaceuticals, environmental sustainability, and health. This section explores the latest trends in the field, highlighting advancements and their potential impact on human health and wellness.

7.1 Advances in marine biotechnology

- **Omics Technologies** Advances in omics technologies (genomics, proteomics, and metabolomics) are unlocking the potential of marine organisms. These technologies assist in the elucidation of the genome link and metabolic network of marine organisms and in the identification of new pharmacologically active compounds. For instance, marine genomics has discovered a gene in microalgae and deep sea bacterial that synthesize materials which are useful in pharmaceuticals (Abdulsalam et al., 2024c).
- **Bioprospecting in Extreme Environments** Bioprospecting in extreme marine environments like deep-sea vents and polar regions is gaining momentum. These areas contain extremophiles which are organisms that are adapted to existence in extreme conditions and can offer new sources of bioactive commodities for industrial and medical uses. Some of the enzymes sourced from thermophiles dwelling in the deep sea are already on the lookout for application in industrial reactors with high-temperature applications (Tiamiyu et al., 2024).
- **Sustainable Solutions** Marine organisms such as algae and seaweed are increasingly seen as sustainable alternatives for biofuels, biodegradable plastics, and other eco-friendly products. Algae-based biofuels offer a lower carbon footprint compared to fossil fuels (Musa et al., 2024b), while seaweed farming can help mitigate ocean acidification and provide renewable biomass.
- **Synthetic Biology and Genetic Engineering** Marine biotechnology is thus born afresh through synthetic biology because the production of GMOs can synthesize bioactive compounds more efficiently. Higher yields of omega-3 fatty acids essential for human health are being produced through genetically manufactured microalgae (Abdulsalam et al., 2024d). In this way, the generation of marine resources for other industries becomes feasible and at a large scale.
- **Marine Microbial Biotechnology** Microorganisms from the marine environment such as bacteria fungi, and yeasts are good producers of bioactive products. In the past few years, metagenomic techniques have been used to find new marine microbial products which possess activity against microbes, tumors and inflammation. These microorganisms could also play their role in environmental sustainability through a process known as bioremediation (Livinus et al., 2024c).

7.2 Potential impact on human health and wellness

- **Marine Bioactive Compounds in Medicine**

Marine-derived compounds have identified therapeutic potential. Organic components isolated from sea organisms including those produced from marine sponges display anticancer effects (Musa et al., 2024c). All these, cone snails and the toxins that they contain are also being looked at as potential analgesics. As patients are being diagnosed and treated according to their specific health conditions, marine-derived compounds may lead to specific treatments.

- **Marine Bio-nutraceuticals and Functional Foods**

Omega-3 fatty acids, marine collagen, and astaxanthin are in focus for having some health benefits to humans. Omega-3s are beneficial to the heart and the brain, marine collagen is an ingredient that is used in antiaging and joint supplements (Šimat et al., 2020). A microalgae-derived antioxidant, astaxanthin, is also well-credited for its prevention of oxidative stress and the occurrence of chronic diseases (Tepper et al., 2021).

- **Marine Compounds for Disease Prevention**

Phenolic compounds isolated from marine origin include polyphenols, flavonoids, and polysaccharides, especially fucoidan and alginate which possess potential in the prevention of some dreaded diseases like cancer and cardiovascular diseases. Potential therapeutic uses of those antioxidants and antiinflammatory agents may open up further preventive health measures (Senthil, 2024).

- **Personalized Wellness**

Marine bioactive compounds will be individualized as the market of personalized nutrition expands. Polyunsaturated fatty acids are the best sources of omega-3s for marines; other bioactive compounds may be prescribed according to genetic factors such as the risks of developing heart disease or senility. More so, there will be a rise in custom-made cosmetic care products containing marine materials (Fonseca et al., 2023).

- **Therapeutic Potential in Aging**

Marine bioactive compounds, particularly antioxidants like astaxanthin, are being studied for their role in combating aging. These compounds help reduce oxidative damage, a key factor in aging and related diseases (Meduro et al., 2023). Marine polysaccharides may also support healthy aging by boosting immune function and aiding cellular repair (Li et al., 2022).

8. Conclusion

Marine biotechnology has a vast potential for the identification of a wide array of bioactive compounds with potential uses in medicine, agriculture and environmental control. However, the industry has some issues such as too much pressure on marine resources, pollution and large-scale production issues such as technology. Responsible farming like aquaculture and seaweed farming is important in protecting the wild fish population, increasing population and by regulation and conservation to use the sea resources in the right manner. Recent advances in bioreactor technology, extraction techniques, and bioengineering hold prospects to address existing production limitations. Innovations in synthetic biology and metabolic engineering also offer the possibility of improving the yields of bioactive compounds making it possible to replace invasive mechanics of extraction with efficiency and sustainability. Such advancements might help marine biotechnology to cater to the increasing market for natural compounds in those sectors including pharmaceutical and nutritional sectors. In the light of the future, marine biomolecules and bionutraceuticals can only thrive through combined efforts of science, sustainable business models and enabling policies. Challenges of achieving sustainable use of resources in marine biotechnology as compared to the protection of ecosystems would be the driving force to the field. Due to continuously developing technology and increasing concern for marine resources or marine sourced compounds, the industry provides progressive contributions to human health and well-being or environmental conservation.

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Chapter 17

Marine plants as pharmaceutically active compounds

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1. Introduction

The maritime ecosystem covers more than 70% of the Earth's surface, which is a rich and largely unexplored reservoir of biological and chemical diversity. Among its many inhabitants, marine plants such as sea grasses, mangroves, and algae (both macro and microalgae) have become important sources of bioactive compounds with potential applications in medicine. It is reported that the FDA has previously approved the use of substances that have been taken from a range of marine species for use as pharmaceuticals at an advanced stage of clinical studies (Aransiola et al., 2024; Stévenne et al., 2021). Over 90% of marine plant species are algae. Due to their extensive chemical diversity, compounds isolated from marine plants such as marine algae and mangroves have been shown to exhibit antibacterial, spasmogenic, analgesic, cytotoxic, hypotensive, and antifungal properties.

The anticancer, antiinflammatory, and antiinfectious activity of secondary metabolites of marine plants have also been proven to be of great significance (Ghareeb et al., 2020; Liang et al., 2019). The blue-green algae have been found to have more than 400 novel metabolites, which include, distinctive, physiologically active polyketide and peptide metabolites that can either activate the protein kinase C family to affect cell signaling or destroy cancer cells by inducing apoptosis (Méresse et al., 2020; Skjånes et al., 2021). Seaweed metabolites have shown exceptional anticancer properties since they are good sources of protein, vitamins, iodine and minerals. In the previous 3 decades, a significant number of scientists have investigated the immune modulating, antioxidant, and anticancer activity of seaweeds (Rosic, 2021).

Mangroves are abundant in the wild and a rich source of secondary metabolites with several applications in pharmacological and medical research (Ramya et al., 2023). Fig. 17.1 below shows the pharmacological activity of secondary metabolites found in mangroves.

Bioactive natural products with distinct chemical and structural properties that are uncommon in bioactive compounds of plants on terrestrial land exist in large quantities in the marine environment. With their high levels of bioavailability and biological activity, these substances have the potential to be developed into strong medications to treat infectious disorders (Liu, El-Hossary et al., 2019, Liu, Zhang, et al., 2019). There is a pressing demand for novel and effective pharmaceuticals due to the rising prevalence of drug-resistant infections, the advent of new diseases, and the shortcomings of existing treatments. The chemical diversity of the marine environment is a promising avenue for the discovery of new bioactive natural products that can fight resistant infections, enhance overall health outcomes, and treat chronic diseases (Carroll et al., 2022a, 2022b). Our knowledge of marine ecosystems and their intricate interactions is improved by the investigation of marine biodiversity. New biological pathways and molecular targets for medication development may be discovered as a result of this knowledge. The study of marine organisms has been reported to advance genomics,

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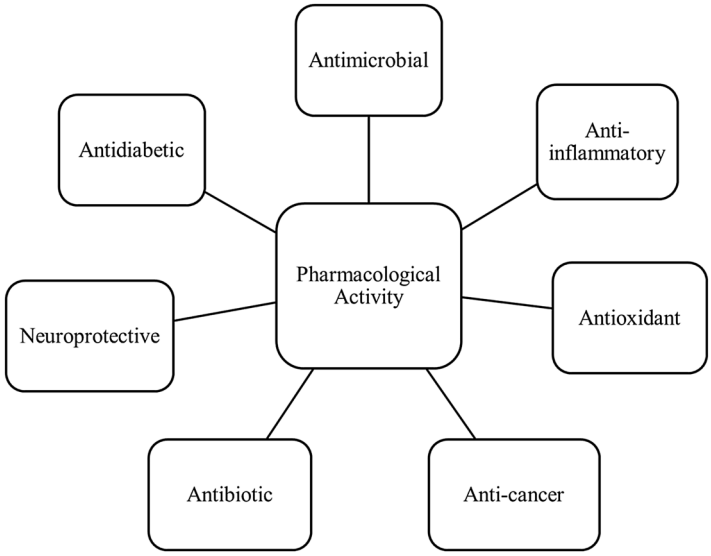

FIGURE 17.1 Pharmacological activity of metabolites in mangroves. *Source: Authors.*

metabolomics, and bioinformatics, which makes it easier to identify and characterize new bioactive compounds (Martins et al., 2019).

A vast array of bioactive substances with unique characteristics are produced by marine plants. An increasing number of novel compounds are being recognized from marine species annually, which facilitates novel medication development for the diagnosis of human ailments such as inflammatory conditions, viral infections, and cancer (Dilipkumar & Khushboo, 2021). The varied habitat and exposure to harsh circumstances of seaweeds, also known as macroalgae, make them well-known producers of bioactive chemicals. As a result, these bioactive substances have strong biological activities in addition to serving as important nutrients. Antioxidant, anticancer, anticoagulant, and antidiabetic properties, for instance, have been observed in polysaccharides and peptides isolated from diverse marine sources (Negreanu-Pirjol et al., 2022). Macroalgae are categorized into three main groups—Chlorophyceae (green algae), Rhodophyceae (red algae), and Phaeophyceae (brown algae). Fig. 17.2 shows the classification of algae in the marine ecosystem. According to reports, brown seaweeds have the most structural variety of all the seaweeds. They differ nutritionally from other seaweeds due to the inclusion of polysaccharides like sulfated fucoidan, laminarin, and alginate. Phlorotannins, fucoidan, and fucoxanthin are examples of bioactive substances found in seaweeds that are known for their antioxidative properties (Kumar et al., 2022). The most abundant biologically active component is fucoidan, a sulfated polysaccharide that is present in brown

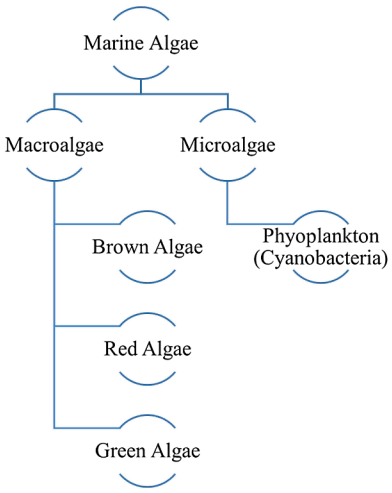

FIGURE 17.2 A representation of classification of algae in the marine ecosystem. *Source: Authors.*

TABLE 17.1 Bioactivities of some fucoidans and phlorotannins obtained from different marine brown algae species.

	Marine species	Bioactivity	References
Fucoidans	*Ascophyllum nodosum*	Antiproliferative	De et al. (2020) and Katiyar et al. (2021)
	Fucus vesiculosus *Cladosiphon novaecaledoniae*	Antimicrobial	Oka et al. (2020)
	Fucus vesiculosus	Antibacterial	Rao et al. (2020)
	Turbinaria decurrens	Antibacterial	Shanthi et al. (2021)
	Ecklonia maxima	Antidiabetic	Daub et al. (2020)
Phlorotannins	*Sargassum carpophyllum*	Antiallergic	Matsui et al. (2022)
	Ecklonia radiata	Neuroprotection	Shrestha et al. (2021)
	Cystoseira sedoides	Anticancer	Abdelhamid et al. (2019)
	Silvetia compressa	Prebiotic	Vázquez-Rodríguez et al. (2021)
	Laminaria japonica	Nutraceutical	Wang et al. (2021)

algae. Fucoidans obtained from different species of brown algae have been reported to possess pharmacological effects such as antiinflammatory, antiproliferative, antimicrobial, and antidiabetic properties as shown in Table 17.1 The chemical structure's diversity and powerful antioxidant activity lend credence to its medicinal potential (Negreanu-Pirjol et al., 2022). In marine brown algae, phlorotannins, constitute a significant class of phenolic compounds. Phlorotannins exhibit an extensive array of bioactivities, such as antioxidant, antibacterial, anticancerous, antiinflammatory, UV radiation protection and antidiabetic activity among others (Kumar et al., 2022).

2. Diversity and distribution of marine plants

There are an estimated 10 million species on Earth, which are mostly situated in aquatic environments. A substantial amount of the earth's surface is covered by the marine environment, which provides a range of habitats for marine life, which is mostly reliant on the salt present in seawater. The health and stability of ocean ecosystems, as well as the provision of all the ecosystem services that benefit people locally, regionally, and globally, depend on marine biodiversity (Kurhekar, 2020). The physical properties of water facilitate improved physicochemical interactions between habitats and the species they sustain, resulting in more adaptable ecosystems with lower dispersal barriers and simpler changes in microbial diversity when compared to terrestrial environments (Dittami et al., 2020). A number of these marine species inhabit harsh environments with low light, high pressure, and extreme cold. Due to these factors, different metabolisms have emerged, providing the opportunity to produce metabolites that differ from those present in the terrestrial environment. This is an excellent source for finding new compounds with interesting biological properties, such as antiviral and antibacterial properties. The marine flora, which includes seaweeds, cyanobacteria, sea grasses, and mangroves, accounts for almost 90% of the biomass in the ocean. Biochemically distinct, physiologically active, taxonomically varied, and mostly productive, they are a fount of prohuman and antibacterial medications. Active medicinal compounds such as polyphenols and sulfated polysaccharides, which have immunostimulatory, antioxidant, and antitumor pharmacological properties, are abundant in marine plants (Kurhekar, 2020). Unicellular microalgae, such as Cyanobacteria (blue-green algae) are small unicellular photosynthetic creatures that float on water yet can not swim against the current. These organisms are also known as phytoplankton. The pioneers of the biosphere, the Gram-negative Cyanobacteria, play a vital role as providers of carbon and nitrogen in the biosphere and, more specifically, the marine ecosystem. It is the most diverse member of marine plants and produces a broad range of important metabolites. Novel biomolecules with probable therapeutic applications can be synthesized from cyanobacteria (Saxena et al., 2021). There are 350 different naturally occurring secondary metabolites that are halogenated in the red sea algae genus *Laurencia*. One of the main compounds it makes is sesquiterpenoids, which are significant for human health (Ishii et al., 2019). Essential oils are among the many bioactive metabolites found in mangroves, much like in other marine plants. With 73 different species found in 123 different countries worldwide, mangroves are significant from an economic standpoint as well as having traditional folkloric therapeutic use (Ramya et al., 2023).

2.1 Distribution and habitats of marine plants

Marine plants are widely distributed and diversified, existing in a variety of habitats all over the world and playing a vital role in ocean ecosystems. These plants, which adapt to different environmental challenges, include mangroves, macroalgae (seaweeds), and seagrasses. Seagrasses are flowering sea plants that have been around for approximately 100 million years. They are found along the coasts of every continent, with the exception of Antarctica. Seagrasses offer a range of biological services in areas with canopy meadows and are significant benthic ecosystem engineers (Tarquinio et al., 2019). Among the most varied marine habitats are mangrove ecosystems, which support a wide range of flora, including trees, bushes, plants, palms, and other adaptive species that can survive in both freshwater and saltwater (Isti'anah et al., 2024). In order to preserve biodiversity and ecological balance, mangroves are essential. In the wetlands that lie between freshwater and saltwater habitats, these distinctive ecosystems flourish along tropical and subtropical coastlines (Andarias et al., 2023).

Marine macroalgae can exist as deep as 270 m and around 8000 different species have been found along the world's coasts. Due to their biochemical content, there are 350 different kinds of red algae, 90 species of brown algae, and 25 species of green algae found along the world's shoreline. A vast reservoir of beneficial algae is found near the coast. Particularly when exposed during low tide, brown algae are more common along stony, shallow beaches. All of the world's oceans are home to seaweeds, which are incredibly diverse in terms of size, color, and form. In India, red algae make up 27.0%, brown algae make up 0.2%, and the remaining 72.8% are made up of various algae (Gimba et al., 2024; Hakim & Patel, 2020). Marine algae live in intricate ecosystems that are subjected to a wide range of harsh environmental factors. Unlike any other species, they can adapt to their environment, which allows them to generate a variety of physiologically active metabolites. By utilizing these metabolites as chemical defense mechanisms, algae can thrive in extremely competitive environments (Ramya et al., 2023).

2.2 Importance of marine plants in marine ecosystems

Without its biological constituents and the intricate web of biological interactions that enable matter to move through the system's internal biogeochemical cycles and sunlight energy to flow, ecosystems would not be able to function. Through photosynthesis, sunlight energy is converted into chemical energy, which is the foundation for practically all ecosystems' ability to function. Most aquatic ecosystems rely on phytoplankton to sustain their food webs, which in turn supports global fisheries (including aquaculture) and enables marine ecosystems to play the function of a human food source (Aransiola et al., 2024; Naselli-Flores & Padisák, 2023). As potential marine food sources, marine algae have long piqued Asian culture's curiosity. The marine ecosystem greatly benefits from the wide variety and abundance of seaweeds. Also, Coastal erosion is stopped by the holdfast that seaweeds provide to the sediments. Animals of all kinds find the brown algal flora to be an ideal food source and habitat (Hakim & Patel, 2020).

Cyanobacteria, play a vital role as providers of carbon and nitrogen in the biosphere and, more specifically, the marine ecosystem (Saxena et al., 2021). Seagrasses are extremely productive primary producers that serve as a habitat for a diversity of species and an important source of food. Due to their ability to lessen wave intensity and turbulence, they are also very significant for protecting coastlines. Additionally, the sequestration of carbon dioxide, or "blue carbon," by seagrass meadows is essential for the mitigation of ocean acidification's effects (Tarquinio et al., 2019).

3. Pharmaceutical compounds from marine plants

Many different species that have adapted to exist in difficult and demanding environments can be found in the marine environment. Because marine creatures can create substances that are helpful for biotechnology, they are the subject of interest (Karthikeyan et al., 2022). According to Gupta et al. (2023), it has been shown that the naturally occurring bioactive chemicals present in marine algae are an abundant source of antioxidant, antibacterial, antihypercholesterolemia, antifungal, antiinflammatory, antiviral, hypolipidemic, and antineoplastic properties. According to Peñalver et al. (2020), in these applications, there may also be a role for primary and secondary metabolites. The proteins, polysaccharides, and lipids which are essential to physiological processes are known as primary metabolites.

Polysaccharides and fibers are the two primary compounds that exhibit promise in the treatment of chronic diseases such as cancer, heart disease, diabetes, and obesity. On the other hand, stressful conditions on seaweed tissues result in the production of tiny molecules known as secondary metabolites. These molecules include sterols, phenolic compounds, terpenes, halogenated chemicals, and short peptides. Among them, UV radiation exposure, salinity and temperature variations, or exposure to environmental toxins have to be emphasized. Their biological activity produces new secondary

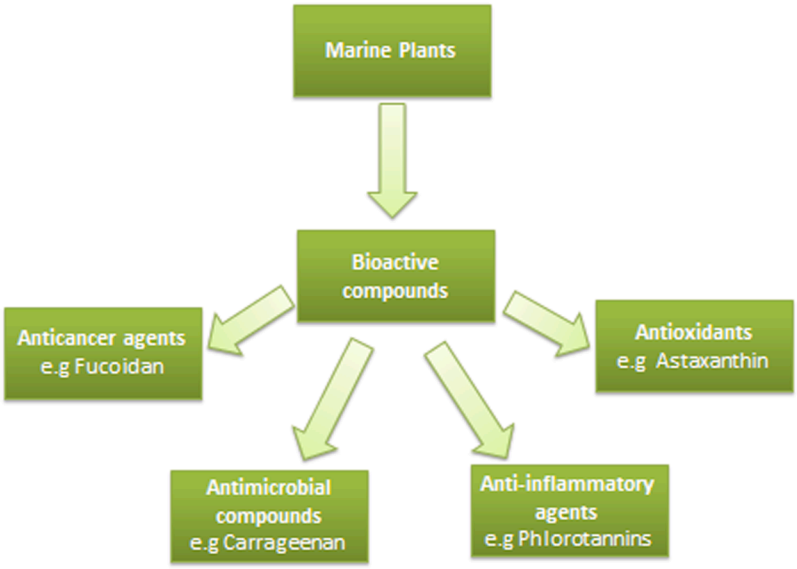

FIGURE 17.3 Schematic diagram of bioactive compounds in marine plants. *Source: Authors.*

metabolites that may have applications in medicine. The marine resource has a high degree of biodiversity and is regarded as a huge source of many biologically active substances. These chemicals are being studied extensively for their bioactive makeup and potential uses in nutraceuticals, which may have a number of health advantages. Several investigations, both in vivo and in vitro, have documented the marine bioactive chemicals' effects in managing various lifestyle conditions. Fig. 17.3 shows various bioactive compounds in marine plants. Their extraction methods are recognized to significantly affect their bioactivity because of their high concentration of bioactive components and nutraceutical value (Amobonye et al., 2023; Rathod et al., 2024). The industries that produce food, pharmaceuticals, and cosmetics have all expressed a great deal of interest lately in marine-derived bioactive compounds that have great capability as therapeutic agents and nutraceuticals (Šimat et al., 2022). The sources, mechanisms of actions and applications of common pharmaceutical compounds derived from marine plants are shown in Table 17.2.

4. Biotechnological approaches in marine plant-based drug discovery

Despite the oceans making up over 70% of the planet's surface, they represent a huge, largely unexplored potential for new bioactive substances (Küfeoğlu, 2022). According to Rivera et al. (2021), due to their exposure to particular environmental circumstances, marine plants—such as algae and seagrasses—evolve different metabolic pathways and produce distinctive secondary metabolites that may have medicinal uses. To effectively identify, characterize, and manufacture these bioactive chemicals, biotechnological approaches to marine plant-based drug development including cutting-edge genomics, metabolomics, and bioengineering techniques are essential (Lin et al., 2023). Recent developments in biotechnology have transformed the drug-discovery industry and made it possible to conduct previously unheard-of-scale research on marine biodiversity (Van Den Heever & Jones, 2019). Today, methods like genetic engineering, synthetic biology, and high-throughput screening are being used to take advantage of the chemical variety found in marine plants. These methods speed up the process of producing new compounds with medicinal promise, increase their bioavailability, and boost their effectiveness (Costa et al., 2024).

In addition to speeding up the drug discovery process, marine biotechnology also solves issues related to the sustainable use of marine resources. Through the use of methods like fermentation technology and metabolic engineering, scientists may generate substantial amounts of bioactive substances without overusing natural environments (Arora et al., 2021). This strategy promotes human health as well as environmental preservation by guaranteeing a steady supply of medications produced from marine sources.

TABLE 17.2 Sources, mechanisms of actions and applications of common pharmaceutical compounds derived from marine plants.

S/N	Name	Source	Mechanism of action	Application
Anticancer agents				
1	Fucoidan	Brown algae (Phaeophyceae)	The arrest of cell cycle, apoptosis induction, and the induction of cytotoxic natural killer cells and macrophages.	Treatment of several cancers, including liver, colon, and breast tumors
2	Phlorotannins	Brown seaweeds (e.g., *Ecklonia cava*, *Sargassum* spp.)	Scavenge free radicals and lower oxidative stress, which is frequently increased in cancer cells.	Treatment of diseases like melanoma, lung cancer, and colon cancer
3	Halomon	Red algae (e.g., *Portieria hornemannii*)	Interferes with DNA synthesis and damaging DNA in cancer cells, halomon causes cell death.	For the development of tailored cancer therapeutics
4	Fucoxanthin	Brown seaweeds (e.g., *Undaria pinnatifida* and *Phaeodactylum tricornutum*)	Triggers apoptosis via the mitochondrial pathway through the increase of proapoptotic protein expression and the decrease of antiapoptotic protein expression	Treatment of cancers, including leukemia, prostate cancer, and breast cancer
5	Kainic acid	Red algae (e.g., *Digenea simplex*)	Overactivates kainate receptors in cancer cells, kainic acid causes excitotoxicity and apoptosis, which ultimately results in cell death.	Treatment of neural tumors and brain cancers
6	Bryostatin-1	Symbiotic algae of marine bryozoans (e.g., *Bugula neritina)*	Stops the development of cancer cells and causes death by modifying the activity of PKC isoforms	Treatment of a range of cancers, such as solid tumors, lymphomas, and leukemia
Antimicrobial				
7	Carrageenan	Red seaweeds (e.g., *Chondrus crispus* and *Kappaphycus alvarezii)*	Attaches itself to the viral particles and stops them from attaching to host cells, thereby preventing the spread of viruses.	Used in pharmaceutical formulations for stopping the spread of sexually transmitted infections (STIs)
8	Phlorotannins	Brown seaweeds (e.g., *Ecklonia cava* and *Sargassum* spp.)	Rupture microbial cell membranes, blocking enzymes necessary for microbial metabolism, and scavenging free radicals that aid in microbial life.	Treatment of diseases caused by microorganisms that are drug-resistant
9	Laminarin	Brown seaweeds, such as *Laminaria digitata*	Improves the host immune response by stimulating the generation of antimicrobial peptides and activating macrophages.	Development of antibacterial agents and immune-boosting supplements for use in personal care, pharmaceutical, and agricultural applications
10	Alginate	Brown seaweeds like *Ascophyllum nodosum* and *Macrocystis pyrifera*	Creates a physical barrier that obstructs microbial adhesion and biofilm development, it also inhibits the growth of bacteria	Used in wound dressings to speed up healing and keep off infections
11	Ulvan	Green seaweeds like *Ulva* spp.	Damages the integrity of cell membranes and prevents the growth of biofilms, which prevents the growth of bacteria	To create antimicrobial agents for use in food preservation, medicines, and agriculture

12	Halogenated furanones	Red algae, such as *Delisea pulchra*	Prevent bacteria from communicating through quorum sensing, which is necessary for the development of biofilms and pathogenicity.	To prevent and treat biofilm-associated infections—which are particularly difficult to treat with traditional antibiotics.
Anti-inflammatory agents				
13	Phlorotannins	The production of proinflammatory mediators such as prostaglandins and leukotrienes is aided by the inhibition of two enzymes: Cyclooxygenase (COX) and lipoxygenase (LOX).		Treatment of inflammatory conditions like rheumatoid arthritis, asthma, and inflammatory bowel disease
14	Fucoidan	The NF-κB signaling system, which is essential for controlling inflammatory responses, is inhibited by fucoidan to provide its antiinflammatory actions.		To treat inflammatory illnesses like colitis, arthritis, and skin irritation
15	Laminarin	Laminarin blocks proinflammatory cytokines (TNF-α, IL-6) and increases the activity of antiinflammatory cytokines (IL-10).		Ability to cure diseases like sepsis, inflammatory skin problems, and colitis
16	Ulvan	Blocks the signaling pathways of NF-κB and MAPK, which are important controllers of inflammation.		To treat inflammatory conditions such as colitis, arthritis, and inflammation of the cardiovascular system.
17	Carrageenan	Lowers the amounts of inflammatory cytokines including TNF-α, IL-6, and IL-1β and as well reduces inflammation by preventing NF-κB and other transcription factors implicated in the inflammatory response from activating.		Treatment of inflammatory disorders like colitis, rheumatoid arthritis, and inflammatory skin ailments
18	Fucoxanthin	Blocks NF-κB pathway and lowers the synthesis of proinflammatory mediators like prostaglandins and cytokines (including TNF-α and IL-1β), and fucoxanthin lowers inflammation.		Treatment of inflammatory disorders such as neuroinflammation, cardiovascular inflammation, and inflammation related to obesity
Antioxidants				
19	Astaxanthin	Microalgae (*Haematococcus pluvialis*) and some red seaweeds	Shields lipids, proteins, and DNA from oxidative damage by neutralizing reactive oxygen species (ROS) and by preventing lipid peroxidation	Utilized in dietary supplements due to The ability to strengthen immunity, Lessen inflammation, and improve skin health
20	Polyphenols	Seaweeds (e.g., *Fucus vesiculosus* and *Ascophyllum nodosum*)	Scavenge free radicals, increase the antioxidant enzyme activity, and stop oxidative stress-induced cellular damage	Potential to cure and prevent diseases Pertaining to oxidative stress like Diabetes, neurological disorders, and Cardiovascular diseases

5. Challenges and limitations in drug development

Pharmaceutical products derived from marine plants offer promising opportunities for drug development, however, they also come with a number of restrictions and difficulties that must be addressed. Drug development is a highly intricate and multidimensional process that faces numerous challenges and limitations. These challenges can impact the efficiency, cost, and success rates of developing new pharmaceuticals. Drug development is one of the most expensive endeavors in the pharmaceutical industry. The total cost can exceed $2.6 billion per new drug, considering costs for discovery, development, and postmarketing activities (DiMasi et al., 2016). Numerous studies, preclinical research, clinical trials, and regulatory clearances are what fuel these expenses. The financial risk is compounded by the high failure rate of drug candidates during development. Furthermore, the drug development process is notoriously lengthy, often taking 10–15 years from initial discovery to market approval. This extended timeline is due to the rigorous phases of preclinical testing, multiple phases of clinical trials, and the time required for regulatory review. A substantial percentage of drug candidates fail during clinical trials. Failures can occur due to a lack of efficacy, unexpected side effects, or problems with drug absorption and metabolism (Renaud et al., 2018).

This high attrition rate contributes significantly to the overall cost and time of drug development. Navigating the regulatory landscape is complex and varies across different regions. Regulatory agencies such as the FDA (U.S.), EMA (Europe), and others have stringent requirements for drug approval, which can delay the process and add to the costs. Meeting these requirements involves extensive documentation, safety testing, and sometimes lengthy negotiations. Identifying viable drug targets, understanding complex disease mechanisms, and developing effective therapies are major scientific and technological hurdles. Bringing marine-derived pharmaceuticals to market involves navigating regulatory hurdles, including safety and efficacy assessments. Also, the high costs associated with marine drug discovery and development may pose challenges for commercialization, especially for small biotech companies or academic research groups. Despite these challenges, the potential therapeutic benefits of marine-derived pharmaceuticals continue to drive research and development in this field. To address these challenges, there must be interdisciplinary collaborations among marine biologists, chemists, pharmacologists, and clinicians, along with technological advancements in drug discovery, formulation, and sustainable resource management. Moreover, increased investment in research and development efforts focused on marine biodiversity conservation and bioprospecting could unlock the full ability of these valuable natural resources for drug discovery and development. Ethical considerations in drug development include obtaining informed consent from clinical trial participants, ensuring the safety of participants, and addressing issues of equitable access to new treatments. Social factors such as public perception and acceptance also play a role in drug development and adoption.

6. Conservation and sustainability

The conservation and sustainability of pharmaceutical products derived from marine plants are critical concerns as the demand for these bioactive compounds grows. Effective conservation strategies and sustainable practices are essential to ensure that marine biodiversity is preserved while meeting the needs of the pharmaceutical industry. The preservation of marine plant species and their ecosystems is greatly aided by Marine Protected Areas (MPAs). Recent research underscores the importance of expanding MPAs to protect key marine ecosystems from overexploitation (Rodríguez-Rodríguez, 2019). MPAs are selected regions in the sea established to safeguard ecosystems, habitats, and species, with the goal of preserving, restoring, and enhancing biodiversity, as well as cultural and economic resources. MPAs encompass a range of protections, including fully protected zones, sanctuaries, and marine parks (Sarker & Mahmudul Islam, 2022). Cultivation and aquaculture are emerging as viable alternatives to wild harvesting. Advances in marine plant cultivation techniques are being explored to reduce pressure on natural populations. Marine plant cultivation involves growing marine plants such as seaweeds, seagrasses, and mangroves in controlled environments or natural habitats for various purposes, including environmental conservation, commercial use, and scientific research. Marine plant cultivation offers significant opportunities for enhancing environmental sustainability, supporting coastal communities, and addressing climate change. As practices and technologies evolve, the potential benefits are likely to expand, contributing to more resilient and sustainable marine ecosystems. García-Poza et al. (2020) conducted a study on the evolution road of seaweed aquaculture, and various cultivation technologies were identified. Marine plant cultivation is a powerful tool for conservation and sustainability. By integrating it into broader environmental management strategies, we can enhance coastal protection, improve water quality, support biodiversity, and mitigate climate change. Effective management and continued research are essential to maximizing these benefits and addressing any challenges that arise.

6.1 Role of biotechnology in sustainable utilization

Biotechnology contributes significantly to the sustainable use of pharmaceutical products derived from marine plants. Biotechnology helps in discovering and identifying novel bioactive compounds from marine plants (for instance, fucoidan from brown algae [*Fucus vesiculosus*] and caulerpin from the green algae *Caulerpa racemosa* [Aransiola et al., 2021; Lomartire & Gonçalves, 2022; Yap et al., 2019], which have shown potential antiinflammatory and anticancer properties respectively). Advanced techniques like genomics, proteomics, and metabolomics help in the systematic exploration of marine biodiversity, leading to the identification of potential pharmaceutical compounds with therapeutic benefits.

Traditional harvesting methods can be destructive to marine ecosystems. Biotechnology offers sustainable alternatives such as **Micropropagation and Tissue Culture**—These techniques allow for the mass production of marine plants without the need to harvest them from their natural habitats. By cultivating plant cells or tissues in controlled environments, it is possible to produce large quantities of desired compounds. For instance, the red algae *Kappaphycus alvarezii* can be propagated through tissue culture techniques to produce carrageenan (Cahyani et al., 2020), a compound used in pharmaceuticals, without disturbing wild populations. **Synthetic Biology and Genetic Engineering**—These techniques allow marine plants or microbes to be modified in order to increase the production of particular bioactive substances. For example, it is possible to introduce the genes needed to synthesize desired substances into organisms that are easily cultivable.

Furthermore, marine plants or their engineered counterparts can be grown in bioreactors, where conditions are optimized for the manufacture of pharmaceutical compounds. This method reduces the impact on natural marine ecosystems and provides a reliable supply of bioactive substances. For instance, marine diatoms like *Phaeodactylum tricornutum* are grown in bioreactors to produce high-value compounds like omega-3 fatty acids, which are useful for cardiovascular health and are used in various pharmaceuticals (Xia et al., 2021). Biotechnology also facilitates the growth of synthetic and semisynthetic methods to produce marine-derived compounds. By understanding the biosynthetic pathways of these compounds, scientists can replicate or modify these pathways in the lab to create the compounds without relying on natural sources. For example, the anticancer drug Yondelis (trabectedin) was originally derived from the sea squirt *Ecteinascidia turbinata* (Cuevas & Francesch, 2009), but due to biotechnological advancements, it is now produced through a complex semisynthetic process that mimics its natural biosynthesis. Nanotechnology and other biotechnological advancements can improve the bioavailability and delivery of marine-derived pharmaceuticals. This includes the development of nanoparticles and other delivery systems that enhance the effectiveness of these drugs, thereby reducing the amount needed and minimizing environmental impact. For instance, the marine-derived compound ziconotide, used to treat severe chronic pain, has improved delivery through the development of intrathecal pumps, ensuring a precise and sustained release of the drug directly to the spinal fluid (Rubiu et al., 2024).

7. Conclusions and future prospects

In summary, the investigation of marine plants as a source of emerging pharmaceutical products presents a promising frontier in drug discovery. The rich biodiversity found in marine ecosystems offers a diverse array of bioactive compounds with significant therapeutic abilities, such as anticancer, antimicrobial, antiinflammatory, and antioxidant agents. As our understanding of the ecological significance and distribution of these organisms deepens, we unlock new avenues for innovation in healthcare. Biotechnological advancements are significant in facilitating the extraction, isolation, and sustainable production of these valuable compounds. Conversely, there are several obstacles in the way of medication development, such as variations in chemical efficacy, regulatory barriers, and the requirement for sustainable procedures. Resolving these issues is crucial to maximizing the benefits of marine plants without sacrificing their ecological integrity.

Looking forward, the future of pharmaceutical products derived from marine plants is bright. Continued investment in research and development, coupled with a commitment to conservation and sustainable practices, will be key to unlocking novel therapies. By fostering collaboration among scientists, policymakers, and conservationists, we can ensure that the benefits of marine biodiversity are preserved for future generations while paving the way for groundbreaking medical advancements.

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Chapter 18

The chemistry of sea foods

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1. Introduction

The current food production system is unable to sustainably feed the more than 9 billion people on the planet, and this trend is predicted to continue as efforts are made to reduce environmental degradation and climate change. It has been predicted that the need for food would increase to a minimum of 70% of the current output level. Research may move toward creating new, sustainable food sources or toward underutilized animals and crops as a result of intensive agriculture's overuse of arable land and decreased access to freshwater; this exacerbates climate change and involves a major toxic effect on the ecosystem (Johnson et al., 2020).

The most precious source of food on Earth has always been the oceans since time immemorial (Simat et al., 2020). Seafood including fish are significant providers of nutrients, including vitamin D, vitamin B12, iodine, selenium, and omega-3 polyunsaturated fatty acids (PUFAs) (Thomsen et al., 2022) One important worldwide source of lean protein is seafood; in fact, a United Nations FAO report estimates that 6% of total dietary protein is derived from seafood (Boyd et al., 2022). Additionally, iodine, which is essential for thyroid health, is frequently found in seafood and whose consumption can help people fulfill their daily requirement of 150 μg/d (Köhrle, 2023).

As was already established, both volatile aroma-active and nonvolatile taste-active ingredients contribute to the flavor of seafood. One crucial area of study has been the isolation and identification of these substances. The taste-active ingredients were the primary focus of early studies on seafood flavor. Early in the 20th century, the first study of this kind was carried out (Drabinska et al., 2023). Since then, the majority of studies in this field have used liquid chromatographic (such as an amino acid analyzer) and/or wet-chemical procedures to quantitatively assess extractive components (such as sugars, nucleotides, inorganic salts, and amino acids) (Le Querre & Lucci 2022). It has been difficult to identify distinctive and significant scent molecules in seafood because they are frequently present at incredibly low concentrations—subparts per billion (Li et al., 2023).

Nearly 200 different types of nutrients and bioactive substances, including phytosterols, sugar alcohols, carotenoids, PUFA, and superoxide dismutase, can be found in seafood. Because seafood wastes are high in proteins, PUFA with a variety of health benefits, such as carotenoids, vitamins, and squalene (Saleh et al., 2022). Because of this, there is increasing interest in the possible use of fisheries wastes as medicines, nutraceuticals, and functional components in a variety of applications, despite the low value that has historically been placed on them. From an economic perspective, this strategy has the advantage of generating extra revenue from a commodity that occasionally has disposal costs. On the other hand, environmental contamination can be significantly decreased by valuing seafood wastes, such as bycatch and byproduct (Carusso et al., 2020). The marine bioprocess sector has a lot of potential to convert and use a significant portion of the high-quality nutrients found in fisheries and aquaculture wastes. For example, fish heads, backbones, tails, and other parts of seafood are excellent sources of proteins with a variety of biological and functional characteristics (Mutalipassi et al., 2021). By using proper packing methods, lowering storage temperatures, using antioxidants, and, in the case of marine oils, microencapsulation, seafoods can be stabilized against oxidative deterioration and aroma reversion

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(Vlcko et al., 2022). The latter method produces a free-flowing powder that is simple to mix into food in addition to prolonging the shelf life of items.

This review discusses the chemistry, nutrition, and health importance of sea food. Furthermore, other miscellaneous benefits that can be derived from sea food have been highlighted.

1.1 Bioactive compounds found in sea food

As mentioned earlier, there are several bioactive compounds present in sea food ranging from protein, PUFA, vitamins, minerals, and other phytochemicals. The abundance of marine nutrition makes it a treasure trove of novel, healthful dietary solutions and nonsynthetically occurring such fish oils, bioactive peptides, and microalgae, macroalgae, and fish proteins. Marine nutraceuticals have been abused for culinary purposes despite their many medical benefits. Marine foods are a good source of quality proteins and lipids with nonsaturated fatty acids (Gosh et al., 2022).

2. The use of marine food sources is critical to sustainable development

A global agenda, that is, Sustainable Development Goals (SDGs) aims to incentivize policies that support social, environmental, and economic sustainability. One of the main stakeholders that make a substantial contribution to global sustainability is the maritime industry worldwide (Merlo et al., 2021). Tropical fisheries are essential to maintaining food security in tropical and extratropical nations. Microbes are diverse in size and structure, and they have a crucial and frequently unique role in the long-term health and functioning of the ecosystem. There are many examples of both prokaryotic domains in the oceanic ecosystem. Apart from them, all other microorganisms were ten times less common in the marine environment than viruses. Because life depends on the continual, microbially mediated shift of chemicals in marine habitats and the bulk of biogeochemical activities on land, microbes play a critical role in maintaining the vibrant balance and uprightness of the ecosystem (Pinnaka & Tanuku, 2019).

3. Metabolites found in marine life

Aquatic microbes are thought to serve as the basis of distinct compounds with a variety of biotechnological applications that are both physiologically and structurally unique. Rare functional groups like dichloroimine, isocyanate, isonitrile, and halogenated functional groups are frequently detected in marine metabolites, together with special physiochemical traits of the marine environment (temperature, osmolality, pressure, and pH). These features have led to the development of bioactive components that have different properties from those found in terrestrial ecosystems (Ghosh et al., 2022). Aquatic foods intake has increased dramatically of recent due to favorable perceptions of seafood and growing public understanding of its health-promoting properties. Compared to desert resources, marine organisms have evolved special features and advantageous elements due to the diversity of their living situations.

3.1 Fishes in marines

For a long time, marine fish have been considered a nutritious dietary source, but recent developments emerging from nutraceutical fields and functional food have demonstrated that their importance goes beyond simple nutrition because they provide us with chemicals in our food that are highly effective in preventing human illnesses. Lately, it has been suggested that even fish industry by-products may include valuable ingredients like collagen and enzymes which may improve well-being or be utilized to create novel drugs (Šimat et al., 2021). The world economy depends heavily on fish, which are the most often consumed marine species. The nutritional benefits of eating fish are attributed to the inclusion of proteins, vitamins (including B12, B3, B6, and D), unsaturated vital fatty acids, and minerals (such calcium, iron, zinc, and selenium). Additionally, it has been discovered that peptides produced from fermented fish following enzymatic treatment can effectively treat a diseases including viral infections, cancer, and hypertension. Aside from this, marine capture fisheries continue to be a major source of essential nutritional inputs, for example, fish oil, for the finfish and crustacean aquaculture industry. This dependence is particularly problematic in intricate aquafeeds for marine shrimp and farmed carnivorous finfish (Kari et al., 2022).

3.2 Microalgae

Algae in sea are macroscopic, unicellular plants that can have one or more cells. Green, red, and blue algae are the three categories of marine algae with pigmentation. Their color is caused by pigments, which include green algae's chlorophyll,

red algae's phycobilins, and brown algae's fucoxanthin. The primary pigments of chlorophyll and fucoxanthin are the components that give brown algae their greenish brown hue. There are perhaps 1500 to 2000 kinds of brown algae in the world (Costa et al., 2024). More research is being done on algae as a potential long-term bioactive compound source. Compounds that are present in food additives and ingredients include fatty acids, vitamins, carotenoids, phycobiliproteins, and chlorophylls. The bioactive chemicals found in microalgae are fascinating topics for investigation, and their potential applications in medicine raise the possibility that they will soon have enormous commercial potential. These characteristics include several therapeutic qualities (Aransiola et al., 2024; Zulhendri et al., 2021). As primary producers in ecosystems, microalgae are essential due to their photosynthetic activity (Nava & Leoni, 2021). More and more research is being done on microalgae as a potential long-term source of bioactive compounds. Compounds that are present in food additives and ingredients include fatty acids, vitamins, carotenoids, phycobiliproteins, and chlorophylls. As primary producers in ecosystems, microalgae are essential due to their photosynthetic activity. Fish oil derivatives include antiviral, antibacterial, antioxidant, and anti-inflammatory qualities that are good for human health. With the use of this supplement, one can prevent many chronic diseases (Camacho et al., 2019). Some of their distinctive features include the capacity to separate microalgae from sea environment (Gallego & Narwani, 2022). Microalgae are thought to be a potential substitute feedstock due to their straightforward development techniques. Unsuitable for conventional agriculture, microalgae can survive in unfavorable conditions including cold or hot springs wastewater and salinity water that is high (Khoo et al., 2020).

3.3 Seaweed and macroalgae

Microalgae, also referred to as seaweed, are comparatively isolated new chemicals that can be employed as nutraceuticals in the food business. These molecules include peptides and carbohydrates. Many bioactive components obtained from algae have shown significant biological effects. These biological actions are linked to the compositional chemicals. Seaweed is an exciting source of novel compounds for use as nutraceuticals. In particular, seaweed contains minerals and peptides. Antidiabetic, anticancer, anti-inflammatory, and immunostimulatory qualities are some of the most promising biological activities present in carbohydrates and peptides. Scientists are now more interested in creating and examining the relationship between biological activity and chemical structures as a result of these link (Lafarga et al., 2020). Macroalgae have developed unique metabolic systems to enable them to thrive in hostile maritime environments. Consequently, these species' naturally occurring physiologically active components have been extracted. Research on marine organisms has led to the discovery of numerous proteinaceous bioactive chemicals. These include, but are not limited to, proteins, amino acids, linear peptides, and substances that resemble amino acids. Additionally, it has been shown that a number of macroalgae species contain significant levels of protein (Brien et al., 2022).

The utilization of aquatic algae for beneficial compounds that can keep people healthy and prevent illness is growing in favor. Only present in marine macroalgae, phenols are a type of polyphenol that have been shown in in vitro experiments and preliminary human trials to have antihyperglycemic and antihyperlipidemic effects (Bocanegra et al., 2021). Global need has led to a resurgence of interest in seaweeds. Seaweeds have long been utilized in Asian cultures, and new research indicates that they have a number of therapeutic benefits. Seaweeds are rich in metabolites with potential medical applications and a range of nutritive components. All things considered, seaweeds are a nutritionally beneficial food (Tuwo et al., 2022).

3.4 Marine fungi

Fungi are symbiotic (growing along with plants and animals) and are crucial to the cycling of nutrients in terrestrial ecosystems. It is expected that wherever there is moisture and a carbon source in the terrestrial biosphere, fungi will flourish. Fungi function as parasites at various trophic levels. More people are starting to notice the function that chytrid fungi play in parasitizing marine phytoplankton. Fungi are important saprotrophs in the ocean, transforming algae and detritus into fungal biomass. This biomass is consumed by other organisms in the food chain and forms a circuit that links polymers made as a result of synthesis. Marine fungus is a significant source of microbial origins because of their wide range of chemical compounds and significant biological functions. Particularly, when it comes to marine fungus, very little of the global fungal population has been studied. One important source of metagenomic data is marine fungus, which have large metagenomes and a variety of genetic ancestries (Wang et al., 2021).

For decades, people have utilized these protein- and polysaccharide-based biopolymers as ingredients in food and nutraceuticals to cure a number of diseases. In the medical field, polymers such complex polysaccharides, chondroitin sulfate, and chitin have been more well-liked lately as treatments for a range of ailments. In addition to being utilized in

animal feed, these compounds exhibit anticancer and wound-healing symptoms (Ganesan et al., 2020). Widely recognized as a group of animal kingdom species, marine invertebrates are rich in distinct functional biopolymers, including proteins, lipids, and polysaccharides, each of which serves a variety of biological purposes. From a health perspective, they are used in many different applications. Using marine nonvertebrates in food and for medical reason is nothing new for coastal people. Two significant commercial products made from edible sea organisms are collagen and gelatin. Nearly one-third of the material in the body of all mammals is collagen. Marine collagen can serve as a suitable substitute and is extensively employed in medical settings (Ganesan et al., 2020). Marine sponges are rich in unusual sterols, which have a variety of uses in biological membranes. Sulfated and alkaloid sterols have been shown to possess antibacterial properties. Prostaglandins are produced by cnidarians, the richest natural producers. Bioactive chemicals have also been extracted from bryozoans. It has been found that a marine polychete (phylum Annelida) can treat disease conditions, such as osteoporosis. amebocyte limulus, lysate, and amebocyte tachypleus. According to John et al. (2021), lysate is the most well-known bioactive substance obtained from marine arthropods. It is an aqueous extract of amebocytes, the blood cells of horseshoe crabs. It has been demonstrated that *Dolabella auricularia* produces a number of cytotoxic and anticancer compounds called dolastatins. The most prevalent bioactive substances identified in metabolites from echinoderms are saponins. These are present in a variety of marine organisms, including sea cucumbers, starfish, and urchins. Asterosaponins are derivatives of sterols, whereas sea cucumber saponins are thought to have terpenoid origins (Papon et al., 2023).

3.5 Marine bacteria

Two marine bacterial species that are being looked into more and more as possible sources of new compounds are archaea and eubacteria. Because many members of the Archaea bacterial group are extremophiles, or organisms that thrive in hostile conditions like the deep ocean, extremely low temperatures, or settings with specific chemical requirements (pH, salinity), the group is fascinating to study. Unlike a catenoid or hopanoid in eubacteria, glycerol tetraethers stabilize the cell membranes of archaea. Marine eubacteria are composed of bacteria and Gram-positive actinomycetes (Hatti-Kaul & Abouhmad, 2020). Actinobacteria produce thousands of naturally occurring compounds that are physiologically active and have a variety of uses. Members of the actinobacteria family were found to have more than half of these bioactive compounds. Recently, there has been increased attention in rare actinobacteria that can be found in a range of settings, such as the sea, high elevations, and volcanic regions. A wide variety of natural compounds have been proposed to be synthesized by physiological or metabolic factors in such harsh environments (Pant et al., 2021).

3.6 Proteobacteria

While Gram-positive Actinobacteria and filamentous fungi have yielded a wealth of bioactive compounds, less research has been done on Gram-negative bacteria (Laheji et al., 2019). Nonetheless, recent investigation has shown that biosynthetic gene clusters likely encoding useful compounds are present in bacteria that belonging to proteobacteria family. The phylum Proteobacteria has a large number of identified toxicants from the family. Proteobacteria is the most common phylum in pelagic marine habitats, although few bioactive compounds have been found (Laheji et al., 2019).

3.7 The cyanobacteria

Cyanophyta is the only phylum of bacteria that uses photosynthesis as a source of energy. Among photosynthetic prokaryotes, it is the only group capable of both absorbing and producing CO_2. Because of their rapid rate of reproduction, the Cyanobacteria are becoming more and more popular in basic research, even though some of them are difficult to cultivate. Over time, both filamentous and unicellular cyanobacteria have been gathered, identified using genetic and morphological criteria, and cultivated in axenic cultures in accordance with accepted practices (Stincone & Brandelli, 2020). Many active chemicals synthesized by cyanobacteria were found through screening efforts. Numerous of these substances have more potentials and affect a range of cellular activities, primarily those that interfere with photosynthetic processes. These substances may be employed as organic herbicides or biocontrol agents since it is believed that they are involved in the succession and management of bacterial and algal populations. Secondary metabolites, which are only present in a small number of taxonomic groups and are not necessary for sustainability, are produced by many cyanobacteria. Among the other significant marine cyanobacterial chemicals found were dolastatin, cryptophycins, and curacin A, which are used as anticancer medications (Khalifa et al., 2021).

3.8 Marine actinomycetes

Gram-positive bacteria classified as actinomycetes are widely known for their ability to produce a wide range of antibiotics. They form symbiotic relationships with many animals and plants. Moreover, actinomycetes have symbiotic interactions with a wide range of marine macrofauna, such as fora-like insects, marine sponges (Axinella polypoides, Haliclona, etc.), invertebrates, and cone snails. From an ecological perspective, these collaborations are important.

4. Metabolites (primary and secondary metabolites)

It is impossible to overestimate the significance of marine fungi and bacteria as possibly viable origins of different bioactive elements. Marine fungi and bacteria are an important source of new chemicals with great pharmacological and therapeutic promise. Chitin, chitosan, carotenoids, algal components, omega-3 oils, and other bioactive ingredients are a good illustration of valuable compounds with potential for usage as functional additives in the nutraceutical domain. Chitosan and other polysaccharides are becoming more and more well-liked. They are considered an excellent lipid sources, containing large amounts of essential fatty acids and protein, which may promote wellness through reduction of cardiovascular disease (Nestel & Mori, 2022).

Mycosporine-like amino acids (MAAs), derived from a range of marine microorganisms with the ability to absorb ultraviolet light, are the most promising MNPs (Rosic, 2021). The secondary metabolites and bioactive compounds produced by bacteria, sponges, crabs, and other marine creatures provide a wealth of nutrient-dense food. Biologically active ingredients present in functional foods include proteins, lipids, pigments, polysaccharides, vitamins, minerals, and phenolic compounds, which are primarily sourced from marine sources. Seaweeds are a promising crop due to their anticancer, anticoagulant, and antiobesity properties. The nutritional profile of food can be enhanced by microalgae and fish oils high in poly-saturated fatty acids (Prabha et al., 2019). The three families of photosynthetic polyphyletic creatures known as algae are Rhodophyceae, Phaeophyceae, and Chlorophyceae. Macroalgae grow quickly in the open ocean, producing large amounts of biomass. In addition to having greater photosynthetic activity compared to biomass on land, macroalgae have the advantage of not being dependent on water or land. Multicellular eukaryotic cells, or red algae, contain phycobiliproteins and chlorophyll. What gives them their characteristic red hue is the high quantity of phycoerythrin. Red seaweed can use floridian starch, which is comparable to amyl, as a food source. Multicellular algae of the brown algae kind can be found in the ocean in a variety of sizes and forms. Some can reach lengths of up to 60 m, while others are only a few centimeters long. More than half of the dry biomass in brown algae is made up of carbohydrates, indicating their high carbohydrate content. Large-scale cultivation of brown algae is done for food and alginate extraction (Noklin-Eide 2023).

4.1 Proteins

The genetic code determines the sequence of 20 amino acids, along with a range of other amino acids, which combine to form polymers known as proteins. Proteins serve as transport proteins (hemoglobin), hormones (insulin), and antibodies in biological and food systems. They are also essential for proper nutrition (immunoglobulins). Seaweeds are used as food or herbal medicine to treat and prevent a wide range of illnesses and maladies because of their abundant nutritional and therapeutic qualities. They are also used in many industrial and pharmaceutical applications as food supplements, fungicides, and herbicides. It has been widely accepted for a number of decades that seaweeds can be used as a reliable protein origin (Pooja et al., 2020).

4.2 Peptides

There has been a lot of interest in using protein hydrolysis for the creation of bioactive peptides, especially the ones from marine proteins. These peptides were isolated from varieties of aquatic organisms. Depending on the sequence, bioactive peptides may have three to 20 amino acid residues. According to Kocaturk et al. (2021), they possess biological attributes like antibacterial, immunomodulatory, antithrombotic, antihypertensive, antioxidant, and anticancer effects. Peptides derived from aquatic protein origins may be advantageous as essential antihypertensive substances that may be added to functional diets (Cunha et al., 2021).

4.3 Amino acids

The water-soluble amino acids, Pro, Gln, Ala, Gly, and Arg are found in large amounts in shellfish muscles. When seafood is prepared lightly, water-soluble components are likely to retain more of their beneficial qualities due to their loss during thermal processing or cooking. Sulfur, Lys, and Thr-containing amino acids are commonly lacking in children's diets, particularly when such diets are grain-based (Li et al., 2021).

4.4 Lipids and fatty acids

The two most prevalent omega-3 polyunsaturated fatty acids obtained from aquatic sources are docosahexaenoic acid (DHA) and eicosapentaenoic acid (EPA). To a limited extent, linolenic acid can be extended and desaturated by humans to produce EPA and DHA. Eating seafood and taking supplements are the only ways to obtain this PUFA. Compared to EPA and DHA, DPA is present in fish oils in incredibly small amounts. But it is almost as important in seal blubber oil as either EPA or DHA. Epidemiological research suggests that consumption of fatty acids naturally may influence the development and course of various medical disorders, including autoimmune illnesses and cardiovascular disease (Kapoor et al., 2021).

4.5 Dietary fiber and carbohydrates

As prominent component of seafood, carbohydrates from marine species demonstrated immunity-boosting and antioxidant properties that provided a crucial basis for antiaging. While some are mono- or oligosaccharides, polysaccharides make up the bulk of the naturally occurring carbohydrates in marine environments. Trehalose is a disaccharide that is commonly found in shrimp and seaweed and has the ability to slow down aging (Wang et al., 2021). There are other types of alginate, such as acid and salt (which are thought to be essential components of the cell wall). In contrast to laminaran and alginate, fucoidan has an extremely intricate and broad structure. The intricate structure of the polysaccharides found in brown seaweed hinders the body's natural enzymes from degrading them. Fucoidan, laminaran, and alginate include dietary fiber. Natural amino-polysaccharides with unique architecture and multimodal properties are chitin and chitosan polymers. With uses such as biomaterials for wound healing and tissue engineering, derivatives of chitin have garnered interest within the last 10 years in the domains of industrial research (Pati et al., 2021). To produce oligosaccharides, and glucosamine, chitin can be partially deacetylated. These chitosan derivatives are more beneficial as nutraceutical ingredients than the fully acetylated, insoluble form of chitin because of their increased water solubility. Despite doubts about chitosan's effectiveness in reducing fat absorption, a number of chitosan products are marketed as cholesterol lowers and fat burners nowadays. Alginate, laminaran and fucoidan are the three forms of fiber found in algae. Insoluble fiber is mostly composed of cellulose (Ning et al., 2022).

4.6 Enzymes, vitamins, and minerals

Enzymes can be used in the food and nutraceutical sectors to convert molecules to useful biotechnological instruments. Enzymes have an impact on processing, storage, safety, and spoiling. Marine sources provide lipase, transglutamase, chitinolytic enzymes, polyphenol oxidase, and red algal enzymes (such as 1, 4-glucanase) that are used in the breakdown of starch (Maddela et al., 2022). They are more capable of catalysis, physics, and chemistry than their terrestrial counterparts. According to Burgener et al. (2020), they can likewise be rendered inactive at a moderate temperature. Minerals and vitamins provide are cofactors in metabolic processes, among other functions in the body. Seaweeds are rich in vitamins and minerals, including iron. A family of enzymes called xylanases is responsible for catalyzing the release of xylose from hemicellulose. A vital source of carbon for bacteria, xylose plays a role in plant–pathogen infection. The organisms that produce xylanases include gastropods, arthropods, bacteria, fungi, and protozoa. Despite this, because of their greater stability and ease of genetic modification, microorganisms are preferred for xylanase synthesis over plant and animal sources. Most marine xylanases have been found to originate from bacteria and fungi, especially actinomycetes. It has been found that marine xylanases have microbial origins (Han et al., 2019). Chitinolytic enzymes are capable of catalyzing the breakdown of chitin. Recently, marine life has emerged as a new source for the industrial separation of enzymes and the production of numerous special and practical compounds (Ghosh et al., 2022). Because seaweeds are rich in calcium and potassium, many varieties are advised as food supplements to meet daily requirements for minerals and trace elements. Selenium, iodine, zinc, magnesium, and calcium are additional nutrients that are found in some shellfish at higher concentrations than, say, in beef. A lower risk of cancer has been linked to increased dietary selenium intake. In certain places where iodine consumption is low, seaweeds can serve as an alternative means of supplying iodine through diet. Seaweed is among the most promising natural iodine sources (Ghosh et al., 2022).

4.7 Probiotics

More than 100 trillion bacteria can be discovered in the human colon, making up the gut flora, a collection of microbial species present in the digestive tract. Prevalent microbes provide a number of beneficial roles for the innate exploitation of

underutilized energy origins. Many strains turn harmful in specific situations. Thus, it has been found that maintaining a healthy environment reduces the number of dangerous species. Numerous strategies for boosting the beneficial effects of intestinal microflora have been put up in this regard. One of the best methods for boosting good bacteria in the stomach is to take probiotic, which are good living microbes for the gut flora and may even lessen the activity of bacteria that cause disease. Prebiotics eventually enable specific alterations in the gut microflora's composition and activity, which enhances the host's general health and well-being. Live strains of Bifidobacterium and Lactobacillus are commonly found in probiotic supplements. Dairy products that have undergone fermentation include yogurts (Savaiano & Hutkins, 2021).

5. Possible health benefits of marine bioactives

As expectations to live long rise, the role that diet plays in preserving human health will only increase. Consumers expect food that is not only wholesome and nutritious but also enjoyable and convenient, which presents a challenge in the food manufacturing circus. It is also anticipated that the consumption of fisheries products would increase. Moreover, people are becoming increasingly conscious of the connection between diet and health. Additionally, there might be variations in the concentrations of metabolites, proteins, carbohydrates, lipids, fiber, and other substances in marine algae. Among the polyphenolic chemicals produced by the maritime environment are flavonoids, phlorotannins, gallic acid, benzoic acid, and quercy (Nailwal et al., 2023; Rivas-Navia et al., 2023).

Since the seas contain a wide variety of creatures and make up 70% of the earth, they are a rich present resource for bioprospecting. With more investigation, it is becoming evident that certain metabolic and genetic pathways have been adapted by as yet unidentified bacteria to produce novel secondary metabolites. Fungal bioprospecting is important because they contain a wide variety of bioactive chemicals with different structures. Numerous bioactive compounds have been discovered to be present in marine fungus, including antioxidants, antivirals, anticancer agents, and antibiotics (Ameen et al., 2021). Polyphenolic components, derived from micro- and macroalgae, are antioxidant chemicals based on their structural makeup. There are ten different categories for phenolic components. The ten groups of compounds include, among others, lignins, flavonoids, anthraquinones, coumarins, xanthones, and phenolic acids. Phlorotannins are polyphenolic components with potent antioxidant properties that have been found in several types of algae. Phlorotannins also possess antibacterial, chemopreventive, and UV-protective properties (Sang et al., 2019). Reactive oxygen species (ROS) are created by microalgae and seaweeds in response to the harsh environmental circumstances (high temperature and intense radiation) to which they are subjected. Excessive ROS levels have been linked to neurological, inflammatory, cancer, and diabetic diseases. Seaweeds, or macroalgae, deactivate ROS by utilizing significantly elevated levels of antioxidant substances in cells, including vitamins, phycobilins, carotenoids, and polyphenols (Ferdous & Yusof, 2021). Microalgal-derived beta-carotene is a "natural" food additive since it has a higher physiological activity than beta-carotene produced artificially. Natural beta-carotene can be ingested in larger amounts since the body's tissues control how it is used (Duan et al., 2024).

5.1 Antiobesity effect

An imbalance in the ratio of energy expenditure to intake results in obesity, a long-term metabolic condition. Excessive fat accumulation results in high blood cholesterol, diabetes, chronic heart diseases, and sleep apnea. Additionally, obesity negatively affects society. Because of their weight, obese individuals may face stigma, discrimination, and a range of prejudices. Due to its increasing prevalence, obesity is seriously becoming a global problem. It has been discovered that fish oil aids with weight loss. Despite the limited number of human investigations and their brief duration, the obtained results have potential applications (Ferdous & Yusof, 2021). Because of their unique functional components, marine goods have a well-established potential health benefit. Among other marine species, bacteria, phytoplankton, invertebrates, and vertebrates produce a number of antiobesity compounds. Algal research has been the primary focus of the focused research effort thus far. Many compounds were extracted from algae, especially brown algae, and their potential to prevent obesity was studied (Remya et al., 2022).

5.2 Prevention of cardiovascular diseases

Fatty fish contains polyunsaturated fatty acids (PUFAs), which have been shown to lower the incidence of coronary heart disease (CHD). In an attempt to establish a connection between consuming fish and a decreased risk of CHD, numerous

studies have been conducted. It has been shown that individuals who consume large amounts of seafood, such as Japanese and Alaskans, are safer when it comes to heart disease risk. According to Manlusoc et al. (2019), omega-3 PUFAs can prevent breast and prostate cancer. A medical condition known as hyperlipidemia is defined by decreasing levels of high-density lipoprotein cholesterol (HDL-C) and increased levels of total cholesterol, total triglycerides, and low-density lipoprotein cholesterol in the blood. According to a study, the presence of alginate in the lumen of the small intestine reduces plasma cholesterol and restricts the consumption of fat in a variety of diets. Increased bile and cholesterol excretion in the feces is most likely the cause (Tall et al., 2022).

5.3 Impact on prebiotics and promoting health advantages

All organisms contain carbohydrates in varying amounts. Macroalgal polysaccharides have the potential to be employed as future prebiotics. Both in vitro and in vivo studies have indicated the advantages of macroalgal carbohydrates. It was gratifying to see that laboratory animals had higher concentrations of Lactobacillus and Bifidobacterium. Both beneficial and harmful bacteria coexist in the GI tract, but research is aimed at restoring a favorable label through eradicating perceived harmful bacteria and promoting the emergence of new organisms that have positively good effects (Lopez-Santa Marina et al., 2020).

5.4 Anti-inflammatory properties

Because they can reduce particular inflammation mediators, polyunsaturated fats (PUFAs), anti-inflammatory properties are a typical feature of omega-3. Numerous studies have shown that enhancing the diet with PUFA can reduce inflammation. Eicosanoids made from omega-6 PUFAs are immunoactive and proinflammatory, whereas those made from omega-3 PUFAs (EPA and DHA) are anti-inflammatory. In Western food, omega-6 PUFA ratios are significantly higher than omega-3 PUFA ratios. Algae have anti-inflammatory properties as well. For example, fucoxanthin (Fx), which is extracted from brown algae, suppresses the expression of the cyclooxygenase 2 (COX-2) protein and decreases the synthesis of prostaglandin E2 (PGE2). Phenophytin from *Enteromorpha prolifera* inhibited the inflammatory and superoxide radical reactions elicited by 12-O-tetradecanoylphorbol-13-acetate in murine macrophages. Another component of the brown algae that has anti-inflammatory properties is Turbinaria ornate polysaccharide (Manikandan et al., 2020).

5.5 Anticancer effect

Cancers are illnesses when cells stop reacting appropriately to chemical cues from other cells. These abnormal cells possess the ability to invade and modify healthy tissues, perhaps resulting in death. Searching for substances capable of inducing apoptosis—the death of cells—becomes imperative. Numerous clinical disorders, including cancer, can be brought on by cell deregulation that happens when proapoptotic cascades are reduced. Therefore, promoting apoptosis is a key goal of anticancer treatment. The connection between eating fish and avoiding cancer has been the subject of numerous studies. Cell growth was suppressed by the complex mixture concentrations of NaCl that comprised the hydrolysates (Abdelhedi et al., 2024; Alabi et al., 2023).

5.6 Effects on neuroprotection

Neurodegenerative diseases are among the major death cause in the elderly population. Therefore, researchers are searching for new neuroprotective medications to stop CNS degeneration, apoptosis, and damage to neural cells. Despite its neuroprotective qualities, synthetic substances can make people feel nervous, uneasy, sleepy, dry mouth, and exhausted. In East Asia, eating fish and sea urchins is associated with lower cases of neurological diseases. Marine algae are another possible source for neuroprotective medications (Hannan et al., 2020).

5.7 Prevention of arthritis

Joint inflammation is the hallmark of arthritis, a condition that mainly affects the elderly. A major part of treating arthritis is preventing inflammation and the associated feelings of pain and limited movement. Positive outcomes included a decrease in the number of troublesome and painful joints that patients reported, the degree of their joint pain, and their usage of nonsteroidal anti-inflammatory medicines after 2–4months of PUFA administration. Taking PUFA supplements may even help relieve joint pain (Gambari et al., 2023).

5.8 Prevention of asthma

Compared to children who only eat fish on exceptional occasions, children who regularly consume fresh, oily fish were less likely to develop asthma. A lower incidence of airway hyperresponsiveness has been linked to fish oil, or fish that contain more than 2% fat. The importance of including carboxylic acid supplements in the diet have also been demonstrated in asthma patients, who report less symptoms, including difficulty breathing, and a need for smaller dosages of medication (Zuniga-Hernandez et al., 2022).

5.9 Prevention of diabetes

Using diet to manage diabetes is to keep blood lipid and blood glucose levels as near to normal as possible to reduce the risk of retinopathy, nephropathy, diabetic neuropathy, and cardiovascular disease. Several physiologically active substances in the marine environment that is still unknown. Using marine resources could provide insightful information with consequences for business and science. Diabetes is a metabolic disease that is a major cause of morbidity and mortality that affects people in both industrialized and developing nations. Many antidiabetics are available commercially, but their primary disadvantages include side effects and economic hardship (Padhi et al., 2020).

5.10 Preventing depression and cognitive decline

Dementia and cognitive impairment are prevalent in older adults and affect their capacity for independent living. As the population ages, dementia and cognitive impairment are expected to become more common. Particularly, marine omega-3 PUFAs and fatty fish are linked to low incidences. Moreover, eating a lot of chlorella algae decreased oxidative stress. While fatty acid intake has been linked to stress in several epidemiological and nutritional studies, n-3 compounds have been shown to be helpful in preventing depressive disorders in clinical investigations. Numerous studies have shown that long-chain n-3 PUFA supplements improve people situation (Kelaiditis et al., 2023).

5.11 Antiaging effect

Marine animals have drawn utmost focus on studies for rejuvenating effect because of their special chemicals. *Caenorhabditis elegans* and *Drosophila melanogaster*, two antiaging experimental animals, were utilized to show the activity and mechanism of pigment, protein, and carbohydrates from sea organisms. They had mycosporine-like amino acids that could absorb UV radiation and reduced using several types of amino acids and cyclohexenone (Wang et al., 2021).

5.12 Anticoagulant and antithrombin actions

Hemostasis depends on the intricate process of coagulation, which helps to form clots. Anticoagulants are drugs that either stop blood clotting from happening or from developing. They are used in life-threatening conditions, such as pulmonary embolisms in order to avoid clotting of blood post operation. Heparin is the most often used anticoagulants. It has been used for the past 15 years to treat thromboembolic illnesses. On the other hand, heparin therapy might result in unwanted bleeding, thrombocytopenia deficits. Many marine sources create compounds like peptides and sulfated polysaccharides (Li et al., 2021).

5.13 Antiallergic activity

An allergic reaction is the immune system's response to generally safe substances found in the environment. The activation of mast cells occurs due to the allergen-induced IgE436-mediated allergic response, critically involved in the allergic disease development. Many intracellular processes are brought on by mast-cell activation, such as the activation of tyrosinase kinase, the generation of reactive oxygen species, which raises microtubule polymerization, degranulation, intracellular calcium ion (Ca^{2+}), and cytokine production (Cunha et al., 2021). Numerous studies indicated that a variety of plants have antifood allergy properties. These chemicals include phenols, flavonoids, and terpenes. New studies have revealed that active substances gotten from marine sources can alleviate allergy symptoms through a variety of mechanisms, including blocking Th2 development, boosting Th1 immune function, blocking basophil, and mast-cell degranulation (Wang et al., 2021).

5.14 Antimicrobial properties

Marine invertebrates do not possess adaptive immunity. Because they only possess the intrinsic reaction, bees must develop defense mechanisms in order to survive in their fatal environment, which is rife with viruses and bacteria. Their filtering action increases their exposure to pathogens. One of the elements of invertebrates' defense mechanisms is antibacterial peptides. They are an animal or plant's initial line of defense against pathogens (Cunha et al., 2021). Marine invertebrates do not possess adaptive immunity. Their filtering action increases their exposure to pathogens. One of the elements of invertebrates' defense mechanisms is antibacterial peptides. They are an animal or plant's initial line of defense against pathogens. Numerous recent investigations have concentrated on the nutraceutical contents of marine algae, with possible health benefits associated with the antioxidants, various bioactives, and three fatty acids present in these organisms. A comprehensive prospectus states that a wide range of bioactive natural chemicals with distinct structures have been created by marine animals, especially sponges, and the fungus and bacteria that live in symbiosis with them. Even though the field of using PLE and SFE to extract bioactives is now regarded as mature, fresh developments that can significantly increase interest in these methods are still required (Abd El-Malek et al., 2022).

6. Conclusion

The inclination of modern consumers toward natural preservatives instead of artificial additives motivates food scientists and the food sector to discover novel and enhanced natural goods. Beyond the ones that are now known, there is definitely a ton of other natural herbal, animal, or microbiological additive ingredients that are just waiting to be found. Additional investigation is required to discover novel natural preservatives, pinpoint their active components, and examine the safeguarding impacts on food items. Apart from these, it is crucial to ascertain the suitable concentrations that can be incorporated into foods. Although seafood plays a significant role in human nutrition, it is highly perishable. Because of this, maintaining the quality of seafood and extending its shelf life are crucial. Natural preservatives not only prolong the shelf life of these goods but also safeguard human health and contribute significantly to the reduction of both food loss and poor nutrition.

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Chapter 19

Comprehensive applications of marine biotoxins resources

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1. Introduction

Biotoxins are naturally occurring toxic substances that are produced by living organisms. These toxins can be found in a variety of organisms, including plants, bacteria, fungi, and certain animals. Biotoxins serve various functions in nature, such as defense mechanisms against predators or to capture prey (Jousset et al., 2010; Smith et al., 2016). Their potency and effect can vary widely, depending on the type and the organism affected (Anderson et al., 2012). Biotoxins differ from man-made toxins in that they are produced by living organisms as part of their biological processes.

Marine biotoxins are a specific type of biotoxin produced by marine organisms, particularly certain species of algae. These toxins accumulate in the marine environment and can have profound effects on the marine food web, including humans who consume contaminated seafood (Kadiri & Isagba, 2018). Marine biotoxins are most commonly associated with harmful algal blooms (HABs), where toxin-producing algae multiply rapidly, leading to high concentrations of toxins in the water. These toxins can contaminate fish, shellfish, and other marine life (Smith et al., 2018).

2. Marine biotoxins and the algae that produce them

2.1 Paralytic shellfish toxins

Under this category are saxitoxins which are a group of potent neurotoxins. These toxins are produced by various species of dinoflagellates, including *Alexandrium spp*. and *Gymnodinium catenatum*, *Alexandrium* spp. and *Pyrodinium bahamense* (Anderson et al., 2012), cyanobacteria, such as *Cylindrospermopsis* spp. and *Lyngbya* spp. PSTs can cause paralysis and even death if consumed in high amounts, particularly through contaminated shellfish (Raposo et al., 2020).

2.2 Diarrhetic shellfish toxins

Okadaic acid and its derivatives are the primary toxins. DSTs are produced by dinoflagellates such as *Dinophysis spp*. and *Prorocentrum spp* (Campos et al., 2020). These toxins primarily cause gastrointestinal distress, leading to diarrhea, nausea, and vomiting in humans (Reguera et al., 2014).

2.3 Amnesic shellfish toxins

Domoic acid is the most well-known toxin in this category; they are produced by diatoms, particularly *Pseudo-nitzschia spp* (Smith et al., 2018). ASTs can lead to memory loss, brain damage, and, in severe cases, death (Kadiri & Isagba, 2018).

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2.4 Neurotoxic shellfish toxins

Brevetoxins are the primary toxins in this group and are produced by the dinoflagellate *Karenia brevis*, commonly associated with red tides (Backer et al., 2015). NSTs can cause neurological symptoms such as tingling, numbness, and coordination problems.

2.5 Ciguatoxins

These are complex polyether toxins; they are produced by *Gambierdiscus toxicus* and other related species (Friedman et al., 2008). Ciguatoxins cause ciguatera fish poisoning, characterized by gastrointestinal, neurological, and cardiovascular symptoms.

2.6 Cyclic imines

Cyclic imines includes gymnodimines (GYM) from *Alexandrium*, pinnatoxins (PnTX) obtained from *Vulcanodinium rugosum*, pteriatoxins (PtTX) from *Pinna* and *Pteria,* while spirolides (SPX) is produced from *Alexandrium* and *Karenia* PtTX has been documented to be a biotransformed end product of PnTX. Studies are still ongoing to determine the toxicity of these biotoxins (Pierina et al., 2016).

3. Effects of biotoxins on living organisms

Marine biotoxins can disrupt ecosystems by killing or impairing marine organisms at various trophic levels. For instance, high concentrations of toxins can lead to mass die-offs of fish, shellfish, and even marine mammals. These events can cause significant ecological damage, as the loss of species can alter the balance of marine ecosystems. The effects of biotoxins on living organisms can range from mild to severe, depending on the type and amount of toxin exposure. In marine environments, these toxins can affect a wide range of organisms, from small invertebrates to large marine mammals, and they often bioaccumulate in the food chain, posing risks to predators, including humans (Pierina et al., 2016).

Humans are primarily affected by marine biotoxins through the consumption of contaminated seafood. Depending on the type of biotoxin, the symptoms and severity can vary: For example, the Paralytic Shellfish Poisoning (PSP) causes numbness, dizziness, and, in severe cases, respiratory failure and death (Anderson et al., 2012). Gastrointestinal symptoms like diarrhea, vomiting, and abdominal pain are symptoms observed in diarrhetic shellfish poisoning (DSP). Although not typically fatal, DSP can cause significant discomfort characterized by Reguera et al. (2014). Other effects of biotoxins in human in amnesic shellfish poisoning include memory loss, confusion, and seizures and death in extreme cases; it can lead to death, particularly in vulnerable populations such as the elderly (Smith et al., 2018). Neurotoxic shellfish poisoning (NSP) show symptomatic conditions such as neurological issues like tingling, muscle weakness, and, in some cases, respiratory problems (Backer et al., 2015). Furthermore, ciguatera fish poisoning (CFP) leads to symptoms from gastrointestinal distress to neurological and cardiovascular effects. Recovery can take weeks or even months. Mechanism of action is activating the sodium and blocking the potassium channels respectively (Traylor et al., 2024).

4. Classification of marine biotoxins

Marine biotoxins are classified based on according to chemical properties, their poisoning symptoms, and their chemical structure.

Marine biotoxins based on chemical properties.
Marine biotoxins based on poisoning symptoms.
Marine biotoxins based on chemical structure.

4.1 Marine biotoxins based on chemical properties

According to the chemical properties of marine biotoxins, they can be classified as lipophilic and hydrophilic marine biotoxins (Gerssen et al., 2010).

4.1.1 Lipophilic marine biotoxins

These are marine biotoxins that have lipophilic properties. Examples include okadaic acid, dinophysistoxin-1 (DTX1) and 2 (DTX2) (Vale & Sampayo, 2002), azaspiracids (Salas et al., 2011), spirolides and gymnodimines (cyclic imines) (Cembella et al., 2000), and brevetoxins (Landsberg et al., 2009).

4.1.1.1 Okadaic acid, dinophysistoxin-1 (DTX1) and 2 (DTX2)

The toxins of okadaic acid, dinophysistoxin-1 (DTX1), and dinophysistoxin-2 (DTX2) are capable of inhibiting the threonine phosphatases PP1 and PP2A and serine, which results in loss of fluids from the cells due to the hyper-phosphorylation of proteins responsible in cytoskeletal joints regulating permeability of the cell (Vale & Botana, 2008). In the past, the first recorded intoxication caused by okadaic acid, dinophysistoxin-1 (DTX1) and dinophysistoxin-2 (DTX2) was in the Netherlands. Presently, there have been reports of high level of okadaic acid group in shellfish or algae along the coast of Australia, Japan, Africa, Canada, South America, and Europe. Within Europe, 160 μg OA-equivalents/kg shellfish has been set as the permitted level for the total amount of OA and analogs; however, the EFSA panel concluded that OA-equivalent/kg shellfish should not go beyond 45 μg (Alexander et al., 2009).

4.1.1.2 Azaspiracids

Other than okadaic acid, dinophysistoxin-1 (DTX1) and 2 (DTX2), azaspiracids are also lipophilic biotoxins produced by *Azadinium spinosum*, a tiny dinoflagellate (Rehmann et al., 2008; Tillmann et al., 2009). About 24 different azaspiracids existed; however, the predominant ones include azaspiracid-1, azaspiracid-2, and azaspiracid-3 (Rehmann et al., 2008). The toxic effects of azaspiracid intoxication are gastrointestinal disorder, abdominal cramps, and diarrhea (James et al., 2004). The mechanisms of action of this form of intoxication are not well understood; however, in vitro research in mammalian cell lines showed alterations in the cytoskeletal structure and an effect on the E-cadherin system, which is accountable for the cell–cell interactions (Ronzitti et al., 2007; Twiner et al., 2005). The first human intoxication as a result of azaspiracid was reported in 1995 in Netherlands after the consumption of mussels from Ireland. Consequently, other azaspiracid outbreaks have been detected in Ireland, France, the UK, Norway, Portugal, South America, the USA, and North America (Alvarez et al., 2010; James et al., 2004; Torgersen et al., 2008). As a result of regular incidence and toxicity to humans, the European Commission has established regulatory boundaries for the occurrence of both okadaic acid -group toxins and azaspiracid in seafood (i.e., 160 μg OA or AZA equivalent per kg of shellfish meat) (EFSA, 2008a, 2008b).

4.1.1.3 Spirolides and gymnodimines

These are lipophilic toxins belonging to the cyclic imines group; they are produced by *Alexandrium ostenfeldii*. Almost 10–15 distinct spirolides have been discovered in either shellfish or algae (Aasen et al., 2005, 2006). The mechanism of action of spirolides intoxication is not fully clear, but, instant death of test animals has been noted in test animals fed with shellfish extracts containing spirolides and gymnodimines (Richard et al., 2000). As a result of this, these toxins have been categorized as fast-acting toxins. No report of human intoxication with cyclic imines has been reported yet. Occurrence of spirolides in shellfishes and algae has been reported in Canada, Spain, Chile, Norway, and Denmark, and the occurrence of gymnodimines has been detected in algae and shellfishes from New Zealand (Aasen et al., 2005; Alvarez et al., 2010; Villar Gonzalez et al., 2006).

4.1.1.4 Brevetoxins

Brevetoxins are lipophilic toxins, which are tasteless and odorless. They are cyclic polyether neurotoxins produced by dinoflagellate such as *Gymnodinium breve* and by the algal species *Karenia* spp. Some brevetoxins have been isolated and identified from cultures of *Gymnodinium breve* as well as from field blooms (Benson et al., 1999; Landsberg et al., 2009). Brevetoxins intoxication can be as a result of consumption of brevetoxin-contaminated shellfish or inhalation of brevetoxins aerosols (Kirkpatrick et al., 2006; Pierce et al., 2005). The effect of inhalation of brevetoxins aerosols includes respiratory disorders, irritation of the eye, and nasal membrane (Kirkpatrick et al., 2006; Pierce et al., 2005). The occurrence of brevetoxins has been limited to New Zealand and the USA; however, no occurrence of the toxin has been implicated in Europe (Heil, 2009; Ishida et al., 2004). The legislation on the regulatory limit of brevetoxins has been set by the Food and Drug Administration as 800 μg brevetoxins-2 equivalent/kg shellfish (FDA, 2001).

4.1.2 Hydrophilic marine biotoxins

These biotoxins are water soluble and exposure to hydrophilic biotoxins represents hazards to human health. These hydrophilic marine biotoxins include domoic acid and saxitoxins (EFSA, 2009; Gerssen et al., 2010).

4.1.2.1 Domoic acid

This biotoxins is produced by the diatom *Pseudo-nitzschia pungens*, one of the most important species responsible for the production of domoic acid. The biotoxins is a neurotoxin and has adverse effects (Jeffery et al., 2004; Kumar et al., 2009). Intoxication of domoic acid in human was reported in 1987 on Prince Edward Island, Canada, which was as a result of consumption of blue mussels. The occurrence of domoic acid in shellfish is a global issue, and more recently, domoic acid occurrence in shell fish has been reported in Portugal, France, Ireland, Canada, Spain, the United States, and the United Kingdom (Bill et al., 2006; Blanco et al., 2006; James et al., 2005). A permitted level of 20 mg of domoic/kg shellfish has been established by the European Union (Alexander et al., 2009). In the opinion of European Food Safety Authority (EFSA), the panel recommended the safe consumption of shellfish with content of less than 4.5 mg domoic/kg shellfish.

4.1.2.2 Saxitoxins

This is a neurotoxin produced by dinoflagellates from the genera *Pyrodinium*, *Gymnodinium,* and *Alexandrium*. There are about 30 different analogs of saxitoxins within the saxitoxin group (Dell'Aversano et al., 2008). Not all the saxitoxin analogs show the same toxicity and currently, toxic equivalent factors have been recognized for most of the well-known analogs (Alexander et al., 2009). In 1920, in California, USA, the first report of saxitoxin intoxication was reported. In 1970, saxitoxin intoxication was detected in North American, European, and Japanese waters. Presently, saxitoxins have been reported in Australia, South-Africa, Chile, and other countries as well (Krock et al., 2007; Pitcher et al., 2007; Robertson et al., 2004). The permitted level of saxitoxin as established by the European Union is 800 μg saxitoxin 2-HCl equivalent/kg shellfish and the EFSA published an opinion and recommended a safe level of less than 75 μg saxitoxin 2-HCl equivalents/kg (Alexander et al., 2009).

4.2 Marine biotoxins based on poisoning properties

According to the poisoning properties of marine biotoxins, they are classified as toxins causing amnesic shellfish poisoning (ASP), paralytic shellfish poisoning (PSP), neurotoxic paralytic shellfish poisoning (NSP), diarrheic shellfish poisoning (DSP) and ciguatera shellfish poisoning (CSP) (Poletti et al., 2003), cyclic imines (McCarthy et al., 2015), palytoxin (Bire et al., 2013), puffer fish poisoning (PFP) (Yoshikawa-Ebesu et al., 2001), and azaspiracid poisoning (AZP) (Nevado et al., 2023).

4.2.1 Amnesic shellfish poisoning

ASP occurs as a result of the production of toxins, domoic acid, and other toxic domoic acid isomers produced mostly by marine diatoms, *Pseudo-nitzschia australis* and *Pseudo-nitzschia pungens*. Domoic acid is an amino acid (cyclic tricarboxylic) and share similar functional and structural properties with kainic acid (an analog to glutamic acid). This toxin is capable of binding to the glutamate receptors within the central nervous system resulting in the overstimulation of these receptors signaling the production of reactive oxygen species, which can lead to death of cells (Schwarz et al., 2014). ASP can be considered as life-threatening, which is characterized by gastrointestinal and neurological effects. Within 24 hours of the consumption of toxic shellfish, gastroenteritis develops with symptoms such as nausea, vomiting, intestinal spasms, and diarrhea. In cases of severity, within 48 hours of consuming toxic shellfish, neurological symptoms such as headache, faintness, seizures, temporary memory loss, respiratory difficulty, coma, or death (Windust & Quilliam, 2002). Several factors are responsible for the deposit of domoic acid in the bivalve tissues which include the existence of *Pseudo-nitzschia* spp and their toxins and domoic acid accumulation and depuration balance by shellfish (Mafra et al., 2010).

Human amnesic shellfish poisoning has not been documented since the first outbreak in 1987 due to an efficient international seafood monitoring programs aimed at detecting domoic acid in shellfish and coastal waters as carried out by several regulatory agencies. Toxic effects of domoic acid have also been reported on marine wildlife. Between 1998 and 2006, a chronic domoic acid epileptic disorder was described in sea lions, which have resulted in the use of sea lions as sentinel species for potential hazard prediction for human health (Lefebvre & Robertson, 2010).

4.2.2 Paralytic shellfish poisoning

This is one of the most studied intoxication with serious neurological symptoms in humans. It is caused by the exposure to the toxins, saxitoxin (STX) and gonyautoxins (GTX) produced by dinoflagellates of the genus *Alexandrium* spp, which occurs along the Pacific and the Atlantic coast (Christian & Luckas, 2008) and the genus *Gymnodinium catenatum* which occurs in the Mediterranean Sea (Berti & Milandri, 2014, pp. 163–198). The toxin produced, saxitoxins PSP, similar to ASP, is a lethal disorder. The symptoms are exclusively neurological and comparable to paralytic occurrence because the toxins are capable of obstructing the excitation current in the muscles and nerve cells (Schirone et al., 2011). The symptoms of human PSP and be categorized in mild, moderately severe, and extremely severe forms. The mild symptoms include unresponsiveness around the lip which spreads to the face and neck, nausea, headache, an itchy sensation in the fingertips and toes, and dizziness (Klopper et al., 2003). The moderately severe symptoms are indicated by muttered speech, progression of itchy sensation to the arms and legs, stiffness and noncoordination of limbs, body weakness and feeling of lightness, slight respiratory difficulty, and fast pulse and back pain (Klopper et al., 2003; Luckas et al., 2005). The extremely severe symptoms involve a more noticeable respiratory difficulty and choking sensation and muscular paralysis. In fatal cases, death occurs as a result of respiratory paralysis, which takes place 2–12 hours after consuming contaminated shellfish especially with lack of artificial respiration (WHO, 2004; Luckas et al., 2005; Klopper et al., 2003; FAO/IOC/WHO, 2004). Blooms of toxic dinoflagellates producing PSP toxins denote a continuous threat to fishery resources and human health. Particularly, PSP has been known for over a period as a clinical entity in some parts of South America (Garcia et al., 2004) and high number of PSP cases in the Philippines (Ching et al., 2015), the coast of Nicaragua outbreaks in Southeast Asia and Latin American with 2%–14% case fatality, and cases of PSP in Europe and North America (Callejas et al., 2015).

4.2.3 Neurotoxic paralytic shellfish poisoning

This is caused by the production of brevetoxins by the "Florida red tide" dinoflagellate *Karenia brevis,* which are responsible for massive fish and marine mammal mortality in the Gulf of Mexico (Cassell et al., 2015) and also along the East coast of New Zealand and United States ("Scientific Opinion on marine biotoxins in shellfish - Emerging toxins: Brevetoxin group," 2010). Brevetoxins are extremely stable, they are capable of withstanding heat up to 300°C and the oral LD_{50} value in about 520–6600 μg/kg (Llewellyn, 2001). Brevetoxins are the causative agents of NSP and asthma-like symptoms in humans (Sun et al., 2016) and characterized by neurological and gastrointestinal effects with symptoms such as nausea, vomiting, diarrhea, cramps, paresthesia, bronchoconstriction, seizures, paralysis, coma, and death in extreme cases (Watkins et al., 2008). NSP can be contracted by ingestion of contaminated shellfish, inhalation or aerosols, or by sexual transplacental transmission. Respiratory effects associated with aerosolized red tide include irritation, burning and itchy sensation of the throat, sneezing; a significant increase of symptoms is observed in asthmatic individual (Bean et al., 2011; Fleming et al., 2007). Treatment of intoxication of brevetoxins is beneficial with the use of inhaled bronchodilators. The inhalation of aerosol toxins can be prevented with the particle masks. Elimination of this marine poisoning has been made possible through government regulation and surveillance using biological assay procedures in mice to control the concentration of brevetoxins in commercial mollusks and crustaceans. Close monitoring of the presence of *Karenia brevis* is conducted to keep the algal bloom density within the acceptable threshold limit (Solter & Beasley, 2013). Furthermore, awareness is given foremost consideration especially with persons that have asthma or other respiratory problems to stay away from beaches during the red tide. (Grattan et al., 2016; Watkins et al., 2008) reported that there has been only a small number of sporadic cases of NSP in the United States in humans with hospitalization with no fatalities. About 11 cases of NSP outbreak have implicated in NSP in Florida between 1995 and 2005.

4.2.4 Diarrheic shellfish poisoning

This is a well-known intoxication caused by dinoflagellates, *Dinophysis* spp, and *Prorocentrum* spp (Nielsen et al., 2016), and they produce diarrheic shellfish poisoning toxins (Berti & Milandri, 2014, pp. 163–198). DSP toxins are grouped into four structural classes on the basis of their distinctive chemical structures, namely, okadaic acid and its derivatives (dinophysistoxin), yessotoxins and its derivatives, pectenotoxin, and azaspiracid (Berti & Milandri, 2014, pp. 163–198).

The okadaic acid group toxins are soluble in fats, hence can pass through the cell membrane resulting in an inhibition of serine and threonine phosphoprotein phosphatase (EFSA, 2008a). The symptom caused by the okadaic acid group toxins begins 30 minutes to few hours after consuming contaminated shellfish and include nausea, vomiting, diarrhea, and abdominal pain, which usually stops within days (Trainer et al., 2013).

Yessotoxins and its derivatives are produced by *Protoceratium reticulatum*, *Lingulodinium polyedrum*, and *Gonyaulax spinifera*. Even though these group have been grouped as DSP group, there is no inhibition of protein phosphatases and do not cause diarrhea (Paz et al., 2008). Their symptoms in humans are still unknown (Visciano et al., 2013).

Pectenotoxins have been associated with diarrhea and other symptoms similar to those caused by okadaic acid group. The main toxin in this group is PTX2 (Poletti et al., 2003). These toxins are capable of disrupting actin present in the cytoskeleton, thereby causing arrest of cell cycle and cell death (Espina & Rubiolo, 2008).

The azaspiracids have a unique spiral ring, which contains a heterocyclic amine and an aliphatic carboxylic acid moiety. They are also nitrogen-containing polyether toxins. The most important ones based on occurrence and toxicity include AZA1, AZA2, and AZA3 (EFSA, 2008b).

Some DSP outbreak have been implicated, such as DSP outbreak in Washington after consumption of contaminated mussels (Trainer et al., 2013), an annual contamination of Portuguese shellfish with DSP toxins (Vale, 2012), and high levels of DSP toxins in shellfish harvested along the Chinese coast (Li et al., 2012),

DSP outbreak in British Columbia after consumption of contaminated Pacific coast mussels (Taylor et al., 2013), regular DSP toxins implicated in shellfish from South European coastal areas (Braga et al., 2016), and DSP outbreak in France (Hossen et al., 2011) and in Northern Italy (Bacchiocchi et al., 2015).

4.2.5 Ciguatera shellfish poisoning

This poisoning is caused by ciguatoxins groups produced by benthic dinoflagellates *Gambierdiscus*, *Prorocentrum*, and *Ostreopsis* species. The toxins move through the food chain from consumption of the toxic dinoflagellates living on the coral reefs by small herbivorous fishes grazing on coral, which is eventually consumed by other bigger carnivores, followed by the consumption of these carnivores by larger predators such as mackerels, coral trout, and moray eels, causing ciguatera fish poisoning in persons that consume these fishes (Klopper et al., 2003). The symptoms produced by ciguatera shellfish poisoning include gastrointestinal, neurological, and cardiovascular symptoms. The gastrointestinal symptoms are characterized by nausea, vomiting, diarrhea, vomiting, and abdominal pain, which is followed by neurological dysfunction characterized by reversal of temperature sensation, muscular aches, dizziness, anxiety, sweating, and numbness and tingling of the mouth and digits, whereas the cardiovascular symptoms are notable with bradycardia and hypertension (Rafuse et al., 2004; Silva et al., 2015). The period of recovery varies from weeks to months to years. To relieve symptoms, initial treatment has been reported within 24 hours with the use of mannitol. No antidote is available but supportive therapy is offered, and survivors recover. There is presently no simple way of measuring ciguatoxin in any seafood product before the consumption of contaminated fishes; hence, absolute prevention of ciguatoxin intoxication depends on total restraints from consuming any tropical reef fish (Rafuse et al., 2004; Tillmann, 2004). The occurrence of ciguatoxin is largely restricted to some specific areas; recently, ciguatoxin fish poisoning has been reported near the Mediterranean Sea and the European coasts. About six outbreaks between 2010 and 2011 involving 28 persons in New York as well as one event in 2012, which recorded 20 cases in Northern Germany have been reported (Mattei et al., 2014).

4.2.6 Poisoning by cyclic imines toxins

The cyclic imine toxins include spirolides, gymnodimines, pinnatoxins, and pteriatoxins. The algal species from genera *Alexandrium* and *Karenia* produce the spirolides and gymnodimines toxins, while pinnatoxins are produced by *Vulcanodinium rugosum* (McCarthy et al., 2015). Recently, researches have shown that pteriatoxins are biotransformation products of pinnatoxins in shellfish (Selwood et al., 2010). There are no acute symptoms of the intoxication of cyclic imines toxins in humans, and spirolides and gymnodimines toxicity is yet being investigated in mammalian models (Marrouchi et al., 2013); however, rapid death is induced within minutes in laboratory mice inoculated intraperitoneally, but they are often co-extracted with lipophilic toxins such as okadaic acid and its analog resulting in false positive in MBA test (Salgado et al., 2015). Gymnodimines and spirolides were first isolated and characterized in the 1990s from New Zealand oysters and along the South Eastern coast of Nova Scotia, Canada, respectively. Pinnatoxins were originally identified in shellfish belonging to the genera Pinna in Japan, while Pteriatoxins were identified from shellfish to the genera Pinna (Rundberget et al., 2011). Only one outbreak associated with genus Pinna has been reported, and no acute poisoning has been linked to pinnatoxins contamination; however, pinnatoxins shows active toxicity when introduced into mice intraperitoneally (Hess et al., 2013).

4.2.7 Poisoning by palytoxin

The palytoxin have several of its analog identified. They are potent nonprotein compounds produced by marine coral of genus *Palythoa* and dinoflagellates of genus *Ostreopsis* (Bire et al., 2013). Several symptoms have been associated with consuming shellfish contaminated with palytoxin, and the symptoms include gastrointestinal malaise, a metallic taste, ataxias, nausea, vomiting, diarrhea, dyspnea, myalgia, dizziness, bradycardia and convulsion. In 2005, exposure of some persons to marine aerosols containing polytoxins resulted in respiratory and cutaneous problems in Italy, while similar symptoms were reported in France between 2006 and 2009 (Bire et al., 2013). However, some fatal cases of polytoxin intoxication have been observed (Aligizaki et al., 2011; Deeds & Schwartz, 2010).

4.2.8 Puffer fish poisoning

This form of poisoning is as a result of tetrodotoxin found in puffer fish, balloon fish, globe fish, fugu, toad fish, blow fish, goby, blue-ringed octopus, various gastropods, newts, and horseshoe crab. Tetrodotoxin is one of the most intoxicating nonproteinaceous toxins, which are accountable for several fish poisonings; it is potent with an LD50 of 2 mg for humans. It has been estimated that the minimum dose required to cause the symptom is 0.2 mg (Yoshikawa-Ebesu et al., 2001). The toxin is mainly distributed in the ovaries, liver, and skin of the fish, while the muscle tissues are normally free of the toxin. There has been much debate on the origin of the toxin whether it is endogenous or exogenous. It is now known that tetrodotoxin comes directly from the fish nutrition. The toxin is produced by bacteria absorbed on with plankton, transmitted to tetrodotoxin-bearing animals such as flatworms, starfish tiny gastropods, which are then transmitted to fishes and large gastropods. Some fishes such as puffers and tropical goby do not accumulate tetrodotoxins even when the fishes consume toxin-containing diets at sublethal doses, rather they process tetrodotoxins (Yoshikawa-Ebesu et al., 2001). The symptoms of puffer fish poisoning within minutes of consuming toxic fishes. Vomiting and nausea may or may not occur. The most common symptoms include dizziness and tingling sensation; the disease may advance to respiratory and muscle paralysis. In case of death, it occurs with 6 hours and sometimes as fast as 20 minutes after toxin ingestion. Persons that do not die within 24 hours of onset of symptoms recover completely (Yoshikawa-Ebesu et al., 2001).

4.2.9 Azaspiracid shellfish poisoning

This poisoning is as a result of azaspiracid shellfish toxins. Azaspiracid shellfish poisoning was perceived to be produced by *Protoperidinium crassipes* (James et al., 2004); however, there was no clear correlation between the high algal count and the toxin levels (Krock et al., 2009). It has been discovered that azaspiracid shellfish poisoning is caused by small dinoflagellates of about 12–16 μm known as *Azadinium spinosum*. Even though there are several azaspiracids that have been described, the most predominant ones are azaspiracid-1, 2, and 3 (Rehmann et al., 2008). The toxic effects of azaspiracid intoxication such as abdominal pain, gastrointestinal disorders, and diarrhea can be explained using the result obtained from the in the in vitro experiments in mammalian cell lines, which revealed alterations in the cytoskeletal structure, which causes cell–cell interaction (Ronzitti et al., 2007; Twiner et al., 2005). Azaspiracid was first reported in the Netherlands where eight persons got sick as result of consuming mussels brought from Ireland, after which several other outbreaks have been noted in other countries such as Norway, France, Ireland, Northern Africa, and Portugal (Alvarez et al., 2010; Elgarch et al., 2008; James et al., 2004; Vale et al., 2008).

4.3 Marine biotoxins based on chemical structure

Marine toxins refer to harmful substances generated by a variety of marine microorganisms, particularly dinoflagellates, cyanobacteria, diatoms, and bacteria. These microorganisms have the capacity for rapid growth, leading to the formation of what is commonly designated as “harmful algal blooms” (HAB), which results in the extensive production of toxins. Consequently, the marine ecosystem suffers adverse effects (Flores-Holguín et al., 2023).

Marine biotoxins are classified into eight distinct groups, each characterized by its distinct chemical structure. This classification system, which is widely accepted within the scientific community, encompasses the following groups: azaspiracid (AZA), cyclic imine (CI), brevetoxin (BTX), okadaic acid (OA), domoic acid (DA), saxitoxin (STX), pectenotoxin (PTX), and yessotoxin (YTX). Two additional groups are also considered: palytoxin (PTX) and ciguatoxin (CTX) (EFSA, 2009; FAO/WHO, 2016).

4.3.1 Domoic acid

This tricarboxylic amino acid is synthesized by diatoms belonging to the genus *Pseudo-nitzschia* (Marine biotoxins. FAO Food and Nutrition Paper 80. Food and Agriculture Organization of the United Nations, 2004). The chemical formula of the substance is $C_{15}H_{21}NO_6$, and its structure has been subjected to analysis using nuclear magnetic resonance and mass spectrometry, with the resulting data indicating the existence of multiple variants. The chemical structure of domoic acid is shown in Fig. 19.1.

4.3.2 Saxitoxins

These are alkaloid compounds, specifically guanidine derivatives, which are produced by certain types of dinoflagellates, namely *Alexandrium*, *Gymnodinium*, and *Pyrodinium* species, as well as certain cyanobacteria. These compounds are renowned for their inhibitory effects on sodium channels. The analysis of these compounds is conducted using advanced liquid chromatography techniques. Their chemical structure is distinctive, comprising a guanidinium-based component. The chemical formula is $C_{10}H_{17}N_7O_4$, and its chemical structure is shown in Fig. 19.2.

4.3.3 Tetrodotoxins

Tetrodotoxin (TTX)—a low-molecular-weight, crystalline, nonprotein organic compound exhibiting weakly basic properties and a colorless appearance—ranks as one of the most potent marine toxins that have been subjected to scientific investigation till date (Katikou et al., 2022). Tetrodotoxin is a selective inhibitor of the gating mechanism of selected sodium channels (referred to as "TTX-sensitive channels"), leading to impaired nerve conduction. It has been demonstrated that the synthesis of tetrodotoxin is carried out by specific bacterial species, including *Pseudoalteromonas tetraodonis* and *Vibrio alginolyticus*. A definitive chemical formula has been assigned, namely $C_{11}H_{17}N_3O_8$, and its chemical structure has been fully elucidated (Lin et al., 2024). Fig. 19.3 represents the chemical structure of tetrodotoxins.

4.3.4 Okadaic acid

It is a sizable polyether compound comprising numerous fused cyclic ether rings, which serve as protein phosphatase inhibitors. Its production is attributable to the activities of the dinoflagellate species *Dinophysis* and *Prorocentrum* (Visciano et al., 2016). The detection of OA is most often accomplished through the use of high-performance liquid chromatography-mass spectrometry (HPLC-MS). The chemical formula of the compound is $C_{44}H_{68}O_{13}$, and its chemical structure is shown in Fig. 19.4.

4.3.5 Brevetoxins

Polyester compounds of this nature are produced by dinoflagellate species such as *Karenia brevis*. BTX comprises ladder-like polyether structures distinguished by the presence of cyclic ether groups that collectively impart a considerable degree of rigidity to the polyether backbone. These structures are defined by the presence of multiple fused rings. They function

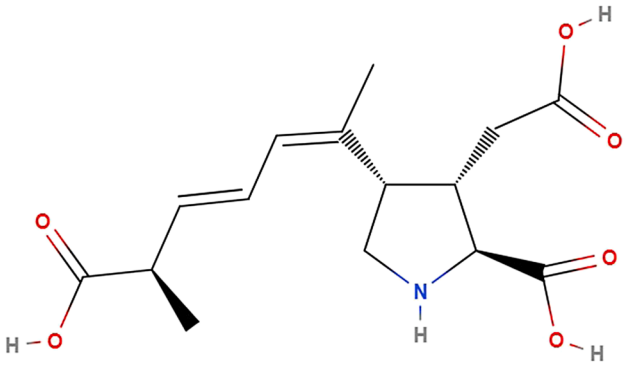


FIGURE 19.1 Chemical structure of domoic acid.

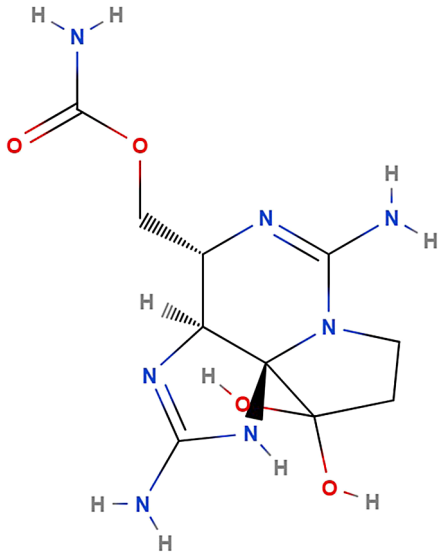


FIGURE 19.2 Chemical structure of saxitoxins.

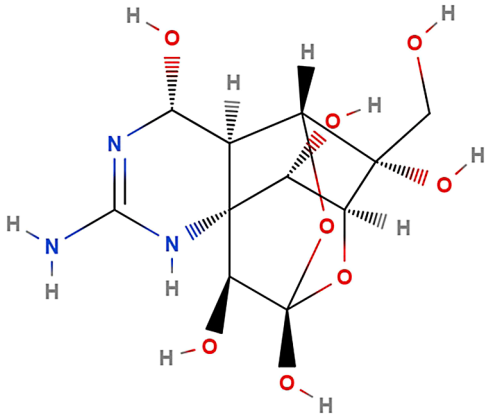


FIGURE 19.3 Chemical structure of tetrodotoxins.

by binding to voltage-gated sodium channels, thereby facilitating the influx of sodium ions into the cell. Mass spectrometry (MS) is a fundamental technique for the identification of BTX congeners. The mechanism of action of brevetoxins involves the activation of sodium channels, resulting in the depolarization of excitable neurons and unstrained muscle cells (Stonik & Stonik, 2010). Fig. 19.5 shows the chemical structure of brevetoxins.

4.3.6 Ciguatoxins

It is a sizable polyether toxin that comprises a fused cyclic ether ring, generated by dinoflagellates belonging to the genus *Gambierdiscus*. It is characterized by the chemical formula $C_{60}H_{84}O_{16}$ and exhibits a distinctive chemical structure. The chemical structure of CTX compounds is that of a complex fused-ring polyether. They exhibit structural similarities to brevetoxins but display differences in their length and configuration of polyether rings. Structural elucidation frequently employs nuclear magnetic resonance (NMR) and mass spectrometry (MS) to trace variants of CTX in disparate geographical areas. The use of advanced MS and NMR techniques has proved instrumental in the discovery of the structural diversity of these toxins. The structure of ciguatoxins is shown in Fig. 19.6.

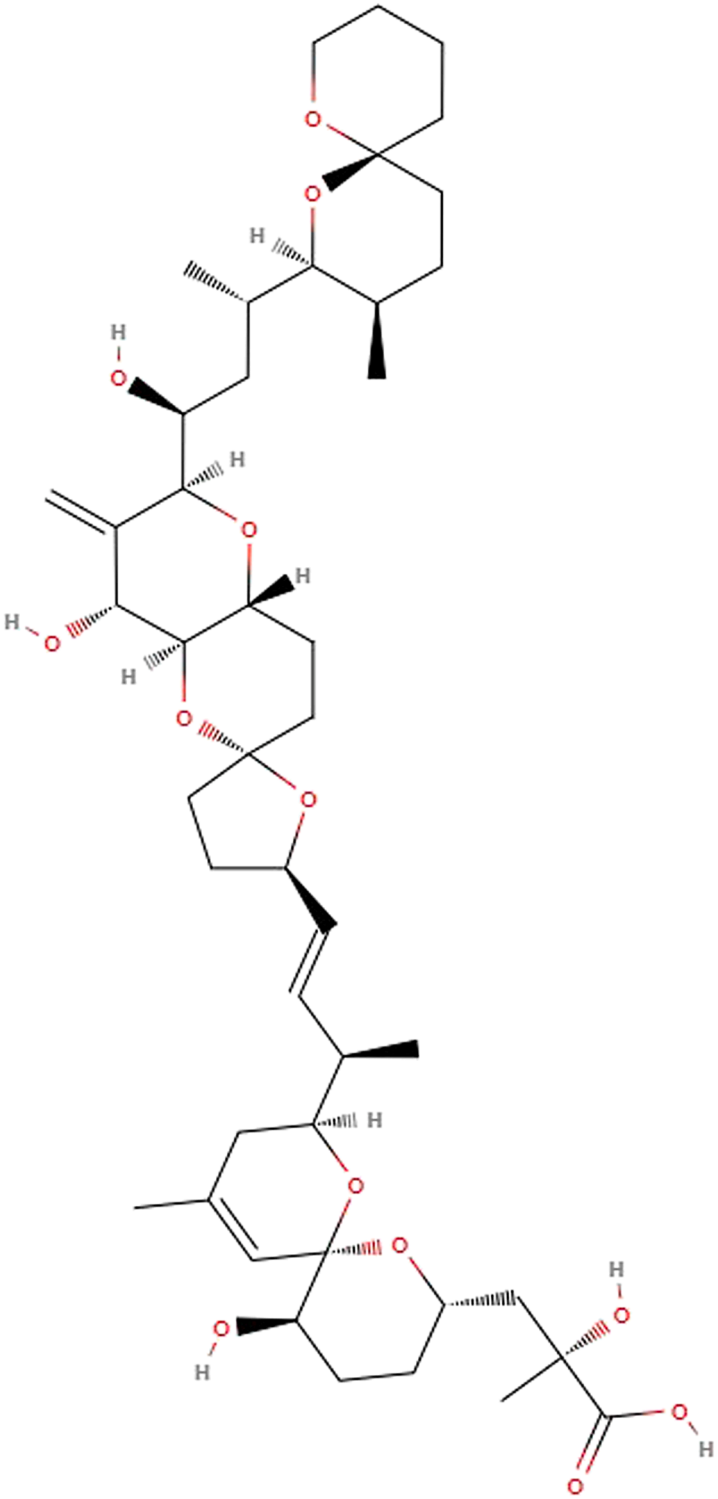


FIGURE 19.4 Chemical structure of okadaic acid.

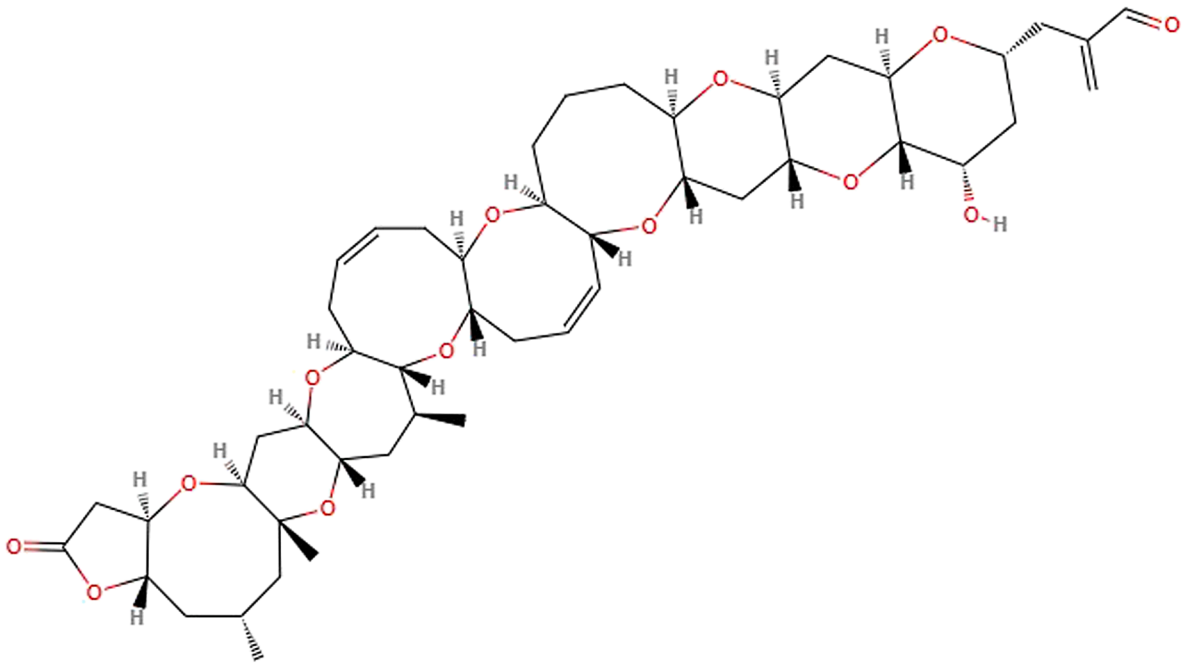


FIGURE 19.5 Chemical structure of brevetoxins.

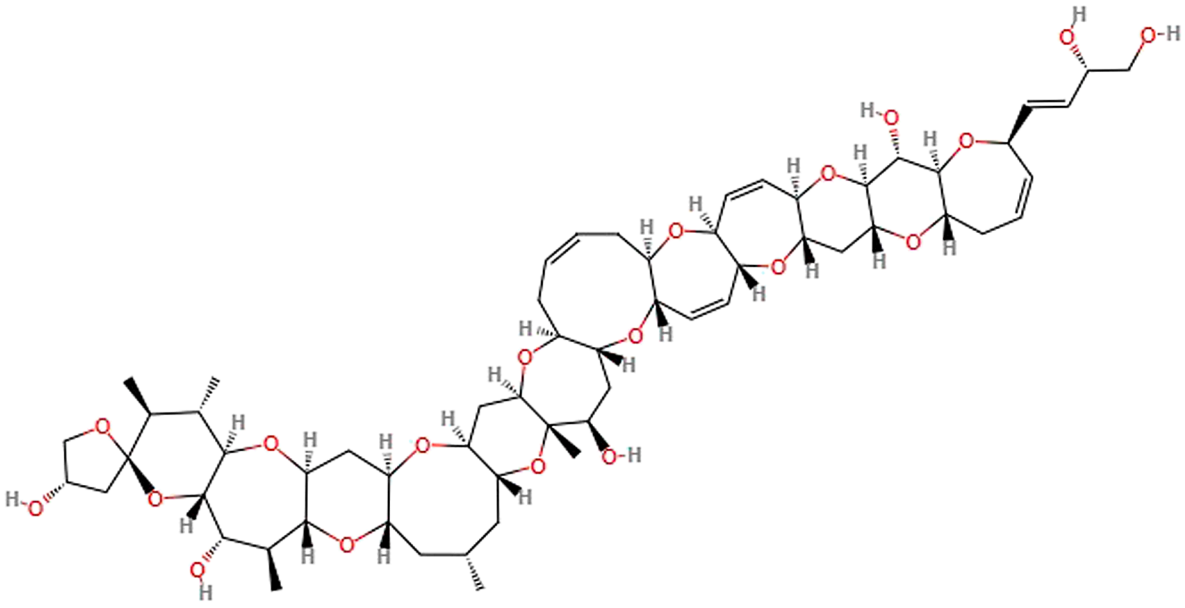
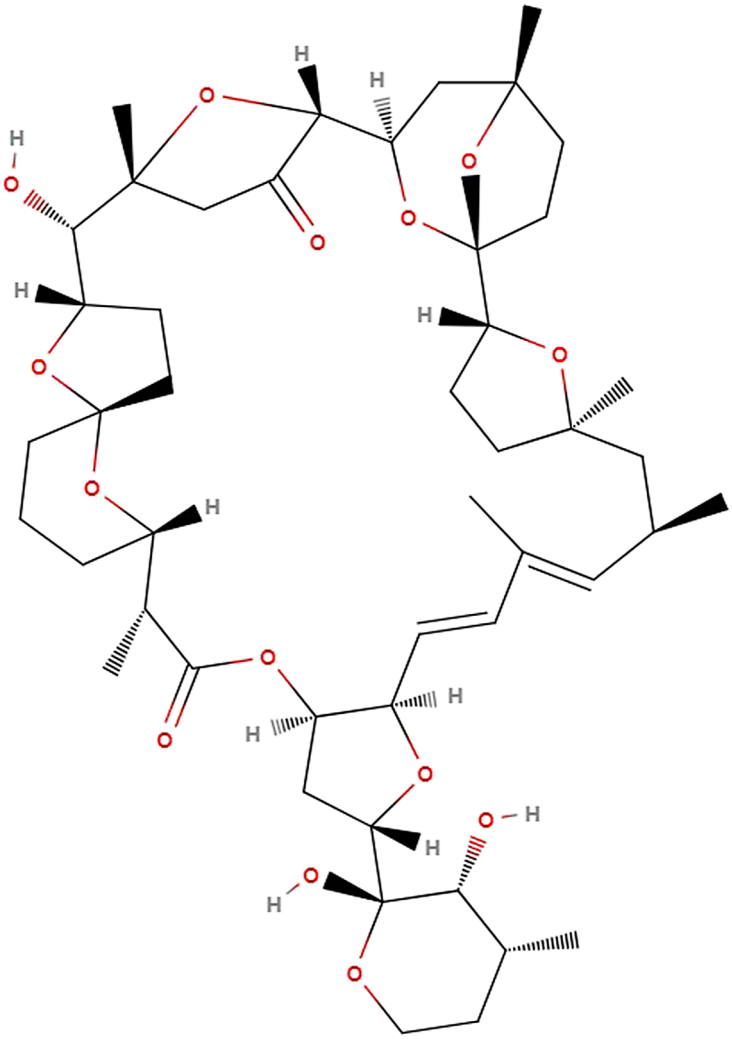


FIGURE 19.6 Chemical structure of ciguatoxins.

4.3.7 Pectenotoxins

These are polyether macrolides, a class of natural products produced by dinoflagellates such as the *Dinophysis* species. Macrocyclic lactones containing multiple ether rings constitute the PTX compounds. Toxin profiling can be conducted using MS-based detection methods. The chemical formula is $C_{47}H_{70}O_{14}$, and the chemical structure is shown as follows. Fig. 19.7 presents the chemical structure of pectenotoxins.

FIGURE 19.7 Chemical structure of pectenotoxins.



4.3.8 Yessotoxins

The YTX compounds represent a class of large polyether toxins that possess a complex structural configuration, comprising multiple ether rings and a spirochetal group. They are produced from dinoflagellates, including *Protoceratium reticulatum* and *Lingulodinium polyera* (Stonik & Stonik, 2010). The structural characteristics of YTXs are determined by mass spectrometry. The structure of yessotoxins is shown in Fig. 19.8.

4.3.9 Azaspiracid

These are polyether compounds that are produced by the dinoflagellate *Azadinium spinosum*. These compounds possess a distinctive cyclic imine structure comprising multiple ether rings, among which is one spiro cycle incorporating a nitrogen atom (Stonik & Stonik, 2010). Their toxicity is attributed to complex polyether structures that are highly intricate and contribute to the overall toxicity profile. The chemical structure of azaspiracid is shown in Fig. 19.9.

4.3.10 Palytoxins

Palytoxins (PLTXs) are highly potent nonprotein marine compounds, which are produced by corals of the genus *Palythoa* and dinoflagellates of the genus *Ostreopsis*. These are polycyclic polyether. These biotoxins possess amphipathic

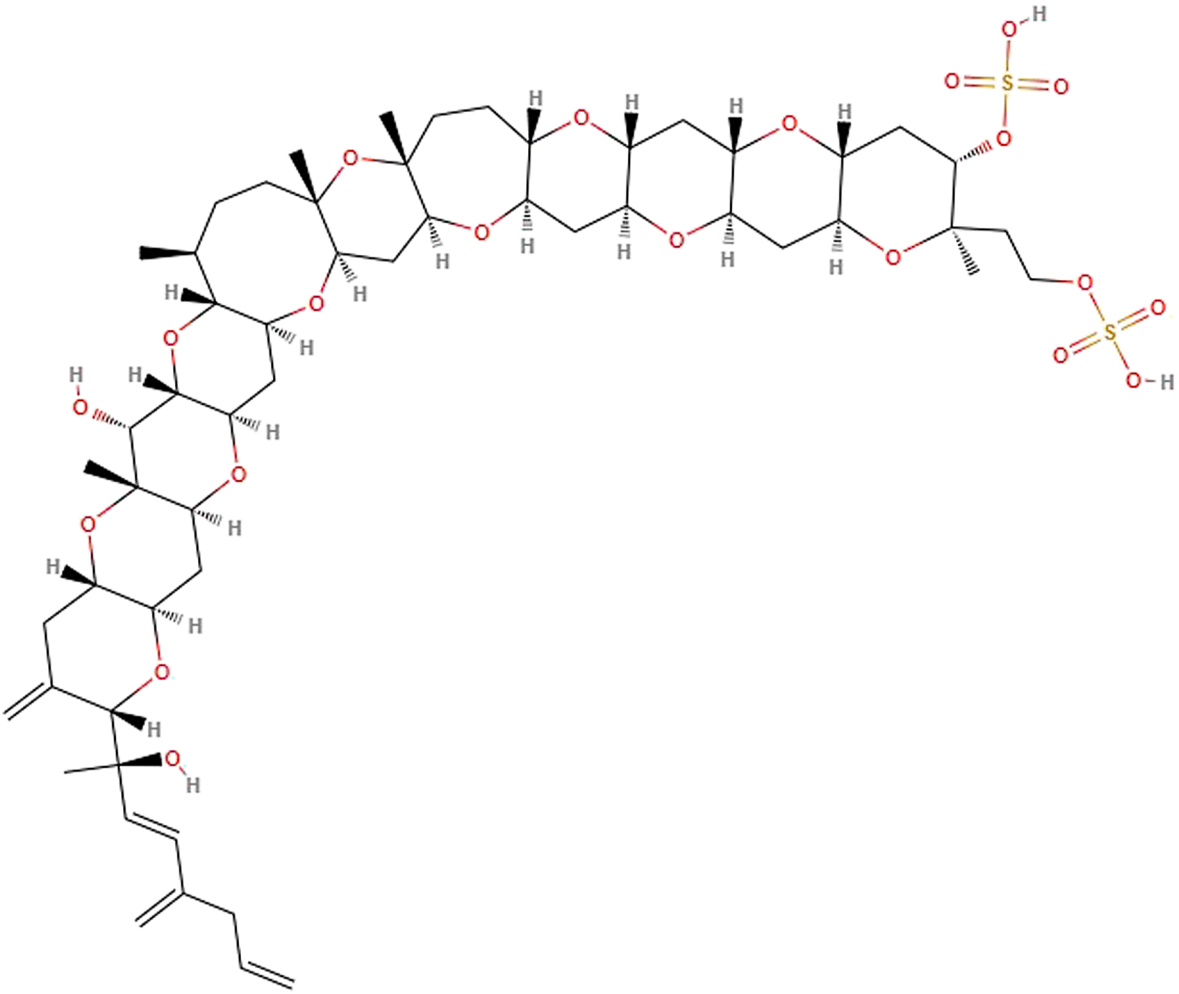


FIGURE 19.8 Chemical structure of yessotoxins.

properties, exhibiting both hydrophilic and lipophilic traits due to their complex polyhydroxylated composition (Alves et al., 2019; Daguer et al., 2018; Louzao et al., 2022) with the following structure (Stonik & Stonik, 2010). Fig. 19.10 represents the structure of palytoxins.

4.3.11 Cyclic imines

They are cyclic alkaloids. The precise mechanisms of action remain under investigation, with a hypothesis that they may possess neurotoxic properties (Visciano et al., 2016). The group encompasses spirolides (abbreviated "SPX"), gymnodimines (abbreviated "GYM"), pinnatoxins (abbreviated "PnTX"), and pteriatoxins (abbreviated "PtTX"). It should be noted that both SPX and GYM are produced by algal species belonging to the genera *Alexandrium* and *Karenia*, whereas the producer of PnTX is identified as *Vulcanodinium rugosum* (McCarthy et al., 2015). The chemical structures of CI indicate that they are macrocyclic compounds with imine and spiro-linked ether moieties (Scientific Opinion on marine biotoxins in shellfish - Emerging toxins: Brevetoxin group, 2010). It is thought that these moieties, which are common to all members of CI, are the primary structural determinants of their toxicity (Visciano et al., 2016).

5. Applications of different marine biotoxins

5.1 Applications of different marine biotoxins in analgesic

The complex chemical structures of marine biotoxins can interact with receptors in the nervous system, making them a promising avenue for developing novel therapeutic strategies for pain management. The following section provides a

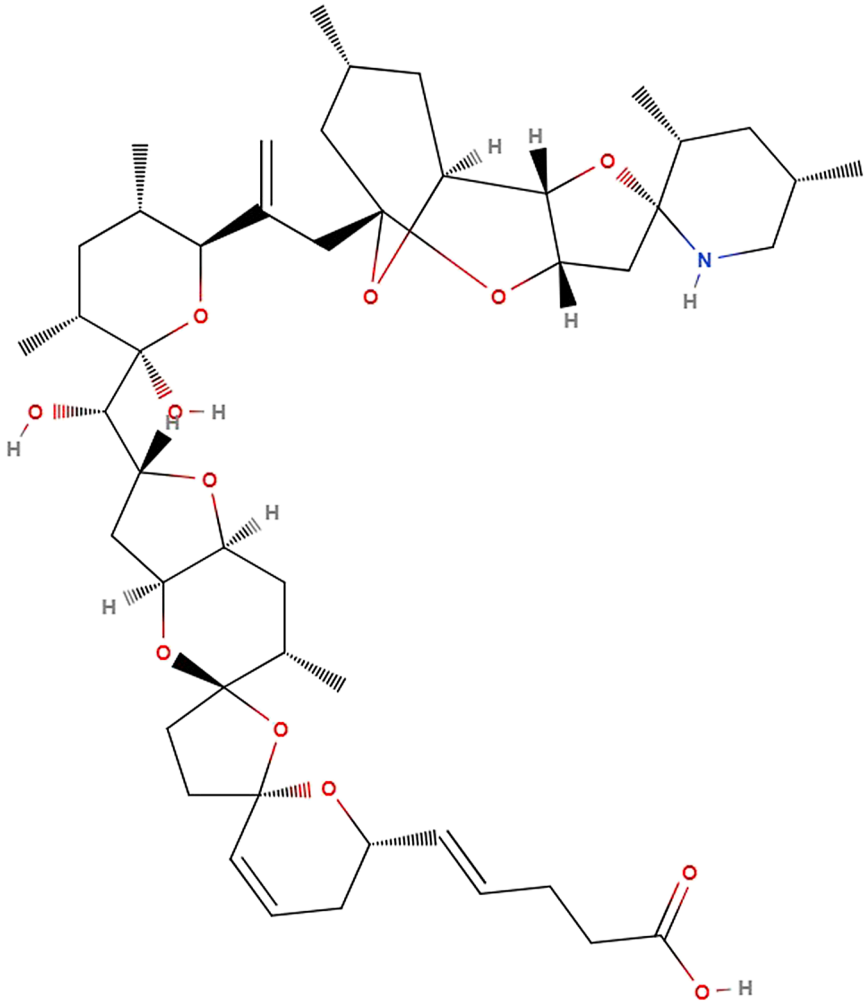


FIGURE 19.9 Chemical structure of azaspiracid.

thorough examination of the ways in which marine biotoxins are employed in the development of pain management therapies (Assunção et al., 2017).

5.1.1 Targeting ion channels for pain management

It has been demonstrated that marine biotoxins, in particular neurotoxins, have evolved to target ion channels in the nervous system. These channels are of vital importance for the transmission of pain signals. A variety of ion channels, including those responsible for sodium (Na^{+}), calcium ($Ca^{2+),}$ potassium (K^{+}), and transient receptor potential (TRP) transmissions, play a role in the experience of pain. The selective inhibition or modulation of these channels enables marine biotoxins to disrupt pain signals at their point of origin (Flores-Holguín et al., 2024).

5.1.1.1 Sodium channel blockers

5.1.1.1.1 Saxitoxin (STX) and its derivatives The primary mechanism of action is the blockade of voltage-gated sodium channels, which are vital for the generation of action potentials in neurons and muscle cells. This property identifies STX as a potential candidate for anesthetic applications, which may result in a reduction of pain sensation and muscle spasms (Flores-Holguín et al., 2024; Assunção et al., 2017). A number of studies have recently been conducted, which have explored a variety of derivatives of STX. In particular, they have assessed the pharmacokinetic properties of these substances as well as their potential as therapeutic agents. The use of these derivatives in combination with other drugs has

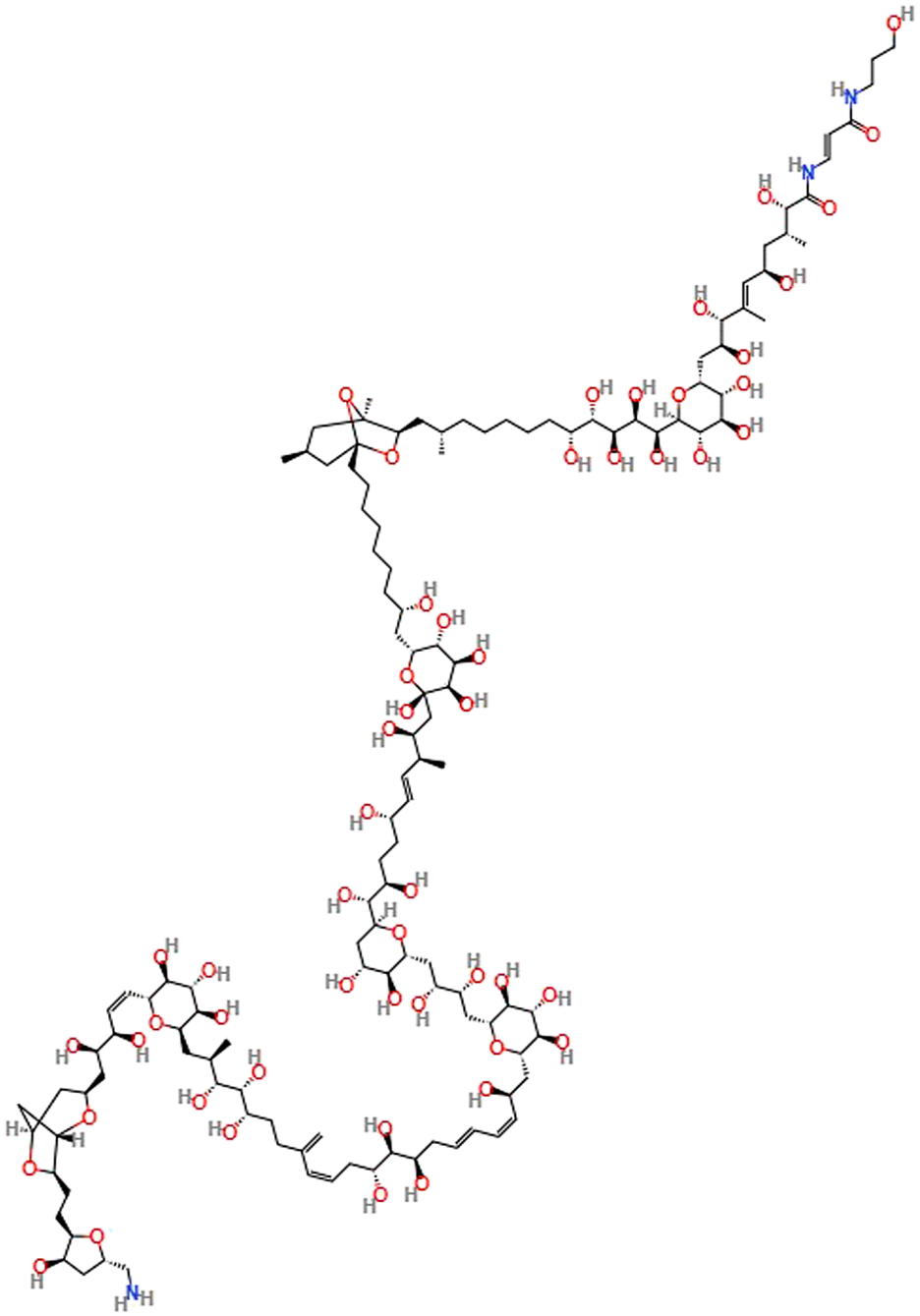


FIGURE 19.10 Chemical structure of palytoxins.

demonstrated the potential for providing prolonged anesthetic effects, particularly within formulations designed for local nerve blocks (Flores-Holguín et al., 2024; Assunção et al., 2017).

Tetrodotoxin (TTX) and its derivatives: Additionally, sodium channels are inhibited, and it is currently undergoing clinical trials to ascertain its efficacy in the management of both cancer- and chemotherapy-related pain. TTX inhibits the propagation of action potentials in neurons, thereby conferring upon it the property of potent analgesia. Investigations are underway to ascertain the efficacy of TTX as a treatment for chronic pain conditions, including neuropathic pain, cancer pain, and postoperative pain. Formulations such as Tocudin are currently being investigated for their efficacy as local anesthetics, thereby demonstrating the versatility of TTX as a pain management agent (Assunção et al., 2017).

5.1.1.2 Potassium channel modulators

A number of marine biotoxins, including those derived from cone snails, have been observed to modulate potassium channels. These toxins have been demonstrated to either block or activate these channels, which consequently affects neuronal excitability. The perception of pain may be reduced by means of a decrease in neuronal excitability. Toxins such as δ-conotoxin, which are found in the venom of cone snails, have demonstrated efficacy in modulating potassium channels for the purpose of controlling pain (Duque et al., 2019).

5.1.1.3 Calcium chanel blockers

Omega-conotoxins derived from cone snails exhibit selective affinity for N-type calcium channels, which play a pivotal role in neurotransmitter release and the functioning of pain pathways. By blocking these channels, omega-conotoxins impede the release of pain-transmitting neurotransmitters, effectively reducing pain perception (Ohashi et al., 2024).

5.1.2 Peptide toxins as potential opioid alternatives

In light of the persisting opioid crisis, there is a growing need for nonopioid analgesics, and marine biotoxins present a promising avenue for exploration as potential alternatives. Peptide toxins derived from marine organisms, particularly—cone snails and sea anemones, have been identified as a promising alternative to opioid pain management due to their efficacy in relieving pain without the risk of addiction (Cheung et al., 2015).

5.1.2.1 Conotoxins

Cone snails are capable of producing conotoxins, which are small peptides that target a range of ion channels and receptors involved in the process of pain signaling. Conotoxins exhibit high selectivity for targeting distinct ion channels, including the N-type calcium channels (ω-conotoxin) and the sodium channels (μ-conotoxin), thereby imparting a localized and pronounced analgesic impact. Ziconotide is derived from the cone snail *Conus magus*, which represents a notable example in the management of severe chronic pain in patients who have not responded favorably to alternative therapeutic modalities (McGivern, 2007).

5.1.2.2 Sea anemone toxins

For example, the species of *Anthopleura*. These are peptide toxins that serve to modulate voltage-gated Na and K channels. These peptides have the potential to inhibit pain pathways by reducing neuronal excitability, thereby acting as a promising analgesic alternative with no adverse effects common with opioid use (Madio et al., 2019).

5.1.3 Peripheral versus central pain modulation

Marine biotoxins can be employed to target pain in either a peripheral or central manner. Peripheral targeting occurs at the site of injury or nociceptive input, whereas central targeting occurs within the spinal cord or brain. The versatility of this approach offers a substantial advantage in the development of pain therapies tailored to specific conditions (Nieto et al., 2012).

5.1.3.1 Peripheral pain inhibition

The action of certain marine biotoxins is to block ion channels in peripheral nerves, thereby preventing pain signals to the spinal cord transmission. For instance, tetrodotoxin's inhibition of sodium channels in peripheral nerves impedes the propagation of pain signals, thereby providing pain relief in a localized region. This approach proves beneficial in the context of postsurgical pain management, whereby the objective is to provide localized, short-term analgesia without any systemic consequences (Nieto et al., 2012).

5.1.3.2 Central pain inhibition

Other biotoxins, such as ziconotide, act centrally by inhibiting N-type calcium channels within the spinal cord, thereby impeding the release of neurotransmitters that convey pain signals to the brain. The administration of central inhibition has been shown to be an effective treatment for chronic pain conditions, such as those observed in cancer patients, wherein systemic pain relief is a necessity (Nieto et al., 2012).

5.2 Applications of different marine biotoxins in antitumor

Marine biotoxins, which are produced by a range of marine organisms, have received considerable attention in relation to their potential applications in antitumor therapy. These compounds, which often possess distinctive chemical structures and biological functions, have shown encouraging efficacy in the targeted treatment of cancer cells (Kang et al., 2018). The following section will examine some of the most significant marine biotoxins and their prospective antitumor applications.

5.2.1 Marine-derived peptides

These marine peptides have demonstrated considerable potential as anticancer agents, operating via a number of different mechanisms.

5.2.1.1 Induction of apoptosis

A significant number of marine peptides have the capacity to induce programmed cell death in cancerous cells, representing a crucial mechanism for the elimination of malignant cells (Kang et al., 2018).

5.2.1.2 Disruption of microtubule dynamics

It has been demonstrated that certain peptides exert an effect on the balance of tubulin-microtubules, which is of vital importance with regard to the division of cells. This results in the inhibition of tumor growth (Kang et al., 2018).

5.2.1.3 Inhibition of angiogenesis

It has been observed that some marine peptides inhibit the formation of new blood vessels that tumors require for growth, thereby limiting their expansion and metastasis (Kang et al., 2018).

5.2.2 The mechanism of alkaloids is as follows

5.2.2.1 Cytotoxic effects

Cytotoxicity in cancerous cells is induced by alkaloids such as ecteinascidins and trabectedins, which disrupt cellular processes (Yu et al., 2024).

5.2.2.2 Cell cycle arrest

These compounds are capable of halting the cell cycle, thus impeding the proliferation of cancer cells (Yu et al., 2024).

5.2.2.3 Inhibition of metastasis

It has been demonstrated that some marine alkaloids have the capacity to impede the pathways that lead to the metastasis of cancerous cells. This property renders them an efficacious treatment for aggressive forms of cancer, such as those affecting the breast and pancreas (Yu et al., 2024).

5.2.3 Bioactive compounds derived from marine algae

These are rich sources of bioactive compounds that have antitumor properties. These algal compounds have the potential to facilitate apoptosis, impede angiogenesis, and destabilize migration and invasion pathways in malignant cells (Alves et al., 2018).

5.2.4 Secondary metabolites derived from marine organisms

They exhibit a wide variety of biological activities, which contribute to their antitumor effects. The distinctive chemical variability observed in marine natural products (MNPs) paves the way for the creation of innovative therapeutic agents that can transcend constraints associated with conventional therapeutic modalities (Ruiz-Torres et al., 2017).

The investigation of marine biotoxins with a view to their potential use in antitumor treatments represents a promising area of research in the field of cancer therapy. The distinctive mechanisms of action and low toxicity profiles of marine-

derived compounds present novel strategies for combating various forms of cancer. Ongoing scientific investigation into these naturally occurring products may result in the creation of new therapeutic agents that improve treatment efficacy while reducing any adverse effects commonly associated with conventional chemotherapy (Ruiz-Torres et al., 2017).

5.3 Applications in immunosuppressive treatment

The dinoflagellate *Gambierdiscus toxicus* produces a toxin called gambierol, which exhibits a molecular structure related to ciguatoxins and brevetoxins, and possesses high neurotoxicity (Fuwa et al., 2015). In vitro and in vivo studies on this toxin have led to the proposal of new immunotherapy treatments (Rubiolo et al., 2015; Yon et al., 2024; Alonso and Rubiolo, 2015). Gambierol has drawn interest due to its possible application as an immunosuppressant in diseases such multiple sclerosis, rheumatoid arthritis, and type 1 diabetes that include immune system malfunction (Zhao et al., 2015). It is a possible therapeutic target for T cell-mediated autoimmune disorders since it stimulates T cell proliferation, immunological induction, and cytokine production (Zhao et al., 2015). Gambierol does not predominantly target VGSCs, in contrast to other marine polycyclic toxins like ciguatoxins. Instead, it strongly modulates voltage-gated K+ channels (Kv) (Cuypers et al., 2008; Ghiaroni et al., 2005). Its selective binding to Kv3.1 channels, which it blocks, allows it to function as an intermembrane anchor. Kv3.1 channels are essential for the regulation of Ca^{2+} signaling, which triggers the production of cytokines, T cell proliferation, and immunological activation. As a result, these channels are considered potential therapeutic targets for T cell-mediated autoimmune disorders (Zhao et al., 2015). Due to its unique ability to inhibit Kv3.1 channels, gambierol is an intriguing candidate for use as an immunosuppressor in illnesses related to immune system malfunction (Beeton et al., 2006).

Nine analogs of Brevetoxin (BTX), which is produced from the dinoflagellate *Karenia brevis*, are categorized according to their backbone structure (Plakas & Dickey, 2010). According to studies, this toxin changes the immune response in alveolar macrophage cells by lowering phagocytosis activity and raising cytokines (TNF- and IL-2) implicated in immune cell activation (Hilderbrand et al., 2011). Other research has indicated that BTX exposure compromise's immunological function, resulting in decreased phagocytosis activity, plaque formation, and/or lymphocyte proliferation (Walsh et al., 2008). Brevetoxin also induces persistent immunosuppression, which may be mediated by its interaction with cysteine cathepsins, found in immune cells and involved in antigen presentation (Van Dolah et al., 2001).

Domoic acid (DA) has not been shown to directly attach to immune cells; however, as a glutamate analog, it is possible that it binds to immune cell glutamate receptor(s) to mediate immunological functions. Mice treated with DA exhibited a decrease of approximately 21% in neutrophil phagocytosis after 24 hours of exposure (Levin et al., 2008). Similarly, monocyte phagocytosis and T-cell proliferation measured 48 hours after exposure were significantly lower in DA-exposed mice than in control mice. In vivo and in vitro exposure to DA affected both innate and adaptive immune cell activities, with effects that appeared to be cell type- and time-specific (Levin et al., 2008). Another study examined the expression of immune-related genes such as HSP90 mRNA and FREP after exposure to DA. FREP mRNA levels decreased significantly in the 50 ng/mL DA-treated group after 48 hours of exposure, while HSP90 mRNA expression levels gradually decreased with increasing exposure time, leading to a significant reduction in comparison to the control group at 48 hours (Chi et al., 2019).

The polyketide-derived polycyclic water-soluble compound known as maitotoxin (MTX) has long been acknowledged as a possible tool for chemical and biological study (Nicolaou & Aversa, 2011). Since MTX has a major impact on inflammation and innate immune responses in mice, it is a useful tool for researching particular aspects of the innate immune response and/or the physiology of inflammatory effector cells (Verhoef et al., 2004).

Other toxins, such as okadaic acid, appear to have the potential for immunomodulatory effects by reducing T cell receptor expression, altering T cell function in immune responsiveness and thereby affecting the immunological response (López et al., 2011). Furthermore, yessotoxins appear to impact immunological function by increasing cytokine expression in J774 phagocyte mammalian cells and lowering phagocytic activity in the J774 cell line (Olesen et al., 2021; Orsi et al., 2010). Additionally, they appear to regulate the immune response of T-lymphocyte EL-4 cells by reversible T cell receptor complex downregulation (López et al., 2011).

5.4 Applications in cytotoxicity

Marine biotoxins, such as okadaic acid (OA), pectenotoxin (PTX), and yessotoxin (YTX), have been documented to induce cytotoxicity. Among these, OA and its equivalents, dinophysistoxins (DTXs), have been extensively studied for their cytotoxic properties. OA and DTXs are specific inhibitors of threonine/serine protein phosphatases (PP1 and PP2A) (Leonie et al., 2024). These enzymes play crucial roles in various cellular processes, including, gene expression,

metabolism, cell proliferation, ion control, neurotransmission, and cell cycle progression (Wera & Hemmings, 1995). Dysregulation of these enzymes can lead to pathway malfunctions. Furthermore, research has shown that OA and its analogs exhibit diverse biological actions, including cytotoxic and genotoxic effects on human cells (Ferron et al., 2016). OA has been found to exert cytotoxic effects on a range of cell types, such as intestinal cells, blood cells, hepatic, and brain cells, mainly through apoptosis and cell growth suppression. It also poses hazards to the immune system and the nervous system (Qiu et al., 2023; Valdiglesias et al., 2013). Okadaic acid is regarded as a strong neurotoxin and, because of its cytotoxic and tumor-promoting qualities, is used as a model to investigate the therapeutic effects of conventional antipsychotic drugs in treating cognitive impairment and neuropathological alterations in schizophrenia and other neurodegenerative diseases (Valdiglesias et al., 2013). The cytotoxicity of OA, PLTX, PTX, and AZA group toxins was assessed using Caco-2 cells, revealing varying degrees of cytotoxicity and genotoxicity. Toxins from different classes had significantly different cytotoxic effects on Caco-2 cells, with PLTXs being the most toxic. The impact of cytotoxicity varied depending on the cell type and concentrations used. Moreover, different compounds of the same set of toxins caused differential toxicity in Caco-2 cells (Qiu et al., 2023). OA has been demonstrated to reduce leukocyte viability to 90% at 1000 nm. Another study used two distinct cell viability assays, NRU and WST-1, to evaluate the cytotoxic effects of OA in Caco-2 cells, obtaining similar results when differentiated Caco-2 cells were exposed to OA doses ranging from 50 to 1000 nm for 24 hours (Dietrich et al., 2019). Recently, the toxicity of binary phycotoxins (okadaic acid, azaspiracid-1, and yessotoxin) on human intestinal Caco-2 cells was investigated (Leonie et al., 2024), revealing increased cytotoxicity when these phycotoxins were combined, likely due to synergistic interactions between the toxins. Both in vivo and in vitro toxicological studies have demonstrated cytotoxicity against various human cell types and an ability to impact cell shape and cytoskeleton structure, particularly in the E-cadherin system (Pradhan & Ki, 2022; Vilariño, 2008).

Numerous cell types originating from different mammalian sources have been shown to be negatively impacted by azaspiracid (AZA). Flanagan et al. found that exposure to coarsely contaminated mussel extract caused cytotoxicity in bladder cancer cells and hepatoblastoma cells. AZA1 caused cytotoxicity in kidney, lung, neuronal, pituitary, and immunological cell cultures in a concentration- and time-dependent manner, according to Twiner et al. (2005). Neurons are susceptible to AZAs, leading to irreversible morphological alterations with brief exposure and cytotoxicity with prolonged treatment. Similarly, prolonged exposure times were necessary for full cytotoxicity in primary CGC cells (Vale et al., 2010). Immune-type cells have been shown to be the most vulnerable to the cytotoxic actions of AZA-1, consistent with in vivo pathological results (Giuliani et al., 2019).

Another group of marine toxins that are well-known for their cytotoxicity are yessotoxins (YTXs). *Gonyaulax spinifera*, *Lingulodinium polyedra*, and *Protoceratium reticulatum* produce YTXs, which are sulfated polyethers, a class of marine toxin. Because of this property, these toxins are among the most polar of all the lipophilic toxins (Paz et al., 2008). Yessotoxins in the supernatant of the growing dinoflagellate *Protoceratium cf. reticulatum* have been shown to exhibit significant cytotoxicity (Paz et al., 2008). Protoceratins I, II, III, and IV are four glycoside polyether that are equally active and present in the extract; and according to Korsnes et al., these substances have demonstrated selective cytotoxicity against human cancer cell lines, with IC50 values typically less than 0.0005 M. PTX-2 has been demonstrated to be cytotoxic in the human metabolically competent hepatoma cell line HepaRG, leading to apoptosis and DNA damage (Ferron et al., 2016). In the same study, CYP3A4 suppression by ketoconazole was also observed.

5.5 Applications in anticholesterol

The presence of cholesterol plays a crucial role in the structure of biological membranes. Upon T cell activation, there is a rapid increase in cholesterol production, facilitating T cell expansion and proliferation. Studies have shown that azaspiracid (AZA), a lipophilic marine biotoxin, regulates T lymphocyte cells and reduces cholesterol formation. Specifically, research by Twiner et al. (2008) revealed that AZA inhibits cholesterol production in human T lymphocyte cells. Furthermore, AZA-1-induced gene expression in Jurkat T cells demonstrated that AZA toxicity alters the transcription of over 400 genes, including upregulation of genes related to cholesterol and fatty acid biosynthesis routes. After exposure to AZA, cellular cholesterol levels decreased by approximately 50% compared to the control group (Twiner et al., 2008). Notably, low-density lipoprotein receptor (LDLR) gene expression and protein levels were upregulated in response to AZA1's reduced intracellular cholesterol levels.

Karlotoxin (KmTx), a linear polyketide toxin produced exclusively by the *Karlodinium* genus (*K. veneficum*), has been found to have various biological effects, including hemolytic, cytotoxic, ichthyotoxic, and antifungal activities. Research by Adolf et al. (2015) suggested that the biological activity of KmTx is influenced by the sterol content of the target cell. Additionally, KmTx's capacity to induce pore formation in cholesterol-containing cell membranes suggests potential applications in treating human health conditions, such as coronary heart disease. Moreover, KmTx's ability to induce cell

death through cholesterol depletion indicates its potential as a novel chemotherapeutic agent for various solid tumor lines, including prostate and breast cancer cells. Waters et al. (2010, 2015) also highlighted the potential of KmTx in treating coronary heart disease and cancer.

5.6 Applications in neurological disease therapeutics

Whenever toxin is mentioned, danger comes to mind because primarily, toxins are known for their toxicity, which means to be poisonous. Biological toxins are produced by organisms cutting across kingdoms; monera, fungi, protozoa, plantae, and animalia in bacteria, molds, algae, castor, and snakes, respectively, as representatives (Suresh & Kumar, 2014). Marine toxins are however produced significantly by diatoms, dinoflagellates, and cyanobacteria, which are all forms of algae. Biotoxins are often produced as secondary metabolites and seems to play a biological function of protecting the producer to be competitive in their habitat (Hansen et al., 2021). When nutrient increases in the marine environment, there is usually an algal bloom with consequent increase in algal biotoxin production and these toxins are transmitted to other marine lives by food chain at various trophic levels (Gao et al., 2024).

Although marine biotoxins, for example, domoic acid, saxitoxin, tetrodotoxin, etc., are highly potent and therefore have very serious health implications upon intoxication (Ettoubi et al., 2020), they have been discovered to possess pharmacological and biotechnological potentials. For example, saxitoxin is applicable in the mitigation of general body pains, tetrodotoxin applicable in the relief of neuropathic pains, and neosaxitoxin produces prolong anesthesia. Others include gambierol, which is useful for prevention as well treatment of neurodegenerative diseases, and yessotoxin, applicable for treatment of allergies and asthma (Assunção et al., 2017).

Tetrodotoxin is one marine biotoxin, which has significantly been studied and found to possess analgesic effect for neuropathic pains by blocking the sodium ion pathway having bound to its voltage gate channel and research findings states that tetrotoxin has the potential of neuroprotection in mouse model levels Gao et al. (2024) and Groome (2023) found that conotoxins, a marine biotoxin peptide of cone snail (*Conus* species), were able to block voltage gate channel where tetrodotoxin failed, proving to have an excellent analgesic potential.

6. Challenges in the application of marine biotoxins

Research is vigorously ongoing on the possibility of using marine biotoxin as therapeutic agents. They have high biochemical complexity and therefore have the potential to bind to biomolecules and consequently modulating physiological processes (Flores-Holguinet al., 2024). This quality is a potential of the therapeutic agent and therefore may be useful precursors for drug development (Suresh & Kumar, 2014).

However, a number of limitations have been found to be associated with exploring this therapeutic potential of biotoxin. Firstly, their isolation, purification, and identification process are complex and highly technical requiring molecular processes and analytical chemistry. When this is combined with the fact that different algae require different analytical procedure, it then makes it cumbersome when trying to harness their positive potential of usefulness in biotechnology and pharmaceuticals. Secondly, their safety if used for therapeutic purpose is yet to be ascertained considering the fact that is primarily known for the negative (intoxication). Their toxicity and pharmacological potential require serious research, which presently is at the infant stage; therefore, their application for therapeutic purpose may still be afar off (Gao et al., 2024).

Lastly, a high level of collaboration is required covering biological sciences, analytical chemistry, material engineering, and chemical engineering, which are difficult to come by. There are therefore obvious challenges facing the application of biotoxin. However, this is not in any way meant to express impossibility (Gao et al., 2024).

7. Future prospects in application of marine biotoxins

There has been a hint on the feasibility of marine biotoxin being used as therapeutic agents from computational chemical characterization of 18 analogs of saxitoxin. This revealed that some of its analogs have drug characteristics from their pharmacokinetic values but failed in their bioavailability values (Flores-Holguinet al., 2024). This implies that even though there is a potential to resolve the disease condition, the biochemical molecule may never get to the site where it is required. There can therefore be an expression of delight on this novel discovery of saxitoxin derivatives having the potential of being used as drug precursor capable of resolving several autoimmune diseases since the limitation of bioavailability may be resolved in the advent of nanotechnology and biorobotic for drug delivery (Le & Shim, 2024).

There is a school of thought which says that if the therapeutic dose is lower than toxic dose, then they may be conveniently used for resolving targeted diseases successfully. Research in the field of marine biotoxin is considered to be a virgin area where novel findings can be made for biotechnological and pharmaceutical benefits.

8. Conclusion

Marine biotoxins, once primarily considered a threat due to their association with harmful algal blooms and seafood contamination, are now being recognized for their diverse potential applications. This chapter has explored the wide-ranging uses of marine biotoxins, including their roles in pharmaceutical development, bioassays, and environmental monitoring. By exploiting their effective bioactivity, researchers are creating new therapeutic agents, diagnostic tools, and even pest control approaches. However, the challenges related with their extraction, purification, and safe utilization remain significant. Continued research is important to unravel the full potential of these natural compounds while guaranteeing environmental sustainability and human safety. As our understanding of marine biotoxins deepens, their role as a valuable resource in biotechnology and medicine will likely expand, suggesting new ways for innovation across numerous scientific fields.

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Chapter 20

Neuroprotective properties of marine bioresources

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1. Introduction

More than 80% of all life on Earth is found in aquatic environments, which are home to a wide variety of species. More than 30,000 fish species that are connected to people and used as a supply of industrial raw materials and protein are included in this group. Interest has been shown in the use of marine bioresources as a source of secondary metabolites that are bioactive for studies on biomedicine, cosmetics, and medications (Cermeño et al., 2020). While marine life is gaining increasing attention, terrestrial species are still the primary source for the production of natural medicines at this time. More than 70% of the land mass of the earth is made up of oceans, which are a major source of natural resources due to the diversity of micro- and macroorganisms that can be found there in different maritime zones, some of which are a result of nutrition, light levels, ion, and even amounts, causing an increase in marine biodiversity. Seaweed, fish and shellfish, and marine microbes are examples of marine-derived organisms that can provide hundreds of unique active chemicals with physiological qualities that are involved in the protection against infections and diseases. Few, nevertheless, have been developed for widespread consumer usage.

For most biological processes, the brain is the body's principal control center as it is essential for several body processes (Akintoye et al., 2023; Asuku, Ayinla, Ajibare et al., 2024). Given that the brain is high in fatty acids, uses a lot of oxygen, and lacks endogenous antioxidants, the significance of oxidative stress in many neurodegenerative illnesses is not unexpected as due to them, reactive oxygen species (ROS) might affect it greatly (Asuku et al., 2022a; Ayinla et al., 2020). Therefore, maintaining brain function is crucial to guaranteeing appropriate operation in all domains of psychological wellness, physiological science, as well as daily life (Asuku, Ayinla, Ajibare et al., 2024). Seagrasses and algae are examples of marine plants that are abundant in neuroprotective compounds that promote brain function and lessen neuronal damage.

2. Neurodegenerative disorders

These forms of degeneration are commonly classified along with various illnesses that could harm the neural functioning of the human body. According to Asuku et al. (2022b), the most common neurodegenerative diseases are Huntington's disease (HD), Parkinson's disease (PD), amyotrophic lateral sclerosis (ALS), and Alzheimer's disease (AD). To keep proteins and organelles under quality control, move molecules back and forth swiftly, and move other components across the cell, neurons require a steady supply of high energy. Several processes like deficits, abnormal function, and dysregulation in calcium and axonal movement, coupled with the disconnection between glia and neurons, abnormal processing of RNA, oxidative process, neuroinflammation, as well as the destruction of DNA, might be responsible for degeneration

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of neurons. Those processes overwhelmed the defense mechanisms, and this causes lack of balance between life and death, which eventually gives rise to cell death through various pathways, causing an array of problems connected with the nervous system.

Those problems range from seizures, pain, muscles fragility, cognitive impairment, and irreversible paralysis to AD. Numerous brain disorders, including PD and AD, are major issues for the world's aging population (Liu & Hsu, 2020).

According to Asuku, Ayinla, Gbonjubola et al. (2024), AD is a particularly common neurodegenerative illness among older people. Brahmachari (2019) reported that almost 45 million people suffering from this disease or other related illnesses and 5 million people reporting new cases each year. This number is expected to increase significantly over the coming decades. The two main characteristics of AD are hyperphosphorylated tau proteins and amyloid plaques, which are abnormal accumulations of amyloid-β proteins. Anitha et al. (2019) state that these could lead to cases of loss or dysfunction in synaptic transmission, inflammatory reactions, dendritic collapse, the disintegration of neural function, and even affecting the microtubule, as well as the axons.

Another neurodegenerative illness to focus on is PD, being the second most pervasive among the list due to its characteristic breakdown of dopaminergic neurons in areas of the basal ganglia, causing a cytoplasmic inclusion and accumulation of Lewy bodies containing α-synuclein (Asuku, Ayinla, Olajide et al., 2024; Niethammer & Eidelberg, 2019; Sharma, 2020). As a multifaceted condition, PD manifests as both systemic and neurological symptoms. Bradykinesia, unilateral rest tremor, stiffness, and problems in gait, balance, and falls are some of these symptoms (Ajagun et al., 2024; Sharma, 2020). There is no known cure for this condition; existing therapies merely serve to reduce some of the psychological and physical symptoms. Globally, life expectancy is rising as a result of ongoing health advancements. Thus, new and effective ways to guarantee neuroprotection are essential because there is an increased chance of acquiring an age-related neurodegenerative illness (Huang et al., 2019). Marine bioresources have been reported to possess antioxidant, anti-inflammatory, and neuroprotective properties (Asuku, Ayinla, Ajibare et al., 2024); hence, there is need to explore their wide potentials in the protection against and treatment of neurodegenerative disorders.

3. Neuroprotection

By using pharmaceutical, genetic, biochemical, physiological, or behavioral interventions that may affect adaptive neuronal processes that counteract pathological alterations, neuroprotection aims to stop the advancement of neurodegeneration and brain dysfunction (Gozes & Levine, 2020). Other methods must be taken into consideration because the neuroplasticity mechanism is usually insufficient and spontaneous neural regeneration does not occur in the central nervous system (Teleanu, Gherasim et al., 2019), and research has been ongoing on the hallmarks relating to neuroprotection and regeneration that naturally occurring materials in the form of scaffolds or nanoparticles have been carried out in this regard (Liu & Hsu, 2020). Meeting the medical and pharmacological needs by bringing down their susceptibility to breakdown and decay in order to lengthen the duration of action can heighten their use as microcarriers to release neuroprotective compounds (Gonzalez-Nieto et al., 2020). Interest has been piqued in the hunt for naturally occurring substances with the potential to be protective toward the neuronal system and useful enough in the fight against these forms of illness being highlighted. A large amount of focus has been put on the identification of antioxidant compounds needed for neuroprotection, due to the idea that oxidative damage caused by stress can be a factor in the genesis and eventual continuance of dementia (Akintoye et al., 2021; Asuku et al., 2023; Teleanu, Chircov, et al., 2019). Studies looking into the neuroprotective qualities of marine biocompounds (Table 20.1) have shown how important the marine setting is for providing medications aimed at the central nervous system. The main division of marine bioresources is marine lipids, marine pigments, marine polysaccharides, and marine glycosaminoglycans as shown in Fig. 20.1.

3.1 Neuroprotective properties of marine lipids and glycolipids

Marine microbial-derived glycolipids are produced by a broad range of bacterial species, which has led to much research on them. According to Floris et al. (2018), these matrices include contaminated soils and creatures like Annelida, Pteroides spinosum, and fish stomachs. Lipids play numerous complicated roles as age, gender, neuron activity, anxiety, as well as trauma, all have an impact on their composition in the brain which can eventually cause disorders relating to memory, learning, and cognition caused by a difference in factors such as their quantity or metabolism (Lange, 2020). Polyunsaturated fatty acids (PUFAs) are the most common chemical compounds in the brain. PUFAs have been overlooked for over 40 years (Ouyang et al., 2020). Still, they are essential for healthy brain development and function as increased omega-3 PUFA intake helps guard against cancer, heart disease, inflammatory disorders, and other chronic illnesses (Huang et al., 2020).

TABLE 20.1 Examples of marine bioresources and their neuroprotective properties and effects.

	Marine bioresources	Neuroprotective properties and effects
1.	Eicosapentaenoic acid	It possesses antioxidant properties which is essential for healthy brain development and functions (Huang et al., 2020).
2.	Docosahexaenoic acid	It has amyloid-β aggregation-negative attributes (El- Shatshat et al., 2019).
3.	Glycolipid	It prevented apoptosis and decreased neuronal damage in rat (Li et al., 2019).
4.	Glycosphigolipids	It reduced loss of synapse, and controlled mitochondrial cell death (Wang et al., 2017).
5.	Astaxanthin	It has ability to increase the brain antioxidant enzymes and decrease lipid peroxidation and pro-inflammatory cytokines level (Guardado et al., 2024; Si & Zhu, 2022).
6.	Fucoxanthin	It possesses antioxidant and anti-inflammatory properties which are essential for neuroprotection (Chen et al., 2023).
7.	Lycopene	It mitigated brain oxidative stress and apoptosis in rats (Huang et al., 2020), elevated the levels of dopamine in MPTP mice model of PD (Man & Bi, 2018).
8.	Chitosan	It showed capacity to decrease the impact of PD in a rat model (Manigandan et al., 2019), effective for in vivo drug delivery in the treatment of neurological illnesses (Asuku, Ayinla, Aransiola, et al., 2024).
9.	Seleno-polymannuronate (alginate)	It showed a significant increase in the membrane potential of the mitochondrial and prevented aggregation of amyloid-β (Bi et al., 2020).
10.	Fucoidan	It possesses the ability to safeguard against amyloid-β clumping as well as neurotoxicity (Alghazwi et al., 2019).
11.	Laminarin	It attenuated reactive gliosis in order to prevent brain damage following cerebral ischemic shock (Lee et al., 2020).
12.	Hyaluronic acid	It decreased activation of microglia induced by lipopolysaccharide in syringomelia rats (Ho et al., 2019).
13.	Chondroitin sulfate	It has antioxidant and anti-inflammatory properties which helps to protect neurons from toxicity caused by advanced products of glycation in rats (Iannuzzi et al., 2019).
14.	Heparin	It reduced the amyloid-β-induced mortality of brain cells, production of pro-inflammatory cytokines in a cerebral ischemic rat model (Ye et al., 2019).

Deficits in omega-3 (ω-3) fatty acids have been linked to a persistent inflammatory condition in the nervous system, which worsens dementia and raises the risk of an ischemic stroke (Zhang et al., 2018). Docosahexaenoic acid, eicosapentaenoic acid, arachidonic acid, oleic acid, and α-linolenic acid are examples of these fatty acids (Gupta & Prakash, 2019). El Shatshat et al. (2019) also discovered that those fatty acids tested had aggregation-negative attributes, thereby stopping the synthesis of amyloid-β40/-β42 fibrillogenesis, ultimately bringing a new way of curating an AD patient. A diet rich in docosahexaenoic acid has been linked to a reduced likelihood of AD alongside other brain issues.

Furthermore, it has been demonstrated that docosahexaenoic acid is essential for neurogenesis, synaptic plasticity, the homeostasis of calcium in neuronal breakdowns, as well as nigrostriatal functioning (Mallick et al., 2019). A lipid molecule and a glycosidic fragment combine to form the large family of naturally occurring compounds known as glycolipids and can be classified into atypical glycolipids, glycoglycerolipids, and glycosphingolipids, which are the three main categories of glycolipids. Chemically speaking, fatty acid residues and sphingosine connected to a ceramide formed from amides without phosphate groups are what constitute a glycosphingolipid. In various organisms, both on land and sea, glycosphingolipids are the vital physiological components (supported by differences in the sugar chains) of the leaflet-like outer layer of the cell membrane. Within lysosomes, reusing is a common occurrence due to the fragmentation of glycosidase (Aerts et al., 2019). A study showed that glycolipids produced from marine sources might both prevent induced apoptosis and lessen neuronal damage (Li et al., 2019). They can also be found in significant amounts in marine echinoderms. In addition to having different types and quantities of sialic acids, these echinoderms differ from mammals in that their basic sugar moiety compositions differ.

In another investigation, both in vitro and in vivo models of AD demonstrated the guarding effects that sea urchin *Strongylocentrotus nudus* isolated glycosphingolipids could have protective effect in the neuronal system. The two main

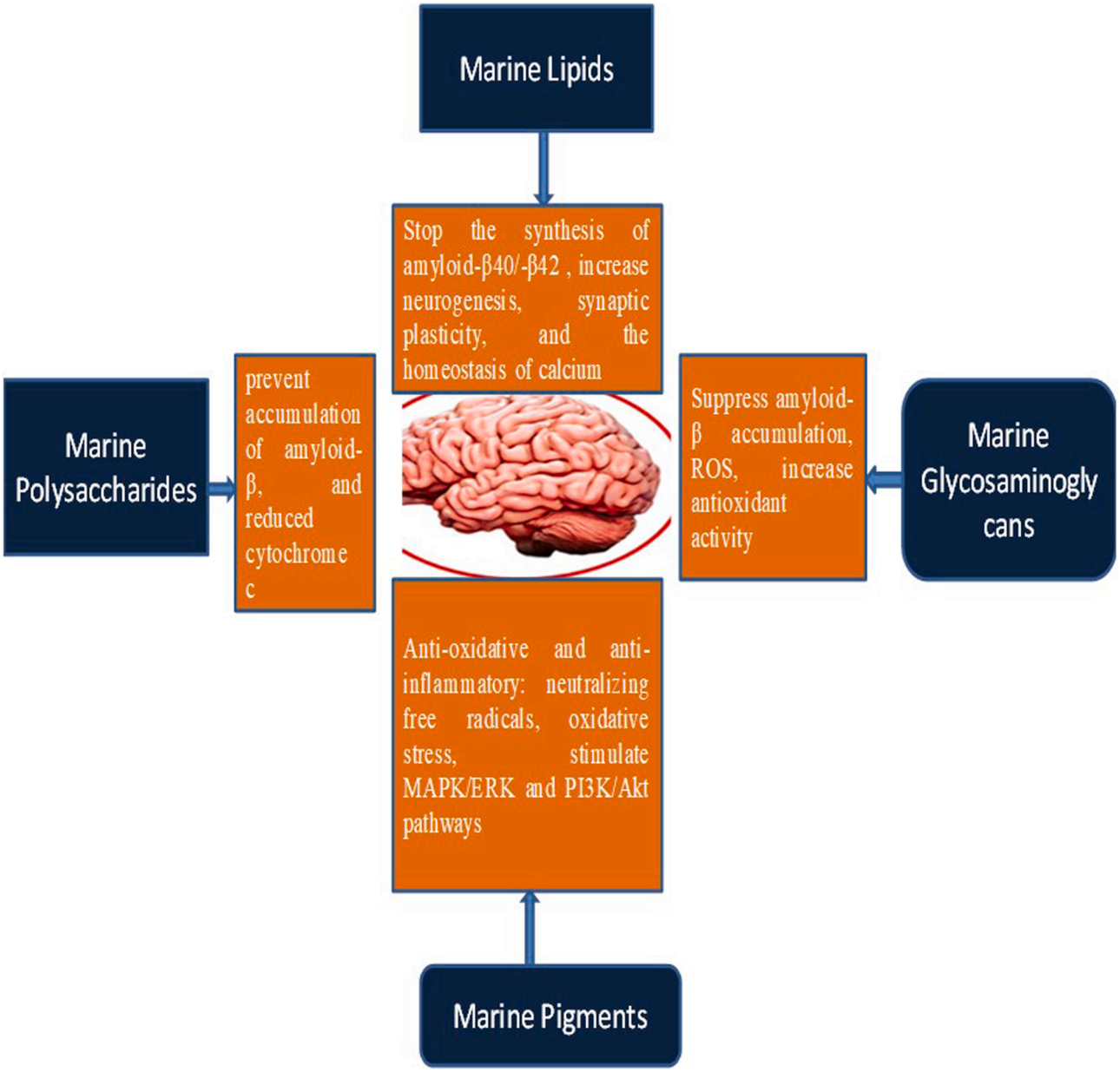

FIGURE 20.1 Division of marine bioresources and their mechanisms of actions.

mechanisms are the reduction of synapse loss and the regulation of mitochondrial cell death, which correlates with tauopathy (Wang et al., 2017).

3.2 Neuroprotective properties of marine pigment

Algae are one of the marine bioresources that contain a great number of natural pigments, which gave them their peculiar colors and various bioactivities (Guardado et al., 2024). The process of quorum sensing might be responsible for the color-producing ability of marine bacteria (Ramesh, Vinithkumar, Kirubagaran, 2019; Ramesh, Vinithkumar, Kirubagaran, Dufossé, 2019). The commonly studied among those marine pigments are chlorophyll, carotenoids, and phycobiliproteins (Jacob-Lopes et al., 2019). The best known carotenoids are lycopene, astaxanthin, lutein, fucoxantin, canthaxanthin, and zeaxanthine. Examples of various chlorophylls are chlorophylls A, B, C, D, E, as well as bacteriochlorophylls. Phycobiliproteins are found in red and cyanobacteria. The common ones are phycocyanins, which is present in bacterial, phycoerythrin, which is present in blue and red algae (Guardado et al., 2024).

The neuroprotective effects of algae-derived pigments have aroused enormous interest from researchers due to their possible use in the prevention and treatment of neurodegenerative illnesses. This is undoubtedly due to their antioxidative and anti-inflammatory properties, which are crucial for neuroprotection, by neutralizing free radicals, oxidative stress, as well as inflammation, that can affect the neurons negatively thereby causing AD and PD.

Finding has shown that astaxanthin has the capability to protect against various neurodegenerative disorders like PD and AD. The potential of astaxanthin to stimulate MAPK/ERK and PI3K/Akt pathways gives it the neuroprotective properties; this causes an increase in the antioxidant enzymes expression and suppresses lipid peroxidation (Si & Zhu, 2022). Moreover, the pigment astaxanthin possesses the ability to scavenge the superoxide radicals (O2−) as well as prevent the transcription factor NF-κB activation, hence decreasing pro-inflammatory cytokines levels. Guardado et al. (2024) reported that astaxanthin is a neuroprotective agent as a result of its antioxidative potential. Al-Amin et al. (2015) reported that astaxanthin decreased the oxidative markers level and elevated the activities of antioxidant enzymes in various brain parts of mice. This pigment also caused neuroprotection in animal model of autism, decreasing oxidative stress, as well as mitigating altered behavior induced by valproic acid during prenatal stage (Al-Amin et al., 2015).

Another algae pigment that has great antioxidant property is fucoxanthin. Coupled with its antioxidant property, it also possesses anti-inflammatory property, which is essential for neuroprotection. Fucoxanthin is very promising for preventing and treating neurodegenerative illnesses (Chen et al., 2023). A plethora of studies have reported the neuroprotective properties of fucoxanthin (Hu et al., 2018; Lin et al., 2017). The neuroprotective ability of fucoxanthin in mouse model of traumatic brain injury (TBI) was investigated by Zhang et al. (2017). It was discovered that fucoxanthin's neuroprotective ability was due to activation of Nrf2-ARE pathway, suppression of brain inflammation and oxidative stress after traumatic injury. The results showed that fucoxanthin has the potential to be a promising agent for the treatment of TBI and other neurodegenerative conditions that have to do with cellular dysfunction and oxidative stress (Zhang et al., 2017). Not quite long, a comprehensive reference for the use of fucoxanthin in neurology was provided by Chen et al. (2023), with emphasis on its possible ability for the treatment of various brain disorders.

Furthermore, lycopene, an example of carotenoids, is a bioresource that has been greatly studied because of its advantageous impacts on the central nervous system.

It has been shown that lycopene has the potential to mitigate oxidative process and decrease cell apoptosis caused by tert-butyl hydroperoxide as major contributor to AD pathogenesis (Huang et al., 2019). Moreover, Cao et al. (2019) reported that lycopene mitigated oxidative process and cognitive deficit through reduction in 8-hydroxy-2-deoxyguanosine and malondialdehyde levels and elevation in antioxidant enzymes activity in rat hippocampal lesions caused by aluminum chloride. The aforementioned studies demonstrated beyond reasonable doubt that lycopene possesses the ability to protect against apoptosis and neuroinflammation. In another study, lycopene displayed neuroprotective ability in MPTP mice model of PD by reducing oxidative stress and elevating the levels of dopamine (Man & Bi, 2018).

3.3 Neuroprotective properties of marine polysaccharides

Carbohydrates, particularly nonsulfated as well as sulfated polysaccharides, are abundant in marine species (Tang et al., 2019). They include chitin, alginate, laminarin, mannitol, and fucoidan. Carrageenans, lignin, funorans, and florideans are examples of red algae. Chitin is one of the common naturally occurring macromolecules known to humans, behind cellulose (Rodriguez-Chanfrau et al., 2019). Some mollusks, nematodes, and fungi can also act as sources, albeit the majority comes from fishing industry waste (Tang et al., 2019). Because of the hydrogen bonds holding them in place, which occurs between the amide bonds, chitin has a high cohesive energy and is generated as an off-white or colorless fine particle that cannot dissolve in polar solvents or hydrous solutions (Tang et al., 2019). Chitin is usually used to make a partial/total alkaline deacetylation product of itself known as chitosan (Sánchez-Machado et al., 2019). Chitosan's potential for neuroprotection has been the subject of numerous investigations. Thus, BV-2 glial cells have shown a more curative side of chitosan nanoparticles when in contact with hydrogen peroxide (Fig. 20.1).

The attributes suited for neuroprotection in chitosan were investigated using PD models. On SH-SY5Y cells treated with rotenone, it showed the capacity to decrease the impact of the disease (Manigandan et al., 2019), and when rotigotine was given to rats with PD caused by haloperidol, it could be observed that a loss of voluntary muscle movement, a turnaround in lethargy, and the return of swimming skills occurred (Bhattamisra et al., 2020). Beneficial effects against multiple sclerosis have also been established in animal models using chitosan nanoparticles loaded with dimethyl fumarate, leading to a significant increase in locomotor scores (Smriti et al., 2019). This corroborates the findings of Asuku, Ayinla, Aransiola et al. (2024), which reported the effectiveness of chitosan-based carriers in in vivo drugs delivery for the treatment of neurological illnesses. Marine polysaccharides are ubiquitously recognized to originate from marine flora; meanwhile, marine algae can serve as a great option for polysaccharides recovery because of their plethora

of bioactivities that are vital for biomedical research and development of drugs (Nechifor et al., 2019; Zargarzadeh et al., 2020).

Alginate is referred to as alginic acid and its derivatives; it could exist as a naturally occurring linear polysaccharide (Alba & Kontogiorgos, 2018). Its production is from brown algae. Alginate's chemical and physical properties include gelation as well as thickness, these properties are affected by the width, block structure, molecular size of the polymer, and the ratio of mannuronic to guluronic; they are all dependent on the isolation source and season of extraction (Alba & Kontogiorgos, 2018). Bi et al. (2020) investigated the neuroprotective property of seleno-polymannuronate, a product of polymannuronate gotten from alginate. The result of their findings indicated that in N2a-sw cells, seleno-polymannuronate showed a significant increase in membrane potential of the mitochondrial, prevent accumulation of amyloid-β, and reduced APP, cytochrome *c*, and BACE1 expressions, demonstrating its ability to attenuate degeneration of neurons.

In a spinal cord model, Nazemi et al. (2020) discovered that paclitaxel-coated polymicrospheres inserted into alginate hydrogels gave rise to a lasting medication delivery mechanism.

Fucoidan, as described by Wang et al. (2019), is a family of long type one and two branching, interconnected strands; they are naturally, soluble in water sulfated polysaccharides. They are commonly produced from the cell wall and mucus matrix of various brown algae species (Wang et al., 2019).

Fucoidans of various types were examined by a group of researchers for their ability to safeguard against amyloid-β clumping, as well as neurotoxicity. They reported that different neuroprotective mechanisms could be used by fucoidans to decrease the levels of amyloid-β in AD (Alghazwi et al., 2019). Furthermore, in a rodent model of PD, the neuroprotective ability of fucoidan was investigated, coupled with its mitochondrial role's preservative ability in dopaminergic neurons. The results showed a decline in mitochondria respiratory function as demonstrated by its oxygen use, improved behavioral deficits, and a reversal of the striatal doperminergic pathways and degeneration of nigral dopaminergic neurons. Fucoidan has been promising in the treatment of rodent model of acute cerebral ischemia by decreasing oxidative damage and stimulation of glial cells. This attenuates the progression and deterioration of the cerebral ischemic injury (Ahn et al., 2019). Laminarin is a safe, linear polysaccharide that can be broken down biologically. It is composed of β-D-glucans joined together in various amounts by (1, 3) and (1, 6) glycosidic connections. It can be originally derived from brown seaweeds such as Laminariaceae and other less common sources (Zargarzadeh et al., 2020). After temporary reduction of blood flow to the forebrain in gerbils, the neuroprotective effects of laminarin have been investigated in a specific aspect of the hippocampus known to be particularly vulnerable to ischemia-reperfusion injury. While pretreatment at 10 mg/kg did not protect neurons, it was successful in reducing some microglia, as well as attenuating reactive gliosis in order to prevent damage following cerebral ischemic shocks (Lee et al., 2020). Even though this dose is somewhat high, more research aimed at clarifying the processes underlying the neuroprotective effect may result in a lower required dose and increased activity.

3.4 Neuroprotective properties of marine glycosaminoglycans

Glucuronate or iduronate, two forms of uronic acid, and N-acetylgalactosamine or N-acetylglucosamine, an amino sugar, repeat are units in glycosaminoglycans, which are long linear heteropolysaccharides (Duan & Amster, 2019). Proteoglycan building units, polypeptides, are bound covalently by glycosaminoglycan chains with the exception of hyaluronic acid. Due to their distinct molecular weight, sulfation, and biological activity, marine glycosaminoglycans have drawn scientific interest; yet, most commercialized glycosaminoglycans come from land animals. The most physiologically significant glycosaminoglycans derived from marine sources that are linked to neuroprotective effects are HA (hyaluronic acid), heparin, chondroitin sulfate (CS), and heparan sulfate (HS). D-glucuronic acid as well as N-acetyl-D-glucosamine polymerize to form hyaluronan (HYA), a naturally occurring polysaccharide that is sulfate-free, linear, and negatively charged. The molecular weight of HYA varies from 50 kDa to 2,000,000 kDa and according to Kumar et al. (2019), can also be safe for biological use, capable of breaking down naturally, and visco-elastic over 10 years. Increasing attention has been given to isolating HA from marine organisms. Due to this, people report taking lower mass molecules of HA from *Amussium pleuronectus* and *Mytilus galloprovincialis,* two marine bivalves, and the opposite weight from the hepatic organ of stingrays (*Aetobatus narinari*) (Hu & Nukavarapu, 2019) (Table 20.1).

The neuroprotective potential of HA in spinal cord damage has been explored as studies have shown that a syringomyelia rat model treated with HA/methylcellulose hydrogel resulted in better tissue or physiological outcomes alongside decreased lipopolysaccharide-induced activation of microglia (Ho et al., 2019). Neuroglobin-loaded sodium hyaluronate nanoparticles have also been shown to be beneficial in treating strokes in rat models as these nanoparticles were able to enter the wounded cerebral parenchyma at an early stage (Blanco et al., 2020). CS is a sulfated linear polysaccharide that is commonly attached to proteins via covalent bonds to form proteoglycans (Rimondo et al., 2019).

Depending on where the sulfate group is located on the polysaccharide backbone, CS can be further classified. Their multifunctionality has brought about a wide plethora of therapeutic, pharmacological, and nutraceutical uses (Khwaldia, 2019). Based on whether the sources are from land or sea, CS has a range of lengths of chains alongside oversulfated disaccharides with varying proportional amounts with these being shark, dogfish, squid, and salmon. According to studies, CS was specifically isolated from the skin of corbs (*Sciaena umbra*), blackmouth catshark (*Galeus melastomus*), and other sharks along with fish-related cartilage (Konovalova et al., 2020). The potential advantages of CS in the therapy of specific neurological conditions have been shown by experimental research (Gromova et al., 2019). However, according to one study, CS protects neurons from the toxicity caused by advanced products of glycation that is affiliated with damage from oxidative stress, inflammation, and the aggregation of amyloid-β (Iannuzzi et al., 2019).

Findings reveal that low-molecular-weight CS and selenium-CS nanoparticles preserve SH-SY5Y cells by suppressing amyloid-β accumulation, reducing ROS and malondialdehyde levels, and increasing glutathione peroxidase levels (Gao et al., 2020). Marine species contribute significantly to the supply of heparin and HS extraction because of their reduced susceptibility to microbial contamination, which results from their distinct evolutionary history from terrestrial mammals. As a result, heparin and HS are abundant in marine mollusks. One study looked at how amyloid-β oligomers impacted populations of cortical and hippocampal cells derived from neural spheroids cultivated from human-induced pluripotent stem cells when paired with heparin, heparinase III, chondroitinase, HA, and an MMP-2/9 inhibitor. It has been discovered that heparin therapy reduces the amyloid-β-induced mortality of brain cells. Heparin injections into gerbils showed that previous treatment significantly minimizes neuronal cell loss and the production of interleukin-1β and tumor necrosis factor-α, thereby offering neuroprotective benefits against cerebral ischemia/reperfusion injury (Ye et al., 2019). HS can be a promising therapeutic strategy that promotes functional recovery by shielding and mending the brain after a stroke.

4. Conclusion

The discovery of novel treatment compounds is an indispensable area of research in neuroprotection against neurodegenerative diseases, given the fact that the available synthetic neurodegenerative drugs are costly and presented with a lot of adverse effects. Marine bioresources have been studied for their role as potential nutraceuticals and drugs with activities against neurodegenerative diseases. They have been widely studied for their bioactivities, which include neuroprotective properties. They have been shown to be efficient and effective in preventing oxidative process and neuroinflammation, which are the main processes in neurodegenerative diseases. Their potentials are corroborated by adequate scientific research and evidence; however, robust clinical investigations are needed to confirm and validate their safety and effectiveness for therapeutic applications in human.

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Chapter 21

Biotechnological potentials of marine bacteria in the production of enzymes

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1. Introduction

Marine biotechnology is a multidisciplinary field that applies organisms in the marine environment and engineers them into beneficial products that serve humanity (Parte et al., 2017). It is a scientific discipline that concentrates on the utilization of biological methods and processes in relation to marine species and their ecosystems. It encompasses the utilization of marine resources for diverse applications, such as bioenergy, food production, pharmaceuticals, and environmental monitoring. Marine biotechnology harnesses the diversity of marine life to address global challenges in health, food security, environmental sustainability, and industrial innovation (Maddela et al., 2024). The field continues to evolve with advancements in biotechnology tools and our understanding of marine ecosystems (Daniotti & Re, 2021). The maritime environment represents a large resource, encompassing waters, sediments, and marine species that offer a distinctive habitat for marine bacteria (Aransiola, Oyewole et al., 2024).

Marine bacteria inhabit diverse niches such as deep-sea polar regions, hydrothermal vents, and saline environments, where they encounter high pressures, low temperatures, and high salinity. These extreme conditions have driven the evolution of enzymes with unique properties suitable for industrial processes (Auta et al., 2022; Zhang et al., 2021). Bacteria in the marine environment can produce a number of enzymes, including proteases, lipases, amylases, cellulases, and chitinases. The various industrial applications of these enzymes include food processing, pharmaceuticals, and the production of biofuel (Aliko et al., 2022; Aransiola, Oyewole et al., 2024; Zhang et al., 2021). Previous studies have shown that marine bacteria are able to produce a number of industrial enzymes (Chapman et al., 2018). Marine bacteria produce several industrial enzymes, including agarase, α-amylase, α-galactosidase, α-glucosidase, cellulases, lipase, protease, and chitinase (Abou El-Hassayeb & Aziz, 2016). Examples of industrial enzymes produced by marine bacteria include Aeromonas sp., Arthrobacter sp., *Alteromonas* sp., *Chromobacterium* sp., *Cytophaga* sp., *Clostridium* sp., *Enterobacter* sp., *Klebsiella* sp., *Flavobacterium* sp., *Listonella* sp., *Pseudoalteromonas* sp., *Moraxella* sp., *Psychrobacter* sp., *Serratia* sp., *Vibrio* sp., *Bacillus* sp., *Streptomyces* sp., and *Marinobacter* sp. (Abou El-Hassayeb & Aziz, 2016; Cheng et al., 2020). Marine bacteria are rich sources of enzymes with a vast biotechnological application, ranging from industrial processes to environmental and pharmaceutical applications. Their unique adaptations to extreme marine conditions make them particularly valuable in enzyme production for diverse industrial and commercial uses (Maldonado-Ruiz et al., 2024; Moon & Ali, 2022; Moran et al., 2022). Marine biotechnology has applications in a variety of areas, including biomining, bioremediation, biofouling, food production, biomass, marine molecular, organic compounds, biomedical products, aquaculture, fishery, cell culture, bioprospecting, bioinformatics, bioprocess biotechnology and biomaterials, genomics, and nanotechnology (Cotas et al., 2024; Vala, 2020; Van Eijk et al., 2017; Velmurugan et al., 2020). Other fields include manufacturing of agrochemicals, food supply, fine chemicals and cosmetics, nutritional

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supplements, medicines, and molecular probes for the development of economically significant enzymes (Ozdal & Gurkok, 2023; Parte et al., 2017).

The enzymes from marine bacteria have shown potential in bioremediation of pollutants, degradation of organic matter, and synthesis of bioactive compounds. For example, enzymes isolated from deep-sea bacteria have been used for the efficient degradation of petroleum hydrocarbons (Babaniyi et al., 2023; Kumar et al., 2019). Enzymes with a vast range of catalytic activity are most likely derived from marine microbial species that thrive in harsh environments. These enzymes are exciting for various industrial applications like biofuel production and medications (Zhang et al., 2021), leather, nutrition, forage, cleansers (Qeshmi et al., 2020), dairy, cosmetic, fabric (Nguyen & Nguyen, 2017), paper (Daniotti & Re, 2021), synthesis of novel polymeric constituents, agrochemicals, and chemicals (Nguyen & Nguyen, 2017) and as catalysts for bioremediation (Zhang et al., 2021). The marine enzymes have much significance in industrial implementations, due to their stability at high temperatures, salinity, and pH, and they have novel chemical and stereochemical properties (Dumorné & Severe, 2018). The marine community hosts a vast diversity of bacteria, many of which are yet to be fully explored. This diversity offers opportunities for discovering novel enzymes with unique properties not found in terrestrial bacteria. This chapter tends to focus on marine bacteria, its biotechnological potential, for enzyme production.

2. Overview of biotechnology

Biotechnology is a multidisciplinary field that applies biological principles and processes to develop products and technologies for a wide range of applications. It cuts across different aspects of biology, chemistry, engineering, and computing to manipulate living organisms or their components for practical purposes (Bentahar et al., 2023). Biotechnology encompasses genetic engineering, synthetic biology, bioinformatics, and more, with applications ranging from medicine (biopharmaceuticals, gene therapies) and agriculture (GM crops, precision farming) to industry (enzyme production, biofuels) and environmental sustainability (bioremediation, wastewater treatment) (Aransiola et al., 2021; Aransiola, Bamisaye et al., 2024, Aransiola, Oyewole et al., 2024; Atencio et al., 2018; Bala et al., 2022; Baquero et al., 2021; Aziam et al., 2021).

Biotechnology is widely applied in a variety of disciplines, including bioremediation, agriculture, and forensics, where DNA fingerprinting is commonly utilized. In a similar vein, recombinant DNA, immunoassays, and polymerase chain reaction (PCR) are widely employed in both industry and medicine. Genetic modification is the primary cause of biology's current reputation as a promising science and biotechnology's status as a dominant sector (Aransiola et al., 2021; Colwell, 2020). Biotechnology has uses in industries, including medicine and agriculture. Biotechnology is classified into numerous branches depending on its applications, including agricultural biotechnology (green biotechnology), medical biotechnology (red biotechnology), industrial biotechnology (white biotechnology), and environmental biotechnology (gray biotechnology) (Ranjit et al., 2021, pp. 17–42). Biotechnology integrates biology with technology and innovation to address global challenges, improve human health, enhance food security, and promote environmental conservation. Ethical considerations and regulatory frameworks play important roles in guiding the responsible development and deployment of biotechnological advancements.

2.1 Meaning of biotechnology

The term "biotechnology" was first used by Karl Ereky (a Hungarian engineer) in 1919 to refer to the science and processes that enable the creation of objects from raw materials utilizing living organisms. Biotechnology is a vast field that uses a number of instruments and technologies to use living cells or substances made from them for purposes related to human welfare. It is a combination of biological sciences and engineering in which living creatures, cells, are employed to produce products and services. Biotechnology is the use of biological systems, organisms, or their derivatives to create goods for specific use. It encompasses a wide spectrum of technological tools that leverage on organisms and biological processes at the cellular and molecular levels. The field integrates principles from biology, chemistry, genetics, and engineering to address various challenges across sectors such as healthcare, agriculture, environment, and industry (Bentahar et al., 2023). Biotechnology, according to the Organization for Economic Cooperation and Development (OECD), is an interdisciplinary field of science and technology that deals with the transformation of living and inanimate matter by using living organisms, their components, or products derived from them. It also involves creating models of biological processes to generate goods, services, and knowledge.

Biotechnology in healthcare leverages the power of live organisms, cells, and biological systems to produce breakthrough tools and procedures to improve human health (Donato et al., 2023). This multidisciplinary field incorporates molecular biology, genetics, bioinformatics, and other scientific disciplines to create innovative solutions that go beyond traditional medical paradigms (Madhavan & Mustafa, 2022). In agriculture, biotechnology has allowed the development of genetically modified organisms that enhance the resistance of crops to diseases and pests, improve nutritional content, and increase yields. This technology has sparked debates over its environmental impact and ethical considerations, but continues to evolve with newer genetic tools and precision breeding methods (Grossman, 2018; Turnbull et al., 2021).

Environmental biotechnology focuses on using biological processes to remediate environmental pollutants, manage waste, and develop sustainable energy sources. Applications include bioremediation, where microorganisms are employed to degrade hazardous substances, and biofuels production from renewable biomass (Farid et al., 2023). Industrial biotechnology involves utilizing biological systems for manufacturing processes, such as producing enzymes for detergents or bio-based chemicals and materials. These applications aim to reduce reliance on fossil fuels, lower production costs, and minimize environmental impact (Danielson et al., 2020). Marine biotechnology describes the applicability of biotechnological techniques and principles to the ecosystems and marine organisms. It involves the utilization of marine resources—such as microorganisms, marine animals, and algae—for various industrial, pharmaceutical, agricultural, and environmental applications (Daniotti & Re, 2021). Recent trends in biotechnology include the rise of synthetic biology, which deals with designing and constructing biological devices and systems for specific applications. This interdisciplinary approach has led to innovations like engineered microbes for producing biofuels and bioplastics, as well as biosensors for detecting pollutants or pathogens.

2.2 Application of biotechnology in different fields

Biotechnology has permeated nearly all segments of human lives, from agriculture and healthcare to environmental sustainability and industrial production. It has various applications across different fields, revolutionizing industries and enhancing our understanding of biological systems. As technology advances, the potential for biotechnology to solve complex challenges and improve human life continues to expand. Some of the major applications in various fields are discussed as follows.

2.2.1 Medicine and healthcare

As healthcare systems strive to meet the evolving demands of an ever-changing landscape, biotechnology emerges as a pivotal force driving transformative advancements (Anyanwu et al., 2024). The significance of biotechnological advancements in healthcare cannot be overstated. These advancements have ushered in an era of precision medicine, personalized healthcare, and diagnostic revolutions. From decoding the human genome to developing targeted therapies and leveraging artificial intelligence for data analysis, biotechnology is shaping a healthcare landscape with better precision, effectiveness, and one that is tailored to individual needs (Biswas et al., 2023). In healthcare, biotechnology enables the production of therapeutic proteins, vaccines, and antibiotics using genetic engineering and bioprocessing techniques. For instance, advances in genetic engineering have resulted in the production of recombinant proteins used in therapies for diseases like diabetes and cancer. Techniques such as CRISPR-Cas9 have revolutionized gene editing, offering potential treatments for genetic disorders (Donato et al., 2023).

Biotechnology can be employed in editing and modifying genes to treat genetic disorders or introduce new therapeutic capabilities. Gene therapy is a method that entails the introduction of genes into cells to treat or avert disease (Slaymaker et al., 2015). This can be accomplished by various techniques, including viral vectors or nonviral approaches like electroporation. Gene therapy has been employed to treat disorders such as muscular dystrophy, cystic fibrosis, and some forms of cancer (Ginn et al., 2018). It can also be employed in molecular diagnostics for disease detection, such as PCR and DNA sequencing, as well as in growing tissues and organs for transplantation.

2.2.2 Food and agriculture

Contemporary biotechnology has been extensively utilized by numerous scientists to discern and alter the genetic composition of organisms for the processing or manufacturing of agricultural products. Creating crops with improved nutritional quality, pest and disease resistance, and environmental stress tolerance. In this context, it can be utilized in plant breeding to enhance and stabilize yields by augmenting their resilience against pests, insects, and other potential threats, as well as combating conditions such as drought and countering diseases related to soil acidity and cold. Biotechnology is used to improve the nutritional content of various foods (Ranjha et al., 2022). The application of

biotechnology to enhance agricultural methods, increase crop productivity, and minimize ecological consequences. Biotechnology is frequently utilized in crop enhancement. In nations experiencing significant food scarcity, fortified crops provide an exceptional food supply, for instance, GM potatoes are mostly grown in India in large quantities to complement the natural potatoes (Ranjha et al., 2022). The GM potatoes are said to contain necessary essential amino acids in significant proportions, such as lysine and methionine (Rajasree & Pugalendhi, 2021). Some other examples are GM golden rice, which is said to contain a higher proportion of beta-carotene (Amna et al., 2020), and GM cowpea, which is largely cultivated in Tanzania (Ranjha et al., 2022). The knowledge of biotechnology has help in the development of BT-cotton (*Bacillus thuringiensis*), which helps in preventing the attack of post on crop thereby increasing the crop yield (Qaim, 2020). A California company, Calgene, created genetically modified tomatoes (Flavr Savr variety) that possess enhanced firmness and extended shelf life (Ranjha et al., 2022).

2.2.3 Environmental conservation and industries

Biotechnology offers diverse tools and strategies that are essential for dealing with environmental problems, promoting sustainable practices, and conserving natural resources. These applications demonstrate its pivotal role in fostering environmental health and resilience. Biotechnology is widely used in bioremediation, phytoremediation, as well as biological waste treatment. Living organisms such as fungi, bacteria, or plants are used to degrade pollutants in soil, water, and air. For instance, bacteria can be genetically engineered to break down specific contaminants like oil spills or industrial chemicals, aiding in cleanup efforts (Baker & Reeves 2018). Biotechnology helps in engineering plants to enhance their ability to absorb and degrade contaminants. It contributes to improving processes for treating wastewater and solid waste. Microorganisms can be utilized to break down organic matter more efficiently, reducing the volume of waste and minimizing environmental pollution (Bentahar et al., 2023; Pandey & Srivastava, 2017). Biotechnology facilitates the generation of biofuels, including biodiesel and bioethanol, from renewable sources such as agricultural wastes, waste oils, and algae. These biofuels are ecologically sustainable alternatives to fossil fuels (Kour et al., 2019a). Biotechnology utilizes fermentation processes to generate various products, such as enzymes, organic acids, vitamins, and antibiotics. These processes are scalable and cost-effective, contributing to industrial productivity. Enzymes produced through biotechnology are employed in various industrial processes, such as the production of detergents, textiles, and paper. They catalyze reactions under mild conditions, reducing energy consumption and waste generation.

3. Marine and marine environment studies

3.1 Definition of marine biotechnology

Biotechnology, in simple terms, refers to the applied science that uses living organisms and their derivatives to produce technologically advanced products (Yang et al., 2019). The American Chemical Society defines biotechnology as the application of biological entities, systems, or processes by diverse businesses to enhance the value of materials and organisms, including medications, crops, and livestock, and to learn more about the science of life. Furthermore, in biotechnology, biological systems such as cells, their components, and natural science are integrated into products and services (Aransiola, Oyewole et al., 2024; Khan, 2020b). The foundation of biotechnology lies in the fundamental biological sciences, encompassing genetics, embryology, microbiology, cell biology, molecular biology, and biochemistry (Khan, 2020b).

The concept of biotechnology is utilizing biological systems and organisms, such as plants, yeast, and bacteria, to perform specific functions or produce valuable resources via biotechnological engineering. Marine biotechnology, also known as blue biotechnology, is one of the most rapidly developing areas within biotechnology. It has gained increased recognition due to its emphasis on resources and innovative materials derived from the ocean, offering potentially boundless opportunities compared to other fields that rely heavily on financial resources (Fig. 21.1) (Rotter et al., 2021). According to Smaal et al. (2019), marine biotechnology, defined broadly, is the study of marine creatures and their parts, systems, and biological processes with the ultimate objective of producing goods and services to promote human well-being. It uses integration to harness the potential of marine creatures to produce goods that benefit humans in a number of ways. To preserve, use, and manipulate the functions of marine species, a wide range of fundamental technologies must be developed.

Marine biotechnology, being multidisciplinary, has its roots in many traditional marine sciences, such as fisheries sciences, marine biology, and marine chemistry. However, it also involves biological research in other fields, including molecular immunology, biology, biochemistry, biotechnology, and pharmacology. Modern techniques, including proteomics, genomics, metabolomics, and bioinformatics, have also been applied recently in the area of marine biotechnology

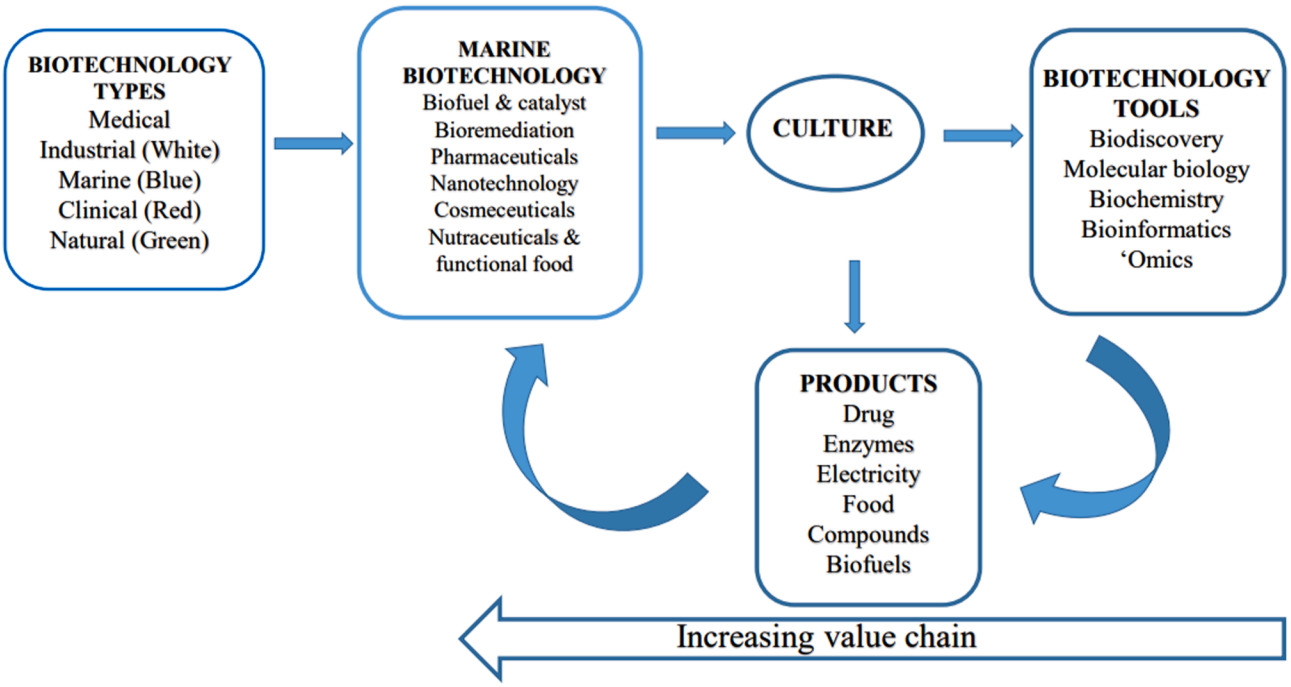

FIGURE 21.1 A pictorial illustration of the marine biotechnology processes. *(source: authors).*

(Ambrosino et al., 2019). The discovery of pharmaceuticals resulting from marine species was brought to light in 1967, when the first-ever drugs from the Sea symposium was held in the United States (Avhad & Bhangale, 2023), drawing attention to the growing body of research on marine natural science and the production of pharmaceuticals derived from marine creatures.

3.2 Abiotic factors affecting the marine environment

Abiotic factors are nonliving components of the marine environment that significantly influence marine ecosystems. These factors play crucial roles in shaping the distribution, abundance, and diversity of marine organisms. Marine ecology is sometimes more complex than the relatively straightforward study of a particular living organism or its surroundings because of the countless factors that affect a given ecosystem as well as the numerous intra- and interspecific interactions between different animals (Turkoglu et al., 2018). In recent times, a number of variables, including rising ocean temperatures, abrupt shifts in weather patterns, acidity of the ocean, glacier melting, and pollution, have contributed to changes that have made these interactions more complex (Turkoglu et al., 2018).

The phylogenetic diversity of the oceans, constituting 70% of the Earth's surface, far surpasses that of terrestrial environments due to differences in temperature, salinity, and location (Liu et al., 2019). By absorbing surplus thermal energy, the marine environment, especially the ocean, contributes significantly to climate regulation (Alosairi et al., 2020), making up around 90% of the overall heat intake. The phenomenon of ocean warming as a whole and the rise in sea surface temperatures are both influenced by this process. The marine ecosystem's diverse life forms are altered either directly or indirectly by rising sea surface temperatures and ocean warming (Segaran et al., 2023).

Important issues concerning the molecular mechanisms that extremophiles have evolved to enable them to flourish at temperatures considerably above the boiling point of water have been brought up by the existence of life at elevated temperatures (Poli et al., 2017). On the other hand, there are the frigid climates that are typically seen as inhospitable due to their physical and chemical characteristics (Fig. 21.2); these have traditionally been described as extremes that are thought to be hardly conducive to life (Gimmler et al., 2016). Marine habitats serve as a plentiful supply of molecules with biotechnological interest (Bollinger et al., 2020). Particularly, marine microorganisms have garnered interest and been effectively used in industrial settings (Bollinger et al., 2020). However, all species within the marine environment are negatively impacted by the growing marine pollution that comes from both point and nonpoint sources (Zhu et al., 2023).

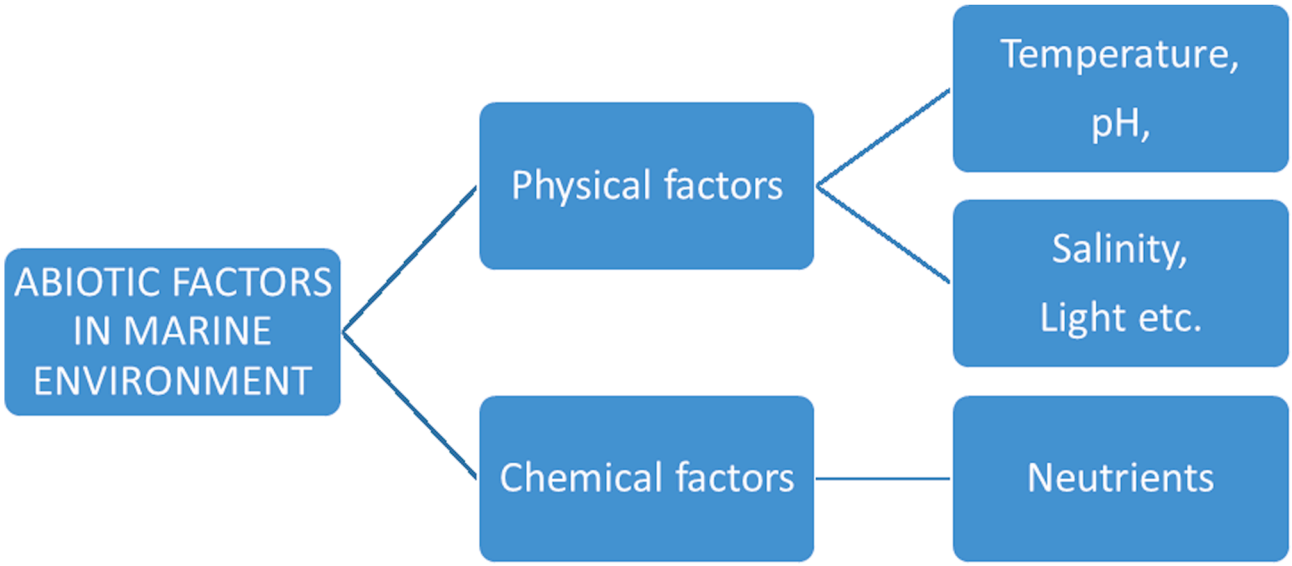

FIGURE 21.2 Schematic diagram showing the abiotic factors in the marine environment. *(source: authors).*

It was discovered that *P. globosa* blooms in the Beibu Gulf were caused by abiotic factor (low temperatures, high nitrate, and low levels of organic phosphorus) (Zhu et al., 2023); these microscopic organisms generate particular blooms in response to changes in their environment because they are extremely sensitive to those changes (Xu et al., 2024). Understanding these abiotic factors and their interactions is crucial for assessing the health of marine ecosystems, predicting responses to environmental changes, and informing conservation and management efforts.

3.3 Degradation activity of microbial communities

This refers to the ability of the microbial community to break down pollutants or organic contaminants such as pesticides, petroleum, hydrocarbons, and industrial chemicals in the environment into simpler compounds or substances (Mishra et al., 2021). In this process, each organism has a specialized function in the breakdown of different compounds. This process often owes its significance to environmental bioremediation. Degradation by microbes can occur both aerobically and anaerobically, depending on the organism in action and the environmental conditions (Rana, 2019).

In microbial degradation, the organism recognizes the organic compound or pollutant to be degraded through various mechanisms, like sensing chemical cues or distinguished receptors on their cell membrane (Samrot et al., 2021). The enzyme released by the organism is based on the compound or pollutant identified as being degraded. When the organism recognizes the compound or pollutant as being degraded, it attaches itself to the substrate through its surface structure, like fimbriae or pilli, facilitating close contact between the organism and the substrate (Pal & Lavanya, 2022; Yadav & Chandra, 2020). The enzyme, after being attached to the substrate, produces and releases extracellular enzymes into the substrate. The extracellular enzymes released into the substrate target certain chemical bonds, breaking complex organic molecules into smaller compounds. These enzymes catalyze certain reactions within the enzymes, such as hydrolysis reactions, which break down chemical bonds like peptides or glycosidic bonds within the substrate, resulting in the production of smaller molecules like amino acids, sugars, or fatty acids, which are then taken in by the organism. These smaller organic molecules taken in by the organism serve as carbon and energy sources for metabolic reactions (Dittmar et al., 2021). Energy from these smaller organic molecules is in the form of ATP, which is used for the production of biomass, which helps the organism grow and proliferate, as well as cellular activities. This degradation process continues until the substrate is fully degraded, at which point the microbial degradation activity slows down. Carbon dioxide and water are byproducts of the degradation activity (Siracusa, 2019).

4. Metagenomics

Metagenomics is a field of genetics that deals with the study of genetic material from entire microbial communities and uncultured organisms. It can also be used to describe the studies of microorganisms' genomic data, which can be

categorized into two main groups based on data such as amplicon and shotgun metagenomics (Nam et al., 2023). Amplicon metagenomics investigates microbial diversity and the data consist of 16S/18S/26S rRNA together with intergenic transcribed spacer (Kinoshita et al., 2021; Liu et al., 2021), while shotgun Metagenomics centralized on metabolisms and mining functional genes and the data comprise all DNA sequences (Kamble et al., 2020, pp. 5–11; Quince et al., 2017). Most gene-based metagenomics has been explored to extract certain parts of each microbe in the environmental samples, including air, soil, and water (Vecherskii et al., 2021). A metagenome involves the collaboration of genomic content of a microbial community within a confined environment that involves the addition of the entire genetic information obtained from all the microbes that are present such as archaea, viruses, bacteria, and eukaryotic microorganisms as unicellular algae and fungi as well as protozoa (Aplakidou et al., 2024; Liu et al., 2024). The extensive microbial analysis, as well as the host of genetic material (DNA and RNA) in samples from patients, has migrated from research to an advanced level of clinical laboratory (Chiu & Miller, 2019).

Marine metagenomics involves the sequencing and analysis of DNA that is derived directly from an environmental sample in the absence of isolating and cultivating individual organisms. The approach gives scientists an opportunity to investigate both the genetic spread and functional capabilities of whole microbial communities. This section addresses the potential of metagenomics as an important tool that reveals the discovery of novel marine bacteria enzymes that possess potential applications in treating many diseases and infections that may arise from microorganisms such as fungi, bacteria, viruses, and parasites, which have shown high prevalent rate according to clinical report (Cerioli et al., 2024; Guo et al., 2024).

4.1 Methods of screening marine bacteria

There are quite methods of screening marine bacteria, which include cultivation-based methods such as agar plating, liquid cultivation, selective media, marine agar, and seawater-based media; marine-specific screening methods include deep-sea simulation, marine sediment simulation and coral reef simulation, molecular biology methods include 16S rRNA gene sequencing, PCR, denaturing gradient gel electrophoresis, quantitative PCR, and next-generation sequencing. These methods in recent times have further provided a distinct approach in the diagnosis of all infectious diseases and facilitated the identification of many important portions of the samples, which were unable to be identified with the use of previous techniques, especially the so-called uncultured microorganisms. Molecular biology methods have also displayed many advantages over previous approaches due to their ability to process even a small quantity of the sample that may be difficult to reproduce (Kharel et al., 2024).

However, great importance has been placed on the synthesis of enzymes from marine bacteria than the conventional enzymes from animals and plants because the microbial enzymes are relatively more stable and reduce the production of greenhouse effect as they minimize the amount of organic waste and pollutants; they are also capable of operating efficiently under mild reaction condition and their cost effectiveness(Noskova et al., 2017). When compared with terrestrial microbes, marine microorganisms are subjected to various physical conditions such as high pressure, acidic pH, high salinity, and extreme temperature, which necessitate their need to develop secondary metabolites like high halogenation, new biodiversity, and novel carbon skeleton (Cheng et al., 2020). Some of the examples of industrial enzymes extracted from marine bacteria include lipase, chitinase, cellulases, α-galactosidase, agarase, α-glucosidase, and α-amylase (Abou El-Hassayeb & Abdel Aziz 2016).

Marine bacteria are usually obtained from different means, such as glycerol stock, and isolated by the IMB of UMT from various marine resources. The jellyfish from Sarawak, mollusks, and horseshoe crab from Sabah, and marine sediment from marine resources require isolating, culturing on marine agar, and incubating overnight at 35°C. The screening of the enzymes from marine bacteria isolates is performed after overnight incubation on a marine agar plate, which employs various kinds of agar content such as spirit blue agar, starch agar, and skimmed milk agar for screening of amylase, lipase, and protease productions from hydrolytic enzymes (Puja & Jyoti, 2015). Proteases are a group of enzymes that cause the breaking of hydrolyzed peptide bonds of proteins into polypeptides or free amino acids (Abou El-Hassayeb & Abdel Aziz 2016). Proteases constitute over 60% of industrial enzymes globally, and generally, the nutrients are obtained from marine broth and the activities of enzymes are determined and the halo zone around the colony with assigned a score of 0 (no inhibition, no halo); 1 (low inhibition, 6–10 mm halo); 2 (moderate inhibition, 11–20 mm halo); and 3 (good inhibition, ≥21 mm halo) determined the strength of the enzyme (Dutta & Ghosh, 2015).

The DNA extraction of marine bacteria enzymes requires the use of isolated enzymes with higher numbers which are usually greater than four and the extraction of DNA are carried out by DNeasy blood and tissue kit, which required 1% agarose gel electrophoresis for DNA loading to visualize the bands, purity, as well as the concentration of the extracted DNA were determined by two absorbance wavelengths (Civitello et al., 2018). The 16S rDNA universal primer pair is an

analysis that is conducted to identify different species of enzymes and consists of 27 F (5′- GAGTTTGATCMTGGCT-CAG-3′) and 1492R (5′-TACGGTTACCTTGTTACGACTT-3′) (Igartua et al., 2023). The condition of analysis of enzyme was taken after MyTaq Mix protocol, except specified, and a specified amount of PCR reaction mixture have 5X MyTaq reaction buffer, such as enhancers, $MgCl_2$, primer-pair, a genomic template of DNA, and sterilized distilled water, was used in the reaction. This follows initial denaturing and cycles of enzyme at certain conditions such as temperature and time and subsequently subjected to primer annealing and final elongation of industrial enzyme production. Amplicons investigation was carried out bidirectional and used an ABI 3730XL DNA sequencer (Subekti et al., 2023).

4.2 Phylogenetic analysis of marine bacteria

This is a way of analyzing purified enzymes from marine bacteria and several methods and techniques with different software have been established over the years, which include 16S rRNA gene sequencing, whole-genome sequencing, multilocus sequence typing, DNA–DNA hybridization, and fluorescence in situ hybridization. The phylogenetic techniques for the analysis of marine bacteria enzymes include maximum parsimony, maximum likelihood (ML), Bayesian inference, neighbor-joining (NJ), and unweighted pair group method with arithmetic mean (UPGMA). Their efficiency is subject to the type of technique, incorporating software tools like ARB (automatic intergenic spacer analysis), SILVA (ribosomal RNA database), MEGA (molecular evolutionary genetics analysis), and randomized accelerated ML. According to Cheng et al., (2020), the phylogenetic tree analysis of industrial enzymes-producing marine bacteria follows 16S rRNA gene sequence method and is constructed by MEGA X software version(Kumar et al., 2018), and the techniques of the trees were based on minimum evolution method, the ML method, and the NJ method.

4.3 Extraction of marine enzymes from marine bacteria

The extraction of marine enzymes from marine bacteria involves a combination of microbiological, biochemical, and biotechnological techniques to harness the enzymatic potential of these microorganisms for practical applications. It involves a systematic process aimed at isolating and purifying enzymes with specific properties and functions from these microorganisms. Microorganisms are a great resource for synthesizing a variety of valuable enzymes, which makes them a useful adjunct to medication research. It has recently been discovered that marine microbial enzymes are environmentally safe, quick to create, and affordable (Al-Agamy et al., 2021). While plants and animals generate enzymes, Raveendran et al. (2018) assert that microorganisms are a more advantageous source of enzymes than plants and mammals. The notable characteristics of microbes compared to other organisms include their cost-effectiveness in production, the predictability and controllability of their enzymatic catalytic activities, rapid growth leading to high enzyme yields in a short timeframe, and the ability to ensure a steady supply of culture due to the lack of seasonal variations. Furthermore, the tissues of plants and animals are regarded as more harmful than those of microorganisms.

Marine bacteria have the capacity to survive in extreme habitats and produce novel metabolites like enzymes, vitamins, pigments, and single-cell proteins in comparison to terrestrial bacteria. Hence, due to these unique features, they are becoming more important in industrial and medical fields. Marine microbes are regarded as primary sources of innovative industrial enzymes. Numerous scientific studies have shown that marine bacteria may create a diverse array of industrial enzymes (Abou El-Hassayeb & Aziz, 2016; Cheng et al., 2020). Industrial enzymes obtained from marine bacteria comprise cellulases, α-amylase, α-galactosidase, agarase, α-glucosidase, protease, lipase, and chitinase (Abou El-Hassayeb & Aziz, 2016; Cheng et al., 2020). Table 21.1 presents some industrial enzymes produced by marine

TABLE 21.1 Examples of enzymes commonly extracted from marine bacteria.

Enzyme name	Source (marine bacterium)	References
Protease	*Bacillus* sp.	Mehta and Satyanarayana (2016)
Protease	*Bacillus* sp.	Sneha et al. (2021).
Amylase	*Psychrobacter* sp.	Cheng et al. (2020).
Lipase	*Marinobacter* sp.	Oves et al. (2017).
Chitinase	*Vibrio harveyi*	Ran et al. (2023).

bacteria, together with their respective marine bacterial sources. Several key steps involved in the process include sample collection and identification of marine bacteria, cultivation of marine bacteria, harvesting the bacterial biomass, cell disruption, enzyme extraction, and purification.

According to a study conducted by Cheng et al. (2020), out of 200 marine bacteria obtained, 163 bacteria isolates were screened. From the 163 bacterial isolates, 112 (68.7%) demonstrated the capacity to create amylases and proteases, whereas 144 (88.3%) produced lipases. The makeup of microbial communities was determined to influence the production of industrial enzymes and the variety of marine bacteria. The extraction of marine enzymes from marine bacteria can be influenced by several factors such as bacterial strain selection, cultivation conditions (including nutrient availability and growth parameters), cell harvesting methods, cell disruption techniques, choice of extraction solvents or buffers, purification methods, enzyme stability considerations, scalability from lab to industrial levels, microbial diversity exploration, and environmental sustainability practices. Addressing these factors systematically can helps optimize the extraction process, enabling the harnessing of marine enzymes for various industrial, biomedical, and environmental applications.

5. Industrial application of marine bacteria enzymes

As of today, the emergencies of marine metagenomics have a broad range of applications including antimicrobial resistance, the microbiome, human host gene expression (transcriptomics), and oncology (Chiu & Miller, 2019). However, the phylogenetic of transglutaminase enzymes responsible for the enhancement of selective cross-linking between protein-bound glutamine and lysine residues was analyzed, and phylogenic inferences and bootstrap values were estimated using UPGMA or ML, NJ, using computer software PHYLIP and MEGA (Reiss et al., 2011). So many previous studies have indicated the potential of 16S rRNA gene sequence analyses of isolated strains of bacteria from marine bacteria such as mollusc-associated bacteria and other marine bacteria. Amplified16S rRNA gene fragments were purified in conjunction with a QIA quick spin PCR purification kit which was used for sequencing templates (Romanenko et al., 2008). On the other hand, spot inoculation method on basal mineral agar (BSA) medium was explored for extracellular hydrolytic enzymes isolation from bacteria in conjunction with a particular substrate of agar supplement where inoculum plates were incubated at a specified temperature and period (2–5 days), and a zone of clearance around the colony revealed the activities of the enzymes (Amaria et al., 2024; Kabeer et al., 2018). The detection of various enzymatic activities such as amylase, lipase, and cellulose were determined by different substrates that contain 1% soluble starch and iodine solution, BSA agar supplement, for amylase identification after certain days of incubation (37°C) that produced clear halos around the colonies. These enzymes constitute about 75% of total enzymes worldwide and act as α-1,4-glycosidic linkages of starch molecules. Microbial amylases are preferred over other microbial sources due to their rate of production and easy accessibility (Aarti et al., 2020; Benhadj et al., 2019). Another enzyme called lipase is determined in a similar approach to amylase by calcium salt crystals of the lauric acid appearance around near the colonies with the growth of BSA agar plate that contains 1% Tween 80 v/v, while cellulose determination involves 1% carboxymethyl cellulose of grown bacteria under specified condition (Gnavi et al., 2016; Kabeer et al., 2018).

Marine bacteria have been proven to possess numerous beneficial bioactivities, such as industrial production of enzymes. Fig. 21.3 illustrates some of the important applications of marine bacteria enzymes. Proteases are major known industrial enzymes that mainly hydrolyze the peptide bond of protein and fragment into smaller portions of polypeptides or free amino acids. They constitute a complex and large group of enzymes of over 60% of the industrial market worldwide, which is responsible for the regulatory and nutritional nature that is necessary for living organisms and they are located in wide marine areas (Abou El-Hassayeb & Abdel Aziz 2016). They are employed in the leather industry, soap industry, and pharmaceutical applications, such as digestive and antiinflammatory drugs (Kowdziejska et al., 1997). Alginate lyase enzymes have been discovered to have numerous industrial applications, such as biofuel manufacturing by breaking down of alginate in seaweed for bioethanol production, enhancing paper strength and quality in textile industries, and removing impurities from fabrics in textile industries. It also has vast applications in agriculture as it improves the uptake of plant nutrients and enhances the fertility of the soil. Alginate lyases also consist of either mannuronate or guluronate lyases, which catalyze alginate degradation of complex copolymer alpha-L-guluronate (Ghattavi & Homaei, 2023). Other alginate lyases applications include the medical field, research, environmental, pharmaceutical, bioplastics, food additives, and cosmetics applications (Cheng et al., 2020; Irianto & Jakarta, 2018). New glucanase and fucoidan from the marine bacteria have acted as a suitable medium with better activity during incubation process at 37°C than many known conventional media and have been considered more appropriate for oral and other healthcare.

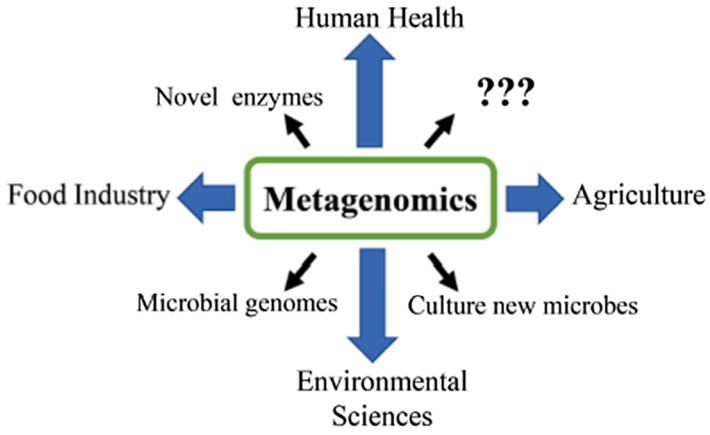

FIGURE 21.3 Major applications of marine enzymes metagenomics and the question mark indicates undiscovered metagenomics. *(source: authors).*

6. Concluding remarks

Bacteria have been employed as whole-cell biocatalysts in several biotechnological processes, including reactions targeting particular products and the advancement of biotransformation and biodegradation reactions. The evaluation of several strains for a specific reaction in whole-cell processes was a crucial method for acquiring valuable catalysts, facilitating the manufacture of diverse chemicals with streamlined procedures and diminished expenses. Nevertheless, recent work has investigated more advanced methods utilizing the cloning and expression of enzymes.

Comparisons of microorganisms from various settings may also be conducted, including optional marine species that exhibit terrestrial strains for study. Furthermore, the proposed biocatalytic approaches must be assessed for productivity and enantioselectivity to enhance the development of large-scale processes, thereby realizing the potential of these marine catalysts. Despite significant advancements in analytical techniques for compound identification, several investigations on organic compounds utilizing whole-cell or enzyme catalysis unable to characterize the resultant products. Regrettably, this is likely due to challenges in purification for the acquisition of materials from biotechnological procedures typically conducted on a modest scale.

The exploration of marine bacteria for their metabolites is rapidly expanding, driven by the unique adaptations of these organisms to extreme environments. While the focus on marine bacteria is promising, it is crucial to balance exploration with sustainable practices to protect marine ecosystems and ensure the longevity of these valuable resources. The efficiency and effectiveness of marine bacterial secondary metabolites, especially in pharmaceutical and biotechnological applications, are making them increasingly attractive as candidates for drug discovery, agriculture, and environmental remediation. Despite their potential, challenges such as limited supply and environmental concerns hinder the development of marine-derived drugs (Banday et al., 2024). Continued research in marine microbiology holds the potential to unlock new metabolites with novel structures and bioactivities that can meet the urgent needs of modern society.

Future biotechnological research and process improvement should depend on molecular biology to provide enzymes with distinctive natural features, similar to those found in marine microorganisms, but enhanced by guided evolution for increased efficiency. Researchers should concentrate on clarifying the enzymatic processes of reactions and broadening the substrate range of the existing enzymes, which would facilitate the identification of novel applications for the examined biocatalysts.

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Chapter 22

Challenges and future directions in marine bioresources innovations

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1. Introduction

Numerous ecosystem services offered by marine habitats assist society (Townsed et al., 2018). These services are primarily linked to the provision of cultural services (tourist), provisioning services (food), and supporting services (nutrient cycling and primary production). Although marine biotechnology is a rapidly expanding sector of the marine economy, efforts to evaluate its value and that of the genetic resources that enable it continue to be controversial (Krusberg et al., 2024). Marine biotechnology has often led to innovations that can help achieve sustainability goals (Blasiak et al., 2023). Recent scientific and technological developments have made it easier to apply marine biotechnology—the identification, extraction, isolation, and characterization of marine organisms and their compounds for use in the pharmaceutical, biomedical, and food and feed industries, among other sectors. In order to survive, adapt, and thrive in the diversity of these competitive ecosystems, marine animals have evolved a wide range of forms, functions, and methods in response to these diverse settings, which include significant variations in temperature, light intensity, salinity, pressure, and other physical, chemical, and hydrological characteristics. One of the many evolutionary features observed in the extant marine phylum that is most encouraging for biotechnology is the generation of biomolecules (enzymes, biopolymers, and secondary metabolites). Along with mediating chemical communication between organisms, forming a barrier against adverse environmental conditions, and serving as weapons to capture prey or protect against pathogens, predators, extreme temperatures, or harmful UV radiation; biomolecules have been developed to help species survive in their marine environments (Blasiak et al., 2023). Biomolecules are crucial for many other life-sustaining processes. In order to counteract the effects of dilution and dispersion that take place in the ocean, they can usually exhibit biological activity even at low concentrations. Because of their unique and complex structures, many marine metabolites can be used in innovative and profitable ways. Apart from biomolecules, other qualities and functions of marine creatures can also be helpful and of interest to many sectors, including the removal and degradation of particular chemical compounds or organic materials, as well as the formation of sophisticated biochemical processes (Newman & Gordon Cragg, 2020).

Marine resources are still, nevertheless, significantly undervalued and underexplored. A streamlined process for marine biotechnology shows that creating products from marine organisms is a multifaceted, interdisciplinary endeavor by nature. In this process, the public, industry, policy makers, and scientific community all have a part to play. The scientific community first establishes the methods for product development, clarifies the structure of bioactive compounds and their modes of action, and conducts systematic bioprospecting and screenings of marine creatures while abiding by the law and ethical standards. Product development funding is frequently determined by society demands and issues (including health, well-being, or environmental preservation) as well as appropriate intellectual property (IP) protection.

Biotechnology research is inherently transdisciplinary, as a result, cocreating knowledge and codesigning processes is an essential step toward accelerating the biodiscovery pipeline, which guarantees faster product acceptance. The gathering of data regarding people's actual and perceived requirements is also a crucial aspect of this. In order to encourage sustainable use of the maritime environment and to get the public involved in its protection, outreach programs are run. Their input to the scientific and business communities, via workshops, other forms of communication, or targeted questionnaires (in the case of market research/analysis aiming to provide feedback on novel food,

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cosmeceuticals, and other products), frequently represents a significant turning point for raising consumer acceptance of bio-based products.

The pharmaceutical, biotechnological, biomedical, and food/nutraceuticals sectors typically handle the subsequent phases in the development of new marine products, such as scale-up, delivery format, validation of potency and toxicity, in vivo testing, and implementation of statistically powered preclinical studies.

2. Innovations in marine bioresources

Marine organisms have evolved over four billion years within their oceanic environment to produce a diverse array of biopolymers and biomolecules. This includes unique secondary metabolites that are generated in response to various external stimuli. These biological functions play a role in enhancing competitiveness, providing chemical defenses against competitors or predators, and assisting in reproduction. While these biomolecules are essential for the organism's survival and well-being in its environment, they are not always critical for growth and development. Furthermore, many substances, such as marine enzymes, exhibit properties like thermostability or tolerance to varying levels of pH levels, salinity, and heat stability that are vital for industrial applications, like in animal feed, horticulture, leather, textile, and bioconversion and bioremediation processes (Rao et al., 2017). Marine biotechnology emerged during the 1960s and 1970s as researchers recognized the potential of living organisms and their natural products for industrial use (Dias, 2012). At first, the focus was on easily available organisms, such as corals and sponges, in addition to macroalgae that had high biomass levels, which serve as indicators of the ecosystems being studied. This exploration resulted in the extraction of numerous natural products from larger organisms known to originate from marine environments. Considering the immense and largely untapped diversity of marine microbes, leveraging marine microbial biotechnology to enhance marine resources is a sensible advancement for the biotechnology industry. It was long thought that just around 1% of all marine microorganisms could be cultivated in a laboratory environment (Krusberg et al., 2024). However, recent studies show that a greater percentage of the microbial population is culturable; an estimated 13%–78% of genera are cultured, depending on the environment (Blasiak et al., 2023; Lloyd et al., 2018). In environments with a high degree of human engagement and disease-driven research, for example, more culturing work is advantageous (Lloyd et al., 2018; Steen et al., 2019). New culturing techniques and developments will increase the fraction of uncultured microorganisms (Krusberg et al., 2024; Steen et al., 2019).

With the use of omics-based culture-independent techniques, uncultured microbes are identified. These techniques include the use of DNA-based or heterologous expression systems, high-throughput sequencing, metagenomics, transcriptomics, proteomics, metabolomics, and bioinformatics resources for the identification of organisms and clarification of metabolic pathways responsible for the production of chemical compounds.

Marine biotechnology also plays a crucial role in environmental and ecological conservation. For instance, certain marine microorganisms have the ability to degrade pollutants and detoxify contaminated sites. By harnessing the metabolic capabilities of these organisms, bioremediation strategies for cleaning up oil spills, chemical pollutants, and other forms of marine pollution can be developed. Additionally, the study of marine genetic resources helps in understanding the resilience and adaptation of marine ecosystems to environmental changes, aiding in the development of conservation and management strategies, biochemical and genetic engineering technologies, are required for the generation of high quality and quantities of proteins, marine oils, and other secondary metabolites.

In order to address significant societal issues like finding new pharmaceutical products and producing food sustainably to meet the exponential growth in population, marine resources represent a largely untapped resource that can be used with a limited carbon and environmental footprint. The most promising technique for the sustainable exploitation of these resources is marine biotechnology; however, there are numerous obstacles in the way of the commercialization of novel goods generated from marines. Through sustainable practices, like responsible collection and cultivation of marine organisms, are essential to prevent overexploitation and preserve marine biodiversity (Dheior, 2023; Krusberg et al., 2024).

The most important instruments for determining the most promising approaches, enhancing the growth prospects of blue biotechnology, and ultimately increasing the quantity of marine-derived products available on the market are analyses of technological advancements and sustainable business models that are driving the market in the approaching years.

3. Applications of marine biotechnology in the pharmaceutical and food sectors

Oceans cover 70% of Earth's surface, and the marine environment is thought to be home to over a million macroscopic species, including fish, mammals, algae, corals, sponges, and mollusks, in addition to about a billion species of microorganisms, including bacteria, viruses, archaea, microalgae, and fungi.

The chemical and physical characteristics of oceanic locations can also vary greatly, including temperature, salinity, light availability, and the concentration of harmful substances. As a result, marine animals have evolved to have distinct characteristics that vary depending on their habitat. Because of the seas' immense size and the variety of species they support, there is a structural diversity of natural products, which is stimulating research into novel bioactive compounds that can be isolated from these animals and have a great deal of promise for industrial use (Krusberg et al., 2024). Because they can produce a large variety of bioactive compounds, algae, which include macroalgae, microalgae, and cyanobacteria, are particularly promising (Matos et al., 2017), in addition to microbes, which are a priceless source of chemicals with particular qualities like resistance to high salinity or temperatures, as well as enzymes because of their capacity to adapt to harsh environments (Casillo et al., 2018). All the same, very little is known about the life that resides in the oceans, and they are still mainly unexplored. Only 9% of marine species are thought to be known, with the remaining 91% awaiting classification, according to scientists (Mora et al., 2011). This knowledge is being enhanced by technological advancements, which also highlight how much more needs to be learned.

Marine biotechnology also known as blue biotechnology is defined as the application of science and technology to living organisms from marine resources, as well as their parts, products, or models, for the production of knowledge, goods, and services. As a result, the field focuses on creating instruments and goods associated with marine bioresources, which are viewed as having two distinct functions: they serve as a source for the creation of high-value products and as the targets of exploratory technologies for the study of the marine environment (OECD, 2017).

The method has a wide range of applications, including the extraction of enzymes for the paper, textile, and detergent industries, as well as laboratory uses. It is particularly useful for producing biofuels, specifically bioethanol, through the fermentation of macro and microalgae (Wijffels & Barbosa, 2010). Among the known instances, the extremophilic sea *microbe Pyrococcus furiosus* produces the enzyme Pfu polymerase, which is frequently utilized for PCR when a high degree of replication fidelity is necessary (Leary et al., 2009). Additionally fascinating and exciting are all the bioactive substances derived from marine species that have use in the culinary, cosmetic, and pharmaceutical industries. For example, fish are the most common, commercial source for the extraction of omega-3 polyunsaturated fatty acids with demonstrated cardioprotective and antioxidant properties; marine biotechnologies are also widely used to extract minerals, fibers, and secondary metabolites such as lipids and carotenoids from macro-, micro-, and microalgae and cyanobacteria for use as food supplements or nutraceutical additives (Suleria et al., 2015). Additionally, these compounds are essential to the cosmetics sector because they offer novel active components that may be added to creams and lotions that have anti-inflammatory, antioxidant, moisturizing, and photo-protective qualities (Corinaldesi et al., 2017).

Regulators have only authorized a small number of therapeutic items made from marine species, nevertheless, as the majority of examined goods fail to advance beyond preclinical testing. Nonetheless, some examples of commercially available medications that are frequently utilized in clinical settings include the antihypertensive Lovaza, the analgesic Prialt, and anticancer medications like Cytosar-U and Yondelis (Martins et al., 2014).

Despite their small quantity, pharmaceutical medicines of marine origin generated over 400 million dollars in sales in Europe in 2020, with the blue biotechnology industry having the largest market share value. More than 60% of the European marine biotechnology market is made up of pharmaceuticals and nutraceuticals (Blasiak et al., 2023). These illustrations show the astounding advancements in marine biotechnology as well as the viability of its use. As a result, they should be viewed as some of the instruments that will have the biggest effects on the economy, contributing to the growth of bio-economy as well as the blue economy, provided that they are properly supported and managed (Barcelos et al., 2018; OECD 2017).

4. Marine biotechnology and biomaterials

Marine biomaterials (such as molluscan shells, corals, bath sponge skeletons, and byssus threads) have been used by humans; since antiquity, the swift advancement of processing technology and marine-cultures has made it possible for these materials to be used on an industrial scale today. Fish, mollusks, and marine arthropod processing products can frequently be used in ways that maximize their efficiency beyond just producing feed. Since there are no potential human pathogens found in marine biomaterials, several of them—such as collagen, gelatin, and keratin—have emerged as alternate sources of lengthy established biopolymers used in cosmetics and medicine. The use of various prefabricated,

naturally occurring 3D skeletal constructions derived from marine invertebrates is the foundation of contemporary scaffolding technologies (Martínez Andrade et al., 2018) for tissue engineering (Matos et al., 2017). Marine biomaterial sources remain abundant despite partial overfishing, significant changes in temperature, and growing industrial waste contamination of the world's oceans (Blasiak et al., 2023; Casillo et al., 2018).

5. Current challenges marine bioresources

In light of new or developed technologies that address the need to protect the marine environment's delicate resources while simultaneously taking advantage of the enormous potential it offers, a plethora of products generated from marine species has been introduced to the market in recent decades. The marine biotechnology industry is currently small and underdeveloped in the European and worldwide markets, despite these advancements. Three categories have been established to represent the primary obstacles that need to be overcome in order for this industry to grow:

1. Discovery of new products
2. Improvement of yield and product characteristics
3. Sustainable production

5.1 Discovery of new products

Due to poor understanding of the marine environment, it is estimated that over 90% of its biodiversity is completely unknown. The main technological obstacle to exploring the marine environment is reaching deep waters; this obstacle could be overcome by innovative technology like robotic data collection technology, which may enable the identification of areas with high biodiversity, and remotely operated vehicles, may facilitate the collection of samples from areas that are inaccessible to humans (Hurst et al., 2016). Additionally, even though a lot of organisms are isolated from the marine environment, studying these organisms is difficult, which makes taxonomic classification difficult and prone to errors that could endanger the entire drug discovery process because it would be impossible to replicate the isolation event and identify the bioactive compound that results (Martins et al., 2014). Thus, cutting-edge analytical methods for the investigation and sampling of new species as well as the separation, purification, characterization, and assessment of the compound's bioactivity would enable it to get around this restriction (Kasanah & Triyanto, 2019). Modern high-throughput screening methods are employed by the pharmaceutical industry to identify novel pharmaceutical leads that come from the marine environment. By automatically testing more than 10,000 possible bioactive compounds every week, these methods greatly increase the success rate and lessen the high expenses and protracted lead times associated with traditional screening programs (Hurst et al., 2016). When looking for new bioactive compounds of marine origin, combining these cutting-edge screening techniques with bioinformatics is more effective than relying solely on experimental methods. Actually, new advances in information technology have spurred the development of computational techniques that provide more targeted and efficient research than the simple analysis of a compound's DNA or structure. Without the need for testing, they enable the optimization of pharmaceutical leads and reveal the mechanism of action (Pereira & Aires-de-Sousa, 2018). Omics technologies have also gained importance recently and are becoming more and more important in determining the genetic potential of marine organisms. The sequencing of multiple microbial genomes has revealed more proteins per genome, pointing to the possibility of an undiscovered reservoir of bioactive substances that are not generated under the typical growth conditions used in labs. Additionally, by analyzing the genetic material and applying metagenomic techniques to the collected samples examining the genetic makeup of environmental samples, we are able to discover previously unidentified bioactive compounds made by microbes that are present in the environment but cannot be cultivated in the laboratory. The incompatibility of the expression elements used in libraries and the impossibility of obtaining intact genes from the environment are the main limitations of this promising technique; however, these issues may be resolved by the most recent developments in synthetic biology (Querellou et al., 2010; Romano et al., 2017).

5.2 Sustainable production

The fragility of marine ecosystems must be taken into account when using marine animals to produce high-value goods and biofuels. In reality, the levels directly supplied by marine organisms do not support the industrial needs or the more limited ones of the drug development process. Therefore, the direct collection of bioactive chemicals and other compounds of economic value is practically never sustainable because many of these species are endangered and their

overexploitation could upset the delicate balance of the environment. Alternative solutions are therefore becoming more and more necessary. Until now, the conventional approaches to chemistry and microbiology have often involved the chemical synthesis or semi-synthesis of an entity similar to the natural product.

However, these processes have a negative impact on the environment due to the large amount of waste they generate and the use of hazardous solvents, so researchers and companies engaged in marine biotechnology can overcome this limitation by developing more environmentally friendly technologies (Murray et al., 2013). Aquaculture and other alternative methods for the cultivation of marine organisms, such as corals and sponges, unquestionably constitute a sustainable production method because toxic compounds are not needed and raw materials can be supplied without endangering delicate marine ecosystems (Leal et al., 2013).

The traditional downstream processes used to extract the product from marine organisms have a negative environmental impact as well. For instance, the conventional method used to produce microalgae is not only energy-intensive and yields organic waste, but it is also frequently prohibitively expensive, sometimes costing up to 80% of the total process cost. Marine biotechnology has the potential to address the pressing need for the development of alternate downstream processes once more (Vinayak et al., 2015). Using fishing industry trash to produce highly valuable compounds is another aspect of sustainable production. In fact, the trash produced annually by the fish processing businesses in conjunction with by-catch amounts to more than dozens of millions of tons, which presents a number of issues with disposal and environmental effects. Nonetheless, because of this waste's extraordinary chemical richness, biotechnological techniques can transform it into very valuable goods like collagen or protein hydrolysates with antioxidant qualities. Thus, this procedure offers a potential substitute for the direct collection of bioactive materials while also providing a means of disposing of trash originating from the fish supply chain (Maschmeyer et al., 2020; Sayari et al., 2016).

Ultimately in order to minimize the usage of hazardous chemicals related to chemical synthesis, mention must be given to the advancement of "green" enzymatic methods for product synthesis. For instance, recently, nanoparticles with special features for chemical, physical, and biological applications have been developed because of their small size. As opposed to the traditional process of synthesizing nanoparticles, which is extremely polluting since it uses organic molecules, using algae or microbes for their manufacture is a more environmentally friendly option (Shakibaie et al., 2010). An abundance of enzymes that can withstand harsh circumstances found in marine environments can be isolated from marine creatures and used to enhance more environmentally friendly conversion processes like biocatalysis.

5.3 Improving the yield and characteristics of the product

A consumer product's large-scale manufacture is inextricably related to its marketing. Numerous promising compounds that undergo laboratory testing are never commercialized because their production costs are too high in comparison to alternatives that are synthesized, produced from fossil fuels, or taken from other creatures. Realizing the full potential of marine resources requires the development of technologies that can produce biomass that has high yields, increases competitiveness, and is compatible with market demand (Camacho et al., 2019). New genetic and metabolic engineering techniques have been developed to achieve this goal, with a focus on microalgae (Mao et al., 2017; Blasiak et al., 2023). Improving the culture conditions of the organism affects the extraction process (Ghorbel-Bellaaj et al., 2013; Tork et al., 2017) as well as the amount and type of secondary metabolites produced (Ale et al., 2014; Zhou et al., 2014). Because bioreactor structures can replicate the marine environment in which organisms thrive to enhance their productivity, technological advancements in bioreactor structures have also allowed volumes to be scaled up greatly. Particularly inventive are systems that can draw their energy from the microbial metabolism itself or in situ systems that employ submerged modules left on the seabed to facilitate the sustainable utilization of marine resources (Zhang et al., 2011).

In some situations, the natural product's qualities need to be enhanced to increase its activity or, in the case of a therapeutic product, to give it characteristics that will appeal to more consumers. An example of this is spirulina, which has a high nutritional value and great medicinal capabilities, but its usage as a food supplement is hampered by its smell and the low amount of proteins it contains that are suitable for human ingestion. Ethanol-based fermentation and extraction techniques have been developed as a solution to this issue. These can improve the availability of nutrients and produce goods that have a flavor and scent that consumers find more appealing (Bao et al., 2018).

6. Conclusion

Marine resources provide a mostly unexplored resource that can be used with a reduced carbon and environmental imprint. Marine biotechnology is the most promising method for the sustainable exploitation of these resources; however, new products made from marines encounter many barriers to commercialization because they do not meet the

requirements for economic viability and volumetric production. The most important tools for determining exceptional promising approaches, enhancing the growth prospects of blue biotechnology, and ultimately increasing the quantity of marine-derived products available on the market are analyses of scientific advancements and sustainable business models.

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Marine Bioresources

Prospects and Obstacles

EDITED BY

Sesan Abiodun Aransiola, Suhasini Bhatnagar, and Naga Raju Maddela

Marine Bioresources: Prospects and Obstacles delves delves into the connections between marine bioresources and biotechnology and the provision of different ecosystem services, providing an in-depth discussion on comprehending the interactions among living and nonliving elements, ecosystem dynamics, biological invasions, ecological restoration, habitat diversity, and conservation strategies. It comprises a comprehensive set of global case studies that tackle the correlation between ecosystem functions and biodiversity, with the aim of contributing to the global endeavors in attaining the sustainable development goals through enriching the scientific literature. This book, edited and authored by experts in the field and taking into account the sustainable development goals (SDGs), presents the most up-to-date resource for students and researchers of marine biology, conservationists, policymakers, and environmental NGOs.

Key features

- Provides a thorough coverage of sustainable marine bioresources
- Covers the biotechnological applications of marine greens in climate change mitigation
- Includes global case studies illustrating the use of marine bioresources in managing the ocean microplastics pollution
- Presents marine organisms and their products as models for studying and treating human diseases

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