

Riti Thapar Kapoor  
Mika Sillanpää  
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Mohd Rafatullah *Editors*

# Biomass Valorization

A Sustainable Approach Towards Carbon  
Neutrality and Circular Economy

 Springer

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Editors

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Carbon Neutrality and Circular  
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*Editors*

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## Foreword

The global demand for energy is continuously increasing due to the rapid growth of population, urbanization, and industrial activities. Currently, approximately eighty percent of energy requirements are met through fossil fuels, which may be exhausted in the next 50 years if current exploitation rate persists. This accelerated use of fossil fuels, driven by population growth and industrial and economic development, has intensified environmental problems. Renewable energy and resource recovery play a significant role in addressing these issues by replacing depleting fossil fuel reserves, reducing greenhouse gas emission, and controlling environmental pollution. Waste biomass, such as agricultural residues, forestry, and livestock by-products, is abundant and can cause environmental problems if not properly disposed of. These waste biomass resources can be potentially converted into multiple products through valorisation process within an integrated biorefinery approach, contributing to the circular bioeconomy. The application of waste biomass in energy production not only adds value to biomass residues but also makes the process more profitable. Industries are increasingly working to minimize their reliance on fossil fuels and petroleum-based industrial components, replacing them with bio-based, sustainable, safe, and eco-friendly alternatives.

Recent developments in integrated biorefineries have significantly enhanced the utilization of waste biomass to produce biofuel, platform chemicals, resins, bioplastics, and other bio-based materials for various applications. The circular economy promotes the principles of reducing, reusing, and recycling materials to minimize waste generation and maximize the value of waste resources.

Biomass-based biorefinery are considered one of the most promising approaches for environment protection and sustainable development, offering renewable feedstock for various applications in the area of energy, food, nutrition, and the chemical industry. First-generation biofuels produced from conventional crops require cultivable land and are not recommended due to their competition with food production. Second-generation feedstocks, such as agricultural and forestry wastes like cereal straw, soybean, corn and sunflower stalk, and grasses, are rich in lignocellulose and do not compete with food crops. These biomass sources can be processed using thermal conversion technologies, such as combustion, gasification, and pyrolysis, which convert biomass into bio-oil and biochar. Syngas can then be further processed into biofuel and electricity.

Third-generation biofuels focus on algae and cyanobacteria, whereas fourth-generation biofuels involve genetic engineering to increase desired traits of organisms used in biofuel production. This approach aims to reduce costs by enhancing carbon capture capacity, increasing biomass production, and improving lipid yields. Microbes such as fungi, yeast, and bacteria can survive under harsh conditions and generate various fuels, including biodiesel, biogas, and biohydrogen, via aerobic and anaerobic fermentation, transesterification, and other processes. Microbes grow rapidly, do not require land, and yield significantly more oil compared to traditional crops. They can also be used in microbial fuel cells for generating bioelectricity while treating wastewater.

Biofuels and bio-based products are among the best alternatives to fossil fuels and synthetic chemicals due to their environmentally benign, sustainable, and feasible nature with net-zero carbon emission. This is a vital contribution to the global ambition of achieving a net-zero economy. Despite several scientific breakthroughs, there are still many technical barriers to developing value-added products from waste biomass. Thus, the development of an integrated biomass-based biorefinery system can be a promising approach in mitigating climate change, reducing carbon footprints, and addressing global energy shortage. This book will be an invaluable resource for researchers seeking to explore about the integrative applications of waste biomass in the development of biorefineries, biomass exploitation in the food, cosmetics, and pharmaceutical industries, and the production of other value-added products by promoting circular economy and carbon neutrality for environmental protection.

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## Preface

The overexploitation of natural resources due to the expansion of industrial activities, a rising global population, and the trend of consumption based on use and throw culture is causing tremendous pressure on waste management. Consumption patterns leading to uncontrolled generation of wastes are becoming a major environmental problem. The unsustainable consumption of global resources is not only posing a threat to the environment but also creating a negative impact on the quality of human lives. This implies the need to develop new production models that use wastes as raw materials for the manufacture of valuable products. With an ever-increasing material footprint, now industrial producers are striving to adopt such production policies that help them to reduce their dependence on non-renewable resources. Therefore, it is necessary to promote sustainable practices in the valorization of waste streams as a strategy for the co-production of bioproducts and bioenergy. In this framework, the development of biorefineries is contemplated as a key with a win–win approach. The untapped availability of plant-based biomass for transformation into a wide portfolio of bioproducts is gaining attention from both researchers and industries as it can offer renewable feedstock for application in different areas such as energy, food, nutrition, and chemical industry. Lignocellulose biomass arises from agricultural and forest residues, organic solid wastes from recycling stations, paper, wood, and pulp, among others. The annual production of lignocellulose biomass is approximately 181 billion tons, out of which only eight billion tons of lignocellulose biomass is utilized in different application areas.

Lignocellulosic wastes can be converted into valuable bioproducts such as biofuels or bio-based chemicals; thus, huge amount of wastes can be managed by favouring the circularity of resources and reducing the impacts derived from end-of-life treatments or disposal. The advancements in lignocellulose biorefinery are paving the path for producing sustainable energy, bioplastics, and other bioproducts from renewable and eco-friendly lignocellulose biomass. Lignocellulose biomass can be easily converted to bioenergy through thermochemical and biochemical conversion routes. Besides, lignocellulosic biomass has the potential to substitute petroleum-based plastics and other petrochemical materials. Thus, the principles of circular economy and carbon neutrality help to reduce the impact on natural resources, carbon footprint, and uplifting of society by enhancing the quality of life and environment protection.

Alberto-Jesus Perea-Moreno and David Muñoz-Rodríguez from Universidad de Córdoba, Córdoba, Spain, present a comprehensive review on the valorization of agro-industrial wastes to energy and other value-added products for environmental sustainability. María Evangelina Vallejos et al. from Universidad Nacional de Misiones, Misiones, Argentina, highlight the top-value bioproducts for forest biorefinery in the current bioeconomy framework. Fit Cintia G et al. from Universidad Nacional de Misiones, Misiones, Argentina, focus on the conversion of agro-industrial wastes into value-added products towards sustainable development. Samia S. Abouelkheir et al. are an interdisciplinary group of authors from multiple institutions, including the National Institute of Oceanography and Fisheries, Alexandria, Egypt, Kafrelsheikh University, and Alexandria University, Egypt, who describe the application of marine resources for production of cosmetic products. Nermeen M. Shokrak et al. from Kafrelsheikh University, Egypt, focus on the application of marine green algae for development of bioplastics with current status and future challenges. Elijah Yanda Shaba et al. are an interdisciplinary group of authors from multiple institutions in Nigeria, focusing on biomass valorization—a sustainable approach towards carbon neutrality and circular economy.

Md. Sejan Hossain and their research team members from Rajshahi University of Engineering and Technology, Rajshahi, Bangladesh, highlight biofuel production from seaweed as a sustainable energy resource. A study by a research group Thushari et al. from Uva Wellassa University, Sri Lanka, and Rajarata University, Sri Lanka, focuses on the utilization of marine green algae for development of bioplastics, challenges, and future prospects. Rachana Bharti et al. from the Institute of Chemical Technology, Mumbai, India, describe the production of bioethanol and biobutanol from seaweed biomass. Md. Sanowar Hossain and their research team members from Rajshahi University of Engineering and Technology, Rajshahi, Bangladesh, highlight the development of the value-added products from unexplored biomass resources. Phetole Mangena from the University of Limpopo, South Africa, describes potential of macroalgae biomass as alternative feedstocks to grain legumes, which contributes towards food security. Siti Suraya Munirah Normi and Siti Baidurah from Universiti Sains Malaysia, Penang, Malaysia, describe the transformation of food waste into nutrient-rich fertilizers, which contributes to carbon neutrality and a circular economy. John Tsado Mathew et al. are an interdisciplinary group of authors from multiple institutions in Nigeria, who describe the potential of marine resources for the generation of clean and green energy for a sustainable future. They also highlighted the significance of seaweed-derived bioactive compounds for pharmaceutical applications. Masajuwa F. Okiemute et al. and their research team members from Nigeria highlight the regulations, policy frameworks, and acts related to the application of marine biomass/recycling in various countries.

This book explores alternative applications for waste biomass, offering a promising avenue for transforming them into valuable by-products and revitalizing production chains. The intended readers for this book include environmentalists, engineers, scientists, industrial personnel, and policy makers who wish to specialize in utilization of biomass-based renewable resources for the production of biofuel and other value-added products, such as biofertilizers, biochar, cosmetics,

pharmaceuticals, nutraceuticals, etc. We would like to extend our sincere gratitude to the authors for contributing chapters and to the numerous learned reviewers who carefully read and provided valuable suggestions on the chapters of this book to enhance its quality. We are also grateful to the Springer Editorial Office, particularly Dr. Sanchi Bhimrajka and Dr. Naren Aggarwal, for bringing us this opportunity and guiding us throughout the publication process. Our heartfelt thanks also go to Ms. Nandhini Viswanathan, Ms. Harshini Punithan, Ms. Pavitra Arulmurugan and Mr. Ashok Kumar for their wonderful assistance and continuous support.

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**Mika Sillanpää** Dr. Mika research work centres on chemical treatment in environmental engineering and environmental monitoring and analysis. His recent research focus has been on the resource recovery from waste streams.

Sillanpää received his M.Sc. (Eng.) and D.Sc. (Eng.) degrees from the Aalto University, where he also completed an MBA degree in 2013. Since 2000, he has been a full professor/adjunct professor at the University of Oulu, the University of Eastern Finland, the LUT University, the University of Eastern Finland, and the University of Johannesburg.

He has supervised over 60 PhDs and served as a reviewer for more than 250 academic journals. Mika Sillanpää has published more than 1300 articles in peer-reviewed international journals. He has served on the editorial boards of several scholarly publications. Having an h-index of 129, his publications have been cited over 81000 times (Google Scholar).

Mika Sillanpää has received numerous awards for research and innovation. For example, he is the first laureate of the Scientific Committee on Problems of the Environment (SCOPE)'s Young Investigator Award, which was presented at the UNESCO Conference in Shanghai in 2010 for his "significant contributions, outstanding achievements, and research leadership in environmental technological innovations to address present water pollution problems worldwide, especially with regard to wastewater treatment and reuse". In 2011, he was invited to serve as a Principal Scientific Reviewer for the GEO-5 report of the United Nations Environmental Programme (UNEP). In 2012, he received the Tapani Järvinen Environmental Technology Award and the Publication Award from the Lappeenranta University of Technology. In 2014, he received the Science Award from the Lappeenranta University of Technology and the Pro Mikkeli Award. In 2017 and 2018, he was recognized as a Highly Cited Researcher by Thomson Reuters. In 2018, he was invited to become a Member of the Finnish Academy of Science and Letters and the Technology Academy of Finland. He also received a literature award from the Water Association of Finland in 2018. In 2019, 2020, and

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**Jakub Zdarta** Dr. Zdarta is an Associate Professor who graduated from the Faculty of Chemistry at Adam Mickiewicz University in Poznań in 2010 and from the Faculty of Chemical Technology at Poznań University of Technology in 2013. In 2017, he obtained his doctorate in chemical sciences in the field of chemical technology, and in 2021, he became an Associate Professor. In 2017–2018 and 2021, he completed internships at the Technical University of Denmark, and in 2019, he interned at the University of Technology Sydney. Since 2018, he has been employed at the Institute of Chemical Technology and Engineering within the Faculty of Chemical Technology of Poznań University of Technology.

He is the author of over 120 scientific publications indexed by Thomson Reuters JCR, more than 10 chapters in monographs, and has delivered several invited lectures at national and international scientific conferences. He is the principal investigator or main contractor for research projects funded by the National Science Centre, the Polish National Agency for Academic Exchange, the Ministry of Science and Higher Education, and various foreign entities that finance scientific research. He is a member of the editorial board, a guest editor for special issues, and a reviewer for numerous scientific journals. He won the Minister's Scholarship for Outstanding Young Scientists in 2019, the Scientific Award of the Polish Academy of Sciences in 2022, and the Prime Minister's Award for Highly Rated Scientific Achievements in 2022.

His research focuses on biotechnology, biocatalysis, enzyme immobilization, biological wastewater treatment, bioremediation, organic pollutant removal, membrane processes, membrane bioreactors, biomass pretreatment and conversion, as well as hybrid materials and biomaterials.



**Mohd Rafatullah** He is currently an Associate Professor of environmental technology at the School of Industrial Technology, Universiti Sains Malaysia (USM), Malaysia. He joined the school in 2008 as a post-doctoral fellow. He completed his education with a Ph.D. in Environmental Chemistry, a Master of Science in Analytical Chemistry, and a Bachelor of Science in Chemistry from Aligarh Muslim University (AMU), India. His research interest includes environmental water pollutants and their safe removal, the preparation of various nanomaterials for environmental protection, water and wastewater treatment, adsorption and ion exchange, microbial fuel cells, advance oxidation process, and activated carbons and their electrochemical properties. His contribution has been recognized by guest editors and members of the editorial boards of various scientific journals. He is listed among the World's Top 2% Scientists by Stanford University and is recognized as a Top 1% peer reviewer in chemistry, environmental science, and cross-field on Publons, as well as on Web of Science. He is a lifetime fellow member of International Society of Sustainable Development and a member of various professional international societies. He has published several review articles and regular research papers in reputable international journals and has presented his research at various national and international conferences. He has also attended numerous workshops and seminars on environmental chemistry. Based on his performance and contribution to research, he has over 9700 total citations and an h-index of 42 according to Scopus.

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# Agro-industrial Wastes Valorisation to Energy and Value-Added Products for Environmental Sustainability

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Alberto-Jesus Perea-Moreno and David Muñoz-Rodríguez

## Abstract

Worldwide, the agro-industrial sector generates an immense volume of waste, which is both a challenge and an opportunity. With the expansion of agricultural and food processing activities to meet the demands of a growing population, the amount of agro-industrial waste has increased considerably. These wastes encompass a wide variety of byproducts, such as crop residues, food processing wastes, and biomass residues. Despite their abundance, these wastes are often underutilised, resulting in environmental pollution and waste of resources. However, in the midst of these challenges lies a promising prospect: the potential conversion of agro-industrial wastes into valuable energy resources and products. This chapter integrates an analysis and literature review of the energy potential inherent in agro-industrial wastes. Brazil, Italy, and India lead in the number of publications. Key institutions focus on bioenergy from sugarcane, diverse biomass sources, and microalgae. Major research areas include biotechnological methods, energy production efficiency, thermochemical processes, water purification, and hydrogen production. It analyses the existing energy potential of agro-industrial wastes by examining the higher heating value (HHV) and other important parameters analysed by the scientific community. In addition, it delves into the scientific communities dedicated to the energy utilisation of agro-industrial wastes, highlighting their remarkable scientific advances and collaborations. Finally, this review explores the existing prediction models for forecasting the calorific value of these wastes.

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**Keywords**

Agro-industrial wastes · Energy · Environmental sustainability · Value-added products · Valorisation

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## 1.1 Introduction

Today, the agro-industry plays a crucial role in the production of food and vital resources for everyday life. However, the sector also faces a major challenge: the proper management of the waste it produces. With a steadily growing population and an increasing demand for agricultural and food products, the amount of agro-industrial waste has reached unprecedented levels (FAO 2022).

The term “agro-industrial waste” covers a wide range of organic residues and byproducts generated along the value chain of agriculture and food processing. These include crop residues such as stalks, husks, and straw, and food processing residues such as peels, seeds, stems, bagasse, kernels, and husk (Gómez-García et al. 2021). Biomass residues from forestry, livestock, and aquaculture also contribute to this complex waste stream (Gogoi et al. 2020). Although traditionally seen as a problem and a source of pollution, these wastes have significant energy value that, if properly harnessed, could be used to drive sustainable development.

The generation of agro-industrial waste has increased significantly in recent years. In agricultural systems, crop residues account for a significant proportion of this volume, with figures suggesting that more than five billion metric tonnes of agricultural residues are generated globally each year (Krishna and Mkondiwa 2023). In parallel, food processing operations contribute significantly to this figure, particularly in fruit and vegetable processing, resulting in the generation of millions of tonnes of byproducts annually (Perea-Moreno et al. 2016). In addition, the increasing intensification of agricultural practices and centralisation of food production leads to a concentration of agro-industrial waste in certain regions, posing additional challenges for its management and environmental protection.

The disposal of unmanaged agro-industrial waste can have a profound impact on the environment. Improper disposal or untreated waste can contaminate soil, water, and air, leading to adverse effects on ecosystems, human health, and biodiversity. For example, the decomposition of organic waste in landfills produces methane, a powerful greenhouse gas that contributes to global climate change. Similarly, agricultural runoff and runoff from food processing facilities can leach nutrients and pollutants into water bodies, leading to eutrophication and degradation of aquatic ecosystems (Pericherla et al. 2020). Furthermore, the open burning of crop residues, a common practice in numerous agricultural regions, releases harmful pollutants into the atmosphere, exacerbating air quality problems and posing health risks to nearby communities (Ravindra et al. 2019). Nevertheless, despite these challenges,

there are opportunities for innovation and transformative change. Agro-industrial waste is increasingly being recognised as a valuable resource for energy production, bio-based products, and circular economy initiatives by researchers, policymakers, and industry players. By utilising the energy and nutritional value of these waste products, it is possible to establish closed-loop systems that minimise waste, decrease reliance on finite resources, and alleviate environmental pollution (Prado-Acebo et al. 2024).

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## 1.2 Importance of Agro-industrial Waste Valorisation

The term “valorisation” refers to the process of converting waste materials into high-value products or energy through the application of innovative technologies and sustainable practices. In the context of agro-industrial waste, this encompasses a wide range of approaches, including anaerobic digestion, pyrolysis, fermentation, and biochemical conversion, among others (Wagh et al. 2024). These technologies facilitate the recovery of valuable resources, such as biogas, biofuels, organic fertilisers, and bio-based chemicals, from waste streams. This creates opportunities for economic growth and environmental sustainability. Furthermore, it is essential to emphasise the pivotal role of agro-industrial waste utilisation in the production of thermal energy. The conversion of agro-industrial waste into thermal energy represents a sustainable and cost-effective alternative to meet the energy demands of various industries and communities. This can be achieved through direct combustion in boilers or through pyrolysis and gasification processes (Wagh et al. 2024; Bača et al. 2024). The utilisation of agro-industrial waste as a source of thermal energy has the potential to reduce dependence on fossil fuels and mitigate greenhouse gas emissions, thereby contributing to climate change mitigation and improved air quality. Furthermore, the valorisation of agro-industrial waste is in accordance with broader sustainability objectives, such as the transition to a low-carbon economy, the promotion of renewable energy sources, and the adoption of circular economy principles. By valorising waste materials, it can reduce greenhouse gas emissions, conserve natural resources, and create new sources of income for farmers and agro-industrial enterprises.

This book chapter integrates an analysis and literature review of the energy potential inherent in agro-industrial wastes. It analyses the existing energy potential of agro-industrial wastes by examining the higher heating values (HHV) and other important parameters analysed by the scientific community. In addition, it delves into the scientific communities dedicated to the energy utilisation of agro-industrial wastes, highlighting their remarkable scientific advances and collaborations. Finally, this review explores the existing prediction models for forecasting the calorific value of these wastes. This analysis provides a scientific perspective on global trends related to energy recovery from agro-industrial waste and outlines possible directions for future research and innovation in this crucial field for sustainable development.

### 1.3 Biometric Analysis of the Energy Potential of Agro-industrial Waste

A bibliometric analysis was conducted using the Scopus database, a comprehensive bibliographic and citation database maintained by Elsevier that covers a wide range of academic and scientific disciplines. The purpose of this analysis was to examine the academic output related to agro-industrial waste and its energy recovery during the past 20 years. The search equation used in this bibliometric analysis is as follows: (TITLE-ABS-KEY(“Agro-industrial waste\*”) OR TITLE-ABS-KEY(“Agro-industrial residue\*”) OR TITLE-ABS-KEY(“biomass residue\*”) OR TITLE-ABS-KEY(“Residual biomass”) AND TITLE-ABS-KEY(energy)) AND PUBYEAR >2004 AND PUBYEAR <2023.

#### 1.3.1 Publication Trends Over Time

A total of 2391 relevant scientific documents addressing the valorisation of agro-industrial waste for sustainable energy production were obtained and represented in Fig. 1.1. These data reflect a steady growth in research on this topic over the years, indicating an increase in scientific interest and attention devoted to the search for innovative solutions for the management and utilisation of agro-industrial waste. The significant number of papers obtained suggests a wide field of study and the need to continue exploring approaches and technologies to promote sustainability and reduce the environmental impact of these wastes.

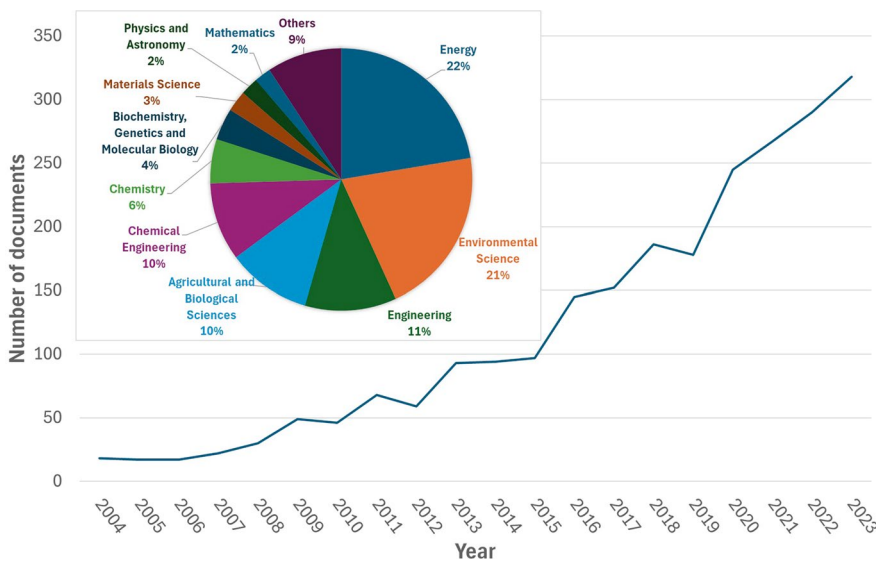


Fig. 1.1 Trend in the number of publications and subjects

Scientific research focused on the use of agro-industrial waste for sustainable energy production has been motivated by a series of causes and policies reflecting the growing concern for global energy and environmental challenges. This has generated significant momentum in research in this field, supported by data and empirical evidence.

Firstly, the increasing scarcity of conventional energy resources has driven the exploration of alternative and renewable energy sources. According to data from the International Energy Agency (IEA), global energy demand has steadily increased in recent decades, surpassing the production capacity of traditional fossil fuels (IEA 2022). This situation has generated renewed interest in the use of alternative energy sources, among which agro-industrial waste has emerged as an attractive option due to its abundance and availability.

Secondly, proper management of agro-industrial waste has become a priority due to environmental and public health concerns. According to data from the Food and Agriculture Organisation of the United Nations (FAO), over one-third of the food produced globally is lost or wasted each year, resulting in a significant amount of organic waste (FAO 2011). The energy recovery of these wastes not only provides a sustainable solution for their disposal but also contributes to the circular economy by converting a by-product into a useful resource.

Thirdly, the mitigation of climate change has driven the search for innovative solutions to reduce greenhouse gas emissions. According to data from the Intergovernmental Panel on Climate Change (IPCC), human activities, including the burning of fossil fuels and deforestation, are responsible for the increase in atmospheric concentrations of greenhouse gases, which contribute to global warming and its associated effects (IPCC 2007). The production of energy from agro-industrial waste can help reduce emissions by avoiding open burning or anaerobic decomposition of these materials, which release large amounts of methane and carbon dioxide.

Finally, government policies and regulations aimed at promoting renewable energy and environmental sustainability have played a crucial role in driving research on the use of agro-industrial waste for energy production. These policies have encouraged investment in energy recovery technologies for agro-industrial waste as a way to meet sustainability goals and reduce carbon footprint (Rijo et al. 2023).

### **1.3.2 Global Distribution of Scholarly Publications: Analysing Countrywise Contribution**

A total of 108 countries published research papers on the valorisation of agro-industrial wastes to energy during the period under study. Brazil leads the list with 397 documents, representing approximately 16.60% of the total number of publications. Italy follows with 270 documents (11.29%), and India with 211 documents (8.82%). Spain and the United States also have a notable presence, with 207 (8.66%)

and 170 (7.11%) documents, respectively. This was followed by China, with 136 published documents (5.69%), and Colombia and Portugal, with 122 (5.1%) and 117 (4.89%) documents, respectively. Mexico and Germany were the two countries that completed the top ten in terms of the number of publications.

### 1.3.3 Publication Distribution per Institution

The results of the search conducted in Scopus were analysed in order to identify the scientific output and keywords used by the top ten international institutions in the field of study. From these, institutions can be grouped according to the keywords used, with those sharing common research lines being identified.

The following Brazilian universities were identified as being engaged in research in this field: Universidade de Sao Paulo (48 documents), Universidade Estadual Paulista Júlio de Mesquita Filho (37 documents), Universidade Estadual de Campinas (36 documents), Universidade Federal do Parana (32 documents), and Universidade Federal de Santa Catarina (27 documents). These institutions share a focus on the utilisation of sugarcane biomass (bagasse and sugarcane) and bioenergy production (ethanol, biofuel and fermentation). The institutions in question concentrate on the utilisation of byproducts derived from the sugar industry for the production of biofuels and energy products.

Portuguese universities (Universidade de Aveiro with 37 documents and Universidade de Lisboa with 25 documents): These institutions concentrate on the production of bioenergy from a variety of biomass sources, including biochar and forest resources. Furthermore, they investigate concepts related to the circular economy and the energy potential of forest biomass.

Italian institutions (Consiglio Nazionale delle Ricerche with 36 documents): Their expertise lies in gasification technologies and the development of alternative fuels. Their research is focused on the utilisation of biomass as a raw material for the production of combustible gases and the optimisation of chemical reactors.

The Spanish university (Universitat Politècnica de València with 25 documents): Their research programme focuses on the production of bioenergy from forest resources, with a particular emphasis on the management of pruning and forest waste for the generation of energy.

The Chinese Academy of Sciences (24 documents) concentrates on the utilisation of microalgal biomass, with a particular focus on lipid extraction and the valorisation of microalgal biomass residues. The primary objective of the research group is the production of biofuels and chemicals from microalgae.

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## 1.4 Involvement of Scientific Communities

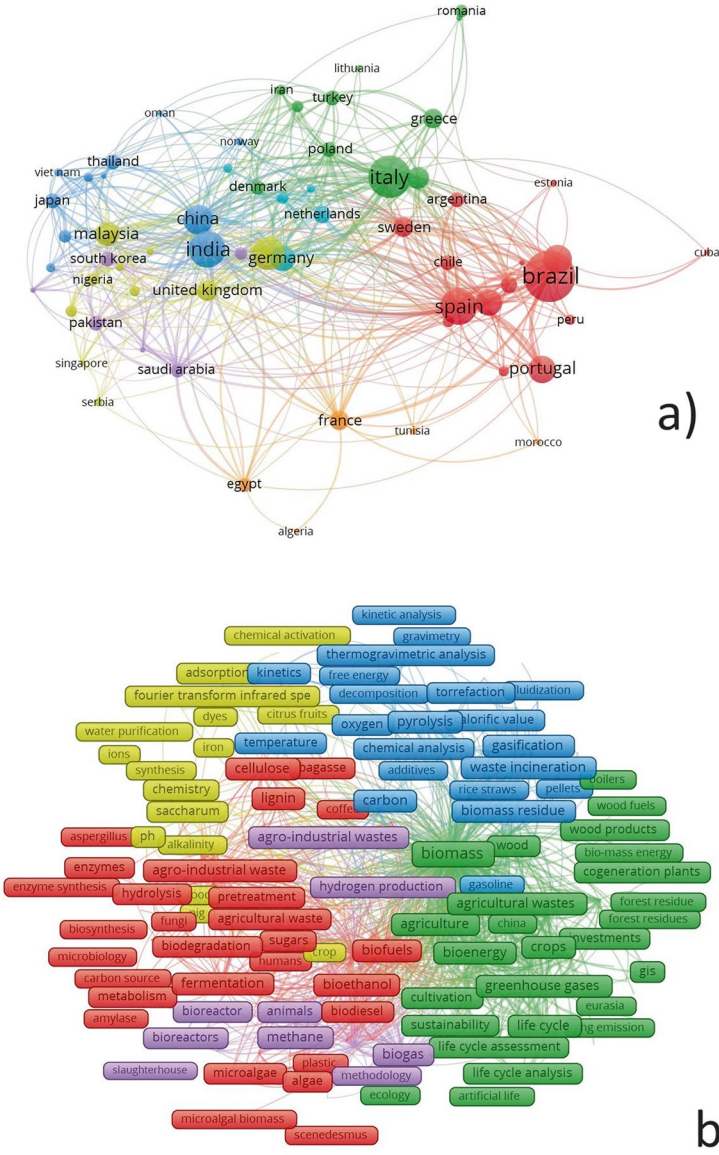
The identification of communities within complex networks has become a pivotal area of investigation in a range of disciplines, including social sciences, biology, computer science, and bibliometrics. A community is defined as a group of nodes

within a network that are more densely connected to each other than to nodes outside the group. The identification of these communities enables the discovery of the underlying structures, patterns, and relationships within the network, thereby providing insights into its organisation and dynamics.

One of the most commonly employed tools for the identification of communities within networks is VOSviewer. VOSviewer is a software tool designed for the visualisation and analysis of complex networks. The software offers a range of functionalities for exploring and understanding network structures, including community detection. By employing advanced algorithms and visualisation techniques, VOSviewer enables researchers to identify hidden communities within large-scale networks in a more efficient manner. The significance of community detection lies in its capacity to reveal concealed structures and patterns within networks, which are frequently not discernible through a mere visual examination (Van Eck and Waltman 2013). A community is defined as a cluster of nodes that share common characteristics, interests, or functions, and thus represents a fundamental unit of organisation in various complex systems (Alcayde et al. 2018).

Figure 1.2a presents a relational analysis of various countries based on their published documents. Each node in the community analysis represents a country, with connecting lines denoting collaborative relations through publications. The size of each node corresponds to the volume of publications from that country, while the thickness of the connecting lines indicates the intensity of collaborations with other countries. The analysis reveals the presence of seven distinct clusters, each distinguished by a unique colour. Cluster 1, shown in red, consists mainly of countries from Latin America (Argentina, Brazil, Chile, Colombia, Costa Rica, Cuba, Ecuador, Mexico, and Peru) and Europe (Czech Republic, Estonia, Finland, Portugal, Spain, and Sweden). Cluster 2, shown in green, includes countries from Europe (Belgium, Croatia, Denmark, Greece, Italy, Lithuania, Poland, Romania, and Turkey), North America (Canada), and parts of Asia (Iran). Cluster 3, shown in blue, includes countries from East and Southeast Asia (China, Hong Kong, India, Indonesia, Japan, Taiwan, Thailand, and Vietnam) as well as Norway and Oman. Cluster 4, shown in yellow, includes countries from several continents, including Africa (Ghana, Nigeria, and South Africa), Asia (Malaysia, Pakistan, Philippines, and Singapore), Europe (Serbia and United Kingdom), and North America (United States). Cluster 5, shown in purple, includes countries from Oceania (Australia) and the Middle East (Saudi Arabia, and United Arab Emirates), as well as South Korea. Cluster 6, shown in turquoise, consists mainly of European countries (Austria, Germany, the Netherlands, Russian Federation, and Switzerland). Finally, cluster 7, shown in grey, includes countries from North Africa (Algeria, Egypt, Morocco, and Tunisia) and France. This geographical distribution reflects different areas of research and scientific cooperation between countries in different regions of the world.

Figure 1.2b illustrates the four communities identified in the analysis, each represented by a distinct colour. The size of each cluster reflects the significance of the keywords defining it, while the thickness of the connecting lines indicates the level of interaction between clusters. Table 1.1 presents a summary of five clusters



**Fig. 1.2** (a) Global networks of international research collaborations. (b) Clustering of scientific communities in the valorisation of agro-industrial wastes to energy research

**Table 1.1** The main keywords used by the communities detected in the topic algorithms for pressure management and leakage reduction in water distribution networks

Cluster	Color	Keywords by cluster	Main keywords	Topic
1	Red	261	Agro-industrial waste, fermentation, enzymes, microalgae, bioethanol, biodiesel, biosynthesis, algae, biodegradation, cellulose.	Biotechnological approaches for sustainable conversion of agro-industrial waste into biofuels and bioproducts using fermentation, enzymes, and microalgae
2	Green	239	Biomass, bioenergy, agricultural wastes, biomass energy, life cycle analysis, crops, forest residues, boilers cogeneration plants	Life cycle analysis of biomass utilisation in energy production: Assessing environmental impacts and efficiency gains in agricultural and forestry settings for boilers and cogeneration plants
3	Blue	200	Biomass residue, waste incineration, thermogravimetric analysis, pyrolysis, gasification, chemical analysis, calorific value, additives, carbon, kinetics	Analysing biomass residue valorisation: Insights from thermogravimetric analysis and chemical assessments for improved energy recovery
4	Yellow	178	Water purification, pH, chemical activation, saccharum, alkalinity, Fourier transform infrared spectrum, iron, adsorption, synthesis, crop.	Utilisation of agro-industrial waste for enhanced water purification: Chemical activation, adsorption mechanisms, and pH adjustment strategies
5	Purple	119	Agro-industrial wastes, hydrogen production, bioreactor, animals, methane biogas, slaughterhouse.	Synergistic approach to hydrogen production from agro-industrial wastes: Bioreactor systems, methane biogas utilisation, and slaughterhouse residue valorisation.

identified in a keyword analysis related to different research areas. Each cluster is distinguished by a color and is associated with a specific set of keywords and a main theme.

The first cluster, identified in red, focuses on the valorisation of agro-industrial waste through biotechnological approaches such as fermentation, the use of enzymes, and the use of microalgae. The main theme seems to be the sustainable conversion of these wastes into biofuels and bioproducts. The article by Sialve et al. (2009) is the most cited in cluster 1 and focuses on the potential of microalgae for biofuels and CO<sub>2</sub> fixation. It highlights the challenges of biomass and fertiliser management for large-scale cultivation. Anaerobic digestion is key to overcoming these challenges and ensuring economic viability. The article identifies key barriers such

as low biodegradability and ammonia release, and proposes strategies such as physicochemical pretreatment to improve methane conversion. It suggests that anaerobic digestion of whole biomass is optimal for energy recovery, especially when the lipid content is below 40%. It also discusses the ability of microalgae to purify biogas and concentrate methane.

The second cluster, identified in green, addresses the use of biomass for energy production, with a focus on life cycle analysis and efficiency in energy production from agricultural waste and forestry residues, especially in the context of boilers and cogeneration plants. The article by González et al. (2004) is one of the most cited in cluster 2. It focuses on the optimisation of the combustion process of different residues in a domestic boiler. The study examines pellets made from biomass residues (tomato, olive pits, and cardoon) together with a forest pellet. Using combustion parameters such as CO<sub>2</sub>, CO, and O<sub>2</sub> contents, the study finds similar behaviour between the residues and the forest pellet. Optimum efficiency (92.4%) is achieved with a mixture of tomato pellets (75%) and forest pellets (25%).

The third cluster, identified in blue, focuses on the valorisation of biomass waste, exploring techniques such as pyrolysis, gasification, and thermogravimetric analysis to improve energy recovery and the synthesis of useful products. The article by Özçimen and Ersoy-Meriçboyu (2010) is one of the most cited in cluster 3. It explores the characteristics of bio-oil and biochar derived from apricot stone, hazelnut shell, grapeseed, and chestnut shell carbonisation. The study reveals that biochar products exhibit high carbon content, high heating value, and low pollution potential, making them promising solid biofuels. Additionally, bio-oil products are identified as environmentally friendly green biofuel options.

The fourth cluster, shown in yellow, focuses on water purification, using chemical activation, adsorption, and pH adjustment strategies, especially by exploiting agro-industrial waste. The article by Chakhtouna et al. (2021) is among the most cited in cluster 4. It investigates biochar derived from banana pseudostem fibres for water remediation, focusing on removing Amoxicillin antibiotic from wastewater. Through slow pyrolysis and nanoparticle impregnation, the biochar demonstrates effectiveness in eliminating various pollutants. Characterisation techniques like XRD, FTIR, SEM-EDX, BET, and TGA offer insights into its properties. Adsorption experiments reveal the hybrid nanocomposite Co-BP350 as a promising adsorbent across different pH and temperature conditions.

Finally, the fifth cluster, identified in purple, focuses on the production of hydrogen from agro-industrial waste, highlighting the use of bioreactor systems and the valorisation of methane biogas, especially in contexts such as slaughterhouses. The article by Levin et al. (2007) is one of the most cited in cluster 5. It highlights Canada's substantial residual biomass production, representing 22% of the country's annual energy use. The study discusses anaerobic digestion's potential to produce methane (CH<sub>4</sub>) from biomass residues, which could significantly contribute to energy production. Additionally, it explores emerging technologies that could generate renewable hydrogen (H<sub>2</sub>) from biomass, offering a sustainable alternative for the hydrogen economy. The article calls for further research to advance both the technical and commercial aspects of microbial bioenergy from biomass.

## 1.5 Advancements in Energy Valorisation

Waste generated by agricultural activity and the food industry, known as agro-industrial waste, possesses significant energy potential that has been the subject of research in recent years. These wastes encompass a wide range of materials, such as fruit peels, sugarcane bagasse, cereal straw, and many other by-products of agricultural and food production (Rani et al. 2023).

The energy valorisation of these wastes relies on their ability to be converted into solid, liquid, or gaseous biofuels, which can be used for heat generation, electricity, or biofuels. One fundamental aspect of the energy valorisation of agro-industrial waste is the determination of its calorific value, i.e., the amount of energy it can produce when burned.

This subsection will review recent advances in assessing the energy potential of agro-industrial wastes, including methods for determining calorific value, predictive models based on chemical and physical analysis, and case studies highlighting the successful use of these materials for energy production. The aim is to provide a comprehensive overview of the energy potential of agro-industrial waste and its role in the transition to a more sustainable and diversified energy system.

### 1.5.1 Energy Potential of Agro-industrial Waste

Table 1.2 provides a comprehensive overview of the composition and energy potential of various agro-industrial wastes, as documented in representative scientific studies. The table encompasses a diverse range of biomass waste types, including fruit and vegetable residues, along with essential characteristics such as HHV, ash content, and elemental composition percentages.

The information obtained from this analysis is of great assistance in estimating the behaviour of agro-industrial residues during combustion and even in determining their propensity to produce slag and dirt. The behaviour of the residues can be estimated by determining the percentage by weight of carbon, hydrogen, nitrogen, oxygen, and sulphur.

The presence of carbon and hydrogen allows for the estimation of the quantity of CO<sub>2</sub> and H<sub>2</sub>O that are formed as a consequence of combustion. The carbon content of a material provides information on the amount of organic matter present and its potential as a renewable energy source. Another essential element is hydrogen, which is present in compounds such as carbohydrates, lipids, and proteins. The content of the material can influence its calorific value and its ability to form chemical bonds during energy conversion processes. The regulation of the CO<sub>2</sub> emissions market necessitates the estimation of the various environmental and economic effects of its emission into the atmosphere.

Nitrogen is a crucial element in agriculture, serving as a vital nutrient. This indicates the presence of proteins and other nitrogenous compounds in the residue. Furthermore, it is a source of the various nitrogen oxides (NO<sub>x</sub>) that are formed during combustion. However, from an environmental perspective, it has another

**Table 1.2** Agro-industrial waste composition and energy potential of a representative scientific study

Biomass	Waste	HHV (MJ/kg)	Ash content (%)	Total carbon (%)	Total hydrogen (%)	Total nitrogen (%)	Total sulphur (%)	Total oxygen (%)	References
Olive stone	Fruit-derived residues	20.46	0.77	51.21	5.98	0.15	0.02	41.83	Mata-Sánchez et al. (2013)
Sunflower	Vegetable-derived residues	20.26	6.90	50.50	5.90	1.30	0.10	34.90	Friedl et al. (2005)
Hemp	Vegetable-derived residues	18.04	3.20	45.70	6.30	0.60	0.00	44.10	Friedl et al. (2005)
Avocado stone	Fruit-derived residues	19.15	2.86	48.01	5.76	0.45	0.10	42.80	Perea-Moreno et al. (2016)
Almond shell	Fruit-derived residues	18.28	0.55	46.40	5.70	0.30	0.20	47.50	García et al. (2017)
Coffee husk	Fruit-derived residues	18.24	5.80	45.10	6.40	2.50	0.50	45.50	García et al. (2017)
Pine kernel shell	Fruit-derived residues	18.89	2.70	47.90	4.90	0.30	0.60	46.30	García et al. (2017)
Pine cone leaf	Vegetable-derived residues	18.63	1.30	47.70	6.30	0.30	0.10	45.60	García et al. (2017)
Vine orujillo	Fruit-derived residues	17.74	12.70	44.20	5.30	1.90	0.60	48.10	García et al. (2017)
Zapote seed	Fruit-derived residues	18.34	2.42	48.12	6.05	0.83	0.05	45.02	Perea-Moreno et al. (2020)
Mango	Fruit-derived residues	18.05	2.14	48.26	3.48	1.04	0.09	49.02	Perea-Moreno et al. (2018a)
Zucchini waste	Vegetable-derived residues	12.85	29.75	33.88	3.70	4.70	0.13	27.84	Callejón-Ferre et al. (2011)
Cucumber waste	Vegetable-derived residues	12.60	27.96	33.81	3.87	3.00	0.24	31.12	Callejón-Ferre et al. (2011)

Eggplant waste	Vegetable-derived residues	16.53	13.12	42.09	4.56	2.18	0.10	37.95	Callejón-Ferre et al. (2011)
Tomato waste	Fruit-derived residues	14.83	18.71	38.17	4.08	2.30	0.50	36.24	Callejón-Ferre et al. (2011)
Bean waste	Vegetable-derived residues	17.01	15.41	42.86	4.81	3.62	0.12	33.18	Callejón-Ferre et al. (2011)
Pepper waste	Vegetable-derived residues	15.26	17.86	39.27	4.17	3.28	0.40	35.01	Callejón-Ferre et al. (2011)
Watermelon waste	Fruit-derived residues	14.26	20.58	37.64	4.62	3.60	0.15	33.41	Callejón-Ferre et al. (2011)
Melon waste	Fruit-derived residues	13.50	24.38	35.50	4.37	4.62	0.17	30.96	Callejón-Ferre et al. (2011)
Orange peels waste	Fruit-derived residues	15.10	0.90	43.80	6.88	1.14	<0.05	50.50	Pulidori et al. (2023)
Tangerine peels waste	Fruit-derived residues	16.50	1.10	44.23	6.91	1.18	<0.05	50.70	Pulidori et al. (2023)
Grapefruit peels waste	Fruit-derived residues	17.20	0.40	42.80	6.89	0.93	<0.03	52.50	Pulidori et al. (2023)
Pomelo peels waste	Fruit-derived residues	15.50	0.70	41.56	6.76	0.76	<0.016	54.00	Pulidori et al. (2023)
Lemon peels waste	Fruit-derived residues	15.90	1.50	41.50	6.63	0.90	<0.026	53.10	Pulidori et al. (2023)
Rapeseed meal	Vegetable-derived residues	21.38	5.43	49.66	6.85	5.30	No data	32.79	Murillo et al. (2021)
Dark roast coffee (spent)	Fruit-derived residues	22.10	1.21	56.49	8.08	2.45	0.09	31.68	Sermiyagina et al. (2021)
Light roast coffee (spent)	Fruit-derived residues	21.56	1.19	54.50	7.81	2.48	0.09	33.93	Sermiyagina et al. (2021)
Dark roast coffee blend (spent)	Fruit-derived residues	23.95	2.81	57.90	7.73	3.70	0.14	27.72	Sermiyagina et al. (2021)

(continued)

**Table 1.2** (continued)

Biomass	Waste	HHV (MJ/kg)	Ash content (%)	Total carbon (%)	Total hydrogen (%)	Total nitrogen (%)	Total sulphur (%)	Total oxygen (%)	References
Green tea (leaf)	Vegetable-derived residues	20.39	4.12	53.14	6.17	4.78	0.23	31.56	Sermyagina et al. (2021)
Black tea (leaf)	Vegetable-derived residues	20.26	3.79	52.93	6.21	4.28	0.18	32.61	Sermyagina et al. (2021)
Rice husk	Vegetable-derived residues	17.94	22.46	45.09	6.62	0.50	0.01	47.78	Fernanelli et al. (2020)
Wheat straw	Vegetable-derived residues	17.35	10.59	43.09	7.28	2.50	0.12	47.02	Fernanelli et al. (2020)
Semi-dried banana leaves	Vegetable-derived residues	19.80	8.70	43.50	6.30	1.30	0.20	48.70	Fernandes et al. (2013)
Wet banana leaves	Vegetable-derived residues	5.50	12.20	15.90	9.20	1.40	0.05	73.40	Fernandes et al. (2013)
Sugarcane straw	Vegetable-derived residues	19.40	11.70	41.60	5.80	0.45	0.08	52.10	Almeida (2008)
Peanut shell	Fruit-derived residues	18.55	4.26	46.42	6.61	0.50	0.54	41.77	Perea-Moreno et al. (2018b)
Leaves coffee	Vegetable-derived residues	19.45	7.17	53.97	6.55	3.54	0.43	35.50	Martinez et al. (2019)
Primary branch coffee	Vegetable-derived residues	19.20	2.42	50.31	6.13	0.92	0.36	42.28	Martinez et al. (2019)
Secondary branch coffee	Vegetable-derived residues	19.20	3.45	51.82	6.40	1.51	0.21	40.06	Martinez et al. (2019)
Stem bark coffee	Vegetable-derived residues	19.20	4.33	54.41	6.59	2.13	0.21	36.66	Martinez et al. (2019)
Stem coffee	Vegetable-derived residues	19.00	1.67	50.64	6.12	1.86	0.21	41.16	Martinez et al. (2019)

Parchment coffee	Vegetable-derived residues	18.30	5.84	50.69	6.23	0.82	0.20	42.05	Martinez et al. (2019)
Sugarcane bagasse	Vegetable-derived residues	14.40	6.70	57.20	6.10	0.35	No data	36.40	Camargo (2006) and McKendry (2002)
Apricot stones	Fruit-derived residues	22.08	1.04	52.38	6.57	1.07	0.15	38.78	Atımtay and Kaynak (2008)
Peach stone	Fruit-derived residues	22.66	1.61	51.35	6.01	0.58	0.14	40.32	Atımtay and Kaynak (2008)

source of emission. The emission of nitrogen oxides into the atmosphere has the potential to influence the greenhouse effect and the ozone cycle in the atmosphere.

Sulphur plays a role in the combustion process, contributing to the formation of sulphur oxides ( $\text{SO}_2$  and  $\text{SO}_3$ ). These are highly polluting in the atmosphere, affecting the environment through acid rain. However, sulphur can also present challenges in the boiler, causing corrosion and dirt. In particular, corrosion can occur in the cold areas of the boiler, such as the gas ducts, due to the combination of sulphur oxides with water.

Oxygen, which can be quantified indirectly or by the use of instrumental techniques, is useful to quantify because it influences the combustion efficiency and thus the heat output of the fuel. It also influences the heat transfer. Inside the boiler, oxygen is a precursor to the formation of nitrogen oxides, soot, or carbon monoxide, and therefore, its control is important. The authors Sheng and Azebedo (2005) in their study carried out for the estimation of the higher calorific value from the results obtained from the basic analysis estimated, among others, the correlation between the higher calorific value and oxygen; the authors showed the neutrality of the element in an increase or decrease of the higher calorific value contrary to what happened with carbon and hydrogen, showing an increasing trend between the higher calorific value and the percentage in dry weight of carbon and hydrogen of the samples considered.

Ash is the inorganic residue that remains at the end of the combustion process of the biomass used as fuel and has a negative influence on the operation of the boiler. One negative influence is the reduction of the calorific value and thermal efficiency, as it lowers the temperature in the burning process by absorbing heat energy and interfering with, or reducing, the contact zone between the fuel and the comburent. Furthermore, if the ash has a low melting point, it will deposit on the boiler walls, forming slag or incrustations. These can prematurely degrade the life of the boiler, obstruct the tubes and surfaces where heat transfer takes place, and emit particles and pollutants.

Finally, the higher heating value (HHV) is a measure of the maximum amount of heat that can be released when biomass is burned, including heat from the condensation of water produced during combustion. This parameter is of great importance in determining the efficiency of the combustion process and the maximum amount of energy that can be obtained. In this context, both the efficiency and the maximum amount of heat supplied influence both the design and the sizing of the boiler and its economic costs.

The initial parameter to be analysed is the HHV. In the preceding definitions, the significance of this parameter in determining the efficiency of the combustion process was emphasised. In consideration of the values presented in the table, biomass residues from rapeseed meal, coffee spent of varying varieties, as well as a combination of these and apricot stones are the five values with the highest heating value, ranging from 21.38 MJ/kg to 23.95 MJ/kg.

The study by Sermyagina et al. (2021) characterises the coffee wells shown in the table and highlights the high moisture content of the samples and the higher calorific values measured. The percentage of moisture in the coffee and tea samples

is 80%. Nevertheless, watermelon waste, melon waste, orange peels waste, sugar cane bagasse, and wet banana leaves exhibited the lowest values, even below the average values shown in the table (17.84 MJ/kg), with wet banana leaves exhibiting the lowest value (5.50 MJ/kg).

The ash content and its implications for the boiler indicate that the lower the percentage of ash in the samples analysed, the more favourable the results. The average ash content of the residues shown in the table is 7.48. In this context, the samples from the fruit skins of tangerine, grapefruit, pomelo, or lemon (Pulidori et al. 2023) or apricot stones (Atimtay and Kaynak 2008) present values close to or lower than the unit as a percentage of dry residue. Regardless of the source of the residue under analysis, the samples highlighted exhibit ash values consistent with those typically observed in wood pellets intended for residential use and classified as A1 and A2, in accordance with the ISO 17225-2:2021 standard. In contrast, the highest values were found in the samples from plant remains, namely, zucchini (29.75%), cucumber (27.96%), watermelon (20.58%), and melon (24.38%), as reported by Callejón-Ferre et al. (2011), or rice husk (22.46%), as documented by Fermanelli et al. (2020).

Carbon constitutes the foundation of the organic structure of most agro-industrial residues. The carbon content provides information regarding organic matter and its potential as renewable energy. The average value of the percentages of residues shown in Table 1.2 is 46.07%. Above this value are residues, with coffee values ranging between 54.5% and 57.9%, studied by Sermyagina et al. (2021), and analysed samples of stem bark coffee (54.41%) and sugar cane bagasse (57.20%) studied by Martinez et al. (2019), McKendry (2002), and Camargo (2006), respectively. Below the average value are the values of pepper, watermelon, and melon, ranging between 35.5% and 39.27%, studied by Callejón-Ferre et al. (2011). In this regard, the percentage of carbon in wet banana leaves stands out, as studied by Fernandes et al. (2013), with a value of 15.9%.

Hydrogen present in agro-industrial residues has a positive impact on the combustion process of agro-industrial residues as it enhances combustion efficiency, increases available energy, and reduces emissions into the atmosphere, although the product formed is water vapour, which can also affect boiler efficiency. The average value of the group of residues shown in Table 1.2 is 6.04%, and above this value are coffee residues (Sermyagina et al. 2021), with values ranging between 7.73% for coffee blends and 8.08% for dark roast coffee residues. In this sense, due to being more than the average value, the value of wheat straw (7.28%) and the value of wet banana leaves (9.2%) are shown. Conversely, below the average value are the values of bean waste, pepper waste, watermelon waste, and melon waste, ranging between 4.17% for pepper waste and 4.81% for bean waste. In this regard, the percentage of sugar cane straw is 5.8%, as studied by Almeida (2008).

The presence of nitrogen in biomass residues affects boilers through the formation of nitrogen oxides, reducing flame temperature, decreasing combustion efficiency, and promoting undesirable substances such as soot. Needless to say, nitrogen oxides emitted into the atmosphere are a source of various environmental problems such as acid rain or ozone depletion. The values shown in the table, regardless of

their origin, have an average value of 1.07%. Although the average is above the estimated according to quality standards (ISO 17225-2:2021), below this value and within the desirable range according to the previous standard, are sugarcane straw (0.45%), peanut shell and rice husk (0.5%), sugarcane bagasse (0.35%), peach stone (0.58%), and olive stone with 0.15%. Based on the parameters shown and the ISO standards used as references, depending on the considered parameter, the materials would be classified as producing pellets equivalent to those classified as A1, A2, and B. Above the average value and therefore undesirable for pellet formation due to the mentioned drawbacks, are, among others, rapeseed meal (5.3%), zucchini waste (4.7%), and melon (4.62%).

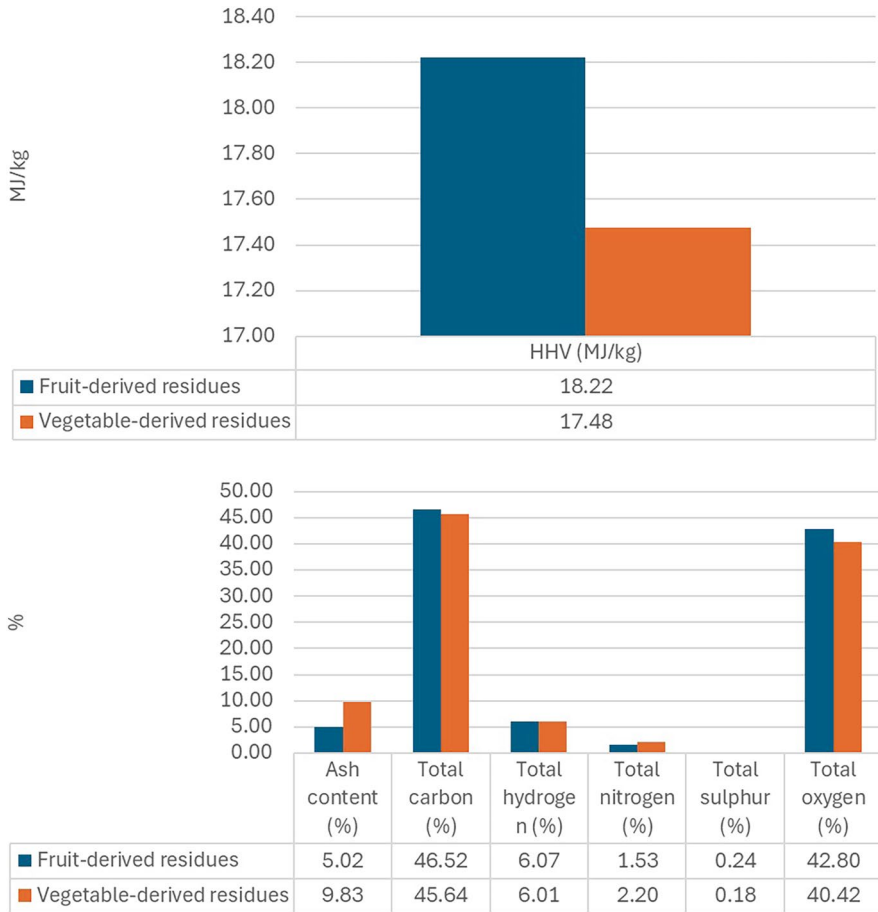
Like nitrogen, sulfur is another element with a low percentage value due to the problems it can cause. If emitted into the atmosphere, sulfur oxides are responsible for acid rain and can lead to the formation of acids inside the boiler, which can cause corrosion and deposits, known as slag, reducing combustion efficiency. The average value of the residues considered is 0.21%, a high value for the limits defined in ISO 17225-2:2021 to classify pellets as A1, A2, and B. Below these levels and the average value are the samples studied by authors Pulidori et al. (2023), Fermanelli et al. (2020), and Mata-Sánchez et al. (2013), among others. In these studies, the values in some cases are below the detection limit by the considered method and around the values necessary to produce pellets classified with the A1, A2, and B categories. Values exceeding the average and the values considered in the quality standard include notable values such as peanut shell (0.5%), pine kernel shell (0.6%), and coffee husk (0.5%).

Oxygen is another element highly present in the vegetal or agro-industrial residues shown in Table 1.2. Inside the boiler, oxygen is necessary for combustion, and excess oxygen increases combustion efficiency, reducing carbon monoxide emissions. However, excessive oxygen can also affect heat transfer and nitrogen oxide formation due to flame temperature. The average value of the biomass residues considered is 41.59%. Above this value are grapefruit peel waste (52.5%), pomelo peel waste (54.00%), and lemon peel waste (53.10%). Below the average value of the values shown in Table 1.2 are zucchini waste (27.84%), cucumber waste (31.12%), and bean waste (33.18%) among others.

By way of summary and comparison, the agro-industrial waste considered in Table 1.2 has been classified into fruit-derived residues and vegetable-derived residues. Figure 1.3 illustrates that, in the parameters deemed desirable for high values, HHV (MJ/kg), total carbon (%), and total oxygen (%), the fruit-derived residues exhibit higher values than those observed in the vegetable-derived residues. Similarly, in the context of low values, which are desirable in biomass residues, the ash content (in percentage form) is lower in fruit-derived residues than in vegetable-derived residues.

### 1.5.2 Predictive Equations of HHV

In the search for sustainable and renewable energy sources, agro-industrial waste has emerged as a promising option. These byproducts, produced by agricultural



**Fig. 1.3** Comparison of fruit-derived residues and vegetable-derived residues

operations and the food industry, represent a significant source of biomass that can be utilised for the generation of energy. However, in order to achieve the greatest possible energy efficiency, it is of the utmost importance to gain a comprehensive understanding of the calorific value of these materials and to accurately predict it. The calorific value, which indicates the amount of energy released during the combustion of a material, is a crucial factor in assessing the viability of a material as an energy source.

This section will review and analyse various HHV prediction equations developed in previous scientific studies. These equations, which are based on the chemical composition and physical properties of agro-industrial wastes, represent fundamental tools for estimating the energy yield of these materials. A comprehensive grasp of these equations will enable researchers and energy professionals to optimise the utilisation of agro-industrial waste for heat and power generation,

thereby contributing to the transition towards a more sustainable and environmentally friendly energy system.

Tillman (1978) proposed an equation for determining the higher heating value of wood residues. Due to its reliability, this equation has been utilised in numerous subsequent studies, notably the study conducted by Yin (2011). Yin performed proximate and ultimate analyses on various biomass residues to propose equations capable of predicting heating values based on the results of these analyses. The robustness of the equation is demonstrated by the mean absolute error between the values predicted by Yin's eqs. (2011) and those predicted by Tillman's eq. (1978), among others, with a mean absolute error of less than 5%. In this context, Perea-Moreno et al. (2016) conducted a study to estimate the heating value of avocado seeds, showing an error of less than 1% between the predicted value using Tillman's eq. (1978) on the results obtained from the ultimate analysis and the measured higher heating value obtained through the protocol established in the UNE-EN 14918:2011 standard.

Abe (1988) conducted a study on the heating value of forest biomass residues in Japan. This study has been cited by authors such as Qian et al. (2021), who investigated the thermal properties and combustion issues of agricultural residues and used Abe's eq. (1988) as a predictive model for the heating value based on the percentages of C, O, and H obtained from the ultimate analysis. Qian et al. (2021) proposed various models referencing Abe's eq. [36] and estimated that the mean absolute errors of the new models proposed by Qian et al. (2021) were lower than those of Abe's model (1988). Similarly, Maksimuk et al. (2020) conducted a systematic study of different equations, including Abe's [36], to predict the heating value of lignin-based on elemental analysis results.

In a study conducted by the Institute of Gas Technology (1978), an equation was proposed to relate the higher heating value and the composition of coal-derived from various biomass residues. More recently, Perea-Moreno et al. (2016) evaluated the model to predict the higher heating value, estimating an error of 2.05% with the values obtained by direct methods (UNE-EN 14918:2011). The same study also evaluated the models of Graboski and Bain (1979), Channiwala and Parikh (2002), Demirbaş (1997), and Jenkins and Ebeling (1985). The model with the best prediction accuracy was proposed by Channiwala and Parikh (2002), with a 0.45% error, followed by Tillman's eq. (1978), while the model with the worst prediction was proposed by Jenkins and Ebeling (1985), with a 9.56% error.

Sheng and Azevedo (2005) proposed two equations for calculating the higher heating value based on ultimate analysis results. They compiled a large amount of data to evaluate the considered equations and their proposed ones, obtaining  $R^2$  values for all studied equations, including those of Tillman (1978), IGT (1978), Graboski and Bain (1979), Channiwala and Parikh (2002), Demirbaş (1997), and

Jenkins and Ebeling (1985). The best determination coefficient values were achieved with Sheng and Azevedo's eqs. (2005), Ec. (8, 9) with values of 0.758 and 0.834, respectively, and Jenkins and Ebeling's eq. (1985), Ec. (7), with an  $R^2$  value of 0.792. The lowest value was obtained with Demirbas's eq. (1997), with a value of 0.081. They also estimated the mean absolute error of the previous equations, measured between the predicted value based on ultimate analysis results and the higher heating value. In most studies, the quantified error was below 5%, with Sheng and Azevedo's eq. (2005) showing the lowest error at 2.59% and Demirbas's eq. (1997) showing the highest error at 6.73% based on ultimate analysis data.

Boumanchar et al. (2019) proposed several equations, shown in Table 1.3, to predict the higher heating value from ultimate analysis results using two methods: multiple regression Ec. (10, 11, and 12) and genetic programming Ec. (13). The statistical parameters considered for each model's performance were the mean absolute error and the correlation coefficient between predicted and measured values. Statistical estimators were also used for model validation against those proposed by other authors, including Callejón-Ferre et al. (2011). The best equation for predicting the heating value based on element percentages from the ultimate analysis was Ec. (13), with a correlation coefficient ( $R^2$ ) of 0.761 and a mean absolute error of 6.088%. The authors conducted the same study with eqs. (17, 18, 19, 20) shown in Table 1.3 by Callejón-Ferre et al. (2011). In this case, the correlation coefficients between measured and predicted values ranged from 0.4187 for Ec. (19) to 0.4789 for Ec. (17).

Callejón-Ferre et al. (2011) proposed various models for predicting the higher heating value of biomass samples from greenhouse crops in the Almeria region (Spain). The study compared directly measured heating values with predicted values, showing a high correlation between them. Among all proposed equations, those shown in Table 1.3 have  $R^2$  values ranging from 0.9890 for Ec. (17) to 0.9917 for Ec. (19). As a quality indicator, the authors estimated the mean square error, with the lowest values among the equations in Table 1.3 being for Ec. (19) and Ec. (20). Bychkov et al. (2017), in a similar vein, proposed eqs. (14, 15, 16) for calculating the higher heating value of various biomass residues, concluding that they are useful for routine and automatic heating value calculations.

Noushabadi et al. (2021) used an algorithmic method to propose eq. (21) and reviewed studies by Callejón-Ferre et al. (2011), Sheng and Azevedo (2005), and Channiwala and Parikh (2002), among others. The correlation coefficient of the proposed equation was 0.92, and they concluded that the proposed model and the reviewed ones could be useful for the design and optimisation of power plants.

**Table 1.3** HHV correlations equation of representative scientific studies

Number	References	Correlation Eq. (MJ/kg)
1	Tillman (1978)	$HHV = 0.4373C - 1.6701$
2	Abe (1988)	$HHV = 0.3391C + 14340H - 0.0970$
3	Institute of Gas Technology (1978)	$HHV = 0.341C + 1.322H - 0.12O - 0.12N + 0.0686S - 0.0153Ash$
4	Graboski and Bain (1979)	$HHV = 0.328C + 1.4306H - 0.0237N + 0.0929S - [1 - (ash/100)] (40.11H/C) + 0.3466$
5	Channiwala and Parikh (2002)	$HHV = 0.3491C + 1.1783H + 0.1005S - 0.1034O - 0.0151N - 0.021Ash$
6	Demirbas (1997)	$HHV = 0.335C + 1.423H - 0.154O - 0.145N$
7	Jenkins and Ebeling (1985)	$HHV = 0.301C + 0.525H + 0.064O - 0.763$
8	Sheng and Azevedo (2005)	$HHV = 0.3259C + 3.4597$
9	Sheng and Azevedo (2005)	$HHV = -1.3675 + 0.3137C + 0.7009H + 0.0318O$
10	Boumanchar et al. (2019)	$HHV = 0.2328C + 6.9703$
11	Boumanchar et al. (2019)	$HHV = 0.2037C + 0.9115H + 2.7329$
12	Boumanchar et al. (2019)	$HHV = 0.2425C + 0.6280S + 6.4386$
13	Boumanchar et al. (2019)	$HHV = C + H + S + [171/(C - 63.3)] + [0.399/(O - 52)] + [0.0727/(C + H + 53.4S - 52.5HS - 1.1N)] - 23.7$
14	Bychkov et al. (2017)	$HHV = 0.4373C - 1.6701$
15	Bychkov et al. (2017)	$HHV = 0.00355C^2 - 0.232C - 2.230H - 0.0512CH + 0.131N + 20.600$
16	Bychkov et al. (2017)	$HHV = 0.328e + 1.4306H - 0.0237N + 0.0929S - [1 - (ash - 40.11 \cdot H)/(100 \cdot C)]$
17	Callejón-Ferre et al. (2011)	$HHV = -3.147 + 0.468C$
18	Callejón-Ferre et al. (2011)	$HHV = -2.907 + 0.491C - 0.261H$
19	Callejón-Ferre et al. (2011)	$HHV = -3.393 + 0.507C - 0.341H + 0.067N$
20	Callejón-Ferre et al. (2011)	$HHV = -3.440 + 0.517(C + N) - 0.433(H + N)$
21	Noushabadi et al. (2021)	$HHV = -0.8738NH^{1.3101} - 0.1583CO^{0.3497} + +0.3856C(HO)^{0.1462} + 2.1436(H/O)^{0.3846} + +0.1076CH^{0.3846} + 0.1098NS - 11.2794(H/C)$

## 1.6 Conclusions

A bibliometric analysis of the past 20 years shows an increase in research on the conversion of agro-industrial waste into energy. This growth is driven by the need for alternative energy sources, environmental concerns, and supportive policies. Brazil, Italy, and India lead in terms of publications. Key institutions focus on bio-energy from sugar cane, diverse biomass sources and microalgae. Key research areas include biotechnological processes, energy production efficiency, thermochemical processes, water purification, and hydrogen production. The global effort reflects a commitment to developing sustainable solutions for the management of agro-industrial wastes.

Recent advances in energy valorisation focus on harnessing the substantial energy potential of agro-industrial wastes, ranging from fruit peels to cereal straws. Various methods, including predictive models and case studies, assess their energy potential, which is crucial for the transition to sustainable energy systems. Compositional analysis reveals key elements such as carbon, hydrogen, nitrogen, sulphur and oxygen that influence combustion behaviour and environmental impact. In particular, fruit residues often have higher calorific values and lower ash content than vegetable residues. Predictive equations, such as those proposed by Sheng and Azevedo (2005) and Boumanchar et al. (2019), facilitate accurate estimation of higher heating values based on elemental composition.

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# Top-Value Bioproducts Selection for the Forest Biorefinery in the Current Bioeconomy Framework

# 2

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## Abstract

The FAO defines bioeconomy as “the production, utilisation, and conservation of biological resources, including related knowledge, science, technology, and innovation, to provide information, products, processes, and services across all economic sectors aiming toward a sustainable economy.” In this framework, the diversity of the forest resources provides potential opportunities to produce innovative and profitable bioproducts, biomaterials, and biofuels that can be obtained from the forest biorefinery, depending on the raw materials, technology, and other defining factors. This wide variety compels selecting the best ones for future biorefinery implementation. Several countries have been working on this selection for a couple of decades. However, it is time to update previous studies due to the changing economic and political context affecting the world markets. This chapter presents potential bioproducts selected by different countries or regions in previous years and defines top-value bioproducts for developing future biorefineries based on data from official organisations.

## Keywords

Bioeconomy · Bioproducts · Forest biorefinery · Sustainable economy

## 2.1 Introduction

The forest biorefinery involves diverse resources providing potential opportunities to produce innovative and profitable bioproducts, biomaterials, and biofuels, depending on the raw materials, technology, and other defining factors. This wide

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variety compels selecting the best opportunities for future biorefinery implementation. Numerous bioproducts, biomaterials, and biofuels are obtained in biorefineries depending on the raw material, technology, and other defining factors, such as the market. In the last two decades, technical reports generated by industry, academia, academic-industry consortia, and organisations to identify and rank building block chemicals based on sustainability, technical, and economic criteria resulted in different lists of proposed bioproducts based on their importance in food, plastic, pharmaceutical, cosmetic, biofuel, and bioenergy industries. The building blocks are molecules with multiple functional groups that can transform into new families of useful molecules. Biological transformations account for most routes from plant raw materials to building blocks. Still, chemical transformations predominate in converting building blocks into molecular derivatives and intermediates, which can transform into high-value biochemicals and biomaterials. Several countries have been working on this selection for a couple of decades. However, it is time to update previous studies due to the changing economic and political context affecting the world markets. This chapter presents potential bioproducts selected by different countries or regions in previous years and defines top-value bioproducts for developing future biorefineries based on data from official organizations.

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## 2.2 Methodology

This study's methodology involves research in internet-based reports generated by official organizations from different countries or regions regarding policy strategies and roadmaps developed and implemented in the last two decades (from 2004 to 2024). The findings were classified depending on the type of source (Table 2.1):

**Governmental:** Publicly government reports from ministries, government agencies, or councils.

**Academic:** Research reports from educational institutions (universities and institutes).

**Industrial:** Research reports from companies or business groups.

**Consortium:** Research reports from international organizations and networks, including academic, business, and government institutions.

The main criteria of interest considered in the selection of bioproducts targeted for research include:

- The product could serve as a platform chemical component for a biorefinery.
- The product is produced using a conversion technology that is widely applicable to multiple products and (or) fuels.
- The product is a direct substitute for an existing petrochemical one.
- The product can be produced with an improved greenhouse gas (GHG) profile over its petrochemical counterpart (life cycle analysis).
- The product has a large market.

**Table 2.1** Screening of internet-based reports based on resource and region/country

Source	Governmental	Academy	Industrial	Consortium
E.U.		2		1
Nordic/Baltic countries	1			1
United States	3	1		2
Canada	1	1		
China		1		1
India	1			
Russian Federation			1	1
Australia	1		1	
Scotland			1	
Brazil			2	
Uruguay	1			
Spain				1
Argentina		1		
Total Reports: 25	8	5	5	7

- The product has unique and desirable characteristics.
- The product can be generated from waste streams from fuel production.
- The product is synthesised using known technology.
- The product is part of a market niche.
- The product is a novel molecule (i.e., not a direct replacement for a petrochemical product).

The main criteria of interest considered in the selection of bioproduct production involve:

- The product should be simple and start with an easy platform chemical to reduce risk.
- The selected technologies must use multiple raw materials, including waste streams from other processes.
- The product must be produced using existing infrastructure.
- The consideration of the economic viability of the target product may lead to targeting a large market or a niche.
- The product must be an environmentally friendly direct replacement for a petroleum-derived product.
- There should be consumer demand and market momentum for the products.

Finally, tables were prepared showing the frequency of selection of each product in all reports. Those with the highest frequency were selected as the top-value bioproducts for the forest biorefinery in the current bioeconomy framework. The data collected were combined in a table to assess the potential of the bioproducts in the global markets.

## 2.3 Top-Value Bioproducts Reported in the Last Two Decades

Figure 2.1 shows countless products derived from the forest biorefinery. However, the technical-economic evaluation of each production means that some are considered more interesting than others. Figure 2.2 presents the high-added-value products considered of interest in all the evaluated cases. It includes the list of products in order of preference according to their frequency of appearance in the different reports.

Other reported products for forest biorefinery (< three times) are formic acid, methanol, Bio-DME (1,2-dimethoxyethane), furfural/hydroxymethylfurfural/2,5-furan dicarboxylic, ethylene, 1,4-butanediol (BDO), wood-bioplastic composites (WPC), carboxylic acids, glycerol, 1,3-propanediol, glycols, propylene glycol, activated carbon, phenols (BTX), other aromatic compounds, sorbitol, pellet, cellulose nanocrystals, bio-polyethylene (BioPE), jet-fuel, vanillin, resins, glutaric acid, 3-hydroxypropionic acid (3-HP), ethyl lactate, 1,3-butadiene, isoprene (2-methyl-1,3-butadiene), fertilisers, fatty alcohols, propene, forage, gasoline, kerosene, epichlorohydrin, 3-hydroxybutyrolactone, lignin-based adhesives, bioplastic from tall oil, adipic acid, cycloalkanes, and isobutyl acetate.

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## 2.4 Regional and Country Strategies and Reports

### 2.4.1 European Union (E.U.)

The BIOREF-INTEG project was funded by the European Commission (2008–2010), coordinated by the Netherlands Energy Research Center (ECN), and supported by 12 other European partners, ranging from small and medium-sized enterprises (SMEs), and industrial, university, and institute partners. Its main objective was to develop advanced biorefinery schemes to integrate them into existing fuel-producing industrial complexes in sectors that use biomass as raw material: sugar/starch (bioethanol), biodiesel, pulp and paper, conventional oil refineries, energy production, food industry, and the agricultural sector. In 2010, the BIOREF-INTEG project published a comprehensive list of products and chemicals derived from biomass processing systems with their technical potential (318 products in total). In addition, it displays the results of the market analysis and a list of 12 products with the most significant potential from their partners' point of view.

In 2018, the BRISK2 project—funded by the E.U. Horizon 2020 programme to contribute to international biofuels research and implementation—identified the most promising bioproducts linked to inherent infrastructure capabilities. Different pathways were explored in Europe toward converting multiple feedstocks into valuable products that replace refinery materials and energy from fossil resources, developing 10 bioproduct value chains based on different biomass types. The expectations were to offer processes and technologies to identify potential high-value chemicals, new biofuels, and biofuel blends (Kraia et al. 2018).

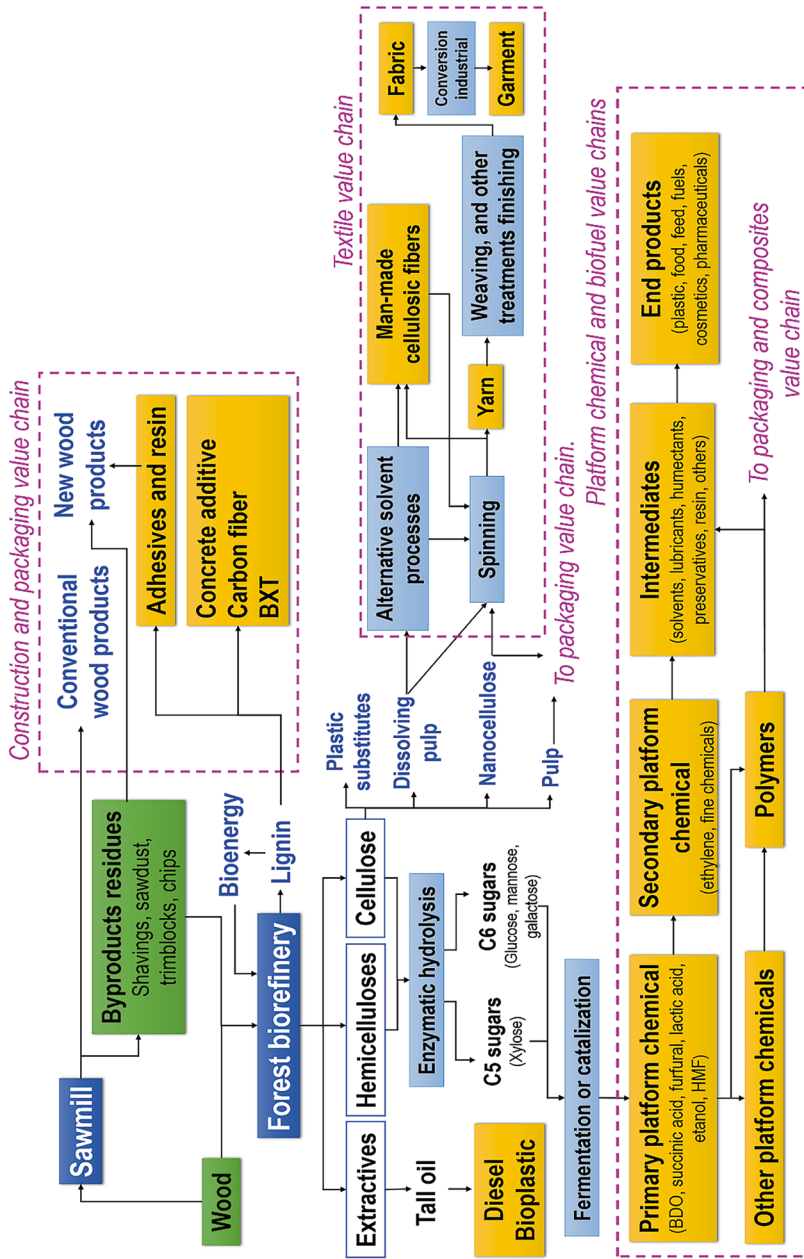
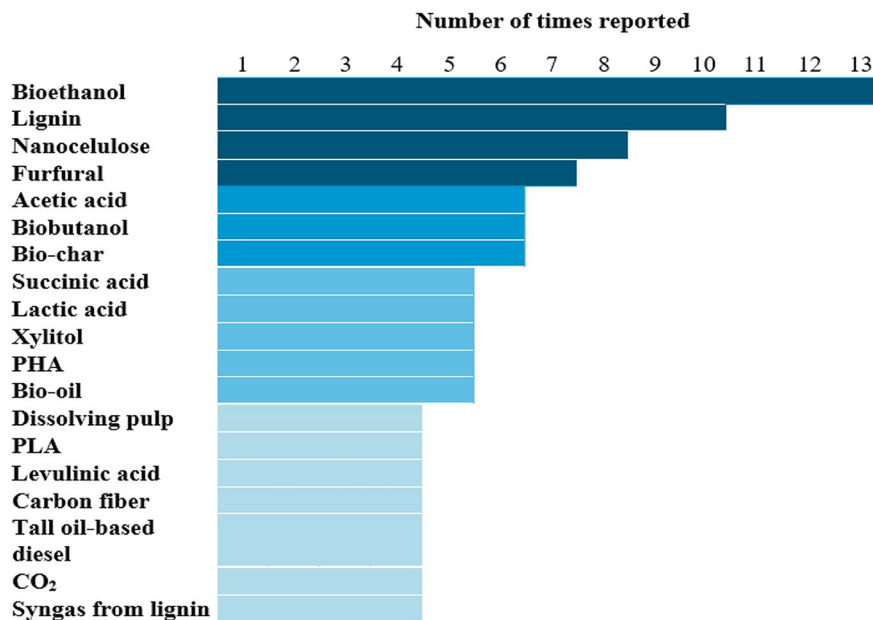


Fig. 2.1 Product chains from the forest biorefinery. (Adapted from Hummekoski et al. 2018)



**Fig. 2.2** Significance of biocomposites, biomaterials, and biofuels in different reports. (*PHA* polyhydroxyalkanoates, *PLA* polylactic acid)

In 2021, the BioMonitor project, based on interviews, surveys, and document analysis, identified 9 among 21 products ordered in 5 categories (construction materials, bioplastics, biochemicals, wood-based composites, and textiles) that can be produced from wood biomass. These products were selected based on technological readiness level (TRL from 5 to 9) or time to market estimation (from <5 years to 9 years). Although some products are obtained at a pre-commercial scale, their markets are mature or well-established in a value chain. BioMonitor project was funded by the European Union's Horizon 2020 to monitor the bioeconomy and its impacts. Lignin-based adhesives and glycols were identified as potential chemicals to produce adhesives, bioplastics, and biofuels. In contrast, plastic materials from bioethylene and tall oil were considered potential bioplastics in the packaging. Wood-based composites were considered potential materials for packaging, single-use items, and bathroom furniture (Hasegawa et al. 2021).

#### 2.4.2 Nordic/Baltic Countries

This study was carried out within the framework of the LigniMatch project among a group of industries, universities, and organizations from the Nordic/Baltic countries to explore the economic potential of lignin. They used information from the literature, patents, and contributions from the project partners. Based on this information, the most promising products in the international market were selected,

excluding those applications that are commercially available (energy products, products in already mature markets, such as dispersants, surfactants, and vanillin). They have focused on applications with developing potential in new markets. The lignoboost process resulted in the technology with the most potential for lignin isolation from Kraft black liquor and the most significant probability of being implemented in cellulosic plants in the short term. Its implementation requires a future lignin market to compensate for the high investments (LigniMatch-Project 2010).

The products of interest were selected based on the following criteria: (i) the products and processes must be relevant to project partners, (ii) the availability of raw materials and the capacity of the production lines must not constitute a barrier, and (iii) property rights considerations. After identifying and evaluating a wide range of products, activated carbon, carbon fibre, and phenols were selected as the relevant products. After a deeper analysis of these products regarding energy and environment, market potential, and innovation system, the conclusion was that carbon fibre production was currently the route with the most significant potential (LigniMatch-Project 2010).

The Nordic Council of Ministers supported a project to fortify the bioeconomy, in which scientists and the governments of the Nordic countries participated to analyse and map the status of the bioeconomy and identify potential opportunities. They have focused, among others, on biofuel, food and feed ingredients, chemical building blocks, new materials, and cosmetics. Norway was characterised by the availability of forestry biomass and commercialised products from wood, with Borregaard as the most significant commercial integrated biorefinery in Norway, producing multiple products, such as cellulose, ethanol, vanillin, lignin, lignosulfonates, and bioenergy. Finland is the country that has the main proportion of forestry and forest-based industries, accounting for several biorefineries (liquid, gas, and solid biofuels, electricity, and heating). Sweden focused on transportation fuels (mainly bioethanol and biogas) and bioproducts from the biorefineries, including platform chemicals, specialty chemicals, pharmaceuticals and fertilisers, and food and feed additives from its forest biomass resources. Denmark identified some value chains from forest biomass, including the sugars and lignin conversion into second-generation biofuels and biomaterials that are at a very early stage (biofuels, bioenergy, fertilizer, chemicals from sugar platforms, and biomaterials). Iceland, the Faroe Islands, and Greenland account for more significant marine bioresources than forest biomass (Lange et al. 2015).

### 2.4.3 Sweden

This 2015 report for the Research Institutes of Sweden (RISE) presented eight complementary work plans on developing value chains for innovative products in the forestry industry, focusing on multidisciplinary and close collaboration between research institutes, universities, industry, and government. RISE, formed by Innventia, SP, Swerea, and Swedish ICT, operates as a centre of excellence and

innovation, with modern testing and demonstration facilities and an extensive network with higher education institutions, government, and the private sector. These work plans are related to (i) the development of conventional products of the paper industry based on the biorefinery concept, (ii) the production of carbon fibre from lignin, (iii) nanocellulose and the production of materials developed from it, (iv) pulp for dissolution and the development of new production processes of textile fibres, (v) composite materials with wood fibres for construction, (vi) the use of byproducts of the pulp industry (heat, CO<sub>2</sub>, nutrients, others) in the food industry, (vii) coal as biofuels for the metallurgical industry, and (viii) biosensors (RISE 2016).

#### 2.4.4 Scotland

Scottish Enterprise presented a report (2015) produced by Chemicals Scotland and Forestry Commission Scotland, based on an analysis of the net forest resources that could be available as resources for bioproducts industries in Scotland, the nature of the existing infrastructure and academic knowledge base, the potential opportunities at global scales of production capacity, and the necessary steps to take advantage of these opportunities. The report indicates that Scotland has limited industrial chemical interest in bioproducts; few relate to relatively simple plant extracts. Only one pulp and paper mill in Scotland uses virgin mechanical pulp wood. In contrast, across academia, industry/industry, and associated knowledge groups, there is a wide range of knowledge on biomass transformation and biotechnology relevant to bioproduct development, but with little attention paid to forest resources. Products identified by previous studies as particularly suitable for exploitation in the United Kingdom were: 3-hydroxypropionic acid (3-HP), butanol, glucaric acid, lactic acid, levulinic acid, methyl methacrylate (MMA), polyethylene, polyhydroxyalkanoates, sorbitol, succinic acid, Syngas, and xylitol (Turley et al. 2015).

#### 2.4.5 Spain

The Spanish Biomass Technology Platforms for the bioeconomy (BIOPLAT) and Sustainable Chemistry (SusChem-Spain) have prepared a biorefineries handbook in Spain (2017) to provide knowledge and identify the advantages that biorefineries would bring to Spain. It is a sector considered as incipient due to its limited implementation. Concerning the forestry sector, the public-private initiatives to date are (i) bioethanol, biogas, bioplastics, bioproducts; pilot/demonstrative scale by Fundación Tecnalia Research & Innovation; (iii) use of forest biomass to produce synthesis gas and biofuel; laboratory/pilot scale in San Sebastián; and (iv) use of forest biomass to produce biofuel (BioH<sub>2</sub>); laboratory/pilot scale in San Sebastián (BIOPLAT-SusChem 2017).

### 2.4.6 The United States

In 2004, the Pacific Northwest National Laboratory (PNNL), National Renewable Energy Laboratory (NREL), and Office of Energy Efficiency and Renewable Energy (EERE) issued a report identifying 12 chemical components produced from sugars through biological or chemical conversions (Werpy et al. 2004). A systematic screen of top-valued products from an initial list of more than 300 compounds using strategic criteria, including estimated raw material and processing costs, sales price, technical complexity associated with the best route of available processing, and market potential for each candidate, involved the following criteria.

***Direct Product Replacement*** They compete directly with existing products and petroleum-derived chemicals. The markets already exist. Cost structures and growth potential are understood. Risks in the market are substantially low. There is strict competition on cost. They compete against depreciated capital. There is a limited “market differentiation” (green label) for bio-based and petrochemical sources.

***New Products*** Those having new and improved properties to replace existing functionalities or new applications. Novel products have unique properties, so cost issues are less critical. There are no competitive petrochemicals routes. The desired performance usually defines the differentiation. New market opportunities. More effective use of the properties inherent to biomass. The unclear definition of the market and the high capital risk extend the time to market.

***Intermediate Building Blocks*** A single intermediate provides the base of a diverse product portfolio. They incorporate the advantages of both replacement and novel products. The investment capital can be distributed among a large number of unit operations. The market potential expands, and product trading strategies reduce market risks. It needs to identify where to focus R&D.

The potential building block candidates resulting from this initial selection were classified according to (i) they exhibit multiple functionalities suitable for further conversion as derivatives or molecular families, (ii) they are generated from both ligno-cellulosic and starch, (iii) they are C1 —C6 monomers, (iv) They are not aromatic compounds derived from lignin, and (v) they are not commodities. Several reports emerged in different countries or regions, identifying the most promising bioproducts or biomaterials according to the economic circumstances and place (Werpy et al. 2004).

In 2010, a report presented by the US forest products industry to position it for long-term sustainable growth aimed at guiding the R&D priorities needed to transform products and manufacturing processes. The main objective was to provide R&D groups with information on the technological needs of the forest products industry. The American Forest & Paper Association (Agenda 2020 Technology Alliance) and the Institute of Paper Science and Technology (IPST, Georgia Tech)

held several workshops that led to this report, involving wood, pulp, and paper-producing companies, suppliers, government agencies, universities, and other organizations. The R&D needs to improve profitability through products with higher added value than conventional ones like pulp, wood-primary industrialised products, energy, fuels, electricity, and chemicals. Requirements are (i) the development of processes to produce materials based on lignin with higher value than its use as fuel; (ii) development of selective catalysts for the conversion of sugars into chemicals, polymers, and fuels; (iii) development of new uses and markets for carbon fibres and nanocellulose-based materials; (iv) design of a viable black liquor gasification process and installation on the market; (v) energy integration in the pulp mill with biorefinery processes; (vi) CO<sub>2</sub> capture and conversion; (vi) development of policies that allow a transition to biorefineries; (vii) improvement in chemical pulp yield to >50%; and (viii) biochemical conversion to valuable products (AF&PA 2010).

A 2015 NREL report presents the results of a market assessment to identify the possibility of promising bioproducts production in the near term (Biddu et al. 2016). This assessment focuses on ready-to-use bio-based chemicals (e.g., solvents) or intermediate products converted into raw material for further processing. These bioproducts can compete with petroleum-based chemicals as direct replacements or provide unique properties exclusive from biomass production. Based on recent economic assessments of technological pathways focused on hydrocarbon production from biofuels, functional replacement, and substitution bioproducts, they could be significant drivers for developing an economically viable and sustainable biorefinery. The initially selected products were reclassified according to the following criteria: high volume or value; high global and domestic growth; interest/financing of the state body; market demand; current scale; market maturity; raw material flexibility; chemical platform; integrated with representative hydrocarbon conversion pathways; no competition with natural gas; with end-user specifications; with bio-process advantage; with favourable life cycle; short-term implementation (high level of TRL, level of technology availability) (Biddu et al. 2016).

Maine-State (2018) supported studies that shared the long-term vision for the forestry sector. It allowed the key opportunities to identify challenges and obstacles in domestic and foreign markets, such as the potential markets that fit forests and other resources. Some of the criteria used to select the most attractive products include (i) increasing the use of conifers available in Maine; (ii) providing a market for waste produced by current industry; (iii) providing long-term sustainable high-value employment opportunities; (iv) providing real, long-term, and lasting added value to the state of Maine; and (v) producing profitable products for local or global markets (Indufor 2018). In addition to chemical bioproducts, traditional products were analysed, including sawn wood (structural), laminated veneer lumber (LVL), orientated strand board (OSB), medium-density fibreboard (MDF), pellets, wood-plastic composites (WPC), bioplastic composites (BPC), activated carbon, and dissolving pulp (Maine-State 2018).

In 2023, a study on decarbonising the US economy identified several biofuels and bioproducts, such as deploying large-scale biorefineries. It provided an economic and environmental analysis of next-generation biorefineries using a novel biomass fractionation method. This study was supported by the Center for Bioenergy

Innovation (CBI) of the US Energy Bioenergy Research Center. This study provided a guide to further research and revealed that the valorisation of lignin to hydrocarbon fuels increases integrated biorefinery competitiveness concerning simple lignin combustion (Klein et al. 2023). In the same way, a recent study entitled “Roads to Removal: Options for Carbon Dioxide Removal in the United States,” published at the end of 2023 by the US Department of Energy, identified several promising biofuels and bioproducts from biomass conversion that can be implemented in the United States by evaluating, among others, conversion pathways, biomass distribution, and plant capacity (Pett-Ridge et al. 2023).

### 2.4.7 Canada

In 2018, a study identified new wood-based products (bioproducts, biofuels, and biomaterials) with potential and attractive markets, including textiles, liquid biofuels, platform chemicals, plastics, and packaging. It provided information on how these wood-based products could offset the projected decline in graphic paper markets in the four major forestry industry countries: the United States, Canada, Sweden, and Finland. The impacts on the use of wood are multiple since many new products use byproducts as raw materials, adopting 2030 as the time horizon for this study, which allows a long enough period for markets to adapt to changing demand. However, it restricts the analysis exclusively to new products that are already in the market or could soon be introduced to the market, reducing the uncertainty of the analysis. The adopted criteria were: high TRL, time to market less than five years, volume potential, availability of raw materials, market attractiveness (competition and competitiveness), cost competitiveness, and sustainability aspects. In addition to new bioproducts and biofuels, results include dissolving pulp for textile fibres, wood-plastic composites (WPC), and cross-laminated timber (CLT). Biochemical markets remain primarily unexplored, partly due to their great complexity arising from the many combinations of feedstocks, pretreatment options, sugars, conversion technologies, and downstream processes. The selected products are platform chemicals used by other companies in the chemicals value network to produce various derivative chemicals and end-use products (Hurmekoski et al. 2018).

In 2022, the United Nations Economic Commission for Europe (UNECE) presented a trade, economics, and industry study for the Canadian Forest Service Natural Resources Canada. It showed that Canada has a domestic market for bioenergy, wood, pulp and paper products, biopolymers, bioplastics, lignin (mainly as a concrete additive), nanocellulose (used in composites, packaging, and personal care products), and cellulose nanocrystals (UNECE 2022).

### 2.4.8 China

Since the late 1970s, China has launched many large-scale “Great Green” projects for afforestation and reforestation in the country for economic reasons, as well as to address climate change and mitigate desertification of arable lands. There is scarcity

of bioresources for wood fibre, which has affected the forest bioeconomy development. The biorefinery projects are related to first-generation bioethanol and biodiesel production. However, technologies for biomass conversion are still in their infancy. China currently produces bioethanol, lactic acid, and 1,3-propanediol from corn (Tan et al. 2010). The planting of more than 360,000 km<sup>2</sup> of forests is planned for 2050. Due to this country's high energy demand, around 500 million tonnes of forest biomass could be allocated to the energy sector, equivalent to 285 million tonnes (tons of coal equivalent) and around 2320 TWh (terawatt hours) (Sillanpää and Ncibi 2017).

Since 2007, the forest bioeconomy has been considered a potential strategy for achieving a sustainable development model focused on the biotechnology industry. It is a new concept that usually is associated with forest bioenergy. China lacked direct strategies or actions related to forest-based bioeconomy; however, the use of paper-based products is increasing due to the new regulations to reduce plastic consumption, promoting the development of bio-based plastics (Verkerk et al. 2022).

## 2.4.9 India

India is one of the largest economies in the world, and it has significant energy demand. In 2012, India's Ministry of Science and Technology produced a report on the long-term goals for achieving sustainable and cost-effective energy development. Some goals indicated 20% biofuel use by 2020 in blends and producing commercially viable lignocellulosic ethanol from agricultural and forestry waste (2G ethanol). Until then, India did not have the technology to produce 2G ethanol. The report proposes the development of technology and optimisation for converting the products: biodiesel, bioethanol, green diesel, algae biofuel, biobutanol, biohydrogen, bioproducts, and fuel cells (Government-India 2012). The government allowed the 2G bioethanol and planned to establish 2G ethanol biorefineries in the country from 2018 to 2024 (Verkerk et al. 2022).

## 2.4.10 The Russian Federation

A consulting company from the Netherlands carried out the market study within the framework of the Dutch-Russian Cooperation. The Russian Federation has established in its Energy Strategy (2009) that energy efficiency could be a priority until 2030. This study seeks to determine the possibilities of Dutch companies to export knowledge and technologies in biomass applications to Russia and the biomass import possibilities of that country. Russia has great potential for using alternative and sustainable energy resources but does not have the technology, nor is there internal demand, so this is a long-term goal (Larive-International 2013).

Regarding bioenergy production, the demand for technology related to equipment for production from wood, as well as torrefaction technology, is expected to increase. Russia is the world leader in forestry resources and owns a quarter of the

world's timber. The wood processing industry is a developed sector. The government policy is to reduce the export of low-value-added wood and logs and increase the processing level within Russia. The potential markets include the production of charcoal, wood pellets, and lignin pellets. The availability and low fossil fuel prices limit the Russian biofuels market. Therefore, biofuels have no direct opportunity; it is an underdeveloped industry. The biofuels with the most significant potential are bioethanol, biodiesel, and bio-butanol. Bioethanol production from wood is more feasible than other raw materials. Russia (Soviet Union era) had some hydrolysis plants that produced ethanol from wood. However, they were left aside after implementing technology for the industrial production of ethanol synthesised from natural gas. Biobutanol production from wood technology is being tested to make it commercial. Bioproducts do not yet have a good market established in Russia. A government policy stimulates its development, which is in its initial stage. The level of consumption of biotechnology bioproducts is relatively low compared to European economies since it imports more than 80% of biotechnology products. Until 2013, biodegradable materials (packaging, automotive plastics) and bioproducts still did not have a market (Larive-International 2013).

A recent study (2020) reported a systematic analysis of forest resources and the potential for carbon sequestration. It includes innovative development for new wood-based products and the forest industry, such as (i) biofuels (pellet, bio-char, bio-oil, biogas, bioethanol); (ii) wood-based textiles (dissolving pulp for viscose, Spinnova and Ioncell-F); (iii) wood-based chemicals (BTX, lignin); and (iv) biodegradable bioplastics from sugars and tall oil (Leskinen et al. 2020).

### 2.4.11 Australia

In 2013, a report in collaboration with the VTT Technical Research Center of Finland analysed the opportunities for the forest and timber products industry and the associated value chain with other Australian manufacturing industries. The analysis was carried out considering (i) products for the construction industry, (ii) paper and packaging products, (iii) bioproducts and bioenergy, and (iv) nanomaterials. Among construction products, sawn and profiled wood, value-added wood products (furniture, carpentry products, among others), and new materials (composite materials reinforced with lignocellulosic fibres) stand out. The paper and packaging products analysed were mainly tissue paper and hygiene products. In addition, it analysed biorefineries' technology for producing biofuels, mainly from the fermentation of sugars, and the pyrolysis technology to produce biofuel oil and bio-char. The biomaterials market focuses on biodegradable bioplastics such as polylactic acid (PLA), polyhydroxyalkanoates (PHA), and starch-based polymers. The market sectors for bioproducts were food, medicines, and cosmetics. In the nanotechnology sector, the different types of nanocellulose and the products obtained from these nanomaterials were considered (Ahlqvist et al. 2013).

In 2014, another report jointly produced by Deloitte Access Economics and Corelli Consulting estimated the economic impacts of a future tropical biorefinery

industry in Queensland. Based on scientific information from industrial biotechnology, case studies, and potential products, it considers the advantages of climate and agriculture that guarantee the high availability of biomass to produce chemicals, plastics, and fuels. In addition, it states that biorefineries would be a viable source of economic growth and diversification of national industries and generators of export income. This initiative proposes the installation of multiple biorefineries throughout the state, placed together with their raw materials (agricultural, forestry, and other lignocellulosic waste). These regional biorefineries would generate a platform of fine chemical products. The selection included seven biorefinery projects for discussion and economic impact analysis, one based on the production of levulinic acid, formic acid, acetic acid, and furfural from forest residues. The other projects analyse other raw materials (mainly sugar cane and sorghum and their waste) for the production of succinic acid and specialty chemicals such as xylitol, furfural, phenolic resins and aviation biofuel, bioethanol, electricity, and animal feed local consumption. The impact analysis economics concludes that biorefineries are viable without government subsidies (Corelli-Consulting 2014). However, some government facilities would help establish the industry. Until 2020, this country lacked a bioeconomy strategy but has developed studies in numerous sectors (agriculture, bio-based chemicals, bio-based packaging, biofuels, bioenergy, biorefining, and others) (Verkerk et al. 2022).

#### **2.4.12 Brazil**

Until the last decade, Brazil had several policies for the forest bioeconomy; however, it lacked integrated strategies (Verkerk et al. 2022). A study carried out by the Planted Forest Base Industry Department of the Basic Inputs Area (Banco Nacional de Desenvolvimento Econômico e Social, BNDES) in 2016 dealing with the development of biorefineries integrated with cellulosic plants in Brazil indicated that the biorefineries of lignocellulosic materials in Brazil have focused on producing second-generation ethanol from sugarcane bagasse, achieving a consolidated technological development, but that it has not yet reached competitiveness concerning first-generation ethanol (Nali et al. 2016).

Regarding the pulp and paper sector, it indicated that various research groups in institutes and universities (Instituto de Pesquisas e Estudos Florestais and Embrapa Floresta, mainly) and large companies in the sector (Suzano, Fibria recently acquired by Suzano, and Klabin) are working on the issue. Between 2012 and 2014, a study group was formed for the creation of a technology centre led by the Centro de Gestão e Estudos Estratégicos (CGEE), similar to the Laboratório Nacional de Ciência e Tecnologia do Bioetanol (CTBE) for sugarcane. This centre would act in association with the CTBE due to the similarities between the research of both biorefinery types (sugar cane and forest biomass) to promote the technological development of biorefineries for the pulp and paper sector. The report mentions a significant interest in using lignin to manufacture higher-value products, such as carbon fibres, vanillin, aromatics, activated carbon, and phenolic resins. Obtaining

nanocellulose and nanocrystals is also a promising alternative, as is the production of sugars and subsequent conversion into biofuels and chemicals. However, bioethanol production would be less economically attractive for companies in the short and medium term due to competition with the sugar alcohol industry, which is more advanced (Nali et al. 2016).

Until 2016, no public data was available to analyse various potential markets considered in this study. However, it was possible to size the market for bioproducts derived from lignin. The alternative technological routes to obtain higher-value products could also depend on technological and market advances, commercial alliances between pulp and paper-producing companies, and the chemical, automotive, capital, and biotechnology industries, implying a cultural change in the sector. In 2020, the *Industria Brasileira de Árvores (IBA)* published the annual report supported by the *Brazilian Institute of Economics (IBRE)* at *Fundação Getúlio Vargas (FGV)*. Its report included a section on R&D, innovation, and new uses in the forest industry, which detailed current and potential markets as dissolving pulp for the textile industry, oils, bio-oils, lignin, nanofibre, nanocellulose, and cellulose nanocrystals (IBA 2020).

### 2.4.13 Uruguay

The Planning Direction of the Planning and Budget Office (OPP) elaborated a report based on the reports prepared by VTT, the Faculty of Engineering of the University of the Republic, and the FAROPPA Forestry Study to identify opportunities for the development of the long-term bioeconomy for the country, deepen the discussion and draw up a roadmap for the forestry sector. The report highlights that the Uruguayan forestry sector has experienced sustained growth over the last thirty years. The planted area went from 26,000 hectares (1987) to more than one million hectares today (2017), and exports from the forestry sector reached USD 1656 million in 2017 (OPP 2018).

The analysis concludes that there is a reconfiguration of the global pulp market: new pulp plants in the southern hemisphere and reconversion of plants in the northern hemisphere toward biomaterials. The replacement of plastics derived from non-renewable raw materials is a clear opportunity for the pulp industry to evolve toward producing containers, packaging, and textiles. Bioproducts show high potential in the medium term due to the lack of forecast in profitability. The bioproducts obtained from the processing of cellulose, lignin, and hemicelluloses are bioplastics, biopolymers, pharmaceuticals, and other biochemicals with great market projections. It recommends the development of local capabilities in education and R&D since they are currently carried out in the headquarters of global companies. The latter could be carried out at the laboratory level or integrated into operating pulp plants (OPP 2018).

Regarding bioenergy, generating electrical energy from forest biomass would not have much potential due to the promotion of lower-cost wind and solar. Solid fuels (pellets, briquettes, and others) seem to have more opportunities due to the

growing consumption of the European market and domestic demand. For biofuels, opportunities are around aviation and marine fuel; however, there are no profitable developments yet (OPP 2018).

#### 2.4.14 Argentina

In 2019, the Inter-American Development Bank (IDB) financed the so-called “Consulting for New forestry-industrial products development in Argentina.” The work was carried out by researchers from the Instituto de Materiales de Misiones (IMAM) at the request of the Ministry of Agriculture, Livestock and Fisheries of the National Government within the framework of the project: “Sustainability as an instrument for strategically productive sectors development.” The study evaluated the possibility of installing a forest biorefinery in the Nordeste region of the country and identified as the most relevant some organic acids (acetic, succinic, lactic, levulinic), furfural, xylitol, lignin, bioethanol, biobutanol, bio-char, bio-oil, nanocellulose, and carbon fibre (Area et al. 2019).

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## 2.5 Conclusions

The bioeconomy is becoming a relevant player in the global economy in most developed and developing countries, considered by all economic organizations, including governments, academia, and industry. Forest resources are one relevant bioeconomy source, so forest biorefinery inclusion is critical. Evaluation of the most promising value-added products and strategies at local and regional levels are key factors to consider.

Several countries are evaluating their bioeconomy from forest sources through different strategies, developing reports, policies, and handbooks, among other documents, to discuss promising alternatives and conversion pathways to implement.

Bioproducts such as bioethanol, lignin, succinic acid, furfural, biobutanol, and other value-added products were identified as promising two decades ago and are still in consideration. However, emerging high-value products like nanocellulose, carbon fibres, and polymers are becoming relevant to reach feasible options in the bioeconomy.

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# Conversion of Agro-industrial Wastes into Value-Added Products: Towards Sustainable Development

# 3

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## Abstract

The recent concepts of bioeconomy and circular economy stand for the growing demand of the world population for raw-based materials and renewable energy and the need to optimize the use of natural resources, reduce waste generation, and maintain the quality of traditional final products. In this sense, the use of agro-industrial wastes for the production of products and services could be a key player in seeking sustainable development. These wastes, now considered resources, represent a suitable feedstock for new value-added biobased product production, including chemicals, pharmaceuticals, composite materials, and energy.

Different strategies for agro-industrial waste use have been developed and implemented to promote these natural resources' exploitation in the last few years. This chapter overviews agro-industrial waste features and their valorization in a biorefinery platform. A comprehensive approach to these resources will be carried out from its characterization, fractionation, conversion, recovery strategies, and promising products, and the main drawbacks to overcome for its implementation at a commercial scale. Besides, it emphasizes the main trends of the valorization alternatives with a focus on sustainable development.

## Keywords

Bioeconomy · Circular economy · Sustainable development · Valorization

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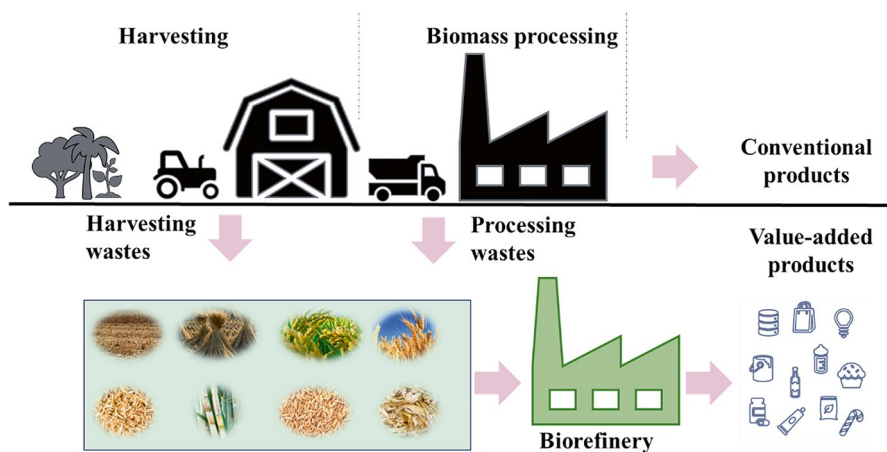
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### 3.1 Introduction

The bioeconomy concept responds to the growing global demand for food, fuel, materials, and chemicals (Clauser et al. 2021). The need to reduce dependence on fossil resources and the consequences of climate change requires the use of new technologies in all the productive sectors that allow the replacement of the current industrialization model through the efficient use of natural resources and the development of more sustainable production patterns (Birner 2018). The bioeconomy encompasses all economic sectors of different scales that are based on the production of goods and services in which renewable resources are involved (Liobikiene et al. 2019).

Biorefinery platforms are commonly used as a strategy to convert renewable sources into value-added products. These platforms use renewable feedstocks to produce energy and value-added products. The transformation of biomass into products has the potential to replace those currently derived from fossil sources (Clauser et al. 2021). Biorefineries can be classified based on the raw material they use: (i) first-generation biorefineries (1G) are those that use food crops as a raw material; (ii) second-generation biorefineries (2G) are those that use non-food crops and biomass from types of forest and agro-industrial waste; and (iii) third-generation (3G) biorefineries which use algae as raw material (Saini et al. 2019).

Second-generation (2G) biorefineries use lignocellulosic biomass (LCB) as feedstock, like residues outcoming from the value chains of these raw materials, such as forest-industrial and agro-industrial wastes. LCB are resources worldwide distributed. The estimated global annual production of LCB is around 1.3 billion tons (Baruah et al. 2018; Devi et al. 2022), and due to the characteristics of LCB (e.g., chemical composition, structure, and others), its valorization needs to be evaluated and improved for implementation at a commercial scale. Figure 3.1 presents a simplified LCB biorefinery implementation.



**Fig. 3.1** Simplified LCB biorefinery from agro-industrial wastes

## 3.2 Agro-industrial Crops and Wastes Overview

Agricultural activities are the conventional chains that produce feedstocks mainly for the food industries. Worldwide, some relevant crops generated by these activities are maize (or corn), wheat, rice, sugar cane, and sorghum. The production of these crops generally depends on regional conditions such as weather and culture. The main producing countries are the United States, China, Brazil, and India. For other specific crops like soybeans and barley, Russia, France, and Argentina are the countries with high production volumes (FAO 2023). In addition, sugar beet (260 million t/year), coconuts, rapeseed, and oil palm fruits, all of which are oil crops, have significant production volumes (FAO 2023). The mentioned crops are commonly used in conventional value chains to produce rice, sugar, and flour. These processes generate several wastes (also called byproducts). The amount of byproducts generated commonly depends on technologies involved in, among others, conversion processes, crop properties, and environmental conditions (Scarlat et al. 2010). Crops have different collection rates; this rate represents the percentage of residues that can be collected over the total generated. Commons rate values are: 40% is reported for wheat, barley, oats, and rye residues and 50% for corn, rapeseed, rice, and sunflower (Aghaei et al. 2022; Monforti et al. 2015). For sugarcane, the collection rate is 100% (Alokika et al. 2021).

The agricultural sectors and the food processing industry are the largest producers of waste. Of the total food production, 30% corresponds to lignocellulosic residues (Tomé et al. 2023). Global crop residues (including its processing) are estimated at more than 5 billion tons/year (Shinde et al. 2022).

These activities commonly generate wastes to valorize, which are considered byproducts. These byproducts can be classified on origin, physical state, and chemical composition (Lemes et al. 2022; Muhammad et al. 2022). One of the most common classifications separates recyclable agro-industrial wastes (which can be re-used as feedstock for another process), non-recyclable industrial wastes, and hazardous industrial wastes (Ogbu and Okey 2023; Sadh et al. 2018). Other authors divide agricultural wastes (including crop residues), and food processing wastes (including fruit and vegetable wastes generated in the poultry industry, slaughterhouses, egg production), and kitchen wastes (as oils) (Sharma et al. 2022). A similar classification considers wastes derived from food processing as industrial wastes (Sadh et al. 2018). Other classifications consist of crop residues (which are products not intended for human consumption), livestock and aquaculture industry wastes, food processing wastes (such as peelings and fruit), and wastes resulting from losses during food production and distribution (Chhetri et al. 2020).

Recyclable agro-industrial wastes can be further sub-categorized as residues from fields which are the residues left after harvesting, including leaves, stems, seeds, stalks, and straws., and the residues generated during crop processing such as husks, bagasse, seeds, roots, and bunches (Ambayieram and Kumar 2023; Sadh et al. 2018; Sharma et al. 2022). These residues have the potential to be converted into value-added products such as fuels, chemical products, and construction materials through several technologies and valorization processes.

Wastes described before are composed mainly of cellulose, hemicelluloses, and lignin. This composition commonly depends, among others, on the biomass type

and weather conditions (Show and Guo 2012). Usually, the agricultural waste composition is 40–50% of cellulose, 20–30% of hemicelluloses, and 10–25% of lignin (Jayakumar et al. 2023). The variation in the composition of agro-industrial wastes is one of the key factors in the process design because the selection of process conversion and value-added products selected, among others, are related to this chemical variation (Ashokkumar et al. 2022; Nair et al. 2022).

Agro-industrial wastes could be subjected to chemical and (or) biochemical processes to separate their components and transform them into biofuels, chemical products, and other commercially useful items (Mohamed et al. 2021). In this way, biorefinery is a promising alternative for sustainable production of bioproducts and biofuels from renewable biomass. The commercial development of a biorefinery is closely linked to the design of its conversion processes, products, and byproducts (Susmozas and Moreno 2018). This design must evaluate mainly the economic and environmental viability of the proposed design.

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### 3.3 Agro-industrial Waste Valorization in a Biorefinery Platform

The use of agro-industrial wastes as a source of lignocellulosic biomass has the advantage of not competing with the food industry, in addition considering its existence in high volumes at low costs that are not optimally used (Cardona Alzate et al. 2019). LCB transformation efficiency is essential for final high-value-added product design in a biorefinery (such as advanced biofuels, bioplastics, and chemicals) and its yield maximization (Özdenkçi et al. 2017). The selection of technologies and integration of processes can improve the overall efficiency of the biorefinery and its profitability.

LCB conversion starts with the fractionation step. Several processes can be used for this purpose, depending on the fraction to utilize (Galbe and Wallberg 2019; P. Kumar et al. 2009). The fractionation objective is to allow the valorization of all biomass fractions, so it is a critical step (Kumar et al. 2009). Common pretreatments like autohydrolysis, acid hydrolysis, and steam explosion are widely used for sugar solubilizations, whereas pretreatments like organosolv and alkaline are mainly used for lignin extraction (Cardozo et al. 2023). Also, there are emerging promising pretreatments like ionic liquids and salts that could be used with a wide range of reagents and solvents to improve biomass fractionation (Cardozo et al. 2023; Dharmaraja et al. 2023; Kumar et al. 2020).

After pretreatment, biomass fractions can be valorized through several processes, considering the final desired product. Processes like fermentation, enzymatic hydrolysis, and catalysis are commonly used, to convert biomass into value-added products (Clauser et al. 2021; Rathore and Singh 2022).

Other usual operations involved in biorefinery design are concentration (e.g., evaporators and dryers), detoxification (e.g., adsorption and filtration), and recovery steps (e.g., distillation, filtration, and precipitation) (Clauser et al. 2021; Usmani et al. 2021).

Table 3.1 summarizes several conversion processes for agro-industrial wastes evaluated in different process configurations, presenting the pretreatment, the

**Table 3.1** Main agro-industrial waste conversion pathways

Feedstock	Conversion pretreatments	Process parameter	Conversion treatments	Process description	Products and Co-products	Ref.
Corn stover	Chemo-physical pretreatment	Using 5% maleic acid and 3% citric acid in an autoclave for 30 min at 110 °C	Enzymatic hydrolysis fermentation	Using cellulase enzyme, 20 FPU for 3 days at 50 °C <i>Saccharomyces cerevisiae</i> yeast, for 36 h at 30 °C	Bioethanol	Elsagan et al. (2023)
Corn stover	Dry acid	Using H <sub>2</sub> SO <sub>4</sub> 7.2% w/w in mild helical agitation for 5 min at 175 °C, LSR 2:1 (w/w)	Simultaneous saccharification and co-fermentation	Using <i>Cellic CTe2</i> enzyme, 12 FPU for 6 h at 50 °C. <i>P. acidilactici</i> yeast for 72 h at 42 °C	L-Lactic acid	Wei et al. (2018)
Corn Stover	Diluted acid pretreatment	Using H <sub>2</sub> SO <sub>4</sub> 1.8% v/v for 22 min at 121 °C	Enzymatic hydrolysis aerobic cultivation	Using <i>Cellulast</i> enzyme for 72 h at 37 °C <i>Mucor Indicus</i> yeast for 48 h at 32 °C	Bioethanol <i>Glycerol, Chitosan, Lipid (biodiesel via transesterification)</i>	Alavijeh et al. (2023)
Rice husk	Acid and alkali treatment	Using H <sub>2</sub> SO <sub>4</sub> solution 4% w/w and NaOH solution 5%, w/w, for 2 h	Calcination, coagulation	At 800 °C using ethanol bath for 30 min. Deionized water bath for 30 min immersed in glycerol (5%, v/v)	Bioplastic film	Karaca et al. (2022)
Rice husk	-	-	Alkaline treatment	Using 10 g of rice husk, refiner/0.5 M NaOH in microwave for 30 min	Bioplastic (cellulose extraction 55.68%)	Syamsidar et al. (2024)
Rice husk	-	-	Alkaline treatment	Using NaOH 6% in an autoclave for 2 h at 121.5 °C, LSR 6:1	Bioplastic (cellulose extraction 50.77%)	Syamsidar et al. (2024)
Rice husk	-	-	Alkaline treatment	Maceration in methanol for 7 days, after washing was dried. Then 10 g of rice husk with 300 mL of NaOH and Na <sub>2</sub> CO <sub>3</sub> 5% w/v, for 5 hours was heated at 80 °C, and the mixture was hydrolyzed using 10% H <sub>2</sub> SO <sub>4</sub> at 50 °C	Bioplastic (cellulose extraction 50.14%)	Syamsidar et al. (2024)

(continued)

Table 3.1 (continued)

Feedstock	Conversion pretreatments	Process parameter	Conversion treatments	Process description	Products and Co-products	Ref.
Rice husk and PLA resin	Drying	Using PLA and RH were dried in a vacuum oven for 10 h at 80 °C	Melt blending	Using PLA 80% and RH 20% with MDI for 3 min at 190 °C	Composites for 3D printing	Tsou et al. (2019)
Rice starch and corn starch, reinforcing fillers: rice hulls and eggshells	Drying	Using the oven for 5 h at 85 °C	Acid treatment	Using 5% acetic acid, and a plasticizer (glycerol, sorbitol, and LSR 1:1). Eggshell powder as reinforcement filler in the ratio of 0:100, 5:95, or 10:90 (% w/v).	Biodegradable bioplastic	Shafiqat et al. (2021)
Barley straw	Alkaline pretreatment	Using NaOH 1.5% w/v in an autoclave at 121 °C	Enzymatic hydrolysis fermentation	Using <i>Cellic Tec2</i> enzyme, 40 FPU for 16 h <i>Yitis</i> yeast 15 mg per gram (compressed baker's), in an orbital shaker for 16 h at 30 °C 231.1–263.7 g of ethanol from 1 kg biomass	Bioethanol	Paschos et al. (2022)
Sweet sorghum bagasse	Alkaline pretreatment	Using NaOH 2% w/v in batch steam autoclaving for 1 h at 120 °C LSR 1:10 w/v	Enzymatic hydrolysis fermentation	Hydrolysis 10% (w/v) using 5 L bioreactor with 3 L of working volume. Using 30 FPU enzyme at 50 °C <i>Saccharomyces cerevisiae</i> yeast for bioethanol at 37 °C <i>Clostridium acetobutylicum</i> yeast for butanol for 72 h at 30 °C	Bioethanol <i>Biobutanol</i>	Su et al. (2020)
Sugarcane bagasse	Acid hydrolysis pretreatment	Using acetic acid 10%, for 45 min at 150 °C	Enzymatic hydrolysis fermentation	Using <i>Celluloclast</i> enzyme, 20 FPU at 50 °C, 15% solid <i>Gluconobacter oxydans</i> yeast at 30 °C	Gluconic acid <i>Xylooligosaccharides</i>	Zhou and Xu (2019)

Sugarcane bagasse	Autohydrolysis	Using hot water for 2 h at 162 °C, LSR 5.5:1	Acid post-hydrolysis fermentation drying grinding pelletized cooling	Using H <sub>2</sub> SO <sub>4</sub> 3%, for 60 min at 120 °C <i>Candida tropicalis</i> yeast for 40 h at 35 °C Using rotary drier (12–17% moisture). Hammer mill <6 mm. High-pressure pelletizer (~1 t/h), 8–5% moisture. Countercurrent air (~20 min)	Xylitol Pellets	Clauser et al. (2018)
Sugarcane bagasse	Autohydrolysis	Using hot water for 2 h at 162 °C, LSR 5.5:1	Acid post-hydrolysis fermentation alkaline delignification and SSF	Using H <sub>2</sub> SO <sub>4</sub> 3%, for 60 min at 120 °C <i>Candida tropicalis</i> yeast for 40 h at 35 °C Using NaOH at 1% w/v for 30 min at 100 °C, LSR 4:1. 10 FPU enzyme 9:1 w/v for 48 h at 50 °C to hydrolyze cellulose for 6 hours, and then yeast and nutrients are added after cooling to 37 °C	Xylitol Bioethanol	Clauser et al. (2018)
Sugarcane bagasse and straw	Acid hydrolysis	Using H <sub>2</sub> SO <sub>4</sub> 100 mg/g of dry matter for 20 min at 121 °C, LSR 1:10	Fermentation	Using <i>Scheffersomyces amazonensis</i> yeast for 24 h at 30 °C	Xylitol	Silva et al. (2020)
Sugarcane trash	Organosolv pretreatment	Using NaOH 20 wt% for 60 min at 140 °C	Enzymatic hydrolysis fermentation	Using <i>Cellic CTe2</i> enzyme, 15 FPU, for 96 h at 50 °C <i>Actinobacillus succinogenes</i> yeast for 48 h	Succinic acid	Pakchamni et al. (2022)

(continued)

Table 3.1 (continued)

Feedstock	Conversion pretreatments	Process parameter	Conversion treatments	Process description	Products and Co-products	Ref.
Sugarcane bagasse and trash	Acid pretreatment	To obtain LA and furfural: Using H <sub>2</sub> SO <sub>4</sub> 3.5 wt% at 215 °C	Second reactor: continuous stirred tank reactor	To obtain LA and formic acid: at 195 °C and 14 bar crude LA was hydrogenated over a 15% carbon catalyst, at 150 °C, 5 bar, flash tank operating at 98 °C, 1 atm (to remove CO <sub>2</sub> ). GVL stream liquid-liquid extractors 3 atm, 32 t h <sup>-1</sup> recyclable n-butyl acetate solvent 98 wt% Insoluble solids for energy	Levulinic acid, furfural <i>Electricity</i> , <i>Gamma valerolactone</i>	Kapanji et al. (2021)
Elephant grass (stem and leaves)	Alkaline pretreatment	Using NaOH 4.5% w/v for 20 min at 85 °C, LSR 1:10	Enzymatic hydrolysis, fermentation	Using <i>Cellic CTec2</i> enzyme 20 FPU for 72 h at 50 °C <i>Saccharomyces cerevisiae</i> yeast at 30 °C. 100 kg of ethanol/t biomass	Bioethanol	Scopel and Rezende (2021)
Elephant grass (stem and leaves)	Acid and alkaline pretreatments	Using H <sub>2</sub> SO <sub>4</sub> 2% v/v in an autoclave for 40 min at 121 °C, LSR 1:10 and using NaOH 4.5% w/v for 20 min at 85 °C, LSR 1:10	Enzymatic hydrolysis fermentation	Using <i>Cellic CTec2</i> enzyme 20 FPU, for 72 h at 50 °C <i>Saccharomyces cerevisiae</i> yeast at 30 °C. 77 kg of ethanol/t biomass	Bioethanol	Scopel and Rezende (2021)
Elephant grass (stem and leaves)	Pressurized liquid extraction and alkaline treatment	Using PLE ethanol/water (1:1 v/v) in an accelerated solvent extractor and using NaOH 4.5% w/v for 20 min at 85 °C, LSR 1:10	Enzymatic hydrolysis fermentation	Using <i>Cellic CTec2</i> enzyme 20 FPU, for 72 h at 50 °C <i>Saccharomyces cerevisiae</i> yeast at 30 °C. 74 kg of ethanol/t biomass	Bioethanol	Scopel and Rezende (2021)

Cocoa pod husk and sugarcane bagasse	Drying and sizing	CPH: using cutting into pieces 1 cm thick, dry at 60 °C for 4 days Sugarcane bagasse: using cutting 3.0 cm × 0.5 cm in size and sun-drying for 4 days	Alkaline treatment drying, and bleaching	Using NaOH solution, 1 mol/L, 75:25 (cellulose to fiber) for 3 h at 100 °C, 40 g CPH/mL	Packaging bioplastic film	Azmin et al. (2020)
Chestnut shells	Alkaline pretreatment	Using NaOH 7.2% for 30 min at 80 °C	Simultaneous saccharification and fermentation Acid precipitation	Using <i>Cellulast</i> enzyme 20 FPU and <i>Saccharomyces cerevisiae</i> yeast at 48.5 °C. The liquid phase was acidified with H <sub>2</sub> SO <sub>4</sub> at 96% until pH 2 for lignin precipitation.	Bioethanol <i>Lignin</i>	Morales et al. (2018)
Spent coffee grounds	Acid pretreatment	Using H <sub>2</sub> SO <sub>4</sub> 1% w/v for 5 min at 170 °C, LSR 10% w/v	Enzymatic hydrolysis, fermentation	Using <i>Cellic Tec2</i> enzyme for 72 h at 40 °C, 6.8% w/v <i>C. Beijerinckii</i> yeast for 48 h at 35 °C	Biobutanol <i>Acetone, Butanol</i>	López-Linares et al. (2021)
Mango seed husk	High shear homogenization-organosolv process	Using ethanol 60% for 15 min at 148.41 °C	–	–	High purity lignin	Bello and Chimphango (2021)

LSR Liquid Solid Ratio, PLA polylactide, RH rice husk, GVL Gamma Valerolactone, LA Levulinic Acid, PLE Pressurized Liquid Extractions, CPH Cocoa Pod Husk, MDI Methylene Diphenyl Diisocyanate

conversion treatment, the conditions selected, and the products to obtain for each selected process.

Product and byproduct design allows for diversifying the range of potential products in a biorefinery platform (Dessbesell et al. 2020; van Eijck et al. 2014). This strategy reduces dependence on a single market or product and takes advantage of the different streams generated during biomass conversion (Cardona Alzate et al. 2019). The efficient valorization of the streams generated in the process directly influences the profitability of the biorefinery (Clauser et al. 2022).

One common strategy to assure process sustainability is all lignocellulosic fractions valorization into value-added products and energy generation. One critical step to evaluate the performance of the proposed processes is the implementation at a commercial scale assessment, usually by economic and environmental methods. The economic assessment's usual metrics are the internal rate of return (IRR), net present value (NPV), return on investment (ROI), and capital recovery factor (CRF), determining variables like investment costs, operational costs, and mass and energy balances (Clauser et al. 2021). In the case of environmental assessment, the usual metrics are carbon and water footprint. These metrics determinations require developing detailed mass and energy balances (Fang et al. 2014; Matušík and Kočí 2021).

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### **3.4 Promising Value-Added Products from Agro-industrial Wastes**

This section develops the potential products that can be obtained from LCB's main components: hemicelluloses, cellulose, and lignin. Each fraction has the appropriate characteristics to produce a different range of products. Limitations arise in the biomass fractionation processes due to their high complexity and differences depending on each type of particular raw material (Timmerhaus and Peters 1991).

When choosing biorefinery products for subsequent process design, it is necessary to identify promising products. These products are those that meet the optimal characteristics based on the technological complexity of the conversion process if the processing technologies have reached a certain degree of maturity, favorable market trends, and if their production significantly reduces the environmental impact in contrast to its analog fossil origin (Bidy et al. 2016).

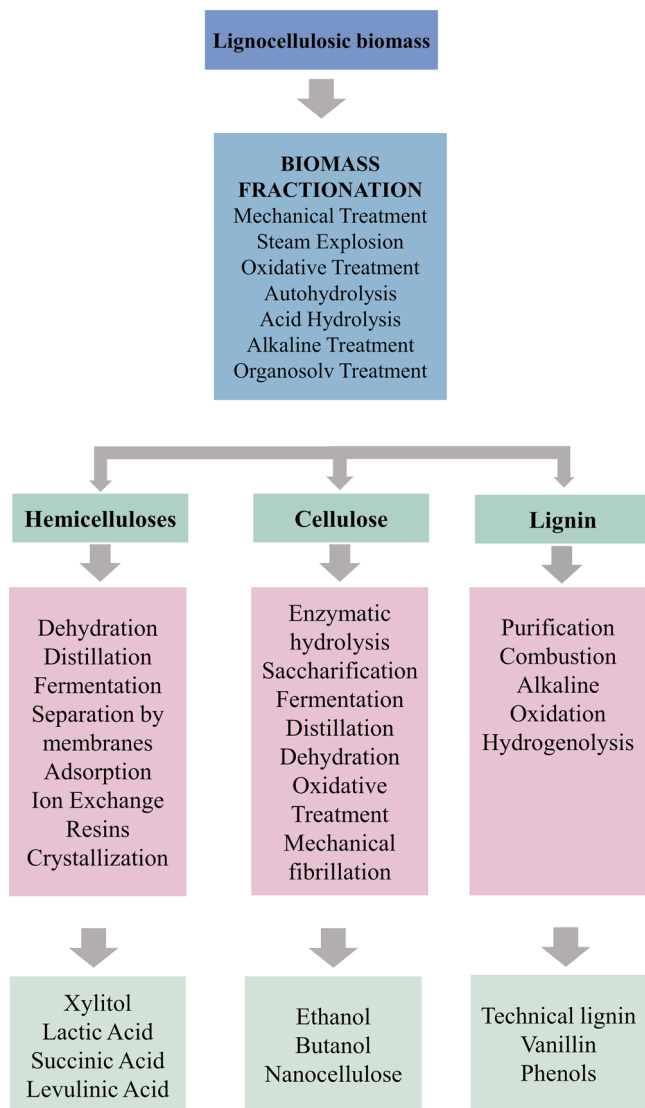
In recent years, diverse value-added products and processes were developed and evaluated to determine the most promising products in a biorefinery platform. Their selection included numerous factors. Some of the most relevant are furfural, levulinic acid, succinic acid, ethanol, and nanomaterials derived from cellulose and lignin fractions.

#### **3.4.1 Multiproduct Models**

A concept of growing interest is the integrated biorefinery. This concept identifies a solution for the limitation of profitability in obtaining a single product since raw material fractionation processes achieve low yields and demand high energy levels.

The multiproduct scheme consists of all fragmented biomass streams processing to obtain several final products to optimize the consumed raw materials and energy, increasing the overall profitability (German Federal Government 2012; Morales-Rodriguez et al. 2016). Figure 3.2 summarizes the biorefinery platform.

There are two process approaches within the multiproduct schemes: (i) bottom-up, which refers to a biorefinery integrated into biomass processing facilities (e.g., pulp and paper mills, sugar mill facilities, and energy generation plants). In this case, waste from the main production stream is used as raw material (second-generation biomass) for new biobased product production; (ii) top-down, involving



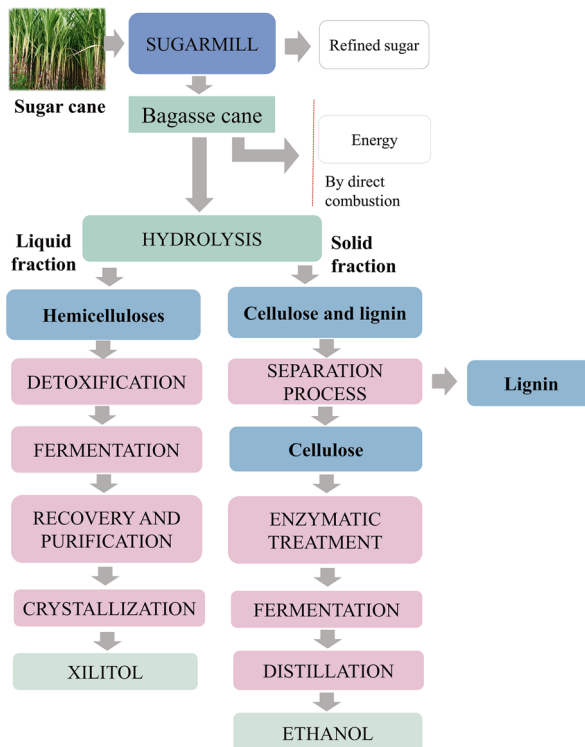
**Fig. 3.2** Multiproduct biorefinery platform

facilities designed exclusively for different biobased product production, entirely using biomass as raw material. These high-tech facilities demand complex requirements to achieve different process combinations, taking advantage of all biomass fractions, optimizing the consumption of energy and water resources, and reducing waste and fixed costs (German Federal Government 2012).

### 3.4.2 Bottom-Up Biorefinery Design

As mentioned earlier, the main limitations faced by second-generation raw material processing are the complexity in the fractionation of biomass components and the recovery and purification of the final products. Yields vary depending on the specific type of raw material (Cardona Alzate et al. 2019). The multiproduct design optimizes overall profitability, taking full advantage of the complex fractionation of LCB into its three main fractions and minimizing waste generation. Since it is possible to obtain a wide range of products from each fraction, the comparative scenario analysis is a relevant decision tool about the best combination of products to be produced (Mandegari et al. 2018; Morales-Rodriguez et al. 2016).

One attractive alternative for bottom-up strategies is conventional sugar mill plants. Figure 3.3 presents one strategy for biorefinery integration. Traditionally,



**Fig. 3.3** Biorefinery integration in a sugar mill process

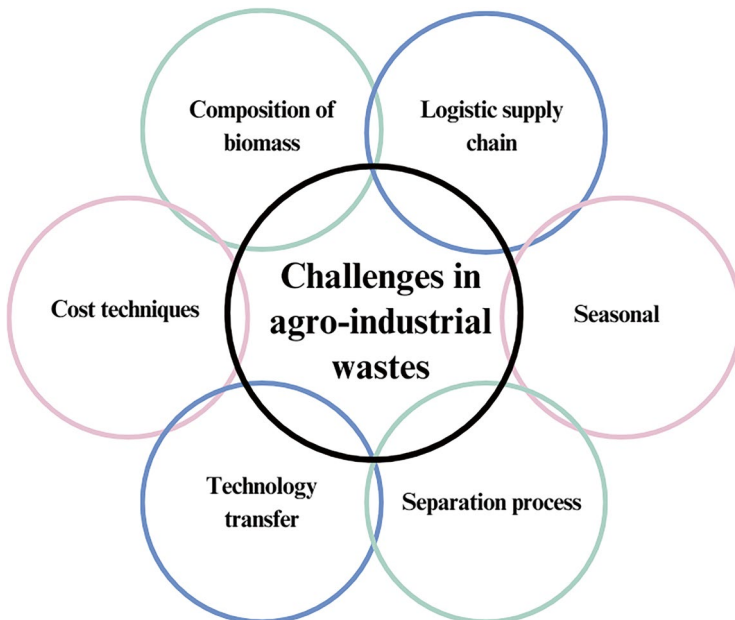
sugar mill facilities process sugarcane as raw material to obtain refined sugar for food consumption. One of the wastes generated is sugarcane bagasse, which is generally burned for energy co-production destined for mill consumption (Mandegari et al. 2018). Under the biorefinery concept, this waste LCB can be valorized to obtain a wide range of chemical products and biofuels of higher commercial value, along with sugar, in total or partial replacement of direct burning. An advantage of this design is the in-situ disposal of second-generation raw materials (Mendes et al. 2017).

### 3.5 Challenges in Agro-industrial Wastes Valorization

The utilization of agro-industrial waste has significantly improved in the last few years. Several technologies and techniques have recently been developed and applied to create new valorization processes and products (e.g., bioplastics, biofuels, and chemicals) (Freitas et al. 2021). However, there are still several challenges to face when these processes are implemented on a commercial scale (see Fig. 3.4).

Several factors require attention since they condition the biomass supply chain. An important factor is the seasonality of biomass. Harvesting takes place over a specific period, so a large amount of resources (labor, equipment) will be required in that time, generating cost increases. Adequate storage facilities will also be necessary to be able to operate continuously. The type of storage and its location are also critical factors for the supply chain (Nunes et al. 2020).

The biomass has a low density and different shapes (chips, bars), which results in the need for larger storage volumes that also affect its transportation



**Fig. 3.4** Challenges in agro-industrial wastes

(Rentizelas et al. 2009) and require customized collection equipment (Rentizelas et al. 2009).

The composition of agro-industrial wastes varies according to many factors, such as climate, species, processing, agronomic conditions, and harvesting, making it difficult to standardize the processes. In addition, any change in composition directly affects the costs of the entire supply chain (Zabed et al. 2023).

The pretreatment process is also a barrier because of the infrastructure required and the associated costs, generating bottlenecks in the valorization chain, which also happens with the saccharification process due to the high enzyme cost (Malacara-Becerra et al. 2022; Obydenkova et al. 2022). Therefore, it will be necessary to find low-cost separation techniques (Yaashikaa et al. 2022). On the other hand, wastewater, generated in large volumes, can be recovered and thus obtain new products but add complexity to the process (Obydenkova et al. 2022).

Although parameters are not similar for different scales, it is possible to develop model optimizations, technical and economic studies, and process simulations for successful transfer between scales (N. Singh et al. 2022). Therefore, industrial-scale technologies look promising, but it is necessary to carry out previous studies involving infrastructure, costs, economic feasibility, and transportation costs, among others (Bhuvaneshwari et al. 2019; Freitas et al. 2021).

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### 3.6 Opportunities of Agro-industrial Waste Conversion Toward Sustainable Development

The conversion of agro-industrial wastes has both economic and environmental advantages. Avoiding waste burning contributes to the reduction of greenhouse gas (GHG) emissions, allows for temperatures to stabilize, reduces changes in natural systems and air pollution, and improves the environment and quality of life of society (Hartley and Turnock 2022; Yaashikaa et al. 2022).

In the economic context, these wastes transformation into high-value-added products, such as biofuels, bioproducts, and energy, will reduce dependence on non-renewable resources and generate new sources of employment (Awogbemi and Kallon 2022; Zhu et al. 2023). Besides, improving crop yields can enhance the efficiency of the production chain itself by improving soil health through biofertilizers produced from agro-industrial waste conversion (Puglia et al. 2021).

Waste management based on the concept of circular economy is necessary. The circular economy seeks waste reduction, reuse, and recycling, allowing cost reduction and social and environmental improvement. This approach will require the support of regulatory policies (Ogbu and Okey 2023; Singh et al. 2021).

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### 3.7 Concluding Remarks

Agro-industrial wastes are valuable resources generated in agricultural value chains like rice, maize, sugarcane, and wheat. They can be valorized in a biorefinery platform, generating high-value-added products and contributing to environmental

sustainability, circular economy, and agricultural development. Processes like pre-treatments, hydrolysis and fermentation, catalysis, and purification are commonly involved in these platforms to produce value-added such as biofuels, chemical products, and materials (e.g., xylitol, lactic acid, ethanol, butanol, and vanillin) through several pathways.

For a commercial-scale implementation of the biorefinery processes, challenges like the supply chain, the high value of the techniques and technologies, the differences in the waste composition, and technology transfer must be overcome. Besides, agro-industrial wastes can reduce dependence on fossil fuels and improve the efficiency of the crop production chain, contributing to the reduction of GHG emissions.

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# Application of Marine Resources for Production of Cosmetic Products

# 4

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## Abstract

The need for physiologically active ingredients is being pushed by the rising demand from consumers for natural cosmetics. Because natural biopolymers and novel bioactive compounds have so many benefits over synthetic ones, customers are looking for cosmetics made of these materials more and more often. As a result, cosmetics made of chemical extracts or biomass derived from plants and marine life are being introduced. Because of their activity as antibacterial, anti-fungal, anti-microbial, and antioxidant qualities, seaweeds have drawn the interest of researchers. Compared to terrestrial species, marine microorganisms have different metabolic routes and adaptation mechanisms, which lead to their distinctive composition, great variety, and significant biological activity. The high concentration of physiologically active compounds and biodiversity can be found in marine ecosystems, which also hold untapped medical, nutraceutical, and cosmetic potential. Marine organisms supply tiny compounds like trichodin A to prevent microbial contamination and ectoine to moisturise skin, in addition to bulk materials like agar and carrageenan that gel and thicken cosmetic formulas. This book chapter focuses on compounds originating from marine environments, including novel chemical entities that have the potential to be used as cosmeceuticals, their modes of action, and the health advantages they offer.

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**Keywords**

Marine resources · Natural resources · Skin care · Natural cosmetics · Active ingredients

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## 4.1 Introduction

Cosmetics are defined as any substance or mixture that is intended to meet the external parts of the human body (skin, hair, nails, lips, external genitalia) or with teeth or oral cavity membranes for the sole or main purpose of cleaning, perfuming, changing appearance, protecting, keeping them in good condition, or changing body odours. One of the most common resources used for cosmetics are plants. Plants and their derived oils and byproducts have been used medicinally for as long as humans have existed, their bioactive and phytochemical extracts are vital to the global cosmetics industry because they are rich sources of vitamins, antioxidants, essential oils, hydrocolloids, proteins, and terpenoids, which offer a variety of applications for consumers' hair and skin care. For instance, shea butter, cocoa butter, olive oil, coconut oil, algae, and fruit seeds and peels are all extracted from plants utilised in cosmetics products (Gupta et al. 2022).

The global cosmetics market is expected to reach \$463.5 billion by 2027, driven by the increasing demand for biologically active cosmetic products for improved appearance and physiological effects, and the need for these cosmetic products to be more sustainable and natural will be a global trend (Mohd-Setapar et al. 2022). Synthetic cosmetics, while accessible, carry environmental repercussions and significant carbon footprints, making it crucial to consider the environmental impact of these products. In addition, transforming the industrial sector to sustainability has put pressure on the cosmetics industry to take serious steps toward becoming a green industry. The wide diversity, countless types, and numerous brands have made the cosmetics and personal care industry a growing industry that generates billions of dollars in revenue every year (Martins and Marto 2023). Marine resources offer a diverse sustainable range of active chemicals that have potential for the cosmetics sector. Algae, both macro and micro, are particularly rich in proteins, amino acids, carbohydrates, essential vitamins like A, B, and C, and trace elements such as copper, iron, and zinc. These components collectively contribute to protective, glossy, firming, and slimming effects in cosmetic formulations (Guillermé et al. 2017). The diverse habitats in the marine system provide a spectrum of environments for chemical exploration. For instance, organisms thriving in shallow waters or tropical climates, exposed to intense sunlight, produce photo-protective compounds. Similarly, microorganisms dwelling in extreme environments like hydrothermal vents yield molecules with potent antioxidant properties. Marine microorganisms from deep-sea hydrothermal vents can yield novel and intricate polysaccharides in laboratory settings, which find application in cosmetics (Guillermé et al. 2017). Furthermore, they produce unique compounds with antioxidant, anti-inflammatory, anti-allergic, and anti-ageing characteristics. Our knowledge about marine microorganisms may

be limited, but what we do know underscores their potential benefits for skincare and cosmetics. As these microorganisms generate a plethora of unique compounds, the cosmetics industry eagerly explores their cosmetic potential. Given the growing emphasis on personal care and appearance enhancement in modern living, consumers are increasingly drawn to products containing active marine ingredients (Alves et al. 2020).

Marine-derived compounds have found their way into the cosmetics industry, where they provide several advantages over synthetic counterparts. Marine organisms, for example, produce bulk compounds such as agar and carrageenan, which are utilised to gel and thicken cosmetic formulas. Furthermore, the marine environment provides access to smaller molecules such as ectoine, which is recognised for its moisturising effects, and trichodin A, which functions as a microbial contamination preventative strategy. Furthermore, as active components in cosmeceuticals, marine-derived compounds provide benefits such as skin lightening (chrysophanol), antioxidant qualities, anti-wrinkle effects, and ultraviolet (UV) protection (Alves et al. 2020).

This book chapter attempts to spotlight the cosmeceutical potential of marine-derived chemicals. It will investigate a wide range of new chemical entities derived from marine natural resources, as well as the advantages they provide. We can better comprehend the opportunities and advantages presented by marine species and their unique bioactive compounds by diving into the world of marine organisms and their unique bioactive compounds.

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## 4.2 Where Beauty Meets the Sea: A Dive into Marine-Based Cosmetics

A variety of marine compounds from micro- and macroalgae, as well as fishing industry byproducts, are present in the cosmetic and cosmeceutical market. However, there remains significant untapped potential in compounds derived from marine fungi and bacteria. Several substances derived from marine fungi and marine bacteria, including glycosides, isoprenoids, polyketides, alkaloids, peptides, proteins, lipids, mycosporines, and mycosporine-like amino acids, and hybrids, have plenty of potential usage in cosmeceutical and cosmetics items owing to their anti-ageing, moisturising, photo-protective, and antimicrobial properties (Imhoff et al. 2011). The cyclosporine and Mycosporine-Like Amino Acids have the potential to be extremely effective natural UV filters with high antioxidant properties. The valuable compounds are not limited to prokaryotes in marine environments, eukaryote thraustochytrid produces polyunsaturated fatty acid (PUFA) and carotenoids may even play a significant role in cosmetic applications (Lyu et al. 2021). Adding to that, antimicrobial substances that are safe for the environment and skin are represented by chitosan and compounds from marine bacteria and fungi, provide a good substitute for other artificial preservatives such as butylated hydroxyanisole (BHA) and butylated hydroxytoluene (BHT). By reducing the usage of synthetic surfactants in cosmetics, the natural and biodegradable surfactants derived from marine

microorganisms may minimise the negative effect on the environment (Corinaldesi et al. 2017).

Marine resources are not limited to microscopic organisms, fish species with high EFA levels, marine collagen, and anti-ageing enzymes like zonase which breakdown the dead skin and extra polysaccharide (EPS) compounds, offer moisturising and anti-ageing properties (Awuchi et al. 2022). Moreover, the fisheries industry produces valuable byproducts, including collagen and chitin, which can be used in cosmetics for skin barrier enhancement, hair care, and photoageing treatments (Espinales et al. 2023).

#### 4.2.1 Marine Bacteria-Based Cosmetics

Marine bacteria are abundant near the ocean's surface but decrease in number with depth. They primarily feed on organic matter. Thriving in oceanic temperatures, marine bacteria produce numerous secondary metabolites, serving as valuable sources of bioactive substances. These metabolites act defensively against other microorganisms. Many of these bioactive compounds hold significant market value and find applications in cosmetics and pharmaceuticals. Marine bacteria yield various substances like glycosides, isoprenoids, peptides, proteins, lipids, mycosporine, and mycosporine-like amino acids (MAAs), offering antioxidant, moisturising, antibacterial, and photo-protective properties (Guillerme et al. 2017).

Other valuable substances are the polysaccharides. Polysaccharides are released into the environment by the bacteria which are known as exopolysaccharides (EPS). The two main bacterial polysaccharides, gellan and xanthan gum, are widely utilised as viscosity regulators and psychosensorial agents. Moreover, bacterial polysaccharides with biological activity like skin regeneration and protection include bacterial cellulose (BC), hyaluronic acid (HA), and levan (Balkrishna et al. 2018). These bacterial polysaccharides are vital components of formulations used in cosmetics (Balkrishna et al. 2018). Deepsane is an exopolysaccharide that is extracted from the marine bacteria *Alteromonas macleodii* and is used to protect sensitive skin from UVB, mechanical, and chemical stress (Balkrishna et al. 2018). An osmoprotectant ectoine (1,4,5,6-tetrahydro-2-methyl-4-pyrimidinecarboxylic acid) generated by various bacterial species under osmotic stress, was first isolated from *Ectothiorhodospira kalochloris* (Graf et al. 2008). Additionally, other halophilic bacteria, such as *Actinobacteridae*, *alpha*- and *gamma*-*proteobacteria*, also synthesise ectoine in highly saline conditions. Like glycerol and other osmoprotectants, ectoine possesses the ability to bind water molecules, providing effective hydration. Ectoine is being studied for its potential as a treatment for moderate atopic dermatitis and for its ability to reduce skin irritation, offering patients a new therapeutic option in the form of topical ectoine treatment (Guillerme et al. 2017). Fatty acid esters, commonly utilised as natural emulsifiers and emollients in cosmetics, are also produced by certain bacteria. Despite higher plants being the primary source of many fatty acid esters in cosmetics, actinomycetes like *Nocardiopsis dassonvillei*, found in the marine sponge *Dendrilla nigra*, are another source. Ethyl oleate, a compound derived from *Nocardiopsis dassonvillei*, serves as both an emollient and

a perfuming agent in cosmetic products, demonstrating anti-inflammatory properties. Consequently, ethyl oleate emerges as a potentially adaptable cosmeceutical for skincare items that could be manufactured with environmental sustainability in mind (Snoch et al. 2023).

### 4.2.2 Marine Fungi-Based Cosmetics

Marine fungi, which are commonly ignored inhabitants of the deep-sea, are now being recognised as a potential source of revolutionary cosmetic chemicals. These distinct species have evolved to flourish in tough habitats and generate a diverse range of bioactive chemicals that may have advantageous effects on skin health and aesthetics (Agrawal et al. 2018a). Marine fungus is a plentiful source of natural antioxidants, which may effectively counteract the harmful effects of free radicals. These free radicals are a significant cause of wrinkles and premature ageing. Fumitremorgin C, derived from the marine fungus *Aspergillus fumigatus*, exhibits substantial antioxidant properties. It efficiently scavenges free radicals, therefore shielding cells from oxidative harm (Hassan et al. 2024). *Pleosporales* sp., a marine fungus, synthesises chemicals that possess antimicrobial and anti-inflammatory effects (Chen et al. 2015). These products can be beneficial in the treatment of acne, reducing redness, and promoting general skin health.

Since there is still much to learn about marine fungi's potential for molecular exploitation, this presents a significant opportunity for bioprospecting. Numerous fungal genome sequences are presently being conducted to assess the metabolic capacity of marine fungi. Table 4.1 lists examples of marine-derived microbes and their potential applications.

### 4.2.3 Marine Algae-Based Cosmetic

Algae, comprising various species such as brown, red, and green algae, are gaining popularity in cosmetics due to their rich composition (Khandelwal and Lens 2023). Their inclusion in skincare products is appealing because of their natural origin and environmental friendliness. Algae-derived compounds offer benefits for dry skin, inflammation, ageing, and sun protection (Alves et al. 2020). Table 4.2 provides comprehensive information on the cosmetic attributes associated with brown, red, and green algae, shedding light on their unique features and bioactive constituents. From moisturizing and anti-inflammatory properties in brown algae to antioxidant and UV-protective capabilities in red algae, and healing effects in green algae, understanding the unique properties of algae facilitates the informed formulation of skincare products tailored to specific needs, harnessing the full potential of these natural ingredients to optimise skincare efficacy.

Moreover, algae can be utilized in cosmetics in various forms. Algal extracts or dried seaweed bits, when broken and crushed, can be integrated into skincare products such as face masks, soaps, lotions, and exfoliating scrubs. Cosmetic items, including lotions and creams, may list ingredients such as seaweed extract, algae

**Table 4.1** List of the different marine microorganism and their activity used for cosmetic products

Microorganisms	Active compound	Activity	References
Bacteria	Not determined	Antimicrobial	Galaviz-Silva et al. (2018)
<i>Bacillus aerius</i>			
<i>Bacillus oryzicola</i>			
<i>Bacillus safensis</i>			
<i>Bacillus boroniphilus</i>			
<i>Bacillus altitudinis</i>			
<i>Virgibacillus senegalensis</i>			
<i>Bacillus</i> sp.			
<i>Novosphingobium</i> sp. PP1Y	Not determined	Antioxidant	Petruk et al. (2019)
<i>Microbacterium aurantiacum</i> FSW-25	Exopolysaccharide	Antioxidant	Sran et al. (2019)
<i>Streptomyces</i> sp.S2A	Pyrrolo[1-a] pyrazine-1,4-dione, hexahydro-3-(2-methylpropyl)	Antimicrobial, enzyme inhibitory, antioxidant, and cytotoxic	Siddharth and Vittal (2018)
<i>Aerococcus uriaequi</i> HZ	Exopolysaccharides	Antioxidant	Wang et al. (2018)
<i>Streptomyces</i> sp. ZZ745	Bagremycins	Antimicrobial	Zhang et al. (2018)
<i>Streptomyces</i> sp. Al-Dhabi-90	3-methylpyridazine, n-hexadecanoic acid, indazol-4-one, octadecanoic acid and 3a-methyl-6-((4-methylphenyl) sul	Antibacterial	Al-Dhabi et al. (2019)
<i>Streptomyces</i> sp.	2-Alkyl-4-hydroxyquinolines	Antifungal	Kim et al. (2019)
<i>Penicillium</i> sp. ZZ380	Abyssomicin	Antiviral	Zhang et al. (2020a)
Fungi	Not identified	Antibacterial	Agrawal et al. (2018b)
<i>Simplicillium lamellicola</i> ,			
<i>Leptosphaerulina</i> sp.,			
<i>Penicillium citrinum</i> ,			
<i>Penicillium chrysogenum</i> ,			
<i>Aspergillus sydowii</i>			

extract, or marine extract on their labels. This typically signifies the presence of hydrocolloids extracted from seaweeds, such as alginate and carrageenan, known for their water-binding properties. These compounds aid in retaining moisture on the skin and hair, thereby enhancing the overall moisture balance. They are commonly found in a variety of products including toothpaste, lotions, creams, shampoos, and conditioners (López-Hortas et al. 2021). Table 4.2 lists example of marine-derived microbes and their potential applications.

**Table 4.2** Cosmetic properties of brown, red, and green algae

	Brown algae (Phaeophyceae)	Red algae (Rhodophyceae)	Green algae (Chlorophyceae)	References
Nutritional profile	Rich in fibre, protein, essential amino acids, minerals, and trace elements	Abundant in polysaccharides, proteins, vitamins, minerals, and fatty acids	Contains essential nutrients including protein, amino acids, and fatty acids	Peñalver et al. (2020)
Bioactive components	Fucoidans, phlorotannins, essential oils	Carrageenans, polyphenols, mycosporine-like amino acids	Ulvans, phycobilins, chlorophyll	Rosic (2021)
Cosmetic benefits	Moisturizing, anti-inflammatory, anti-ageing	Antioxidant, photo-protective, wound healing	Emulsifying, skin-soothing, anti-inflammatory	Hentati et al. (2020)
Cell wall polysaccharides	Fucoidans	Carrageenans	Ulvans	Hentati et al. (2020)
Specific compounds and sources	<i>Laminaria saccharina</i> extract, purified phlorotannins	<i>Porphyra</i> spp., purified carrageenans	<i>Ulva lactuca</i> extract, phycobilins	Hentati et al. (2020)
Functional applications	Collagen promotion	UV protection, skin hydration, wound repair	Emulsion stabilisation, moisturisation, antioxidant	Salehi et al. (2019)
Polyphenolic functions	Antioxidant, anti-ageing	Anti-inflammatory, anticancer	Antioxidant, photo-protective	Salehi et al. (2019)
Roles of polysaccharides	Moisturizing, wound healing	Thickening, emulsifying	Moisturizing, emulsifying, texturising	Dini (2023)
Amino acid content	High arginine levels, collagen synthesis stimulation	Natural moisturizing factor (NMF) maintenance, collagen synthesis	Essential for NMF maintenance, protein synthesis	Dini (2023)
Fatty acid abundance	Rich in omega-3 fatty acids	Abundant in omega-3 fatty acids	Contains omega-3 fatty acids, beneficial lipids	Dini (2023)
Phlorotannins in cosmetics	Anti-ageing, skin rejuvenation	UV protection, skin revitalisation	Antioxidant, anti-ageing, UV protection	Arunkumar et al. (2021)
Mycosporine-like amino acids (MAA)	Photoprotection, antioxidant	UV protection, skin repair	Photoprotection, antioxidant	Rosic (2021)

### 4.3 Marine Natural Products for Next-Generation Cosmetics

Because of their large oceans and biodiversity, researchers are looking into the potential of marine natural products. Marine organisms exhibit unique structural features, making them a valuable reservoir of bioactive natural products. However, the marine environment remains underexplored for discovering novel products. As life expectancies increase, cosmetic manufacturers are turning to nature for cosmetic ingredients (Juliano and Magrini 2018). The marine environment is being recognised as a promising source of cosmetic ingredients due to its unrivalled biological and chemical diversity (Ding et al. 2022).

#### 4.3.1 Ageless Elegance

Skin ageing is a long-term damage caused by various stressors, including genetics, ethnicity and sex, exposure to UV radiation, harsh weather, pollution, smoking, stress, poor sleeping, eating habits, and exercise. It involves alterations in DNA repair, mitochondrial function, cell cycle, apoptosis, ubiquitin-induced proteolysis, and cellular metabolism. Age-related decrease of physiological hormones is a major factor in the initiation of ageing.

Anti-ageing cosmetics are categorised into moisturizing, antioxidant, and biological activities. As bioactive components research advances, active ingredients like scavenging free radicals, cell repair, moisturizing, and UV absorption are being used. Scavenging free radicals, such as vitamin E, vitamin C, superoxide dismutase, coenzyme Q10, zinc sulfate, ferulic acid, green tea, idebenone, polyphenols, and carotenoids, are essential for skin health. Vitamin E penetrates the skin, preventing light ageing and reducing wrinkles. Combining vitamins (E & C) in sunscreens is more effective. Coenzyme Q10 can inhibit collagenase expression by UV ray irradiation. Cell-repairing ingredients like vitamin A, retinoic acid, tartaric acid, cell growth factor, collagen protein, beta hydroxy acid, and beta-glucan can help reduce skin ageing and wrinkles. Retinol and retinyl propionate can reduce facial wrinkles at low concentrations, while retinol skin permeation effect is better than retinol esters (Mukherjee et al. 2006). Vitamin A can enhance skin elasticity, and improve complexion, and texture. Retinoids can improve fine wrinkles, pigmentation, and facial nevus. Retinoids may also contribute to water retention, increasing skin thickness and collagen synthesis (Mukherjee et al. 2006). Moisturizing is crucial for anti-ageing as it increases skin moisture content and prevents skin peeling. Key ingredients include pyrrolidone carboxylic acid salt, sorbitol, glycerol, polyethylene glycol, cholesterol, oleic acid, HA, lactic acid, and microbial fermentation metabolites, with HA being the most widely used. UV radiation can cause DNA damage, apoptosis, and growth arrest, leading to skin barrier degradation, wrinkles, and pigmentation. Therefore, using sunscreen and UV absorbers is crucial for anti-ageing (Broitman 2015). Algoronic acid, a powerful regenerative compound produced by microalgae, has been used in anti-ageing skincare formulas since 2011. Algenist® Skincare introduced algoronic acid in 2011 and claims it minimises wrinkles, improves skin firmness, and delivers a more radiant appearance (Alparslan et al. 2018).

Other important compounds called carotenoids, particularly  $\beta$ -carotene, are used to prevent skin ageing and are considered active principles with anti-ageing properties. The main marine source of  $\beta$ -carotene is the halotolerant microalga *Dunaliella salina*, which produces over 10% of its dried weight and biosynthesises 9-cis- $\beta$ -carotene. *D. salina*, rich also in minerals like magnesium, potassium, calcium, glycerin, and iodine, is a key ingredient in cosmetic products for skin rejuvenation and relaxation (Alparslan et al. 2018). Deepseane, an exopolysaccharide was discovered in *Alteromonas macleodii* subsp. from deep-sea hydrothermal vents, is commercially available in cosmetics under the name Abyssine® by LucasMeyers for soothing and reducing skin irritation (Alparslan et al. 2018). Erika Bauer, a pioneer in skincare, developed the first marine anti-ageing line, Celumer, in 1984. The line, now known as Celumer, symbolises the origin of humans from the sea and the importance of the sea for natural beauty. Over time, Celumer evolved into the exclusive Celumer marine extract, which remains the basis of all anti-ageing lines. Extensive studies have shown the unique combination of active ingredients leads to extraordinary results (dalton-cosmetics.com 2024).

### 4.3.2 Ocean's Embrace for Clear Skin

Acne vulgaris, a skin disorder that primarily affects teenagers and young adults, is a widespread condition. Symptoms include blackheads or whiteheads, pimples, greasy skin, and possible scarring. Left untreated, acne can last for years and may lead to lifelong scars, disfigurement, and negative physiological effects. The disease is multifactorial and has a complex pathogenesis (Firlej et al. 2022).

Acne is caused by a combination of hormonal, microbiological, and immunological factors, including androgen-mediated stimulation of sebaceous gland activity, follicular hyperkeratinisation, and inflammation (Firlej et al. 2022).

Although acne is primarily an inflammatory disorder, it can also be influenced by factors such as hair follicle keratinisation, sebum secretion, and bacteria. Acne is commonly caused by *Staphylococcus epidermidis*, *Staphylococcus aureus*, and *Pseudomonas aeruginosa*, whereas *Propionibacterium acnes*, a Gram-positive anaerobic bacterium, is usually related to acne vulgaris. Historically, antibiotics such as clindamycin and erythromycin were used to treat acne vulgaris caused by bacterial growth. However, antibiotic overuse has resulted in bacterial resistance (Patel and Bhatia 2021).

It should be noted that antibiotics might cause skin sensitivities and inflammation. Extracting bioactive components from algae may thus provide a natural and safe approach. Recent research has discovered that macroalgae extracts contain novel antibacterial and antifungal factors. The antibacterial activity of these extracts against cutaneous germs was investigated. Furthermore, some macroalgae extracts have anti-inflammatory characteristics and can control growth factors and collagen levels. This could perhaps help to strengthen acne-prone skin and speed up skin restoration (Silva et al. 2020). Ruxton and Jenkins (2013) discussed the anti-acne action of a seaweed oligosaccharide-zinc complex isolated from *Laminaria digitata*

which lowers acne symptoms by decreasing sebum production. *Fucus evanescens* extract exhibited antibacterial activity against methicillin-resistant *S. aureus* and *P. acnes*.

Choi et al. (2011) tested 57 seaweed species for antimicrobial activity against *P. acnes*, and 15 of them showed anti-acne activity. With a maximal MIC of 0.31 mg/mL, the methanol extracts of *Ecklonia cava*, *Ecklonia kurome*, *Ishige sinicola*, and *Symphyclocladia latiuscula* showed strong action. Phlorotannin's extracted from *Eisena bicyclis* inhibited the growth of human acne-causing bacteria such as *Propionibacterium acnes*, *Staphylococcus aureus*, and *Staphylococcus epidermidis*. Carrageenan isolated from red algae of the genus *Corallina* inhibited the bacterium *S. epidermidis* with a MIC of 0.325 mg/mL, while sulfated galactan from *Corallina* showed bactericidal action against *Enterococcus faecalis* and *S. epidermidis*. This research determined that the seaweed chemical can operate as an ingredient in an anti-acne treatment due to its inhibitory action against *P. acnes*, *S. aureus*, and *S. epidermidis* (Sebaaly et al. 2014).

### 4.3.3 Anti-dandruff

People are increasingly prioritising self-cleansing, particularly in the form of shampoo, which helps remove excess oils and dandruff. However, commercial shampoos can cause scalp problems like dandruff, allergies, and irritation. Dandruff, a condition affecting over half of the world's population, is caused by the overproduction of skin cells on the scalp. Chemical-based shampoos can cause serious hair and scalp issues. Natural compounds, particularly herbs, are becoming more popular as hair care products, as they are more beneficial for the skin (Sang et al. 2023). Lallemand company is a global leader in microbiology, focusing on yeast, bacteria, and specialty ingredients to enhance health and nutrition for humans, animals, and plants. They offer original solutions through plants, distribution centres, and commercial offices (Bustamante et al. 2020). The demand for transparent cosmetics products is increasing due to consumer preference for purity and transparency. For instance, the piroctone olamine compound, with its good solubility, is particularly suitable for clear products, particularly in the anti-dandruff shampoo segment. A transparent shampoo formulation with 0.5 g of piroctone olamine demonstrated its suitability in this application. By 2025, half of the world's population will live in water-stressed areas, changing consumer behaviour. Clariant has applied 0.5% piroctone olamine to a dry shampoo powder formulation for environmental protection (Schmidt-Rose et al. 2011).

### 4.3.4 Whitening Agents

Skin whitening is widely used all over the world to produce fair and perfect skin. Tyrosinase inhibitors derived from marine byproducts have shown significant potential in the cosmeceutical sector due to their skin whitening and post-sunburn

depigmentation properties, as well as their use in treating human and animal skin hyperpigmentation (Prajaputra et al. 2024; Zolghadri et al. 2019). Marine microorganisms, including *Pseudomonas*, have been found to produce methylene chloride, a tyrosinase inhibitor, which suppresses human melanocyte pigmentation. Tyrosinases have been isolated and purified from plants, animals, and microorganisms like Sahara soil *Actinobacteria* and mushroom tyrosinase from *Agaricus bisporus* (Zolghadri et al. 2019). Tyrosinase catalyses two independent important processes in melanin synthesis: the hydroxylation of L-tyrosine to 3,4-dihydroxy-L-phenylalanine, which is then oxidised to dopaquinone and subsequently transformed to melanin. Sunlight promotes the formation of tyrosinase and melanosomes. Different seaweed components can be potent tyrosinase inhibitors and are widely advocated for skin whitening, and brown algal extracts are as effective as kojic acid (Dolorosa et al. 2019).

Similarly, Park et al. (2021) reported that the red alga *Pyropia yezoensis* extracts could be offered as a safe and effective agent for improving skin whitening and preventing or alleviating the production of skin wrinkles. The extracts reduced tyrosinase activity significantly, but not as significantly as arbutin. However, arbutin may have side effects, but these aqueous seaweed extracts increased collagen formation and improved skin brightness in a trial with 23 participants.

Due to the wide range of activities, different fractions of seaweeds have been mixed to achieve complementary actions, such as phenolics and polysaccharides. Furthermore, seaweed mixes can be investigated for their dermo-cosmetic potential, such as a cream mask including antibacterial, cell proliferation, moisture retention, and tyrosinase inhibitory activities, as well as high spread and sticky abilities while being non-irritant and safe (Thu et al. 2018).

Furthermore, the combination of other marine ingredients, such as nano melanin from *Halomonas venusta* isolated from a marine sponge *Callyspongia* sp., incorporated in a cream fortified with concentrates of seaweed *Gelidium spinosum*, demonstrated antioxidant, antimicrobial, and wound healing activity, as well as improved texture (Poulose et al. 2020).

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## 4.4 Marine Fish-Derived Compounds

Marine fish also could be used in cosmetics industries such as collagen and fish oil. Marine-derived collagen extracted from fish has garnered significant interest in the skincare industry due to its potential for skin repair and regeneration. Collagen, a crucial protein for maintaining skin structure and elasticity, diminishes with age, leading to the emergence of wrinkles and sagging skin. However, collagen sourced from marine fish, including varieties like cod, salmon, and tilapia, presents a promising solution to counteract these signs of ageing (Zhang et al. 2020b). Fish oil is extracted from a variety of marine fish components, such as the skin, viscera, head, and body of salmon, tuna, and other oily fish species. It is used as an ingredient in cosmetic products. Fish oil can also be extracted from the leftovers of canned oily fish. According to the Fishmeal and Fish Oil Organization (IFFO), more than half

(51%) of the world's fish oil is obtained from discarded by products of seafood processing (Ferraro et al. 2013). Fish oil can improve the severity of some skin disorders such as photoageing, skin cancer, allergy, dermatitis, cutaneous wounds, and melanogenesis. There is growing interest in the link between fish oil and skin protection and homeostasis, particularly in relation to omega-3 polyunsaturated fatty acids (PUFAs), docosahexaenoic acid (DHA), and eicosatetraenoic acid (EPA) (Huang et al. 2018). Other PUFAs, such as -linolenic acid (ALA) and linoleic acid (LA), are also good for the skin. The main mechanisms by which PUFAs reduce cutaneous inflammation are competition with inflammatory arachidonic acid and reduction of proinflammatory eicosanoid synthesis. PUFAs in fish oil, on the other hand, may operate as regulators of cytokine synthesis and activity to promote wound healing (Huang et al. 2018).

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#### **4.5 From the Deep Blue: Industrial Production of Marine Microbial Cosmetics**

Beyond the lab, marine-derived cosmetics are making a splash in the beauty industry, with major brands leading the charge. BIOMAR Microbial Technologies is a biotech company established in 1996 that specialises in marine microbiology and natural product chemistry. The company attempts to discover, develop, and supply new compounds and products of industrial interest. Innovation and sustainability underpin the company's strategy. They provide innovative products and services based on marine microorganisms and the compounds they produce. Over 20 years of investigation and 170 bio prospects worldwide have led to the company's extensive marine microorganism collection. The strains' genetic diversity and fermentation expertise provided extracts full of metabolites and a broad variety of chemicals with 24% uniqueness. The chemical library includes over 1000 pure natural compounds, accessible upon request. About 300 pure natural items are available for shipment in amounts ranging from 5 mg (about half the weight of a grain of table salt) to grams in the stock compounds catalogue. Their success in developing cosmetic products and techniques is due to the variety of their libraries, their team's technical proficiency, and their extensive research project planning and implementation experience (Füllbeck et al. 2006). Ocea Marine Cosmetics Pvt. Ltd., established in 2008, is an Indian company that specialises in marine cosmetology. Under the leadership of managing director Harsukh Pathar and CEO Gayatri Sali, the company has made significant strides in the beauty and skincare industry. Ocea Marine started as the sole distributor for Thalgo Cosmetics in India, Nepal, and Bhutan, offering a wide range of products for skincare, body care, sun care, nutritional supplements, and equipment for beauty solutions. The company has also expanded its product range, including Perron Rigot, the world leader in Stripless waxing, and aromatherapy Associates, which promotes physical, mental, and emotional wellbeing (Ferreira et al. 2021). Dalton, founded by Erika Bauer, is a German skincare brand that focuses on the beauty of the sea products. Founded in 1976, the brand has been a pioneer in professional care cosmetics, using the best ingredients from the

**Table 4.3** Examples of natural compounds at the industrial level as care products

Commercial name	Active ingredients	Active source	Beauty effects	Application
Lallhair® P&R	The ultimate hair shields	<i>Saccharomyces</i> ferment lysate filtrate	Clinically proven, protects and repairs hair, stimulates the scalp	Hair care
Lallbiome™ 300	Advanced prebiotic	<i>Saccharomyces</i> lysate extract	Nourishes skin microbiome, Moisturiser, anti-ageing	Face care Body care Sensitive skin
Lallbiome™ 201 Lallbiome™ 202	Tyndallized probiotics	<i>Lactobacillus casei</i> <i>Lactobacillus rhamnosus</i>	Boosts skin immunity, enhances barrier function, defends skin microbiome, anti-ageing	Face care, body care, makeup, sun care, sensitive skin
Lallskin® hydra	Moisturizing postbiotics	<i>Lactobacillus helveticus</i> supernatants	Clinically proven moisturiser, skin microbiome friendly	Face care, body care
Lallskin® Zn	Smart postbiotic zinc	<i>Saccharomyces</i> lysate extract, zinc sulfate	Reduce acne, antioxidant, anti-dandruff, high bioavailability	Face care, body care, makeup, hair care

sea for its products. Erika's commitment to the sea's power has been a cornerstone of her brand. DALTON is a professional skincare brand that focuses on tailoring products to individual skin types and concerns. With over 45 years of experience in marine cosmetics, they use natural ingredients from the sea, create cruelty-free, gentle formulas, and are made in Germany. Their range is designed to be easily combined, allowing customers to find their own personal skincare routine. More examples of products are listed in Table 4.3.

## 4.6 Nano Cosmetics

NanoFacial is a treatment method that uses a hand-held wand to infuse skincare ingredients, increasing their efficacy. This process breaks down bulkier ingredients into refined options, allowing for greater permeability. Nanotechnology is advancing in the formulation of active ingredients, allowing greater permeability without tools and built-in to the product. Nano-cosmeceuticals, which have been around since 1998, are the fastest-growing segment in skincare, encapsulating active ingredients that protect and enhance effectiveness. Nanotechnology in cosmetics enhances skin structure, respiration, fibroblasts, collagen production, and firmness, providing an ageless, ageless look, improved texture, and even skin tone. This exciting field is still developing and is expected to continue growing in the skincare industry (Gupta et al. 2022). Tiny nanosomes can penetrate the skin with minimal resistance, delivering nutrients like antioxidants and proteins. They are used in

skincare to deliver stem cell-derived proteins and retinol nano-capsules, ensuring uncompromised delivery and delivery of nutrients effectively. Liposomes, a transdermal delivery system, encapsulate active ingredients, increasing their penetration into skin layers. This is beneficial for treating conditions like cellulite. Nanoparticles also protect encapsulated ingredients like vitamin C from oxidation and UVA/UVB light exposure and nourish the skin at the same time (Souto et al. 2020). However this approach was successful, and more research is needed to employ it with marine-derived compounds.

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## 4.7 Conclusion

The vast ocean has a wealth of untapped opportunities for the cosmetics sector. Marine organisms possess a wide range of natural substances that provide UV protection, antioxidant properties, and antibacterial effects. These can function as secure and efficient substitutes for artificial preservatives and sunscreens. Furthermore, the investigation of natural surfactants obtained from marine microorganisms offers a chance to reduce the ecological impact caused by cosmetics. As scientific investigations progress in revealing the mysteries of the ocean, it is clear that the future of the beauty industry rests in utilising marine resources to create cutting-edge and environmentally friendly cosmetic products.

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# Application of Marine Green Algae for Development of Bioplastics: Current Status and Future Challenges

# 5

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## Abstract

There has been a lot of attention lately on using marine algae to produce bioplastics. Algae, especially marine green algae, present a viable source of renewable and sustainable resources for bioplastic and have many benefits over conventional polymers derived from petroleum. It is superior to other sources of bioplastics by nature. Additionally, during cultivation, they consume carbon dioxide and nutrients, lessening their influence on the environment and aiding in bioremediation and the mitigation of climate change. Proteins and polysaccharides are examples of biopolymers that can be separated and converted into bioplastics using a variety of chemical and bioengineering techniques. These bioplastics made from algae offer advantageous qualities including low toxicity and biodegradability, which make them a good substitute for conventional plastics. Furthermore, the problem of plastic waste can be addressed while reducing dependency on fossil fuels by producing bioplastic from marine green algae. The utilisation of marine green algae has great promise to support a more sustainable and ecologically friendly future as research and development in this field advance.

## Keywords

Green algae · Green economy · Bioplastics · Biodegradability · Sustainability

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## Abbreviations

CCS	Carbon capture and storage
PLA	Polylactic acid
PHA	Polyhydroxyalkanoates
PHB	Polyhydroxybutyrate

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## 5.1 Introduction

Plastics and plastic products are undoubtedly crucial in everyday life (Samir et al. 2023). As a result of the rising demand for plastic, the global output of fossil-based plastics has increased considerably. The quantity of plastic made worldwide is expected to go up from 9.2 billion tonnes in 2017 to 34 billion tonnes by 2050 (Chandran et al. 2020). Since conventional plastics are not easily recycled and are not biodegradable, plastic pollution has become a serious challenge for sustainable development. The majority of fossil-based plastics take hundreds of years to degrade; instead, they release methane: a potent greenhouse gas, over time (Evode et al. 2021). Consumption of fossil-based plastics is expected to reach 20% of global annual oil consumption by 2050 (Shams et al. 2021). Although fossil-based plastics are useful in complying with performance requirements in many applications, their usage leads to an increase in CO<sub>2</sub> production, which contributes to global warming and its associated global phenomena such as ocean acidification (Lavers et al. 2022). In addition, most, if not all, plastics are single-use items which leads to the accumulation of plastic waste and pollution, resulting in many environmental problems and harm to aquatic creatures such as fish, sea turtles, and seabirds. These creatures are harmed or even killed by these microscopic particles if they mistake them for food. Microparticles are created when plastic debris builds up on beaches due to surface embrittlement and microcracking brought on by weathering degradation. Waves or the wind may carry these particles into the open sea (Issac and Kandasubramanian 2021). Microplastics, unlike the inorganic particles found in saltwater, microplastics tend to draw and concentrate persistent organic pollutants from the surrounding polluted water. The health of species that consume microplastics as well as marine ecosystems may be seriously threatened by the buildup of contaminants on their surface. Microplastics disrupt the reproductive systems of marine creatures, resulting in population declines (Evode et al. 2021). Indirectly, the transportation of plastic raw materials and finished goods contributes to carbon emissions.

Due to their non-renewable origins, the majority of frequently used plastics are not biodegradable and instead accumulate in landfills and the environment rather than breaking down. In addition to the adverse effect of plastic to marine ecosystems, large plastic debris harms, suffocates, and frequently kills marine life, especially endangered and protected species like sea turtles. Most of the plastic pollution affects sea turtles, and some jellyfish species that restrict their oesophagus and build up in whales' stomachs (Dhairykar et al. 2022). It also decreases stomach capacity, which lowers appetite and the amount of fat that is deposited as a result. It causes

other abnormalities, including intestinal blockage, ulcers, necrosis, perforations, and wounds, all of which lead to the animal's death (Carlin et al. 2020). Moreover, hazardous chemicals that are released by chlorinated plastics into soil have the potential to leak into nearby water sources. The creatures that consume this water may suffer serious consequences as a result. Adding to that, numerous bacteria in landfills accelerate the biodegradation of plastics, which results in the production of methane, a primary greenhouse gas contributor (Inubushi et al. 2022). Other plastics' chemical ingredients such as vinyl chloride, bisphenol-A, styrene, acrylonitrile, methyl methacrylate, etc., partially degrade over a long time; their widespread use also impairs the quality of drinking water over time. Occasionally, the reproductive and respiratory systems are harmed by bisphenol-A (Biswal 2020).

Despite the benefits of using fossil-based plastic, its drawbacks and rising toxicity to humans and wildlife put pressure on the development of less toxic and more environmentally friendly alternatives. As a result, scientists have worked hard to produce bioplastic alternatives that are more environmentally friendly and biodegradable. Bioplastic can be produced from different renewable biodegradable biomass resources. One of these resources is plant-based biomass in the form of starch, sugars, and cellulose. Starch is a complex carbohydrate and is derived from plants like corn, castor oil plant, potatoes, or wheat. Sugars as sucrose and glucose, are derived from sugar cane and other sugar-rich plants. Starch and sugars are a building block for polylactic acid (PLA) bioplastic (Samir et al. 2023), while cellulose is derived from plant fibre as non-food crops and wood. Since these plants can also be used for food or animal feed, there are sustainability issues because of the competition with food production and changes in land use (Brizga et al. 2020). The alternative for that is the use of biological waste that is not intended for direct consumption, instead, it is meant to be discarded. These unusable resources are waste products such as agriculture waste, food scrapes, and wastewater sludge, which could be converted to plastic polymers as polyhydroxyalkanoates (PHA) and polylactic acid (PLA) (The most common types of bio-based biodegradable plastics), through bacterial and fungal fermentation, and enzymatic hydrolysis (Katrin Jogi 2020). Although, the valorisation of waste into value-added products like plastic could be a great and useful application besides the decreasing of tons of landfills that are sources for methane and greenhouse gases, it still needs pretreatment requirements (i.e., physical, chemical, and biological processes) to guarantee the partial or complete release of monomers from food waste (such as lignocellulosic components), to improve the accessibility of proteins, lipids, and polysaccharides (such as cellulose and starch) for further processing so it will be prolonged and costive process. Microbes came as the third resource for bioplastic formation. Although microbial bioplastics are attractive, their scalability and cost-effectiveness are limited, and these bioplastics are still in the early stages of development (Brizga et al. 2020; Tsang et al. 2019).

Since algae cannot compete with food crops, can grow quickly enough to allow for efficient production, and survive in saline water on non-arable land, algae-based bioplastic is considered a viable sustainable resource. They can also be produced in open ponds or photobioreactors. Their growth requires sunlight, water, carbon

dioxide, and nutrients like phosphates, nitrates, and iron. Proteins, lipids, carbs, and starches can all be produced naturally in algae. These elements can be taken out and converted into polymers that the plastics industry can employ (Sreenikethanam and Bajhaiya 2022). Algae are classified by their colour and size. Microalgae possess a basic cellular structure and rely on light, carbon dioxide, water, and nutrients to support their growth through photosynthesis (Garbowski et al. 2019). They are classified as green algae (Chlorophyta), brown algae (Phaeophyta), and red algae (Rhodophyta) based on their colours (Hamid et al. 2019). Because water covers 75% of the Earth's surface, there is plenty of room for algae. Using them may convert waste into something valuable while also aiding in the battle against climate change (Balaji et al. 2013; Madadi et al. 2021). The selection of the biomass source is influenced by various factors, including desired bioplastic properties, cost, availability, and environmental impact. To reduce the environmental footprint and advance the principles of circular economy in the production of bioplastics, a sustainable strategy takes algal biomass into account. And, the primary factor that makes algae a promising sustainable source for the biopolymer industry is its exceptionally high biomass availability and productivity, which is 5 to 10 times faster than that of conventional food crops (Das 2023).

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## 5.2 Green Algae

Green algae are gaining increasing attention for their potential in various fields. Their rapid growth, ability to produce valuable compounds like biofuels and pigments, and potential for wastewater treatment make them promising candidates for sustainable practices (Mahmoud et al. 2022). It is commonly known as seaweed; it is a diverse and abundant organism that plays a vital role in marine ecosystems. These photosynthetic organisms belong to the *Chlorophyta* division and can be found in various marine habitats like rocky shores, coral reefs, and estuaries. These algae produce a wide range of secondary metabolites, such as polysaccharides, polyphenols, pigments, and peptides that exhibit various biological activities. For instance, certain polysaccharides derived from marine green algae have antioxidant, anti-inflammatory, and immunomodulatory properties. These compounds have the potentiality to be utilised in developing new drugs or as functional ingredients in nutraceuticals and cosmeceuticals (Demarco et al. 2022).

### 5.2.1 The Advantages of Algae Cultivation for the Environment

Algae benefits both the environment and humans, and it has great potential for solving nutritional and environmental challenges (Diaz et al. 2023). Algae can be grown in controlled photo-bioreactor systems or in open pond systems, both with strengths and weaknesses. Despite their low operating costs and simplicity of scaling up, open systems have low productivity, a significant risk of contamination, and are impractical for large-scale production of pure strains. The closed photobioreactor

system, on the other hand, has a high photosynthetic rate, stimulates the development of a single algal species, and is less prone to contamination. However, the cost of scaling up is higher as compared to an open pond system (Xie et al. 2022). Green algae, as previously mentioned, may be used to make biofuels, biodegradable plastics, natural textiles, and a variety of other important biological products. It also contributes to improved water quality and the absorption of hazardous components, which improves water quality and lowers pollution (Chia et al. 2020). The conversion of algae into bioplastics has increased the appeal of the algae-based bioeconomy. Although algal biomass is low in lignin, it is high in long-chain hydrocarbons. As a result, extracting high-purity cellulose for the creation of bioplastics is now economically possible. Algal-based bioplastics are considered environmentally favourable products. Because they biodegrade organically in a couple of months, they are less harmful to the environment. Biodegradable polymers derived from marine green algae, as opposed to petroleum-based plastics, have received a lot of interest due to their greater rates of biodegradability in ambient conditions (Coppola et al. 2021). It is a bright hope for meeting our future challenges in innovative and effective ways combining environmental and economic benefits.

### 5.2.2 Algal Bioplastics and Green Economy

Algal bioplastics play a critical part in the rapidly expanding green economy, which aims to promote sustainability, reduce environmental impact, and limit carbon emissions (Zaher and Ibrahim 2023). To implement sustainable bioplastics that are stronger and more resilient than conventional plastics, polymers extracted from algae must meet a number of criteria, including polymer size, molecular weight, moisture content, biodegradability, feedstock renewability, degradation rate, brittleness, and consumer acceptability (Thakur et al. 2018). By using algae for bioplastic production, it acts as a carbon sequester that actively contributes to carbon capture and storage (CCS), aligning with the green economy's objective represented in minimising greenhouse gas emissions (Alam et al. 2020). Furthermore, the biodegradability of algal bioplastics contributes to the transition to a circular economy. It can be composted or degraded by microorganisms, returning to the ecosystem as organic matter via the mineralisation process (Thiruchelvi et al. 2020). Algal bioplastics' versatility extends to diverse industries such as packaging, cutlery, and single-use products. Their properties, like durability and transparency, resemble traditional plastics, allowing for various product applications.

### 5.2.3 Algal Bioplastic Is Gaining Popularity

The use of marine green algae to produce bioplastics utilises plentiful and renewable resources that may be cultivated in a variety of environments such as saltwater, wastewater, and brackish water. In addition, unlike conventional plastics, they are

very easy to grow and process since the entire process is linear and continually generates dangerous gases such as CO<sub>2</sub> (Xie et al. 2022).

It is gaining popularity as a viable and sustainable alternative to plastics. When people have the correct mindset, such as caring for the environment or the confidence that their activities would help reduce the carbon footprint of plastic usage, they participate in pro-environmental behaviours such as employing bioplastics. Adoption of such green items, however, may be difficult due to people's differing degrees of awareness and attitudes about the environmental consequences of their consumption (Stasiškienė et al. 2022). More efforts are needed to increase the awareness of the customers and to enhance bioplastic usage. Thus, proper rules are necessary to encourage large-scale bioplastics manufacture and market acceptance. People, who are the most crucial stakeholders in achieving environmental sustainability, must accept new sustainability initiatives, technology, and products such as bioplastics for them to be effective (Stasiškienė et al. 2022).

### 5.2.4 Algae and Wastewater Treatment

Algae may be cultivated in industrial wastes and sewage without putting a strain on natural water supplies. Moreover, microalgae are effective in cleaning up wastewater by assimilating organic and inorganic elements such as nitrogen and carbon. They also aid in the recovery of phosphorus in an environmentally sustainable and cost-effective manner (Abdella et al. 2023; Stávková and Maroušek 2021). They may implement zero-waste rules and transform current garbage and microalgae into valuable products in biorefineries (Stasiškienė et al. 2022). For instance, *Chlorella vulgaris* absorbs the most CO<sub>2</sub> and is widely explored for bioplastic synthesis. The presence of carboxyl, hydroxyl, and sulphate groups in algal cells might be exploited to generate bioplastics, specifically for food, pharmaceutical, and medical packaging (Niu et al. 2021). The cultured strain, growth conditions, harvesting, and extraction of algae cells and their components in an ecologically responsible manner are all critical factors to consider when producing bioplastics from algae (Stasiškienė et al. 2022).

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## 5.3 Transformation of Algal Biopolymers into Bioplastics

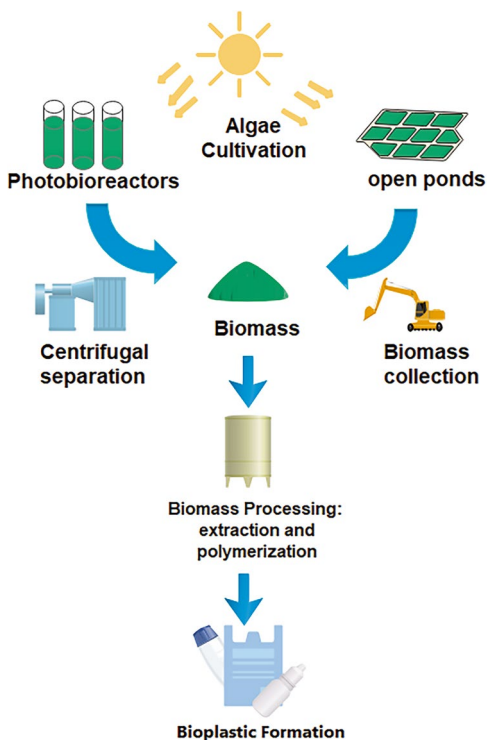
Several processes are involved in the conversion of algal biopolymers into bioplastics. Initially, algal biomass is collected and treated to obtain biopolymers. Depending on the biopolymer of interest, this can be accomplished by physical, chemical, or enzymatic methods. Following extraction, the biopolymers are purified further and prepared in a suitable state for polymerisation. Breaking down the biopolymers into smaller molecular units, such as monomers or oligomers, which may subsequently be polymerised to generate the final bioplastic material with new or desired properties (Mal et al. 2022). Algae-derived biopolymers, encompassing polysaccharides and proteins, form the essential building blocks for bioplastics.

Within this realm, diverse bioplastics sourced from green algae, including alginate, polyhydroxyalkanoates (PHAs), carrageenan, agar, chitosan, and ulvan, exhibit distinctive properties and applications, as shown in Table 5.1. These biopolymers can be extracted from various types of algae, including macroalgae and microalgae (Khanra et al. 2022). PHAs are also a type of biodegradable plastic that can be derived from the cells of microalgae. PHAs are synthesised from neutral lipids that accumulate within the microalgae cells (Costa et al. 2018). The cultivation conditions need to be precisely controlled, and materials such as vinasse, molasses from sugar production, or even waste frying oil can be used in the process (Gomaa 2023). Polymerisation of algal biopolymers can be accomplished through various techniques, including traditional methods such as heat or other chemical methods, as well as emerging approaches like enzymatic or microbial processes. These methods enable the production of bioplastics with diverse properties, such as flexibility,

**Table 5.1** Examples and characteristics of algal-derived bioplastics

Bioplastic name	Algae source	Most important characteristics	References
Alginate-based bioplastics	Brown algae (e.g., <i>Macrocystis</i> , <i>Laminaria</i> )	Biodegradable Water-soluble Non-toxic	Lim et al. (2021)
Polyhydroxyalkanoates (PHAs) from algae	Various algae species	Biodegradable Thermoplastic Versatile	Adrah et al. (2020) and Jain et al. (2023)
Carrageenan-based bioplastics	Red algae (e.g., <i>Chondrus crispus</i> )	Flexible Transparent Good film-forming properties	Das (2023), Mondal et al. (2020) and Varghese et al. (2022)
Agar-based bioplastics	Red algae (e.g., <i>Gracilaria</i> )	Biodegradable Thermoplastic Good film-forming properties	Asif et al. (2021)
Chitosan-based bioplastics	Green algae (e.g., <i>chlorella</i> )	Biodegradable Antibacterial Antifungal	Abdo et al. (2024)
Ulvan-based bioplastics	Green algae (e.g., <i>Ulva lactuca</i> )	Biodegradable Lightweight Good mechanical properties	Manikandan and Lens (2023)
Fucoidan-based bioplastics	Brown algae (e.g., <i>Fucus</i> )	Biocompatible Antioxidant Antibacterial	Hamid et al. (2019)
Sargassum-derived bioplastics	Brown algae (e.g., <i>Sargassum</i> )	Lightweight UV-resistant High tensile strength	Mohammed et al. (2023)
Gelidium-derived bioplastics	Red algae (e.g., <i>Gelidium</i> )	Gel-forming Biodegradable Thermoreversible	Mouga and Fernandes (2022)

**Fig. 5.1** Steps of bioplastic production from marine algae



strength, and biodegradability, depending on the intended application (Stoica et al. 2022).

PHAs can be produced from microalgae by cultivating them under environmental stress conditions (Abdo and Ali 2019). It is also reported that under phosphate-limited conditions, other algae such as the blue-green *Spirulina* can produce homo-polymers like polyhydroxybutyrate (PHB), which belongs to the family of PHAs (Costa et al. 2018).

Unlike other PHAs, PHBs are composed of a short-chain homopolymer of hydroxybutyrate, with the backbone of the biopolymers containing four carbon atoms. Additionally, PHBs are predominantly associated with polyesters, which enhance the material's rigidity and brittleness (Röhl et al. 2023). Figure 5.1 illustration depicts the different steps on the production of bioplastic from algae.

## 5.4 Applications of Algal-Derived Bioplastics

Algae-driven plastics were successfully employed in many applications: In packaging, algae-based bioplastics provide a sustainable solution to address environmental concerns associated with conventional plastics. They can be employed to produce a variety of packaging materials, such as films, bags, and containers, offering a

biodegradable option that reduces the environmental footprint of plastic waste (Coppola et al. 2021). Their exceptional barrier properties make them well-suited for food packaging and other products, effectively protecting them against moisture and oxygen. As a result, they are becoming the preferred choice for disposable items like shopping bags and food packages, aiming to minimise environmental harm (Coppola et al. 2021). In agriculture, bioplastics sourced from algae find practical applications in manufacturing biodegradable agricultural films and mulches. These films serve various purposes, including preserving soil moisture, inhibiting weed growth, and managing soil temperature. Their inherent biodegradability eliminates the need for post-use removal from fields, streamlining labour requirements, and reducing plastic waste associated with traditional plastic mulches (Singh et al. 2022). The medical and pharmaceutical sectors recognise the potential of algae-based bioplastics. These materials can be used to produce biocompatible and biodegradable medical devices, such as sutures, drug delivery systems, and tissue scaffolds. The advantage of biodegradability is particularly beneficial in medical contexts, where the removal of implanted devices can lead to complications and discomfort. Biodegradable bioplastics offer a natural decomposition process over time, reducing the need for surgical extraction and enhancing patient well-being (Ang et al. 2020). Additionally, algal-based bioplastics are utilised in the production of disposable cutlery and tableware, addressing environmental concerns associated with single-use plastics in the food service sector. These bioplastics are both naturally degradable and suitable for composting, eliminating the need for extended disposal methods. The shift to algal-derived bioplastics in the food service industry, which generates significant plastic waste, reflects a positive move toward environmental awareness and responsibility (Berry et al. 2022).

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## 5.5 Algal Bioplastics and Environmental Footprint

In recent times, there has been a growing global awareness of the urgent necessity to tackle environmental issues, especially those linked to fossil-based plastic pollution and resource depletion.

### 5.5.1 Biodegradability and Disposal

The biodegradable nature of algal bioplastics presents a sustainable substitute for conventional plastics, with the ability to decompose in natural settings. However, the speed and level of degradation are influenced by elements like polymer makeup, environmental factors, and microbial presence. Adequate waste management systems and composting facilities are vital for optimising the eco-friendly advantages of biodegradable algal bioplastics while mitigating land and water pollution risks (Mal et al. 2022).

### 5.5.2 Mitigating Ocean Pollution

Global marine plastic pollution is a substantial issue. Bioplastics sourced from marine green algae can make a significant contribution to mitigating this pollution. As these bioplastics naturally degrade within marine ecosystems, they disintegrate into non-toxic elements that are less detrimental to marine life and ecosystems. The substitution of conventional plastics with algal bioplastics in products like disposable cutlery, which frequently ends up in the oceans, enables us to actively participate in lessening the environmental harm caused by plastic waste (Mal et al. 2022).

### 5.5.3 Circular Economy

The algal bioplastics adoption corresponds with the assumptions of a circular economy, striving to reduce waste and encourage the permanent utilisation of resources. These bioplastics, originating from renewable sources and engineered for biodegradability, sustain the Earth's inherent regenerative mechanisms. They can be employed, discarded, and reintegrated into the environment in ways that decrease environmental damage, diverging from the conventional linear model of "take-make-dispose" linked with traditional plastics (Rosenboom et al. 2022).

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## 5.6 Challenges and Future Directions

There are many challenges in the production of bioplastics from marine algae. These are listed hereunder;

### 5.6.1 Cost Competitiveness and Market Dynamics

The challenge of cost competitiveness and market dynamics in marine algae-derived bioplastics emphasises the delicate equilibrium between economic viability and market forces, influencing their feasibility and acceptance in modern markets. Essentially, the competitiveness of bioplastics from marine algae relies on their ability to match or surpass traditional petroleum-based plastics and other biopolymers in production costs and pricing. Achieving this parity or superiority is critical for wide adoption, necessitating refined cultivation, extraction, and production processes to minimise expenses while maximising output (Behera et al. 2022). However, obstacles abound in scaling up algae cultivation sustainably to industrial levels while maintaining efficiency and sustainability. Marine algae cultivation complexities, including nutrient management and infrastructure, contribute to production costs and logistical challenges. Furthermore, efficient extraction and processing technologies are needed to balance effectiveness with cost-effectiveness (Vieira et al. 2022).

To overcome these difficulties, diverse approaches are required. This means using new technology, teaming up, making helpful rules, and educating the people. Collaboration with everyone is essential for getting the most out of marine algae-based bioplastics. This is crucial for fighting plastic pollution and climate change.

### 5.6.2 Environmental and Sustainability Considerations

Creating bioplastics from marine green algae poses significant challenges related to the environment and sustainability. It involves carefully examining and lessening the ecological impacts at each step. Growing marine algae for bioplastics needs to be done reliably to avoid harming habitats and using up too many resources (Tarangini et al. 2023). Also, the methods used for extracting and processing the algae can lead to carbon emissions and environmental harm if not managed well. The use of land and water with conservation efforts is crucial. We need sustainable practices like managing nutrients efficiently and recycling waste to ensure the long-term success of algae-based bioplastic production (Zaher and Ibrahim 2023). Additionally, concerns about displacing natural habitats and disrupting marine ecosystems must be addressed. To tackle these challenges, new methods such as advanced cultivation techniques and eco-friendly extraction processes are being explored. Collaboration among researchers, industry stakeholders, and policymakers is vital to establishing sustainable practices and regulations.

### 5.6.3 Extraction and Processing Methods

Extracting and processing methods present significant hurdles in producing bioplastics from marine algae. The extraction of bioplastic precursors like polysaccharides and polyhydroxyalkanoates (PHA) from algae biomass demands efficient and eco-friendly techniques. Common methods often involve chemical solvents or energy-intensive processes, which can harm the environment and raise production expenses (Khandelwal and Lens 2023). Furthermore, turning extracted bioplastic precursors into usable materials requires careful optimisation and innovation. Processes like polymerization and formulation must be adjusted to ensure the quality, strength, and usability of the bioplastic products. Balancing high-performance materials with sustainable production practices is vital to minimize environmental harm and boost the overall sustainability of algae-based bioplastics (Dalal et al. 2023). Tackling these challenges calls for the development of new extraction and processing technologies that prioritise efficiency, environmental consciousness, and cost-effectiveness. Innovative methods such as enzymatic hydrolysis, mechanical disruption, and eco-friendly solvents offer hope in reducing energy use, cutting down chemical usage, and enhancing the eco-friendliness of bioplastic production (Kurniawan et al. 2023).

## 5.7 Conclusion

Using marine algae among other biomass resources for making bioplastics is a big step toward greener plastic options. Green algae, commonly found in oceans, are great for making bioplastics because they grow fast, can survive in different environments, and do not need a lot of resources.

One big advantage of growing algae is that it is good for the environment. Unlike regular plastic made from fossil fuels that harm the environment, algae absorb CO<sub>2</sub> from the air during photosynthesis, which helps reduce greenhouse gases. Using algae to make bioplastics can lower our carbon footprint and help save resources. Also, it can help create an eco-friendlier economy. Algae-based bioplastics have become more popular lately as a substitute for regular plastics. Better technology and more research have made it easier to produce algae bioplastics on a larger scale. These bioplastics can be used in many industries, from packaging to medical fields, offering a wide range of possibilities. As people become more eco-conscious, algae bioplastics can also change the way we make and use materials, making our world more sustainable.

However, there are still challenges to overcome before algal bioplastics can be widely used. We need to figure out better ways to grow algae, improve the quality of bioplastics, and make production more efficient. Despite these challenges, converting algae into bioplastics has the potential to make a big positive impact on the environment and economy. Looking forward, turning algae into bioplastics can help us move toward a greener future.

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# Biomass Valorisation: A Sustainable Approach Towards Carbon Neutrality and Circular Economy

# 6

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## Abstract

Biomass valorisation stands as a pivotal strategy in the pursuit of carbon neutrality and the establishment of a circular economy. As the world transitions towards sustainable practices, biomass derived made from organic sources including forestry waste, crop residues, and specially cultivated energy crops, seems as an abundant renewable resource with tremendous potential. This study gives an

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extensive overview of biomass valorisation, highlighting its significance in mitigating carbon emissions, promoting resource efficiency, and fostering economic development. The principles of biomass valorisation encompass a range of conversion technologies, including thermochemical, biochemical, and physicochemical processes, each offering unique pathways for transforming biomass into valuable products. These products, including biofuels, biochemicals, biomaterials, and biocomposites, find diverse applications across sectors such as energy, agriculture, industry, and transportation. The environmental and economic benefits of biomass valorisation are substantial, contributing to greenhouse gas mitigation, waste reduction, and rural livelihood enhancement. However, challenges such as feedstock availability, technological scalability, and market acceptance require concerted efforts for widespread adoption. Future perspectives, this study underscores the importance of biomass valorisation as a cornerstone of sustainable development, offering insights into its role in achieving carbon neutrality and advancing the circular economy agenda.

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**Keywords**

Biomass valorisation · Renewable energy · Circular economy · Carbon neutrality

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## 6.1 Introduction

In the face of escalating environmental challenges and the urgent need to transition towards sustainable practices, biomass valorisation emerges as a pivotal strategy in the pursuit of carbon neutrality and the production of and consumption of materials that prioritises reusability and sustainability. As the global population continues to multiply and industrial activities escalate, the depletion of finite resources and the exacerbation of climate change have become pressing concerns (Mondal and Palit 2022). In this background, biomass derived from organic sources like dedicated energy crops, forestry waste, and agricultural residues stands out as a renewable and abundant resource with immense potential to address these challenges. Biomass valorisation holds profound significance in the transition towards a sustainable future for several reasons. Firstly, biomass serves as a carbon-neutral alternative to fossil fuels, offering the possibility to mitigate emissions of greenhouse and combat climate change. Unlike fossil fuels, which release carbon dioxide sequestered millions of years ago, biomass-derived fuels and products cycle carbon through the atmosphere, soil, and biomass, thereby maintaining equilibrium and minimising net carbon emissions (Simões et al. 2023). Additionally, biomass valorisation promotes resource efficiency by harnessing organic waste streams and underutilised biomass resources, thereby reducing dependence on virgin materials and minimising environmental degradation. Moreover, biomass valorisation is consistent with the circular economy's principles which emphasise resource conservation, reuse, and recycling in order to reduce waste and increase value production. Biomass valorisation is fundamentally centred on transforming biomass feedstocks into higher-value products using a range of technological processes.

These processes can be broadly categorised into thermochemical, biochemical, and physicochemical conversion pathways. Thermochemical conversion encompasses processes such as pyrolysis, gasification, and combustion, which utilise heat to break down biomass into biofuels, syngas, and biochar. Biochemical conversion, Conversely, entails employing microorganisms or enzymes to ferment biomass, yielding biofuels, biochemicals, and bioproducts. Lastly, physicochemical conversion methods, including hydrothermal processing and solvent extraction, employ physical and chemical means to transform biomass into fuels, chemicals, and materials (Adams et al. 2018). The successful valorisation of biomass relies on the effective implementation of various conversion technologies tailored to the specific characteristics of the feedstock and desired products.

The products derived from biomass valorisation find various applications across sectors such as energy, agriculture, industry, and transportation. Biofuels, including bioethanol, biodiesel, and biogas, serve as sustainable alternatives to fossil fuels in transportation and heating applications, reducing emissions of greenhouse gas and dependence on imported fuels. Biochemicals, such as organic acids, enzymes, and biopolymers, find use in food, pharmaceutical, and chemical industries, offering renewable and biodegradable alternatives to petrochemical-derived products. Biomaterials and biocomposites, derived from lignocellulosic biomass, are utilised in construction, packaging, and manufacturing, providing eco-friendly alternatives to conventional materials. Additionally, biomass-derived products contribute to the development of rural economies, creating opportunities for income generation and livelihood enhancement in agricultural communities (Kabeyi and Olanrewaju 2022). Utilising the abundant potential of biomass as a renewable resource, biomass valorisation presents a route toward achieving carbon neutrality, resource efficiency, and embracing circular economy principles (Kapoor and Rafatullah 2022). This chapter offers a thorough examination of biomass valorisation, covering its importance, underlying principles, technological methodologies, diverse applications, environmental and economic advantages, as well as the challenges and future prospects within the realm of sustainable development.

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## 6.2 Biomass as a Sustainable Resource

Biomass, sourced from organic materials like plants, trees, agricultural remnants, and organic waste, emerges as a renewable and sustainable resource of significant potential. Unlike finite fossil fuels, biomass is abundant, widely accessible, and can be naturally replenished through processes like photosynthesis. Its versatility and varied origins render it invaluable in addressing a spectrum of environmental and energy-related challenges (Kuyah et al. 2020).

An eminent advantage of biomass lies in its capacity to function as a carbon-neutral, and at times, carbon-negative energy reservoir. When biomass undergoes combustion or conversion into biofuels, any carbon dioxide released during these processes is counterbalanced by the carbon dioxide absorbed by plants during their growth stages. This closed carbon cycle aids in mitigating greenhouse gas emissions and combatting climate change. Moreover, biomass holds the potential to curtail dependence on fossil fuels and foster energy autonomy. By harnessing biomass for

electricity generation, heat provision, and as transportation fuels, nations can diversify their energy portfolios and diminish reliance on imported oil and gas. This not only bolsters energy security and resilience but also spurs local economies through the establishment of biomass supply chains and associated industries (Olujobi et al. 2023).

In addition to its energy applications, biomass offers numerous environmental benefits. Sustainable biomass production practices, such as agroforestry and perennial cropping systems, can improve soil health, enhance biodiversity, and protect ecosystems. Biomass residues and organic waste can be recycled through composting or anaerobic digestion, reducing landfill waste and methane emissions.

Moreover, biomass-based products and materials have the potential to replace conventional, fossil fuel-derived products in various sectors, including construction, packaging, and textiles. For example, bio-based plastics, derived from biomass feedstocks such as corn starch or sugarcane, offer a renewable alternative to petroleum-based plastics, reducing reliance on non-renewable resources and mitigating plastic pollution (Atiwesh et al. 2021).

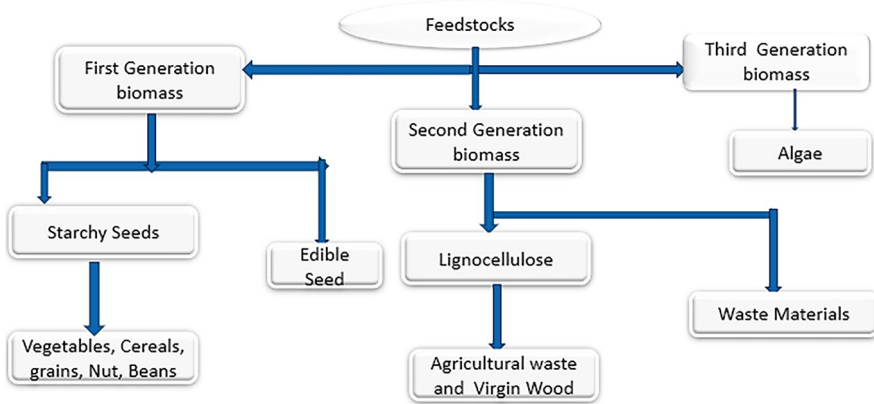
One of the key advantages of biomass is its abundance and widespread availability. Biomass resources include a diverse range of materials, including forestry residues, agricultural crops and residues, organic waste from households and industries, and dedicated energy crops. This abundance ensures that biomass can be sourced locally, reducing transportation costs and energy consumption.

The utilisation of biomass for energy and material production offers opportunities for waste reduction and resource efficiency (Kapoor et al. 2023). By valorising organic waste streams through processes such as anaerobic digestion or pyrolysis, biomass can be converted into valuable energy and products, reducing the burden on landfills and promoting the circular economy. Furthermore, biomass-based products and materials have the potential to replace fossil-based counterparts, contributing to resource conservation and sustainability (Rasheed et al. 2021).

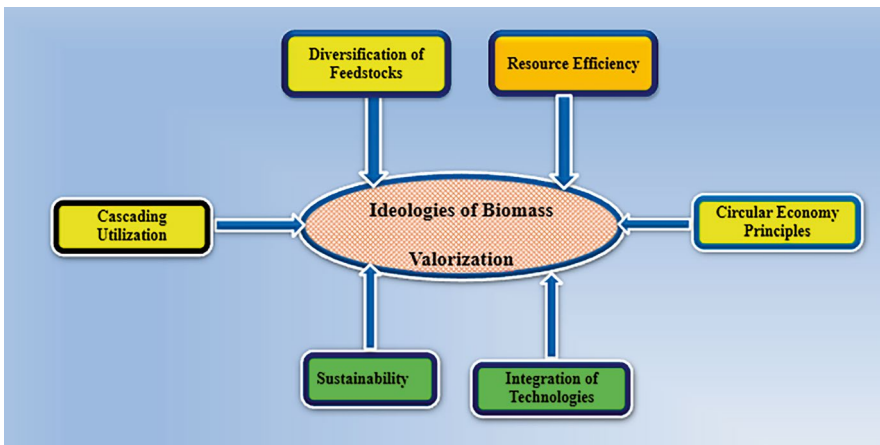
In conclusion, biomass represents a sustainable and renewable resource with diverse applications across energy, industry, agriculture, and waste management sectors. Its abundance, renewable nature, carbon neutrality, and versatility make it an essential component of efforts to achieve environmental sustainability, combat climate change, and transition toward a circular economy. Harnessing the potential of biomass through innovative technologies and sustainable practices will be crucial in realising its full benefits and advancing toward a more sustainable future. Different types of biomass used for the valorisation process are shown in Fig. 6.1.

### 6.2.1 Principles of Biomass Valorisation

Biomass valorisation refers to the process of converting biomass resources into valuable products, energy, and materials through various technological pathways. The principles of biomass valorisation encompass a range of approaches aimed at maximising the utilisation and sustainability of biomass resources (Pfab et al. 2019). Different ideologies of the biomass valorisation are shown in Fig. 6.2. These principles include the following:



**Fig. 6.1** Different biomass used for valorisation



**Fig. 6.2** Different ideologies of biomass valorisation

**6.2.1.1 Resource Efficiency**

Resource efficiency is a fundamental principle guiding biomass valorisation practices. It involves optimising the use of biomass resources to minimise waste generation and maximise the extraction of value-added products and energy. By adopting efficient conversion technologies and integrated biorefinery approaches, biomass valorisation aims to extract the maximum possible value from biomass feedstocks while minimising resource consumption and environmental impacts (Chen et al. 2023).

**6.2.1.2 Diversification of Feedstocks**

Biomass valorisation promotes the use of diverse feedstocks to broaden the resource base and enhance resilience to supply chain disruptions. This principle encourages

the utilisation of various biomass sources, including energy crops, agricultural residues, organic waste, forestry residues, and algae. Diversifying feedstocks helps to mitigate competition for land and resources, reduce dependence on specific feedstock types, and optimise biomass availability for different applications (Velvizhi et al. 2023).

### 6.2.1.3 Cascading Utilisation

Cascading utilisation involves extracting multiple products and benefits from biomass resources through sequential processing steps. This principle emphasises the importance of maximising resource efficiency by valorising biomass in a cascading manner, where the primary biomass feedstock undergoes multiple conversion steps to produce a range of products and energy outputs. For example, lignocellulosic biomass can be transformed into biofuels, platform chemicals, and high-value bioproducts through sequential processes such as hydrolysis, fermentation, and catalytic upgrading.

### 6.2.1.4 Integration of Technologies

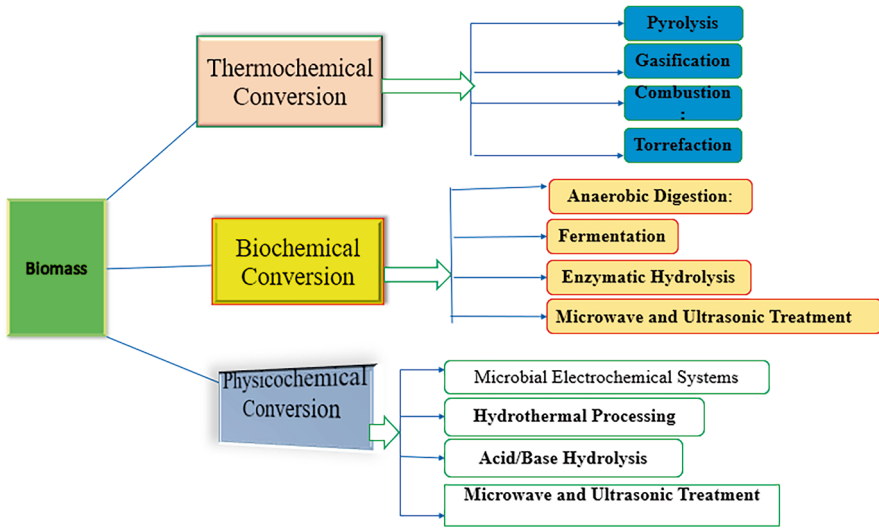
Biomass valorisation relies on the integration of diverse conversion technologies to optimise resource utilisation and product yields. This principle emphasises the importance of synergistic interactions between different conversion processes, such as thermochemical, biochemical, and physicochemical methods. Integrated biorefinery concepts leverage the complementary nature of these technologies to maximise the overall efficiency of biomass conversion and enhance the economic viability of valorisation pathways (Velvizhi et al. 2023).

**Sustainability** Sustainability is a central guiding principle in biomass valorisation, encompassing environmental, social, and economic considerations. Sustainable biomass valorisation practices aim to minimise environmental impacts, conserve natural resources, promote social equity, and enhance economic viability. This involves adopting environmentally friendly technologies, ensuring responsible sourcing of biomass feedstocks, minimising greenhouse gas emissions, and supporting local communities and economies (Mukherjee et al. 2023).

### 6.2.1.5 Circular Economy Principles

Biomass valorisation is in harmony with the tenets of the circular economy, advocating for resource efficiency, minimising waste, and maximising the utilisation of by-products and waste streams. Circular economy principles emphasise closing the loop of material flows and minimising the use of finite resources by reusing, recycling, and repurposing biomass-derived materials and products. Biomass valorisation contributes to the circular economy by transforming biomass residues and waste into valuable resources; this approach diminishes dependence on new materials and encourages a more sustainable strategy for managing resources (Ambaye et al. 2023).

In general, the principles of biomass valorisation encompass resource efficiency, diversification of feedstocks, cascading utilisation, integration of technologies,



**Fig. 6.3** Biomass conversion process

sustainability, and circular economy principles. By adhering to these principles, biomass valorisation can contribute to sustainable resource management, environmental stewardship, and the transition towards a more circular and bio-based economy.

## 6.3 Conversion Technologies for Biomass Valorisation

Conversion technologies for biomass valorisation encompass a diverse array of processes that transform biomass feedstocks into various value-added products, including biofuels, biochemicals, bioproducts, and bioenergy. These technologies play a vital role in realising the complete potential of biomass resources and enabling their incorporation into sustainable and circular economy frameworks. Below are some key conversion technologies used in biomass valorisation: Fig. 6.3 shows the biomass conversion process.

### 6.3.1 Thermochemical Conversion

Thermochemical conversion processes involve the use of heat and/or pressure to decompose biomass feedstocks and convert them into energy carriers, such as biofuels, syngas, and biochar (Rasaq et al. 2024). Major thermochemical conversion technologies include:

**Pyrolysis** Pyrolysis is a thermal process that involves the decomposition of organic materials in the absence of oxygen. It occurs within a controlled environment, typically at temperatures ranging from 300 °C to 800 °C. During pyrolysis, biomass, agricultural residues, and various waste products undergo heating, causing complex organic molecules to break down into simpler compounds, volatile gases (such as methane, hydrogen, carbon monoxide, and carbon dioxide), and biochar.

The solid residue produced, known as biochar or charcoal, contains carbon-rich material suitable for applications like soil amendment. Pyrolysis offers numerous benefits, including the production of bioenergy, biofuels, and value-added products from renewable biomass resources. Moreover, it aids in carbon sequestration by trapping carbon in biochar, thereby reducing greenhouse gas emissions. Additionally, pyrolysis facilitates the management of organic waste streams, transforming them into useful products while minimising environmental pollution. Overall, pyrolysis presents a promising avenue for biomass valorisation, contributing to the generation of clean energy, climate change mitigation, and sustainable resource management practices (Rasaq et al. 2024).

**Gasification** Gasification is a thermochemical process that converts biomass, or any carbon-containing feedstock, into a gaseous mixture known as synthesis gas or syngas. This process occurs at high temperatures and in the presence of a precise amount of oxygen, steam, or a combination of both (Sansaniwal et al. 2017). During gasification, biomass undergoes several chemical reactions, including pyrolysis, combustion, and reduction, leading to the production of syngas. The primary components of syngas are carbon monoxide (CO), carbon dioxide (CO<sub>2</sub>), and hydrogen (H<sub>2</sub>) along with smaller amounts of methane (CH<sub>4</sub>) and other trace gases. Gasification can be carried out using various reactor configurations, such as fixed bed, fluidised bed, and entrained flow reactors, each offering specific advantages and limitations (Luo et al. 2028).

**Combustion** Combustion is one of the primary methods for converting biomass into usable energy. It involves the rapid oxidation of biomass in the presence of oxygen, typically in the form of air, to release heat. This exothermic reaction produces carbon dioxide (CO<sub>2</sub>), water vapour (H<sub>2</sub>O), and various other combustion by-products, depending on the composition of the biomass feedstock (Behera and Varma 2017).

**Torrefaction** Torrefaction is a mild thermal treatment of biomass which involves subjecting biomass feedstocks to moderate temperatures in the range of 200–300 °C, typically under controlled conditions, to improve their energy density, stability, and handling characteristics. This process, often referred to as torrefaction or mild pyrolysis, induces physical and chemical changes in the biomass structure, resulting in a range of beneficial properties (Adeleke et al. 2021).

One of the major objectives of mild thermal treatment is to lower the moisture content of biomass, which can be as high as 50–60% in raw biomass materials. By removing moisture through torrefaction, the energy density of the biomass is significantly increased, making it more suitable for combustion, gasification, or pelletisation. The removal of moisture also improves the stability of the biomass, reducing the risk of biological degradation and extending its shelf life.

In addition to moisture removal, mild thermal treatment also leads to the devolatilisation of volatile organic compounds, such as hemicellulose and some lignin components, within the biomass structure. The biomass's total weight decreases as a consequence and an increase occurs in its carbon content, further enhancing its energy density. The removal of volatile compounds also contributes to the improved handling characteristics of the biomass, reducing the risk of spontaneous combustion and making it easier to transport and store.

Furthermore, mild thermal treatment can result in the formation of a porous structure within the biomass material, which enhances its reactivity and combustion efficiency. The increased porosity allows for better air circulation and heat transfer during combustion or gasification processes, leading to a more complete and efficient conversion of the biomass into energy (Akinyemi et al. 2018).

### 6.3.2 Biochemical Conversion

Biochemical conversion processes utilise microorganisms, enzymes, and fermentation techniques to transform biomass carbohydrates, proteins, and lipids into biochemicals, bioproducts, and biofuels. These processes encompass various technologies, among which anaerobic digestion holds a significant role:

**Anaerobic Digestion** Anaerobic digestion is a biological process that occurs in the absence of oxygen, facilitated by a consortium of microorganisms including bacteria, archaea, and fungi. These microorganisms work together to decompose organic matter and produce biogas and digestate. The process begins with hydrolytic bacteria breaking down complex organic molecules like carbohydrates, proteins, and lipids into simpler compounds such as sugars, amino acids, and fatty acids. Acidogenic bacteria then ferment these intermediates into volatile fatty acids (VFAs), alcohols, and other organic acids. Acetogenic bacteria further metabolise these compounds into acetate, hydrogen, and carbon dioxide (Harirchi et al. 2022).

Methanogenic archaea play a crucial role in the final stage of anaerobic digestion, converting acetate, hydrogen, and carbon dioxide into methane ( $\text{CH}_4$ ) through methanogenesis. Biogas, the primary product, typically comprises 50–70% methane, along with carbon dioxide and trace gases like hydrogen sulphide and nitrogen.

Biogas generated from anaerobic digestion serves as a renewable energy source for electricity generation, heating, or vehicle fuel. It can be combusted directly in gas turbines or boilers, or upgraded to biomethane for injection into natural gas pipelines or as a transportation fuel. Additionally, anaerobic digestion produces

digestate, a nutrient-rich by-product used as an organic fertiliser or soil conditioner in agriculture. Digestate contains essential nutrients like nitrogen, phosphorus, and potassium, along with organic matter, enhancing soil structure and fertility (Kabeyi and Olanrewaju 2022).

**Fermentation** Fermentation is a metabolic process carried out by microorganisms such as bacteria, yeast, and fungi to convert biomass sugars into biofuels, such as ethanol and butanol, as well as biochemicals. This biological conversion process occurs under anaerobic or aerobic conditions and is widely used in various industries, including biofuel production, biorefining, and food and beverage fermentation. During fermentation, microorganisms utilize sugars, typically derived from biomass feedstocks such as sugarcane, corn, lignocellulosic materials, or waste streams, as a carbon source to produce energy and metabolites (Zabed et al. 2016).

**Enzymatic Hydrolysis** Enzymatic hydrolysis plays a crucial role in the conversion of lignocellulosic biomass into fermentable sugars, essential for producing biofuels like ethanol. This process employs enzymes to degrade complex polysaccharides found in biomass, particularly cellulose and hemicellulose, into more accessible sugars such as glucose, xylose, and other monosaccharides. These sugars serve as the substrate for microbial fermentation to produce biofuels and biochemicals (Vasić et al. 2021).

**Microbial Electrochemical Systems (MES)** Microbial electrochemical systems (MES) represent a cutting-edge technology that integrates microorganisms with electrochemical processes to convert organic matter, including biomass, into valuable products such as electricity, hydrogen gas, and various organic chemicals. In MES, microorganisms serve as biocatalysts to facilitate the oxidation or reduction of organic compounds, while electrochemical reactions occur at the surface of electrodes to transfer electrons between the microorganisms and the electrode material. The core components of a typical MES setup include an anode, a cathode, and a microbial biofilm or suspension that bridges the two electrodes. The anode is typically populated by electroactive microorganisms capable of oxidising organic substrates, while the cathode supports reduction reactions, such as oxygen reduction or hydrogen evolution. The electrochemical reactions at the anode and cathode generate an electric potential difference, leading to the flow of electrons through an external circuit, thereby producing electrical power (Thapa et al. 2022).

### 6.3.3 Physicochemical Conversion

Physicochemical conversion processes involve the application of mechanical, chemical, and physical treatments to biomass feedstocks to extract valuable

components or modify their properties. Major physicochemical conversion technologies include:

**Supercritical Fluid Extraction (SFE)** SFE employs supercritical fluids, commonly carbon dioxide ( $\text{CO}_2$ ), as solvents to extract bioactive compounds from biomass. By bringing the solvent to a supercritical state, where it displays characteristics of both a liquid and a gas, SFE enables the penetration of solid biomass matrices and the dissolution of desired compounds, facilitating their extraction (Da-Silva et al. 2016).

**Hydrothermal Processing** Hydrothermal processing is a versatile technique used for the treatment of biomass by subjecting it to hot pressurised water. This process involves the hydrolysis of lignocellulosic components present in biomass, resulting in the production of biofuels, chemicals, and other valuable products. Biomass is normally processed hydrothermally in a reactor vessel, where it is combined with water and heated to high pressures and temperatures (Antero et al. 2020).

**Acid/Base Hydrolysis** Acid/base hydrolysis is a chemical treatment method used to break down lignocellulosic structures present in biomass and release fermentable sugars. This process involves the use of acids or bases to catalyse the hydrolysis of complex carbohydrates, such as cellulose and hemicellulose, into their constituent monosaccharides, which can then be fermented into biofuels or other value-added products (Leong et al. 2022).

In acid hydrolysis, strong mineral acids such as sulfuric acid ( $\text{H}_2\text{SO}_4$ ), hydrochloric acid ( $\text{HCl}$ ), or phosphoric acid ( $\text{H}_3\text{PO}_4$ ) are commonly used. These acids protonate the hydroxyl groups in cellulose and hemicellulose molecules, disrupting the glycosidic bonds between the sugar units and breaking down the polymer chains into shorter oligomers and monomers. The resulting mixture, known as acid hydrolysate, contains a mixture of sugars, organic acids, and other by-products. Acid hydrolysis is typically carried out at elevated temperatures and pressures to accelerate the reaction kinetics and improve sugar yields.

In base hydrolysis, alkali reagents such as sodium hydroxide ( $\text{NaOH}$ ) or potassium hydroxide ( $\text{KOH}$ ) are used to catalyse the hydrolysis reaction. These bases deprotonate the hydroxyl groups in cellulose and hemicellulose, leading to the cleavage of glycosidic bonds and the formation of alkali metal salts of the resulting sugars. Base hydrolysis is often conducted under milder conditions compared to acid hydrolysis, typically at lower temperatures and pressures (Zhou et al. 2023).

Both acid and base hydrolysis have advantages and disadvantages. Acid hydrolysis is generally faster and more efficient at breaking down lignocellulosic biomass but requires careful control of reaction conditions to prevent degradation of sugars and formation of inhibitory by-products such as furfural and hydroxymethylfurfural (HMF). Base hydrolysis, on the other hand, is less prone to side reactions and

by-product formation but may require longer reaction times and higher alkali concentrations to achieve comparable sugar yields. After hydrolysis, the resulting sugar-rich hydrolysate can be further processed through fermentation to produce biofuels such as ethanol, butanol, or biogas, as well as biochemicals such as organic acids, solvents, and platform chemicals. Acid/base hydrolysis is a key step in biomass conversion pathways and plays a critical role in unlocking the energy and value potential of lignocellulosic feedstocks for sustainable bio-based industries. Continued research efforts are focused on optimising hydrolysis conditions, developing efficient catalysts, and minimising environmental impacts to enhance the overall efficiency and sustainability of biomass valorisation processes (Wang et al. 2023).

**Microwave and Ultrasonic Treatment** Microwave and ultrasonic pretreatment are advanced techniques used to enhance the efficiency of biomass conversion processes, particularly enzymatic hydrolysis, by applying microwave or ultrasonic energy to biomass feedstocks. These methods have gained significant attention due to their ability to disrupt the lignocellulosic structure of biomass and increase the accessibility of cellulose and hemicellulose to enzymatic hydrolysis, thereby improving biofuel yields and reducing processing times (Fia and Amorim 2023).

In microwave pretreatment, biomass is exposed to high-frequency electromagnetic radiation in the microwave range (typically 300 MHz to 300 GHz). The interaction between microwaves and biomass causes rapid heating and localised thermal effects within the biomass matrix, leading to the disruption of lignin-carbohydrate complexes and the breakdown of crystalline cellulose structures. This results in increased porosity, surface area, and accessibility of biomass components to enzymes during subsequent enzymatic hydrolysis. Microwave pretreatment is known for its rapid heating rates, uniform energy distribution, and scalability, making it suitable for industrial-scale applications (Fernandes et al., 2023).

Ultrasonic pretreatment involves the application of high-frequency mechanical waves (ultrasound) to biomass slurries or suspensions. Ultrasonic waves create cavitation bubbles in the liquid medium, which collapse violently near the solid biomass surface, generating localised heating, shock waves, and micro-turbulence (Kausley et al. 2022). These physical effects disrupt the lignocellulosic structure of biomass, causing the fragmentation of cellulose fibres and the release of hemicellulose and lignin fragments. Ultrasonic pretreatment can enhance the enzymatic digestibility of biomass by increasing the accessibility of cellulose and hemicellulose to hydrolytic enzymes and promoting the release of soluble sugars.

Both microwave and ultrasonic pretreatment methods offer several advantages for biomass conversion processes. They can be applied to a wide range of biomass feedstocks, including lignocellulosic residues, agricultural residues, energy crops, and algae. These techniques are relatively energy-efficient and environmentally friendly compared to traditional pretreatment methods such as steam explosion or acid hydrolysis, as they require lower temperatures, shorter processing times, and minimal chemical usage. Additionally, microwave and ultrasonic pretreatment can

be integrated into existing biomass processing facilities with minimal modifications, making them attractive options for enhancing the overall efficiency and sustainability of biofuel production processes (Ambaye et al. 2021).

Despite their promising potential, microwave and ultrasonic pretreatment techniques also have some limitations and challenges. These include equipment costs, scalability issues, and potential variations in pretreatment effectiveness depending on biomass composition and pretreatment conditions. Further research is needed to optimize pretreatment parameters, develop cost-effective processing technologies, and evaluate the techno-economic feasibility of integrating microwave and ultrasonic pretreatment into commercial-scale biomass conversion processes.

### **Valorisation of Biomass By-products and Waste Streams**

Valorisation of biomass by-products and waste streams involves the conversion of residual materials generated from biomass processing and utilisation into valuable products, thereby maximising resource efficiency, reducing waste, and contributing to sustainable development. This approach aligns with the principles of circular economy, where resources are used in a closed-loop system to minimize environmental impact and promote economic viability (Vianna et al. 2024). The following are key strategies and technologies for the valorisation of biomass by-products and waste streams:

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## **6.4 Biomass Residues and By-products Utilisation**

**Agricultural Residues** Crop residues (straw, stalks, husks), fruit and vegetable peels, and other agricultural by-products can be converted into biofuels (biodiesel and bioethanol), biochemicals (enzymes and organic acids), biopolymers, animal feed, and soil amendments through various conversion processes (Blasi et al. 2023).

**Forestry Residues** Logging residues (branches, tops and bark), sawdust, and wood chips can be utilised for bioenergy production (e.g., wood pellets, biogas), pulp and paper manufacturing, biochemical production, and soil stabilisation (Braghiroli and Passarini 2020).

Food Waste Valorisation:

**Organic Waste** Food scraps, kitchen waste, and organic residues from food processing industries can be anaerobically digested to produce biogas, composted to produce organic fertiliser, or used as feedstock for insect farming and animal feed production (Ferdeş et al. 2022).

**Food Processing By-products** By-products generated during food processing operations (e.g., pomace from fruit juice extraction, spent grains from brewing) can be valorised for the production of value-added products such as dietary supplements, functional foods, and bioactive compounds (Alghoul et al. 2019).

Municipal Solid Waste (MSW) Management:

**Organic Fraction** Organic waste streams from households and commercial establishments can be separated and processed through anaerobic digestion, composting, or thermochemical conversion to produce biogas, compost, and biochar (Zamri et al. 2021).

**Plastics and Packaging Waste** Non-recyclable plastics and packaging materials can be converted into alternative fuels (e.g., refuse-derived fuel, pyrolysis oil), recycled into new plastic products through chemical recycling, or used as feedstock for the production of biodegradable polymers (Norouzi and Dutta 2022).

### **Industrial By-product Valorisation**

**Agro-industrial Waste:** By-products from the agro-food industry, such as sugar beet pulp, olive pomace, and brewery spent grains, can be valorised for biofuel production, bioplastics, animal feed, and high-value chemicals (Paini et al. 2022).

**Pulp and Paper Mill Residues** Residual lignin, cellulose, and hemicellulose from pulp and paper production processes can be converted into bio-based chemicals, adhesives, and materials through biorefining and chemical processing (Eugenio et al. 2019).

Waste-to-Energy Technologies:

**Incineration** Thermal treatment of waste streams to generate heat and electricity, with the potential for recovering metals from ash residues (Phua et al. 2019).

**Gasification and Pyrolysis** Conversion of solid waste materials into syngas or bio-oil through high-temperature thermochemical processes, which can be utilized for power generation or chemical synthesis (Maitlo et al. 2022).

In general, the valorisation of biomass by-products and waste streams offers a sustainable solution for resource recovery, waste reduction, and energy generation, contributing to the transition towards a circular economy and carbon-neutral society.

Products made from biomass are essential for reducing the emissions of greenhouse gases, reducing dependence on finite resources, and promoting resource efficiency. Through innovative conversion technologies and integrated biorefinery approaches, biomass valorisation unlocks the full potential of organic materials, transforming them into value-added products with environmental and economic benefits. By understanding the broad spectrum of applications for biomass-derived products, we can appreciate their significance in fostering sustainability across various industries. From renewable energy generation to waste valorisation and carbon sequestration, biomass-derived products offer promising solutions to address pressing environmental and societal challenges. Table 6.1 highlights specific applications and the role of biomass-derived products in promoting sustainability, resource efficiency, and circular economy principles.

#### **6.4.1 Environmental and Economic Benefits of Biomass Valorisation**

Biomass valorisation serves as a multifaceted solution to global challenges, spanning from curbing greenhouse gas emissions and combatting climate change to catalysing economic growth and bolstering rural development. By tapping into renewable biomass reservoirs like agricultural residues, forestry waste, and organic by-products, we can markedly diminish our reliance on finite fossil fuels, curtail waste production, and advocate for sustainable land management practices. Furthermore, the process of biomass valorisation breathes life into local economies, generating employment opportunities and fortifying energy security through the diversification of energy sources and the reduction of reliance on imported fuels. Through the application of cutting-edge technologies and comprehensive approaches, biomass valorisation charts a course towards a more sustainable and resilient future one where resource efficiency, environmental stewardship, and economic vitality take centre stage.

Table 6.2 summarises the positive impacts of biomass valorisation on the environment, economy, and society.

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### **6.5 Key Findings**

- (i) Biomass can be converted into various forms of renewable energy, such as biofuels (e.g., bioethanol, biodiesel) and biogas (produced through anaerobic digestion). These energy sources can replace fossil fuels, reducing greenhouse gas emissions and mitigating climate change.
- (ii) Biomass-based products and processes can facilitate carbon sequestration, thereby contributing to efforts to offset carbon emissions. For instance, utilis-

**Table 6.1** Applications of biomass-derived products

Biomass-derived product	Application	Industry	Environmental benefit	Economic benefit	References
Bioethanol	Transportation fuel	Biofuel	Reduced greenhouse gas emissions, renewable energy source	Job creation, energy security	Hou et al. (2020)
Biodiesel	Diesel substitute for vehicles	Biofuel	Reduced air pollution, renewable energy source	Job creation, energy security	Kumar et al. (2020)
Bioplastics	Packaging materials, consumer products	Packaging, plastics	Reduced plastic waste, biodegradability	Sustainable packaging, market diversification	Irshad and Mushtaq (2020)
Biochar	Soil amendment, carbon sequestration	Agriculture, land remediation	Improved soil fertility, carbon sequestration	Soil health, climate change mitigation	Prasanth et al. (2021)
Bio-based chemicals	Specialty chemicals, pharmaceuticals	Chemical, pharmaceutical	Reduced reliance on fossil fuels, lower toxicity	Green chemistry, market competitiveness	Varma (2019)

**Table 6.2** Environmental and economic benefits of biomass valorisation

Benefit	Description	References
Greenhouse gas reduction	By keeping organic waste out of landfills and substituting renewable materials for goods made from fossil fuels, biomass valorisation lowers greenhouse gas emissions.	Okafor et al. (2022)
Resource conservation	Utilising biomass as a feedstock reduces dependency on finite fossil resources, preserving natural resources for future generations.	Antar et al. (2021)
Waste reduction	Valorising biomass by-products and waste streams minimises the amount of organic waste sent to landfills, reducing environmental pollution and mitigating the risk of soil and water contamination.	Karić et al. (2022)
Job creation	Biomass valorisation industries create employment opportunities across the value chain, including farming, processing, manufacturing, and distribution, thereby stimulating local economies.	Panoutsou et al. (2020)

- ing biomass for biochar production can lock carbon in stable forms, promoting soil health and fertility while mitigating atmospheric carbon dioxide levels.
- (iii) Biomass valorisation enables the utilisation of organic waste streams from various sectors, including agriculture, forestry, and municipal solid waste. By converting these wastes into value-added products such as bio-based chemicals, materials, and bioenergy, biomass valorisation promotes resource efficiency and reduces reliance on virgin resources.
  - (iv) Biomass valorisation aligns with the principles of the circular economy by creating closed-loop systems where biomass resources are utilized efficiently and waste is minimised. By transforming biomass into multiple products and cascading its use through various value chains, biomass valorisation fosters a more sustainable and circular approach to resource management.
  - (v) Biomass valorisation can stimulate local economies by creating new opportunities for farmers, foresters, and rural communities. By diversifying income streams and fostering local value chains, biomass valorisation supports rural development while enhancing resilience to economic shocks.
  - (vi) Continued research and development in biomass valorisation technologies are essential for unlocking its full potential. Advances in biorefinery processes, bioconversion technologies, and biomass feedstock optimisation can improve the efficiency, cost-effectiveness, and environmental sustainability of biomass valorisation pathways.

### 6.5.1 Challenges and Opportunities in Biomass Valorisation

The challenges and opportunities in biomass valorisation represent a complex landscape that requires innovative solutions and collaborative efforts to overcome barriers and unlock the potential of biomass as a sustainable resource. Key challenges include limited feedstock availability, technological development barriers, policy

and regulatory complexities, market penetration challenges, and environmental sustainability concerns. However, these challenges also present opportunities for innovation, research, and collaboration. By exploring alternative biomass sources, improving conversion technologies, developing supportive policy frameworks, raising market awareness, and promoting environmental sustainability, the value-adding of biomass can play a major role in the shift to a more circular and sustainable economy (Schipfer et al. 2022) (Table 6.3).

### 6.5.2 Future Perspectives and Emerging Trends in Biomass Valorisation

As the world continues to grapple with the challenges of climate change, resource scarcity, and environmental degradation, the role of biomass valorisation in promoting sustainability, carbon neutrality, and circular economy principles is becoming increasingly prominent. Looking ahead, several future perspectives and emerging trends are shaping the trajectory of biomass valorisation:

**Technological Advancements** Continued research and development efforts are expected to lead to significant advancements in biomass conversion technologies. Emerging techniques such as advanced pyrolysis, hydrothermal processing, and biorefinery concepts hold promise for improving the efficiency, scalability, and cost-effectiveness of biomass valorisation processes.

**Integration of Biorefinery Concepts** The concept of biorefineries, which aims to integrate various biomass conversion processes to produce a range of value-added products, is gaining traction. Biorefineries offer a holistic approach to biomass valorisation, enabling the simultaneous production of biofuels, biochemicals, biomaterials, and bioenergy from diverse biomass feedstocks.

**Circular Economy Principles** The adoption of circular economy principles is expected to drive the development of closed-loop biomass valorisation systems. By maximising resource efficiency, minimising waste generation, and promoting the reuse and recycling of biomass-derived products and by-products, circular economy models can enhance the sustainability and resilience of biomass valorisation processes.

**Valorisation of Lignocellulosic Biomass** Lignocellulosic biomass, including agricultural residues, forestry residues, and dedicated energy crops, represents a vast and underutilised resource for biomass valorisation. Future trends in biomass valorisation are likely to focus on the efficient conversion of lignocellulosic biomass

**Table 6.3** Challenges and opportunities in biomass valorisation

Part	Challenges	Opportunities	References
Feedstock availability	Limited availability and variability of biomass feedstocks due to seasonal fluctuations, geographic constraints, and competition with food and feed production.	Diving into alternative biomass sources, including agricultural residues, energy crops, algae, and organic waste streams, offers a promising avenue for expanding biomass utilisation. By embracing sustainable land management practices and diversifying crop cultivation, we can bolster the availability and dependability of feedstock supplies, paving the way for more robust biomass valorisation efforts.	De-Meyer et al. (2024)
Technological development	Technological barriers include high capital costs, inefficient conversion processes, and limited scalability of biomass conversion technologies.	Research and development initiatives aimed at enhancing the efficiency, cost-effectiveness, and scalability of biomass conversion technologies represent a critical aspect of advancing biomass valorisation. Through innovation and collaborative efforts, strides can be made in process intensification, catalytic conversion, and the integration of renewable energy sources. These advancements are poised to elevate overall process efficiency and accelerate the transition towards sustainable biomass utilisation.	Morales et al. (2020)
Policy and regulatory	Regulatory complexities, inconsistent policies, and lack of supportive frameworks hindering investment and market growth in the biomass valorisation sector.	Development of clear and consistent policy frameworks, incentives, and regulations to promote investment, innovation, and market development in the biomass valorisation sector. Collaboration between governments, industries, and stakeholders to establish sustainable biomass utilisation strategies and standards.	Okafor et al. (2022)

(continued)

**Table 6.3** (continued)

Part	Challenges	Opportunities	References
Market penetration	Limited market awareness, consumer acceptance, and infrastructure for biomass-derived products, resulting in market penetration challenges.	Education and outreach initiatives to raise awareness about the environmental and economic benefits of biomass valorisation among consumers, industries, and policymakers. Investment in infrastructure development for biomass processing, distribution, and utilisation to facilitate market growth and adoption of biomass-derived products.	Panoutsou et al. (2020)
Environmental sustainability	Potential environmental impacts associated with biomass cultivation, harvesting, and processing, including land-use change, biodiversity loss, and water consumption.	Adoption of sustainable practices such as agroforestry, conservation agriculture, and water-efficient cultivation techniques to minimize environmental impacts and enhance ecosystem resilience. Implementation of life cycle assessments and sustainability certifications to ensure the environmental sustainability of biomass valorisation processes and products.	Haregu et al. (2023)

into biofuels, biochemicals, and bioproducts, leveraging advanced pretreatment, enzymatic hydrolysis, and fermentation technologies.

**Biogenic Carbon Capture and Utilisation (BCCU)** Biomass valorisation can play a crucial role in biogenic carbon capture and utilisation (BCCU) strategies, which involve capturing carbon dioxide from the atmosphere through photosynthesis and converting it into value-added products. Future trends in biomass valorisation may explore synergies between BCCU technologies and biomass conversion processes to achieve carbon-negative or carbon-neutral outcomes.

**Policy Support and Market Incentives** Government policies, regulatory frameworks, and market incentives will play a pivotal role in driving the adoption of biomass valorisation technologies and promoting sustainable biomass supply chains. Supportive policies, such as carbon pricing mechanisms, renewable energy mandates, and subsidies for bio-based products, can create favourable conditions for investment and innovation in the biomass valorisation sector.

**Stakeholder Collaboration and Knowledge Sharing** Collaboration among governments, industries, academia, and civil society is essential for accelerating the

deployment of biomass valorisation technologies and addressing common challenges. Knowledge sharing, capacity building, and technology transfer initiatives can facilitate the dissemination of best practices and foster innovation in biomass valorisation.

The future of biomass valorisation holds tremendous potential to contribute to carbon neutrality, resource efficiency, and sustainable development. By embracing technological innovation, circular economy principles, and collaborative partnerships, biomass valorisation can play a vital role in shaping a more sustainable and resilient future for generations to come.

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## 6.6 Conclusion

In conclusion, biomass valorisation offers a sustainable approach towards achieving carbon neutrality and promoting circular economy principles. Through the efficient conversion of biomass into biofuels, biochemicals, biomaterials, and bioenergy, biomass valorisation mitigates greenhouse gas emissions, reduces dependence on fossil fuels, and fosters resource efficiency. By harnessing renewable biomass resources, such as agricultural residues, forestry residues, organic wastes, and dedicated energy crops, biomass valorisation contributes to carbon sequestration, ecosystem restoration, and sustainable land management practices.

Moreover, biomass valorisation supports the transition towards a circular economy by maximising the utilisation of biomass feedstocks, minimising waste generation, and promoting the reuse and recycling of biomass-derived products and by-products. Biorefinery concepts, which integrate various biomass conversion processes, enable the production of a diverse range of value-added products, thereby enhancing the economic viability and environmental sustainability of biomass valorisation systems. Despite its significant potential, biomass valorisation faces several challenges, including technological barriers, feedstock availability, market competitiveness, and policy support. Addressing these challenges requires concerted efforts by policymakers, industry stakeholders, researchers, and civil society to create an enabling environment for investment, innovation, and collaboration in the biomass valorisation sector.

Looking ahead, future advancements in biomass conversion technologies, the development of circular economy models, and supportive policy frameworks are expected to drive the widespread adoption of biomass valorisation as a key strategy for achieving carbon neutrality and achieving sustainable development goals. By harnessing the power of biomass resources in a responsible and environmentally conscious manner, biomass valorisation holds the promise of ushering in a more sustainable and resilient future for generations to come.

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# Biofuel Production from Seaweed: A Sustainable Energy Solution

# 7

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## Abstract

The global demand for sustainable energy sources has increased the amount of research being done on alternative methods of producing biofuel. Seaweed biofuel production is a viable source of sustainable energy with many social, economic, and environmental advantages. Seaweed biofuel has the potential to lessen greenhouse gas emissions, lessen dependency on finite fossil fuels, and promote economic growth in coastal areas by using the enormous resources offered by marine ecosystems. Seaweed-derived biofuels have various environmental benefits, including the capacity to absorb carbon, reduce land usage, and be carbon-neutral. To reach its full potential, though, a number of obstacles must be overcome, including improving growing techniques, creating effective conversion technologies, and integrating seaweed biofuel into the current energy system. Technological developments, regulatory support, and interdisciplinary research collaborations may enable seaweed biofuels to reach their full potential. This chapter provides a complete overview of the present study's findings about the challenges, prospects, and state of seaweed-based biofuel production. To guarantee that the production of seaweed biofuel remains a feasible and sustainable energy source in the long run, attention must be paid to resource efficiency, ecological resilience, and sustainable agricultural practices.

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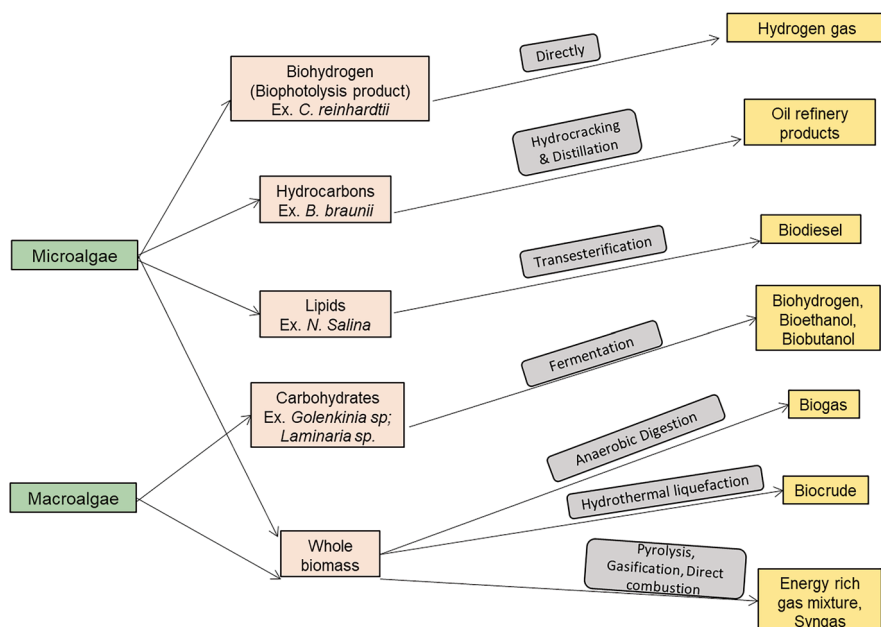
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## 7.1 Introduction

In 2014, a report from the Energy Information Administration predicted a 56% increase in global energy consumption by 2040, reaching 820 quadrillion Btu from 524 quadrillion Btu in 2010. This surge could spark an energy crisis as fossil fuel reserves deplete rapidly, worsening CO<sub>2</sub> levels and global warming. Scientists caution that climate change impacts may be underestimated, with evidence showing a conservative outlook. Global CO<sub>2</sub> emissions have surged by 51% in the past two decades due to fossil fuel combustion, highlighting the unsustainable reliance on these resources for energy (Kapoor and Rafatullah 2022; Kibria et al. 2023, 2024). So, in pursuing sustainable and environmentally friendly energy sources, marine resources such as seaweed and microalgae have emerged as promising candidates for biofuel generation (Islam et al. 2019; Mourshed et al. 2022; Hoque et al. 2015). This innovative approach holds immense importance in addressing the challenges of climate change, diminishing fossil fuel reserves, and the need for cleaner energy alternatives. In this study, we explore the significance of converting marine resources (especially macroalgae) into biofuels.

It is essential to turn seaweed and microalgae into biofuels for a number of reasons. Primarily, these marine resources provide a plentiful and sustainable substitute for conventional fossil fuels, aiding in lowering reliance on non-renewable resources that worsen the environment. Due to their quick development rates, microalgae and seaweed can be harvested sustainably and speedily. Furthermore, growing these organisms may help sequester and trap carbon dioxide, which will help slow down global warming (Mourshed et al. 2023; Joardder et al. 2019). A change towards a more sustainable and environmentally friendly energy landscape is encouraged by the biofuels made from seaweed and microalgae, such as biodiesel and bioethanol, which burn cleaner and release fewer greenhouse emissions. Macroalgae, encompassing various aquatic eukaryotes from Chlorophyta, Streptophyta, Rhodophyta, Phaeophyceae, and Xanthophyceae, offer significant advantages in sustainable biofuel production compared to terrestrial plants. With minimal lignin content, they are easily digestible by microbes, facilitating biofuel processing. Figure 7.1 shows an illustration of different conversion techniques of bio sources into biofuel.

They thrive without the need for agricultural land or freshwater, boasting productivity comparable to the most fertile land plants and tropical rainforests. Moreover, macroalgae's chemical compounds find applications in food, fodder, and industry before their biomass is utilised for biofuel. Post-fuel conversion, the remaining biomass serves various purposes such as fertiliser, heating, or as a substrate for alternative biofuel production (Suutari et al. 2015). The adoption of seaweed and microalgae as major biofuel sources is expected to gain momentum in the coming years as technology advances and awareness of the environmental benefits continues to



**Fig. 7.1** Different conversion techniques of bio sources into biofuel. (Kumar et al. 2016)

grow. Several techniques are employed to convert seaweed and microalgae into biofuels, each with its own set of advantages and challenges. Common methods include:

- **Thermochemical conversion:** Processes involve pyrolysis and gasification that apply heat to break down the biomass into biofuels.
- **Biochemical conversion:** This method utilises enzymes or microorganisms to ferment the sugars in seaweed and microalgae into biofuels.
- **Hydrothermal liquefaction:** Biomass is subjected to high temperature and pressure in the presence of water, leading to the production of bio-oils.
- **Biodiesel production:** Extraction of lipids (oils) from microalgae and seaweed, followed by transesterification, results in biodiesel.

The investigation of seaweed-derived biofuel production has become a fascinating path with broad ramifications in the search for sustainable energy sources. In order to create a more sustainable and financially viable biofuel business, research is being done to optimise these processes, increase their efficiency, and lower the costs involved in large-scale manufacturing. A viable avenue for the production of clean, green energy is the conversion of seaweed and microalgae into biofuels (Mourshed et al. 2023). As technology continues to advance and global initiatives prioritise sustainable energy sources, the integration of marine resources into our energy portfolio holds the potential to reshape the future of energy production, mitigating environmental impacts and fostering a more sustainable planet. This chapter

explores the complex world of seaweed biofuel and provides information on its possible use as a green energy source. Given the current state of environmental concerns and the limited supply of fossil fuels, seaweed biofuel is becoming increasingly important as a sustainable substitute.

This chapter also aims to explore the technological and logistical difficulties involved in producing seaweed biofuel, including important factors like growing strategies, harvesting tactics, and conversion procedures. Through an analysis of recent research results and technical developments, this chapter seeks to present a thorough picture of the prospects and difficulties associated with the production of seaweed biofuel. In the end, this chapter acts as a springboard for more research and discussion on the place of seaweed biofuel in the shift to more sustainably produced energy. This chapter aims to clarify the potential of seaweed biofuel as a workable and scalable renewable energy source by utilising an interdisciplinary approach that incorporates ideas from environmental science, engineering, and economics.

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## 7.2 Global Scenario of Biofuel Generation from Seaweed/Microalgae

The notion of using seaweeds to produce bioenergy has gained more and more traction in recent years. Global production of biofuels from microalgae and seaweed has been rising rapidly, according to the most recent data. Various countries and research institutions have been investing in research and development to enhance cultivation techniques and optimise the conversion processes. It is crucial to remember that the move towards large-scale commercial production is still in its infancy.

Fossil fuels appear to have competition from biofuels made from algal biomass, which emits zero net CO<sub>2</sub> (Islam et al. 2024; Mourshed et al. 2024). In order to generate biofuel, researchers have been experimenting with various macro- and microalgae utilising a variety of techniques. Patel et al. used hydrothermal carbonisation (HTC) process to produce hydrochar (Patel 2019). The HTC investigation was applied in a batch reactor at various periods and temperatures. When the hydrochar was heated to 220 °C for 120 minutes, it showed the highest carbon content (48.5%) and heating value (18.93 MJ/kg), with a greater energy density and carbon-to-nitrogen ratio than raw seaweed (Patel et al. 2021). Pourkarimi et al. (2019) compiled the data on pyrolysis process used for different marine resources for producing biofuel and the works on co-pyrolysis of algal biomass and plastic were summarised by Kositkanawuth et al. (2014). Table 7.1 shows the algal biomass conversion technologies through pyrolysis.

In the process of producing biofuel from algal biomass, Gautam et al. examined and compiled the work done on genetic modification and CO<sub>2</sub> biosequestration as a long-term solution to the fuel problem (Gautam et al. 2015). After analysing the impacts of using palm oil and microalgae as feedstocks for biodiesel on the environment and food security, Ahmad et al. found that microalgae was a more sustainable source of biodiesel (Ahmad et al. 2011). Wei et al. covered a lot of ground, including the characteristics of seaweed, how to grow and harvest it, and the essential

**Table 7.1** Studies on pyrolysis of algal biomass (Pourkarimi et al. 2019)

Algae type	Algae strain	Biofuel generation technique	Plant type	Condition	Yield
Microalgae	Sptrulina sp.	Pyrolysis (slow)	Fixed bed reactor	Biomass: 125 g, temperature: 450–600°C, gas flow rate: 30 ml/min, heating rate: 8°C/min, reaction time: 60 min	Bio-oil: 46% (550 °C) Bio-char: 33% (500 °C)
Microalgae	Lipid-extracted Tribonema minus	Pyrolysis (slow)	Fixed bed reactor	Biomass: 5 g, temperature: 300–500°C, gas flow rate: 10 ml/min, heating rate: 8°C/min, reaction time: 60°C min	Bio-oil: 29.82% Bio-char: 50.35% Gas: 19.83% (450 °C, 50 ml/min)
Microalgae	Scenedesmus dimorphus	Pyrolysis (slow)	Fixed bed reactor	Biomass: 10 g, temperature: 300–600°C, gas flow rate: 100 ml/min, heating rate: 40°C/min	Bio-oil: 39.6% (500) Bio-char: 36% (300) Biogas: 25% (600 °C) Bio-oil: 24–31% Bio-char: 30–33%
Microalgae	Chlorella vulgaris	Pyrolysis (fast)	Quartz tube reactor	Biomass: 0.100 g, temperature: 500–900°C, gas flow rate: 0.08 m <sup>3</sup> /h, residence time: 500 s	Bio-oil((syngas): 91.09% (900 °C) Char: 8.91% (900 °C)
Macroalgae	Laminaria digitata, Fucus serratus, Black Sea	Pyrolysis (fast)	Fluidised bed reactor	Biomass: 90 g, temperature: 500°C, gas flow rate: 0.64 m <sup>3</sup> /h, residence time: 1–2 s	Bio-oil: 32–37% (500 °C)
Macroalgae	Undaria pinnatifida	Pyrolysis (fast)	Packed tube reactor	Biomass: 6–8 g, temperature: 300–600°C, gas flow rate: 50 ml/min, particle size: 0.8 mm, reaction time: 60 min.	Bio-oil: 37.5–47.4% (500 °C)

(continued)

**Table 7.1** (continued)

Algae type	Algae strain	Biofuel generation technique	Plant type	Condition	Yield
Macroalgae	Saccarina japonica	Pyrolysis (fast)	Fixed bed reactor	Biomass: 15 g, temperature: 350–550°C, gas flow rate: 100, 300, 500 ml/min	Bio-oil: 40.91% char: 37.14% Gas: 21.95%
Macroalgae	Saccarina japonica	Pyrolysis (fast)	Fixed bed batch or continuous	Biomass: 40 g/150 g/h, temperature: 470°C, gas flow rate: 0.5, 45.37 l/min, particle size: 600–1000 µm, reaction time: 10 min.	Bio-oil: 37.9%

processes in turning seaweed biomass into biofuels. They also talked about the developments in the fermentation of sugars from seaweed biomass using either naturally occurring or artificially created microbial cells. (Wei et al. 2013). Nielsen et al. focused on the effects of halogenated chemicals on various biohydrogen generation methods while discussing the anaerobic digestion of algae for biofuel production (Nielsen et al. 2020). Singh et al. focused on how nanoparticles influence various biohydrogen production processes and included a broad review of the various types of algae and the mechanism of biohydrogen generation (Singh et al. 2023). With the ongoing escalation of global energy requirements and the diminishing availability of fossil fuel reserves, marine macroalgae, commonly referred to as seaweed, is emerging as a focal point in the quest for sustainable fuel and chemical production. The abundant marine plant biomass presents numerous advantages over its terrestrial counterparts when used as a feedstock.

Biohydrogen, touted for its minimal environmental impact and diverse sustainable production methods, stands out as a sought-after alternative energy source garnering significant interest and demand. Algae-based biological hydrogen production techniques are particularly captivating due to the broad range of environments in which they thrive, their rapid growth rates, and their polyphyletic nature.

However, despite the promise, several challenges hinder the widespread and commercial adoption of algal biohydrogen generation (Singh et al. 2023). The main challenges are low biomass concentration, low yield, restricted light penetration, and expensive downstream procedures. A diversified strategy is required to address these issues. Using algal variety to increase yield and biomass production while enhancing light penetration capacities is one potential approach. Incorporating nanomaterials also has the potential to speed up the process of producing biohydrogen by altering the underlying processes. Algal variety is being used by several studies as a tactical tool to increase the generation of biohydrogen (Nielsen et al. 2020). They are investigating how nanomaterials affect several biohydrogen

generation processes, such as direct and indirect biophotolysis, dark fermentation, and photo-fermentation. It is feasible to offer insights into the potential of several algae groups combined with nanomaterial technologies to overcome present restrictions in biohydrogen generation by looking at recent accomplishments and current obstacles. Recent advancements in metabolic engineering have unlocked the potential to convert a wide range of carbohydrates derived from seaweed biomass into liquid biofuels, such as bioethanol. These breakthroughs highlight the untapped promise of seaweed biomass as a source for biofuels, offering a relatively unexplored yet promising avenue to address the world's energy needs while mitigating environmental impacts associated with fossil fuel consumption. This growing interest in seaweed-derived biofuels signals a shift towards innovative and eco-friendly solutions in the global energy landscape, driving further exploration and investment in this renewable resource.

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### 7.3 Biofuel Generation Techniques from Seaweed

A critical consideration in identifying viable bio-renewable resources is their high biomass productivity. Algae, thriving in aquatic environments, offer significant advantages over land-based plants in this regard. Their ability to grow in water conserves land space and enables continuous cultivation. Furthermore, algae exhibit superior efficiency in converting light energy into biomass compared to terrestrial plants, with rates ranging from 5–10% versus 0.5–3% observed in various studies (Gao et al. 2020).

There are four process options available for thermochemical conversion: liquefaction, gasification, pyrolysis, and combustion. Anaerobic digestion and ethanol fermentation are the two primary process strategies used in biochemical conversion. To create biofuel from macroalgae, several techniques have been used, including liquefaction, anaerobic digestion, and ethanol fermentation (Gao et al. 2020). One method of classifying the extraction of energy from macroalgae is based on whether an initial drying step is necessary. This division results in two distinct categories of processes and the summary is presented in Table 7.2 (Milledge et al. 2014):

Methods requiring dry macroalgae:

- (i) Direct combustion.
- (ii) Pyrolysis.
- (iii) Conventional gasification.
- (iv) Conversion to biodiesel through trans-esterification.

Methods for extracting energy from wet macroalgae:

- (i) Hydrothermal treatments.
- (ii) Fermentation to produce bioethanol or biobutanol.
- (iii) Anaerobic digestion.

**Table 7.2** Selected projects for the production of biofuel from seaweed (Kumar et al. 2021)

Country	Project name	Project cost (USD)	Output
United States of America	Autonomous tow vessels	909,901	An autonomous marine tugboat for the implementation of extensive seaweed cultivation systems
	Ocean energy from macroalgae	496,483	Innovative system architecture and extensive macroalgae “ranching” employing modelling, imaging, and remote sensing technologies
	Performance and impact of macroalgae farming	995,978	Instruments to enhance the biological activity of marine algae systems in offshore environments
United Kingdom	Teleconnected SARGassum risks across the Atlantic: Building capacity for transformational adaption in the Caribbean and West Africa (SARTRAC)	1,210,263	The goal of the project is to comprehend why sargassum seaweed is being neglected on the beaches of the Caribbean, Central America, and West Africa
	GCRF global seaweed-safeguarding the future of seaweed aquaculture in developing countries	7,483,903	The goal of this initiative is to increase the capacity for innovation and research in developing nations that cultivate seaweed
Australia	Marine bioproducts and biotechnology corporative research center (bid in progress)		Recognising and creating bioproducts from marine resources, like microalgae and seaweeds
	Seaweed solutions for sustainable aquaculture	USD4,097,309	Collaborative effort to create an integrated multi-trophic aquaculture (IMTA) model that is sustainable and enables the production of seaweed for commercial use
New Zealand	Turning a pest seaweed into a high-value agricultural products	USD52,584	Species of seaweed pests developing <i>Undaria pinnatifida</i> into a valuable, sustainable crop
	A cattle feed supplement to reduce greenhouse gas emissions	USD70,112	Seaweed as a feed supplement at pilot-scale
Norway	SeaBest (SME-instrument)	USD1,963,892	Large-scale organic seaweed-to-food cultivation
Denmark	Algae-based climate feed additive for methane reduction in dairy cows (climate feed)	USD1,908,018	Provide appropriate techniques for growing, harvesting, processing, and drying seaweed to produce final products

Transesterification is crucial for converting seaweed or macroalgae into biofuels, mainly biodiesel. This chemical process transforms triglycerides from seaweed oil into biodiesel and glycerol. Initially, seaweed biomass is pretreated to extract oil and undergoes esterification to decrease free fatty acids. During transesterification, seaweed oil is mixed with alcohol (often methanol or ethanol) and a catalyst (like sodium hydroxide or potassium hydroxide) in a reactor. Controlled temperature and pressure conditions facilitate the conversion of triglycerides into biodiesel and glycerol. After the reaction, biodiesel is separated from glycerol through purification.

Transesterification offers benefits for seaweed-based biofuel production, including high efficiency, compatibility with diesel engines, and the potential for glycerol co-production with industrial uses. However, challenges like optimising reaction conditions, developing effective catalysts, and managing by-products need attention to enhance sustainability.

#### Pros:

- **Biodiesel production:** Converts seaweed oil into biodiesel, a renewable fuel.
- **Utilizes seaweed:** Utilizes lipid-rich seaweed species, reducing competition with food crops.
- **Renewable resource:** Abundant and renewable seaweed does not compete with land or freshwater resources.
- **Greenhouse gas reduction:** Biodiesel from seaweed helps reduce greenhouse gas emissions.

#### Cons:

- **High processing costs:** Requires specific equipment and chemicals, contributing to high processing costs.
- **Feedstock availability:** Dependence on availability and consistency of lipid-rich seaweed species.
- **Environmental impact:** Cultivation may have environmental impacts like habitat alteration and nutrient runoff.
- **Competition with food supply:** Potential concerns if seaweed competes with food crops for cultivation space.

#### Cost:

- **High initial investment:** Significant investment for equipment and infrastructure.
- **Feedstock costs:** Expenses for sourcing, harvesting, and transporting seaweed to processing facilities.
- **Chemical costs:** Costs related to chemicals used in the transesterification process.
- **Operating costs:** Ongoing expenses for labour, energy, and maintenance.

Overall, while transesterification offers potential for seaweed-based biodiesel, challenges include high costs, feedstock availability, and environmental impact. Ethanol fermentation is an ethanol production that primarily utilises first-generation

sources like corn and sugarcane, commonly employed as automotive co-fuels globally. However, their use raised food security concerns due to significant consumption as food crops. Consequently, there has been a shift to second-generation bioethanol from lignocellulosic biomass to mitigate these issues (Islam et al. 2023). Despite its potential, second-generation bioethanol faces challenges in processing and scalability, largely due to lignin hindering cellulose and hemicellulose breakdown. Nonetheless, macroalgae, with low lignin content, present a promising alternative as their polysaccharides can be easily converted to ethanol. Consequently, interest in macroalgae-derived bioethanol is increasing (Gao et al. 2020).

Fermentation represents a promising pathway for biofuel production from seaweed or macroalgae. In this process, sugars extracted from seaweed biomass are fermented by microorganisms to produce bioethanol or other biofuels. The fermentation process typically involves enzymatic hydrolysis to break down complex carbohydrates into fermentable sugars, followed by fermentation to convert these sugars into biofuels. While fermentation offers advantages such as versatility and compatibility with various seaweed species, challenges include the need for efficient sugar extraction methods and optimisation of fermentation conditions to maximise biofuel yields.

- Pros:
  - Converts sugars from seaweed into bioethanol.
  - Relatively mature technology.
  - Can utilize various species of seaweed.
- Cons:
  - Requires energy-intensive preprocessing to extract sugars.
  - Limited to certain types of biofuels (e.g., bioethanol).
- Cost: Moderate, with significant preprocessing costs.

Anaerobic digestion (AD): The first industrial digestion facility was founded in Bombay in 1859, and anaerobic digestion (AD) has a long history. Biogas is a byproduct of sewage treatment that was first utilized in Exeter, England, in 1895 for street lighting (Mourshed et al. 2023). Cellulosic materials, including straw and manure, have traditionally been used in China to produce methane for cooking. AD shows promise in the treatment of concentrated wastes from different industries, livestock manure, and sewage biosolids. There is now more interest in AD research and its commercial uses because of rising costs associated with fossil fuels and worries about greenhouse gas emissions and global warming. Global biogas output almost doubled between 1990 and 2016 (Kibria et al. 2024; Mourshed and Mustafi 2018). By using microbes to break down seaweed material in the absence of oxygen, anaerobic digestion is a biological process that produces biogas, mostly methane. Methanogenic bacteria first hydrolyse seaweed biomass to produce organic chemicals, which are subsequently transformed into biogas. The benefits of anaerobic digestion include the possibility of nutrient recycling and high energy recovery efficiency (Mourshed et al. 2023). Challenges include the need for efficient pre-treatment methods to improve seaweed digestibility and the management of digestate

by-products. Hydrolysis, acidogenesis, acetogenesis, and methanogenesis are the four stages of AD. The process that limits the pace and plays a crucial role in determining the final amount of biomethane generated is hydrolysis (Gao et al. 2020).

- Pros:
  - Converts seaweed biomass into biogas (methane).
  - Can utilize various types of seaweed.
  - Produces biogas suitable for electricity or heat generation.
- Cons:
  - Requires preprocessing to optimize biogas yield.
  - Limited to methane production.
- Cost: Moderate, with preprocessing costs and ongoing operational expenses.

Liquefaction is a technique that shows promise for turning macroalgae or seaweed into biofuels is hydrothermal liquefaction (HTL). To create bio-oil, seaweed biomass is cooked at high temperatures and pressures in the presence of water in HTL. Diesel and gasoline, two fuels used in transportation, may be made from this bio-oil. High conversion efficiency and the capacity to treat wet biomass are two benefits of HTL. Large-scale infrastructure requirements and process parameter optimisation are challenges in ensuring environmental sustainability and cost-effectiveness. Originally intended for coal, liquefaction converted solid materials into liquid fuels under high pressure and moderate temperatures (573–673 K), although it was previously dependent on carrier gases such as hydrogen or carbon monoxide. These days, it includes any thermochemical conversion process that produces liquid products as its main output. Because algae have a high water content, this method works well with materials that have varied moisture content. By changing its physical and chemical characteristics close to or over its critical point (374 °C, 221 bar), water can favourably affect liquefaction and accelerate the breakdown of biomass. Modern liquefaction methods include supercritical liquefaction, direct catalyst liquefaction, and liquefaction at high temperatures and pressures (Goh et al. 2019).

- Pros:
  - Converts wet seaweed into bio-oil through high temperature and pressure.
  - Efficient utilisation of whole seaweed biomass.
  - Can produce high-quality bio-oil suitable for various fuels.
- Cons:
  - Higher energy needs as a result of elevated pressure and temperature.
  - Challenges in product separation and purification.
- Cost: High initial investment and operational costs.

Algae oil extraction for biodiesel production is another approach for biofuel production from seaweed or macroalgae that involves extracting oil from lipid-rich species for biodiesel production. This process typically involves mechanical pressing or solvent extraction to obtain algae oil, which is then transesterified to produce biodiesel. Algae oil extraction offers advantages such as high lipid content in certain

seaweed species and the potential for co-production of other valuable co-products. Challenges include the optimization of extraction methods and the development of scalable and cost-effective processes.

- Pros.
  - High lipid content in seaweed.
  - Rapid algae growth.
  - Minimal land use required.
  - Carbon dioxide sequestration potential.
  - Possibility of valuable co-products.
- Cons.
  - High production costs.
  - Nutrient requirements and environmental concerns.
  - Purity challenges and contamination risks.
  - Difficulty in efficient harvesting.
  - Energy-intensive processes.
- Cost: Costs vary based on cultivation, harvesting, and processing methods, as well as the scale of production. Factors include initial investment, operational expenses, and resource availability. Despite advancements, algae-based biodiesel remains relatively costly compared to conventional sources, though ongoing research aims to improve economic feasibility.

Pyrolysis is defined as heating biomass to a temperature that causes it to break down oxygen-free, pyrolysis yields non-condensable gases, liquid bio-oil, and solid bio-char. Numerous variables, including temperature, heating rate, residence duration, reactor configuration, and catalysts, affect these compounds' properties. Seaweed biomass is cooked in the absence of oxygen in this thermal breakdown process to create biochar, syngas, and bio-oil. It is possible to turn the bio-oil into liquid biofuels like biodiesel by processing it further (Kibria et al. 2024). Benefits of pyrolysis include excellent energy efficiency and the use of various forms of seaweed material. The handling of by-products like biochar and the requirement for high temperatures and sophisticated processing equipment present difficulties, though. The process of biomass pyrolysis can be simplified into three main steps:

1. Biomass  $\rightarrow$  water + unreacted residue;
2. Unreacted residue  $\rightarrow$  (volatile + gases)<sub>1</sub> + (char)<sub>1</sub>;
3. (Char)<sub>1</sub>  $\rightarrow$  (volatile + gases)<sub>2</sub> + (char)<sub>2</sub>.

Internal changes such as the release of moisture and volatiles, bond breaking, and the formation of free radicals take place during the first stage of biomass breakdown. In the process, carbonyl and carboxyl groups, CO and CO<sub>2</sub> gases, and mostly a main charred residue are formed. Tar, gases, and secondary char can result from subsequent processes involving the residual organic components in the initial char,

such as cracking, dehydration, and polymerisation (Pourkarimi, Hallajisani, Alizadehdakhel, and Nouralishahi 2019).

- Pros:
  - Converts seaweed biomass into bio-oil, gas, and char.
  - Can utilize a wide range of seaweed species.
  - Bio-oil can be further processed into various fuels.
- Cons:
  - Requires high temperatures and controlled conditions.
  - Complex process with challenges in product separation.
- Cost: High initial investment, moderate operational costs.

Macroalgal biomass represents a promising and versatile resource for the production of various biofuels, contributing significantly to the pursuit of renewable energy sources. However, realising the full potential of macroalgal biofuels entails overcoming significant technological challenges to ensure both energy efficiency and commercial viability. As the biofuel industry progresses, identifying the optimal method or combination of methods for harnessing energy from macroalgae remains uncertain, necessitating further exploration and refinement. At present, anaerobic digestion emerges as a frontrunner in the journey towards industrial implementation. Its simplicity in terms of engineering and infrastructure makes it an appealing choice. Additionally, anaerobic digestion demonstrates the capacity to effectively utilize the organic carbon content inherent in macroalgae, rendering it a highly efficient process. Moreover, its ability to tolerate high moisture content proves advantageous, eliminating the need for additional energy input to manage such conditions.

While anaerobic digestion shows promise as a standalone method, its potential is further enhanced when integrated with complementary techniques. This synergistic approach allows for improved efficiency and flexibility in biofuel production from macroalgae. With ongoing advancements and concerted research and development efforts, anaerobic digestion holds the potential to become the cornerstone of biofuel production from macroalgae. It could play a pivotal role in meeting energy demands while simultaneously mitigating environmental impacts.

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## 7.4 The Potential of Biofuel Production from Seaweed

It is possible to demonstrate a comprehensive strategy for making biofuels from macroalgae in the future, which is a promising alternative. Numerous biochemical processing techniques have been discovered by research investigations to produce biofuels, bioproducts, and valuable biochemicals from a wide range of macroalgal species that belong to all three taxonomic groupings. Given the vast potential for producing sustainable energy from macroalgae, nations are participating in

several projects involving the production of biofuel from seaweed as presented in Table 7.2.

The aforementioned data indicates that countries are increasingly leveraging marine algal resources to develop sustainable alternative fuel options. When it comes to traditional feedstocks, algae present a possible substitute for third-generation biofuel production. Although producing biofuel from microalgae has received a lot of attention lately, there could be more economically feasible uses for both macroalgae and microalgae. Algae have a lot to offer beyond just being a possible source of biofuel. They are important for human health, animal and aquatic nutrition, medicines, cosmetics, and the creation of valuable colours, bio-active chemicals, and biomedical materials. They also help control environmental pollutants. Algae farming may be combined with wastewater treatment and flue gas CO<sub>2</sub> reduction (Suganya et al. 2016). Additionally, if marine algae species are utilized, algae farming can be conducted using seawater as a medium, offering a viable option for biofuel production in densely populated and arid coastal areas (Suganya et al. 2016). These depict a strong potential for biofuel generation from algal biomass. Furthermore, Academic and industry research on macroalgae as feedstock for biofuel is still in its infancy for large-scale, cost-effective applications, in contrast to microalgae. The potential of macroalgae is further enhanced by their higher carbohydrate content, which ranges from 28.7% to 43.6% CDW. Algal carbohydrates mostly consist of cellulose and hemicellulose, with very little lignin. These algae-derived carbohydrates are a formidable rival to lignocellulosic materials as feedstocks for biofuels because of their easy saccharification and anaerobic digestion elevated carbohydrate levels, ranging from 28.7% to 43.6% CDW. Cellulose and hemicellulose are the primary constituents of algal carbohydrates, with minimal lignin content. These carbohydrates derived from algae offer the advantage of facile saccharification and anaerobic digestion, making them a strong competitor against lignocellulosic materials as biofuel feedstocks (Abomohra et al. 2018). At present, achieving cost-effective bioenergy production from seaweed remains a challenge. However, through the implementation of enhanced management strategies, such as streamlining various cost factors, particularly labour expenses, or enhancing productivity at each stage of the seaweed supply chain, there exists the potential to attain a more feasible production cost (Soleymani and Rosentrater 2017). This necessitates a comprehensive approach encompassing improved cultivation techniques, optimised harvesting methods, efficient processing protocols, and streamlined logistical operations. Additionally, advancements in technology and innovation could play a pivotal role in driving down production costs and bolstering the economic viability of seaweed-based bioenergy production. By addressing these factors holistically, the prospect of economically sustainable bioenergy production from seaweed can be realised, thereby contributing to the diversification of renewable energy sources and fostering environmental sustainability.

## 7.5 Life Cycle Assessment of Biofuel Production Plant

An extensive analysis of the environmental effects connected to every phase of the production process, from seaweed growing to biofuel distribution, is part of the life cycle assessment (LCA) of a plant that produces biofuel from seaweed or macroalgae. In order to determine possible areas for development and to comprehend the overall sustainability of the biofuel-producing system, this study is essential. In order to verify and enhance the sustainability of the seaweed-based biofuel manufacturing process, researchers are conducting an energy analysis and subsequent life cycle assessment (LCA). The life cycle evaluation conducted by Morales et al. in Nordic circumstances on the biofuel generation from brown seaweed revealed that the production of seaweed biogas is more sustainable than that of ethanol (Alvarado-Morales et al. 2013). Electricity was generated from seaweed production, which reduced 961 kg of CO<sub>2</sub> per unit. The produce phase accounted for 95% of the overall energy consumption, and the energy analysis indicated that seaweed production was the most energy-intensive stage (Alvarado-Morales et al. 2013). Utilizing life cycle assessment, Aitken et al. claim that using the existing techniques, it is feasible to sustainably generate bioenergy from macroalgae cultivated in Chile. The most sustainable technique of cultivation and processing was found to be using bottom-cultivated *G. chilensis* to manufacture bioethanol and energy from biogas (Aitken et al. 2014). Using a biochemical platform, Fasahati et al. evaluated the bioenergy generation from seaweeds; The most environmentally friendly type of transportation was determined to be grinding and pumping after the techno-economic, uncertainty, and life cycle evaluations were completed; it was discovered that the sugar platform offered the best economics for producing biofuel (Fasahati et al. 2022); For the sugar platform, a minimum environmental effect calculation was made. The LCA includes these processes for sustainable analysis of biofuel production from seaweed:

- Seaweed cultivation: The LCA begins with assessing the environmental impacts of seaweed cultivation, including energy inputs, water usage, and any associated emissions. Factors such as the type of cultivation method (e.g., offshore, onshore) and nutrient management practices can significantly influence the environmental footprint of this stage.
- Harvesting and processing: The harvesting and processing of seaweed into biofuel involve energy-intensive processes such as drying, grinding, and extraction. The LCA evaluates the energy consumption, emissions, and waste generation associated with these activities, as well as any potential impacts on marine ecosystems and biodiversity.
- Biofuel conversion: During biofuel conversion, seaweed biomass is typically converted into liquid biofuels through processes such as fermentation, pyrolysis, or hydrothermal liquefaction. The LCA examines the energy efficiency, emissions, and waste generation of these conversion processes, as well as the poten-

tial for co-product generation (e.g., biochar, biogas) to minimise waste and maximise resource utilisation.

- **Transportation and distribution:** The transportation of seaweed biomass and biofuels to and from the production plant incurs additional energy consumption and emissions. The LCA assesses the environmental impacts of transportation modes (e.g., shipping, trucking) and distances travelled, considering factors such as fuel efficiency and greenhouse gas emissions.
- **End use and disposal:** Finally, the LCA considers the environmental impacts associated with the end use of biofuels, including combustion emissions and any potential impacts on air quality and human health. Additionally, the disposal or recycling of by-products and waste streams generated during the production process is evaluated to minimise environmental pollution and resource depletion.

All things considered, the life cycle assessment of a seaweed-based biofuel production plant offers insightful information about the environmental sustainability of the production system and aids in locating chances to maximize resource efficiency, lessen environmental effects, and improve sustainability overall. Achieving environmentally sustainable bioenergy solutions can be facilitated by stakeholders making informed decisions via the integration of life cycle assessment (LCA) concepts into the design and operation of biofuel-producing facilities. According to sustainable life cycle assessments, the production of biodiesel appears less appealing than the production of bioethanol and bio-oils from wet macroalgae, whereas microalgae biomass with a high lipid content is more competitive (Chen et al. 2015). More sustainable thermodynamic, techno-economical, and LCA analyses are required in this field (Rajkumar et al. 2014). In the same way that greenhouses are used throughout the seaweed biofuel production process to recycle materials and benefit the environment, algal biomethane may be made to compete with natural gas in a number of areas through ecodesign. An improvement in the marine eutrophication index, a reduction in ozone depletion, a decline in greenhouse gas (GHG) emissions, and a drop in fossil fuel depletion (Langlois et al. 2012). In conclusion, seaweed may soon be able to compete with terrestrial feedstock for the manufacture of biofuel.

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## **7.6 Performance of Biofuels from Seaweeds and Other Available Resources**

Macroalgae are regarded as the third generation of biofuels and a potential future resource for biorefineries. Seaweed, also known as marine macroalgae, are multicellular, macroscopic organisms categorised into three main groups: Chlorophyta (green algae), Rhodophyta (red algae), and Ochrophyta-Phaeophyceae (brown algae). Despite recent studies focusing on macroalgae, the global market for non-fuel products derived from them surpasses that of microalgae by 100 times in wet

tonnage. Macroalgae contain high water content and significant levels of carbohydrates (25–50%), protein (7–15%), and lipids, making them suitable sources (1–5%) for producing biodiesel, bioethanol, and biohydrogen. Furthermore, seaweed growth offers the potential for carbon sequestration, a factor to consider in assessing the carbon balance of macroalgae-derived biofuels from aquaculture (Khan et al. 2022). Recently, macroalgae have also been used for biofuel production co-culturing along with microalgae and other marine microorganisms (Ray et al. 2022). Comparing macroalgae to microalgae, there are comparatively fewer techno-economic and life cycle assessments (LCA) available. Although there is a dearth of information from commercial seaweed farms, EnAlage has created an easily understandable macroalgae production economic model in Microsoft Excel. Additionally, there is ambiguity around the processes' scaling up, necessitating the need for more data, especially on a commercial scale (Milledge and Harvey 2016). To create scalable and sustainable non-lignocellulosic biomass resources, such as marine macroalgae (seaweeds), for use as next-generation feedstocks, different approaches and technologies are consequently needed (Wargacki et al. 2012). There are varieties of algae being used in oil extraction for biofuel production and numerous works are being performed on these phenomena (Gengiah et al. 2022). Several methods are applied in the biofuel production from marine resources and some of the performance analyses are provided in Table 7.3.

Biofuel production from macroalgae offers a promising pathway towards sustainable energy. Macroalgae, or seaweed, are rich in carbohydrates and other organic compounds, making them valuable feedstocks for biofuel production. Through various conversion processes, such as fermentation or pyrolysis, macroalgae can be transformed into biofuels like biodiesel or bioethanol. This renewable resource holds potential for reducing greenhouse gas emissions and diversifying the energy mix towards a more sustainable future.

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## 7.7 Environmental Impact Due to Marine Resource Conversion

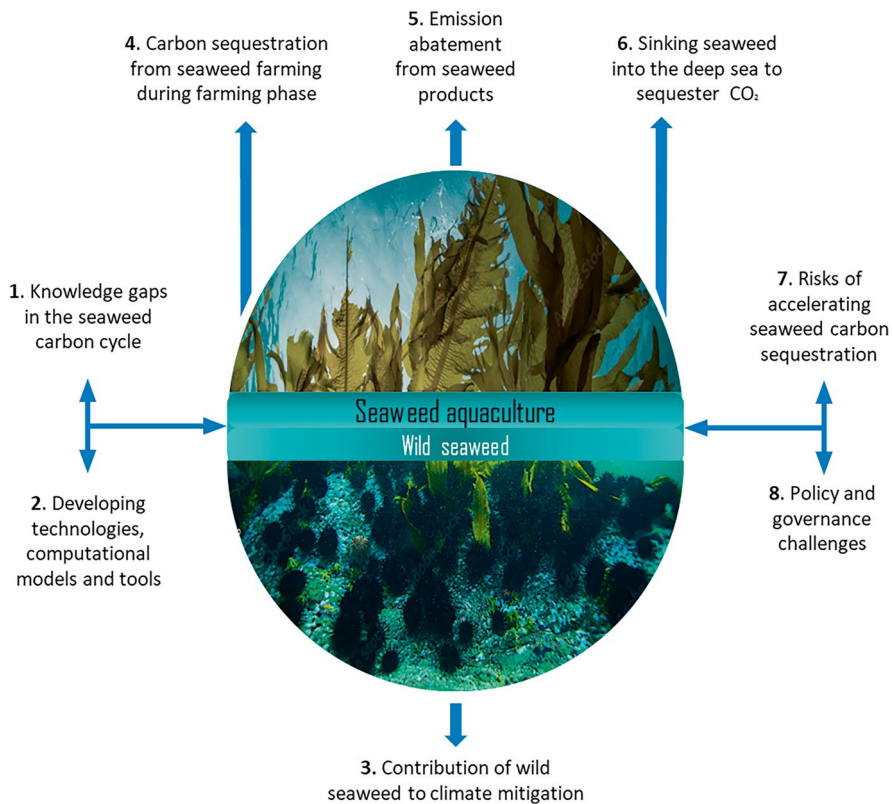
A number of variables, such as the techniques used, the extent of the impacted region, and the characteristics of the seaweed population, influence how macroalgae farming or harvesting affects the ecosystem. It is imperative to take into account carbon emissions stemming from various activities such as transporting algae to processing facilities, oven drying, and equipment maintenance. Longer transportation distances tend to result in heightened emissions. However, when scrutinised through a lifecycle analysis lens, utilizing macroalgae for biogas production showcases a significant reduction in greenhouse gas emissions, ranging from 78% to 91%. In addition to cultivation and harvesting practices, the sustainable disposal of post-processing residues emerges as a crucial consideration. It is imperative to address this aspect with a forward-thinking approach, ensuring that residues are managed sustainably. One promising avenue involves nutrient recovery, wherein post-processing residues are utilized to fertilise cultivated algae. This not only

**Table 7.3** Performance of biofuels from seaweeds and other available resources

Bio source	Biofuel generation technique	Emission (CO <sub>2</sub> equivalent)	Performance metrics	Generation rate (litres/tonne)	Biofuel quality (ASTM standards)	Ref.
Seaweed	Anaerobic digestion	Low	Energy yield, methane content	100–200	ASTM D396 (diesel), ASTM D6751 (biodiesel)	Nielsen et al. (2020)
Seaweed	Thermochemical conversion	Moderate	Energy efficiency, by-products	150–250	ASTM D4806 (ethanol), ASTM D6751 (biodiesel)	Kan et al. (2014)
Seaweed	Alcoholic fermentation	Low	Ethanol yield, process efficiency	300–400	ASTM D4806 (ethanol)	Huesemann et al. (2012)
Seaweed	Transesterification	Moderate	Biodiesel yield, purity	200–300	ASTM D6751 (biodiesel)	Abd El Baky and El Baroty (2017)
Corn	Ethanol fermentation	Moderate	Ethanol yield, feedstock efficiency	350–450	ASTM D4806 (ethanol)	Bothast and Schlicher (2005)
Soybeans	Transesterification	Moderate	Biodiesel yield, sustainability	300–400	ASTM D6751 (biodiesel)	Li et al. (2012)
Palm oil	Transesterification	High	Biodiesel yield, environmental impact	500–600	ASTM D6751 (biodiesel)	Lee et al. (2015)
Algae	Algal oil extraction	Low	Oil yield, cultivation efficiency	400–500	ASTM D396 (diesel)	Mulbry et al. (2009)
Algae	Hydrothermal liquefaction	Moderate	Bio-crude yield, conversion efficiency	350–450	ASTM D396 (diesel)	Guo et al. (2015)
Jatropha	Transesterification	Low	Biodiesel yield, land use efficiency	250–350	ASTM D6751 (biodiesel)	Tapanes et al. (2008)

minimises waste but also fosters a closed-loop system, promoting sustainability across the entire process chain.

Even with the possible advantages, thorough studies on the precise environmental effects of various farming and harvesting techniques are still few. This emphasises the significance of exercising caution, whichever course of action is selected. By prioritising sustainability and environmental stewardship, stakeholders can navigate the complexities of macroalgae cultivation and harvesting while minimising adverse impacts on marine ecosystems and surrounding environments (Roberts and Upham 2012). Due to its potential to mitigate climate change, seaweed or macroalgae have gained interest on a worldwide scale. Seaweed has been proposed for usage in the following four categories to mitigate climate change: To potentially mitigate climate change, there are four potential co-benefits associated with (1) preserving and reestablishing wild seaweed forests; (2) growing sustainable nearshore seaweed aquaculture; (3) using seaweed products to offset industrial CO<sub>2</sub> emissions; and (4) sinking seaweed into the deep sea to sequester CO<sub>2</sub>. (Ross et al. 2023) (Fig. 7.2).



**Fig. 7.2** Diagram detailing how the identified research challenges relate to either seaweed aquaculture and/or wild/naturally occurring seaweeds. (With permission from Ross et al. 2023)

Recent research has shown that seaweed forests have a large primary production and the capacity to sequester carbon, hence maintaining and restoring these forests has been suggested as a way to produce co-benefits for reducing climate change. It is predicted that wild seaweed sequesters around 173 Tg OC year<sup>-1</sup>, or 11% of the world's net seaweed production, each year. With a total area of  $7.2 \times 10^6$  km<sup>2</sup>, these woods are the world's largest vegetated coastal environment. Their net primary output is approximately 60% higher than other vegetated coastal habitats, with a recent revision of 1.32 Tg C year<sup>-1</sup>. Roughly 90% of the carbon sequestered by wild seaweed is thought to happen through carbon export to the deep sea, with the other 10% being buried in sediments found in both coastal and deep-sea environments. Another factor influencing the carbon budgets of wild seaweed forests is calcification, which reduces seawater alkalinity and diminishes its CO<sub>2</sub> uptake capacity. This process may offset some of the CO<sub>2</sub> sequestration benefits of seaweed forests by increasing the biomass of calcifying organisms [44]. Rising atmospheric CO<sub>2</sub> levels result from human activities like fossil fuel use, deforestation, and expanding farmland. Efforts initially targeted halting deforestation and farmland expansion to enhance CO<sub>2</sub> absorption by forests, but now focus on curbing fossil fuel consumption and promoting carbon-neutral energy. Wood, crops, and renewable sources like solar and wind power are considered for carbon-neutral energy, yet liquid or gas fuels are essential for transportation. Land scarcity poses challenges for biofuel production, risking exacerbating food shortages. Therefore, marine plants are proposed for biofuel production over terrestrial plants to address these challenges (Notoya 2010). Although developing second-generation fuels like bioethanol and biodiesel from crops cultivated on arable lands, notably utilizing oil-seeds, has increased food costs, researchers have looked into using seed oils for biofuel production. The struggle between food and fuel can be resolved with third-generation biofuels made from algae cells cultivated on non-arable land. Screening and improving strains is one way to improve algal production for increased lipid output. One efficient way to lessen the environmental impact of algal biomass cultivation is to use wastewater and flue gasses (Singh et al. 2011).

Industries and governments are facing mounting pressure to devise effective strategies for mitigating the impacts of climate change, with seaweed emerging as a potentially valuable solution. In contrast to terrestrial carbon sinks and other vegetated blue carbon sinks like seagrass beds, mangroves, and tidal marshes, the accounting for carbon stored in seaweed is still a complicated and undeveloped field. Although carbon sequestration documentation in known blue carbon systems is standardised, seaweed efforts lack comparable standards. The lack of basic knowledge about carbon fluxes and sinks in seaweed ecosystems and the paucity of studies showing carbon sequestration and CO<sub>2</sub> absorption in response to particular activities such as seaweed farming and restoration are the main causes of this knowledge gap. Additionally, the absence of effective monitoring and evaluation techniques further compounds the challenge of accurately assessing and quantifying the carbon sequestration potential of seaweed (Ross et al. 2023).

To recapitulate, biofuel production from seaweed offers a range of positive environmental impacts. Firstly, seaweed cultivation acts as a carbon sink, absorbing

carbon dioxide from the atmosphere and mitigating climate change. Secondly, biofuels derived from seaweed emit fewer greenhouse gases compared to fossil fuels, aiding in reducing overall emissions. Thirdly, seaweed cultivation requires minimal land use, avoiding competition with food crops and preserving terrestrial ecosystems. Additionally, harvesting seaweed for biofuel production helps improve water quality by removing excess nutrients from coastal waters, benefiting marine ecosystems. Moreover, seaweed habitats support biodiversity by providing essential habitats and food sources for marine organisms. Lastly, by providing a renewable alternative to fossil fuels, seaweed biofuels promote sustainable energy practices and contribute to a cleaner energy future. Overall, biofuel generation from seaweed presents a promising solution for addressing environmental challenges while advancing sustainable energy development.

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## 7.8 Conclusion

In conclusion, research into the generation of biofuel from seaweed offers promise in the search for environmentally friendly energy sources. This developing sector has several advantages for the environment, the economy, and society in addition to providing a sustainable fuel substitute for fossil fuels. We can tackle urgent problems like energy security, climate change, and rural development by utilizing the enormous potential of marine resources, especially seaweed. Using seaweed to produce biofuel is a viable strategy to lower greenhouse gas emissions and decrease our dependency on limited fossil fuel resources. Seaweed converts carbon dioxide from the atmosphere into carbon dioxide through photosynthesis, making it a great carbon sink that helps combat global warming. Furthermore, the growing and harvesting of seaweed for the production of biofuel may boost local economies and promote job creation in places where conventional industries may be in decline.

However, coordinated efforts on several fronts are needed to realise the full potential of seaweed biofuel. To increase the overall effectiveness and scalability of seaweed biofuel production, research and development activities must concentrate on refining conversion processes, thereby enhancing harvesting procedures, and optimising cultivating strategies. Furthermore, problems like resource management, environmental sustainability, and societal acceptability require creative solutions. Governments, businesses, universities, and local communities must work together to promote innovation, ease the sharing of knowledge, and remove obstacles to implementation. In order to encourage investment in research, infrastructure, and technological development as well as to build the seaweed biofuel business, policy support, financial incentives, and regulatory frameworks are essential.

In summary, while challenges and uncertainties remain, the prospects for biofuel production from seaweed are undeniably bright. With continued dedication, innovation, and collaboration, seaweed biofuel has the potential to emerge as a cornerstone of the sustainable energy landscape, offering a renewable, environmentally friendly, and socially beneficial alternative to traditional fossil fuels.

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# Utilisation of Marine Green Algae for Development of Bioplastics: Challenges and Future Prospects

# 8

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## Abstract

Plastics are a tricky material affecting the environment, economy, and social well-being. Recently, plastic has been distributed in every corner of the world and it has become a danger to human life and other living beings in various ways. Hence, bioplastics is identified as a possible solution to combat with strongly established conventional petroleum-based plastic sector. Out of various types of bioplastics, marine green algae-based bioplastic production and supply chain were identified as green technology to support the circular economy in a sustainable way. On the other hand, marine algae cultivation, production and use as raw materials for plastic production contribute to blue bioeconomy. This chapter provides insightful overview about types of marine green algae, their abundance & distribution, technological aspects of biopolymer extraction from marine algae, algae-derived bioplastic production & applications, advantages & disadvantages, challenges, and future forecasts. The marine algae-based bioplastics are biodegradable and compostable, hence environment-friendly. Therefore, the bioplastic-based industries will be supportable in the future. As a raw material, marine green algae cultivation will be more profitable to the rural communities while helping to carbon sequestration and reducing global warming.

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**Keywords**

Marine resources · Bioplastics · Biodegradation · Sustainable · Green algae · Plastic pollution

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## 8.1 Introduction

Annual plastic production is more than 300 million tonnes and 14 million tonnes of plastics are introduced into the world's oceans (Plastic Pollution Blogger 2023). Plastic pollution is a serious environmental concern in the conventional plastic industry. Environmental plastic pollution is induced due to the mismanagement of plastics. For instance, improper disposal of waste, and reduced recycling of single-use plastic litter items could increase the plastic waste inputs in different environmental compartments. Plastic pollution has a significant impact on the environment by making changes to chemical, physical, and biological contexts and results in ecological and toxicological effects (Pinto Da Costa et al. 2020). Moreover, plastic wastes especially microplastics pose a major threat to biodiversity, due to their durability, persistence and abundance. The size of the microplastics is comparable with the food particles, and likely to be ingested by plankton and organisms representing higher trophic levels (e.g., aquatic birds, marine mammals and fish). Ingested plastics could cause toxic effects on biological compartments via different ways: chemicals (additives of plastics) leakage, induced adsorbed organic contaminants (Persistent Organic Pollutants: POP) by microplastics and discharging, stress responses such as energy consumption (e.g., egestion) and physical blockage in the digestive tract (Pinto Da Costa et al. 2020). Additionally, marine plastic pollution causes socio-economic consequences indirectly and directly. As an example, marine litter damages the ships by crash or entanglement with litter items and results in additional economic expenditures in the shipping sector. The presence of marine litter has a negative impact on the tourism industry (cultural service) by reducing the recreational value through reduced attractiveness and aesthetic value along the coastal belt and beaches. Similarly, marine litter affects the commercial fishery industry through severe damage to the fishing gear, equipment, and vessels. Also, fish harvest can be reduced by the contamination of resources by plastic debris. Further target commercial stocks: fin fish and shell fish species recorded significant death rates by abandoned, lost or otherwise discarded fishing gear: ALDFG (nets, and traps) (Kershaw Peter 2016). Additionally, plastic pollution related to mismanaged wastes causes serious health problems in humans. High concentrations of plastic-related compounds and materials (e.g. flame retardants) have been recorded in residents closer to the areas with poor plastic management and recycling facilities (e.g. informal electrical and electronic litter recycling facilities) (Kershaw Peter 2016).

Accordingly, previous literature has recommended short-term, mid-term, and long-term plastic pollution control measures during the manufacturing, utilisation, and management of wastes concerning the priorities. The mid-term activities, enhancing the plastic recycling process (effective waste collection, deposit

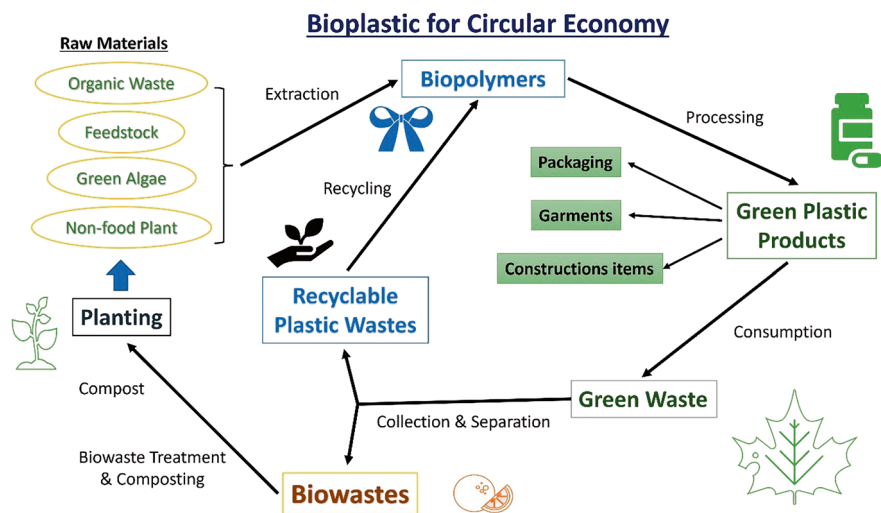
refunding mechanism), establishment of systematic waste collection process, reducing and recycling plastic litter during production, responsibilities on waste disposal towards extended producer responsibilities (EPR) and promoting energy conversion from wastes (chemicals, and energy sources recovery) are recommended (Prata et al. 2019). The same literature recommends short-term measures: promoting recycled plastic products using financial incentives, taxes on virgin plastics, regulatory framework on selected plastic (harmful and toxic polymers) production process and consumption (e.g. taxes and bans), environmentally friendly plastic alternatives, minimise plastic consumption (avoid unnecessary packaging), environmental education, awareness, and labelling to address the plastic pollution issue. Similarly, long-term measures such as promoting the recyclability and proper disposal mechanism of e-waste using energy recovery, life cycle assessment of product and production process with promotion of the eco-design: recycling, reuse, repair, consumption of renewable energy sources for plastic waste collection, and recycling, special concern on end-of-life of the products (reducing production of degradable plastics which generate microplastics, promoting bioplastics in specific applications such as agriculture: providing special wastes collection and treatment techniques for wastes management) are proposed to overcome the plastic wastes accumulation in the environment (Prata et al. 2019).

Among the aforementioned strategies, the blue bioeconomy is an emerging, sustainable, and eco-friendly approach to overcoming plastic pollution. Blue bioeconomy is defined as the economic activity related to the use of renewable aquatic biological resources for production (Report, European Union 2018). For instance, blue bioeconomy is widely used for products such as animal feeds, cosmetics, pharmaceuticals, drugs, foods, food additives, nutraceuticals, construction materials, energy sources, and clothing. Blue bioeconomy corresponds with the wide business sector which covers access to raw materials, extraction, refining, processing, conversion into biological compounds, and developing related advances, technologies, and equipment (Report, European Union Report 2018). Blue bioeconomy is connected with the circular economy by ensuring economic development at the regional scale. This approach further makes a sustainable, biological transition by enhancing the utilization of aquatic resources (Albrecht and Lukkarinen 2020). As per the FAO records, finfish varieties (mainly bony fish and cartilaginous fish to a lesser extent), crustaceans, mollusks, macro- (seaweeds) and microalgae can be considered as the key inputs for utilization by wild catch, capture fisheries (inland: 11.5 Mt., marine: 81 Mt), mariculture (57.1 Mt), and inland aquaculture (48.9 Mt) for blue bioeconomic activities (FAO 2017; EUMOFA 2018). Currently, the blue bioeconomy has gained attention in EU policy and incorporated into national government strategic planning for creating a sustainable environment. However, the blue bioeconomy concept is still not implemented by most of the countries to combat plastic pollution. Under the marine algae, seaweeds have a high potential to use in blue bioeconomic sector (e.g., animal feed, cosmetics, drugs, and food sources) due to nutritional, mechanical, and pharmaceutical properties (presence of bioactive compounds), and characteristic faster-growing capacity of seaweeds. Similarly, marine microalgae are potentially used as a raw material to produce bioplastics, biofuels,

skincare nutritional supplements (omega, vitamin, and protein-rich products), fish feed (alternative for fish meal), cosmetic products, and human food. Microalgae are used for biological treatment and recycling of wastewater in aquaculture operations to overcome environmental pollution as a profitable, low-energy medium with affordable cost. Accordingly, marine macro- and micro algae ensure the achievement of UN sustainable development goals towards sustainable development and blue bioeconomy. Also, a marine algae-based bioeconomic industry can provide not only business opportunities (e.g.: jobs) but also energy and food sources for other aquatic communities showing the expansion potential of the mariculture sector.

Algae production industry acts as one of the most effective sectors to achieving the goals of blue economy approach. For instance, it is predicted that the world seaweed market will be around US dollars 12.85 billion by the year 2027. Further, the boosting trend of macroalgae production was recorded from Japan, Korea, China, Indonesia, and Philippines, and some other countries in Asia (Mancini 2022). The Mediterranean region has significant potential to expand algae production as a blue bioeconomic industry (Mancini 2022). This will be a promising trend to overcome plastic pollution with economic development.

Biodegradable plastics and bioplastics which are extracted from renewable biomass (feedstocks) (Harding et al. 2017) could be used as an alternative material to conventional plastics. Bioplastics are advantageous over conventional plastics in different ways: reduction in energy consumption, decreasing level of carbon footprint and discharges of greenhouse gas, development of technology, removal of agricultural film, increasing job opportunities, social benefits, enhanced composting of biodegradable wastes, decreased load of wastes, and different options for the end-of-life in product (Melnik et al. 2019) (Fig. 8.1). In general, green raw materials are subjected to polymerisation and converted to the final product during bioplastic



**Fig. 8.1** Chain of bioplastic production and circular economy

production, and then consumers will use the final product through wholesalers and retailers. Sustainable options are available at the end of the life of the product such as conversion to organic fertiliser or recycling without causing harmful effects and discharge of toxic substances into the environment (Muhammad Shamsuddin 2017) (Fig. 8.1). In addition, recent high prices for crude oil, and the potential market for agricultural materials in bioplastics are driving an economic push towards expanding the bioplastic industry and providing better alternatives for sustainable development of the future environment (Nandini et al. 2010). The textile industry is one of the most promising industries for bioplastic-based clothing with innovative approaches (Friedrich 2021). Applications of bioplastics are gaining significant attention nowadays. Accordingly, biopolymers or bioplastics have been directed to exploring marine green algae as an alternative renewable source for fossil fuel by increasing recyclability and waste management practices (Napper and Thompson, 2019).

Green macroalgae (seaweeds) have been widely used for the extraction of bioactive compounds due to their characteristic huge biomass and cosmopolitan distribution during past decades. However, marine green seaweeds are still unexploited among the other macroalgae groups such as Rhodophyta and Phaeophyta. Green seaweed is rich in alkaloids, peptides, lipids, carotenoids, polysaccharides, and phenols. The presence of active ingredients in green seaweeds makes a promising trend in applications of different industries such as the pharmaceutical sector (Kellogg and Lila 2013). Moreover, seaweed-based bioplastics is an innovative alternative approach for non-biodegradable synthetic plastics by conservation of the environment (Farghali et al. 2023). Compared to the terrestrial plants (cellulose level: 26–43%, lignin level: 21–31%), lignin level is lower and additional long-chain hydrocarbon content in seaweed-based biomass. Accordingly, pure cellulose can be extracted from seaweeds for bioplastics at the commercial scale (Zanchetta et al. 2021). Further, polysaccharides (e.g., carrageenan, agar, and alginate) which act as the natural raw materials of bioplastics can be extracted using seaweeds and used for manufacturing the bioplastics (Tavassoli-Kafrani et al. 2016).

Further, seaweed-based polysaccharides are suitable candidates to expand the bioplastic industry due to the unique mechanical and thermal properties, safety, biocompatibility, and long lifespan of the product (Lomartire et al. 2022). Currently, seaweed-based bioplastic has vast industrial applications such as the food packaging sector. For instance, seaweed-based bioactive compounds: alginates and carrageenan are used as biodegradable packaging items and bio-polymerised film. Marine algae-based bioplastic makes a promising change in the plastic industry through an environment-friendly approach. Seaweed-based bioplastic products ensure environmental conservation and health benefits by addressing environmental pollution and ecosystem damage (Lomartire et al. 2022). Concurrently, seaweed-based bioplastics play a vital role in the sustainable socio-economic development of the global population. Accordingly, this paper will critically review the current status of marine green algae, advances in algae-based bioplastic development, implications of the sector, expanding potential, emerging challenges, issues, opportunities, and future perspectives toward a sustainable, green economy.

## 8.2 Marine Green Algae as a Resource Globally

Marine green algae are a polyphyletic group of photosynthetic algal organisms that belong to the phylum Chlorophyta (Lewis and McCourt 2004). These algae encompass a wide range of photosynthetic organisms that can be found in different marine aquatic habitats ranging from intertidal zones to deep-sea habitats, and play substantial roles in marine environments as primary producers and contributors to reef-building processes (Guiry and Guiry 2022). The taxonomic scrutiny of marine green algae is essential for interpreting their evolutionary relationships, ecological roles, and biogeographic distributions. The understanding of their taxonomy with significant features, classification systems, and current progressions in molecular phylogenetics is vital for various studies such as ecological assessments, biodiversity studies, evolutionary investigations, and industrial practices (Leliaert et al. 2012). The classification of marine green algae is incessantly progressing with the incorporation of ecological, morphological, and molecular data, leading to a more extensive estimation of their evolutionary relationships and diversity (Leliaert et al. 2012).

### 8.2.1 Classification of Marine Green Algae

#### 8.2.1.1 Taxonomy and Diversity

In the past, morphological traits like cell structure, colouration, and reproductive characteristics have been used to classify marine green algae (Guiry and Guiry 2022). However, the way these organisms are classified has changed significantly as a result of advances in molecular phylogenetics. According to the current definition, green algae are not a single, cohesive species; rather, they belong to the wider Viridiplantae group, which also includes terrestrial plants (Lewis and McCourt 2004).

Chlorophyta, another name for marine green algae, is a broad category of photosynthetic organisms that are present in marine habitats. All green algae, including marine species, are members of this phylum. They display a diverse array of physical and ecological traits. They are divided into a number of classes, orders, families, genera, and species according to taxonomy. A number of classes such as Charophyceae, Chlorophyceae, Micromonadophyceae, Pleurastrorphyceae, and Ulvophyceae make up the phylum Chlorophyta (Enamala et al. 2018). Most of the prominent marine green algae, however, belong to a single class known as Ulvophyceae (Leliaert et al. 2012). There are roughly 920 species of the extremely varied family Ulvophyceae, which are found in all of the world's seas (Lewis and McCourt 2004).

Several orders of marine green algae exist (Guiry and Guiry 2022), including;

Ulvales: Species like *Ulva* and *Enteromorpha* that are filamentous, blade-like, or tubular belong to this group.

Cladophorales: Species like *Cladophora* that contain branching or filamentous forms that are seen in different marine environments.

Bryopsidales: Including genera like *Halimeda* and *Caulerpa*, these organisms are distinguished by their calcified, spherical, or branching morphologies.

Siphonocladales: These include *Codium* and *Bryopsis*, which are distinguished by multinucleate tube structures.

Dasycladales: *Acetabularia*-like species, made up of calcified, branching forms that have distinct internodal cells.

Based on physical and reproductive traits, these orders are further separated into families, genera, and species. However, because of phenotypic flexibility and species convergence, the traditional morphological classification frequently encounters difficulties.

### 8.2.1.2 Progress in the Field of Molecular Phylogenetics

Recent developments in molecular methods, especially DNA sequencing, have completely changed how marine green algae are classified. Molecular phylogenetic investigations utilising mitochondrial genes, plastid-encoded genes (e.g., *psbA*, *rbcL*), and ribosomal RNA genes (e.g., 18S rRNA) have yielded important insights into the genetic diversity and evolutionary relationships of marine green algae (McCourt et al. 2002). These molecular researches have made it possible to reclassify genera and families, as well as to identify evolutionary links among taxa and cryptic species complexes (Kooistra 2002; Leliaert et al. 2012). For instance, the phylogenetic placement of taxa that have proven challenging, like the genus *Caulerpa* within the family Bryopsidaceae, has been resolved with the aid of DNA data (Kooistra 2002; Lam and Zechman 2003).

However, there are still difficulties with the classification of marine green algae, despite tremendous advancements. Reconstructing strong phylogenies and precisely drawing species boundaries need the integration of morphological, ecological, and molecular data (Leavitt et al. 2016). Furthermore, there are intriguing prospects for future research due to the discovery of new taxa and the investigation of maritime ecosystems that have received little attention (Costello et al. 2010). Moreover, the significance of continuing taxonomic studies for conservation and management initiatives is highlighted by the effects of environmental conditions, such as ocean acidification and climate change, on the variety and distribution of marine green algae (Gao et al. 2018).

Therefore, the area of marine green algae taxonomy is dynamic and always changing due to advancements in environmental sciences and molecular biology. By combining molecular phylogenetics with conventional morphological methods, we can better comprehend the variety, evolution, and ecological functions of these creatures in maritime environments. Sustained investigation is essential to decoding the details of marine green algae classification and tackling novel conservation obstacles.

### 8.2.2 Abundance and Distribution

There are numerous elements that affect the worldwide distribution and abundance of marine green algae, such as salinity, light intensity, temperature of the water, and type of substrate (Guiry and Guiry 2022). Generally, environmental factors and anthropogenic pressures interact to affect the distribution and abundance of marine green algae, making them significant markers of ecosystem health and biodiversity in marine habitats across the globe (Gao et al. 2018).

Intertidal zones, or the spaces between high and low tide, are home to a wide variety of marine green algae species. Algae have a variety of habitats due to the variations in temperature, salinity, and air exposure in these zones. In these zones, they can adhere to rocks, shells, and other surfaces to form large mats or patches (Sun et al. 2010; Yoo 2003). Coastal waters which flourish in nutrient-rich conditions are home to marine green algae. These regions have plenty of sunshine for photosynthesis and are frequently characterised by shallow depths that let light reach the seafloor, promoting the growth of algae (Lemley et al. 2019).

Tropical marine areas which have warm water conditions are also favourable for wide distribution of marine green algae, because of the ideal growth conditions found in those places. Rapid algal development is facilitated by the warm temperatures and nutrient-rich waters, which create thriving underwater habitats like coral reefs, where algae are essential for the food and habitat of a variety of marine species (Mejia et al. 2012). Temperate oceanic zones can also accommodate marine green algae, even though their quantity may vary periodically due to changes in water temperature and nutrient availability. Algae populations often rise in the warmer months; dormancy or slower growth rates may result in the cooler months (Neto and Pinto 2019).

In spite of the bitter cold, polar regions are home to marine green algae, especially in places where summertime sea ice melts. These algae sustain the food chain and give marine life vital nutrients by contributing to primary production in polar habitats (Wiencke and Amsler 2012). Several species of marine green algae can also be found in open oceans, although they are more frequently found in coastal and shallow areas. These algae can be found scattered throughout the water column or floating close to the ocean's surface, where they support the marine phytoplankton ecosystem (Neto and Pinto 2019; Van Baren et al. 2016).

In addition to that, several triggers caused by anthropogenic activities such as habitat damage, overfishing, and pollution can have an effect on the amount and distribution of marine green algae. For instance, excessive nutrient runoff from cities and farms can cause toxic algal blooms, which can damage marine ecosystems and endanger human health (Guiry and Guiry 2022; Muruganandam et al. 2023).

### 8.2.3 Current Utilization and Application of Marine Green Algae

Since marine green algae are widely distributed in marine ecosystems and have potential uses in a variety of sectors in addition to their vital ecological roles as

primary producers and subsidise significantly to marine food webs, they have attracted a lot of attention (Beetul et al. 2016). The situation of marine green algae uses and application today, including their use in the food and feed industries, the manufacturing of biofuel, pharmaceutical, cosmetic, and environmental remediation industries (Rasala and Mayfield 2015). Therefore, scientists have made more attempts to explore the diverse applications of marine green algae beyond their ecological significance in recent years.

The food and feed industry is one major sector where marine green algae are widely used (Kovač et al. 2013). Marine green algae, including the species *Ulva* and *Enteromorpha*, have long been used as food in many different cultures around the world (Abdel-Aziz and Ragab 2017). They are abundant in vital elements, such as omega-3 fatty acids, proteins, vitamins, and minerals. Furthermore, because marine green algae are more sustainable and have higher nutritional content than conventional feed sources, there has been an increase in the production of these algae for use as aquafeed supplements (Ning et al. 2022).

Recent years have seen a significant increase in interest in the potential of marine green algae as a feedstock for the manufacture of biofuels (Jeong and Park 2015). Due to their high lipid content, these algae are good candidates for the lipid extraction and transesterification processes used to produce biodiesel (d'Ippolito et al. 2015). Additionally, as a sustainable substitute for traditional biofuel sources, the use of marine green algae for the fermentation of their biomass which is rich in carbohydrates is being investigated for the manufacture of bioethanol (Ramachandra and Hebbale 2020).

Indeed, a variety of bioactive chemicals with potential use in medicine and nutraceuticals can be found in marine green algae (Ruslan et al. 2021). Isolated from marine green algae, compounds such as polysaccharides, polyphenols, and pigments have shown a range of biological actions, including anti-inflammatory, antibacterial, antioxidant, and anticancer effects (Lee et al. 2013). These bioactive substances have the potential for use as functional food components and as novel pharmaceutical medicines (Lauritano et al. 2016).

Marine green algae are also valuable ingredients in cosmetics and personal care products because of their distinct chemical composition (Resende et al. 2021). Because they are moisturising, anti-ageing, and UV-defensive, extracts from marine green algae are used in skincare products (Berthon et al. 2017). Moreover, substances like carrageenan, which are extracted from specific species of green algae, are used in cosmetic goods as stabilisers and gelling agents (Ariede et al. 2017).

Moreover, marine green algae are important environmental remediators because they are both phytoremediators and bioindicators of aquatic environments (Chekroun and Baghour, 2013). By accumulating organic contaminants, heavy metals, and excess nutrients from water bodies, these organisms can reduce eutrophication and pollution (Agarwal et al. 2022). Additionally, the growth of marine green algae in wastewater treatment systems helps to provide biomass for a variety of uses and purify effluents (Dorhoi et al. 2018). Although marine green algae have many interesting uses, there are still some issues that need to be resolved before they can be used sustainably (Beetul et al. 2016). These include creating effective methods for

gathering and processing biomass, making sure that enterprises based on algae are environmentally sustainable, and refining cultivating techniques to increase biomass productivity. Furthermore, in order to fully realise the potential of marine green algae and investigate novel applications, interdisciplinary research efforts are required.

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## **8.3 Bioplastic Development from Marine Green Algae**

### **8.3.1 Introduction to Biomass Extraction and Biopolymer from Marine Green Algae**

The uptick in interest surrounding biomass extraction from algae is a testament to their potential to revolutionise the production of eco-friendly bioplastics, along with other green innovations. Central to this process is the refinement of extraction methods that ensure the optimal yield while keeping the biomass's essence intact. These techniques span mechanical, chemical, and biological realms, each tailored to meet the unique characteristics of varying algae types and the specific requirements of the intended products (Arora et al. 2023; Kartik et al. 2021; Nanda and Bharadvaja 2022; Park and Lee 2022; Sudhakar et al. 2023, 2024). Equally pivotal is the commitment to sustainable extraction practices. Our techniques for cultivating and extracting algae must safeguard against disrupting marine ecosystems or diminishing the algae's natural populations. Finding this balance is crucial for the efficiency of algae-based projects and for upholding the environmental virtues that these endeavours promise.

### **8.3.2 Techniques and Methods for Algae Biomass Extraction**

Efficient biomass extraction from marine green algae involves various techniques despite the current limitations in bioplastic production from algae due to factors such as raw material availability, production costs, process optimisation, and a general lack of knowledge (Park and Lee 2022). The methodologies for producing bioplastics include a direct approach, which utilises melted biomass, and an indirect approach, which involves processing fermented biomass with the aid of microbes (Sudhakar et al. 2024). In addition, an alternative method consists of the production of biopolymers through the use of cellular factories within the algae biomass and the combination of biomass with additives (Chia et al. 2020; Kartik et al. 2021; Nanda and Bharadvaja 2022). Biopolymer extraction can be conducted through various methods: mechanical approaches such as centrifugation and filtration work by separating algal cells from water-based on size and density; chemical methods employ solvents or pH adjustments to liberate valuable compounds from the cells; and biological strategies use enzymes or other microorganisms to break down the cell walls, thus facilitating the release of the intracellular substances (Kartik et al. 2021). Meanwhile, biological methods leverage enzymes or other microorganisms

to break down cell walls and facilitate the release of intracellular materials. Each extraction technique comes with its own benefits and drawbacks, typically dependent on the algae type and the targeted compounds. Advances in extraction technologies strive to enhance efficiency, diminish energy requirements, and reduce solvent usage, thereby fostering the development of more sustainable algal bioproducts.

Moreover, genetic engineering emerges as a promising approach to boost biopolymer production in microalgae and cyanobacteria, thanks to their relatively simple cellular structures that facilitate genetic manipulation. This method has proven effective in species like *Chlamydomonas reinhardtii* and various strains of *Synechococcus* sp. and *Synechocystis* sp., which are notable for their well-defined metabolic pathways and robust genetic integration capacities. Techniques such as random mutagenesis and metabolic engineering have been applied to augment pathways for polyhydroxybutyrate (PHB) production, leveraging organisms like *Ralstonia eutropha* and converting non-PHB producers such as *E. coli* into efficient biopolymer producers. This advancement not only has the potential to reduce production costs but also broaden the range of substrates that can be used, enhancing the commercial feasibility of algal bioplastics (Chia et al. 2020; Mal et al. 2022; Nanda and Bharadvaja 2022).

Methods including the overexpression of specific genes and inverse metabolic engineering are being explored to amplify bioplastic yields more effectively than simple gene insertion could achieve. However, despite its advantages, genetic engineering presents its own set of challenges, such as the environmental risks associated with releasing genetically modified organisms into nature and the potential for the loss of inserted genes across generations. Nonetheless, this technology promises significant strides in the field of algal bioplastic production, offering more profound insights into biological systems and the possibility of lower manufacturing costs (Chia et al. 2020; Mal et al. 2022; Nanda and Bharadvaja 2022). Furthermore, the isolation of biopolymers from algal biomass combines both classic and modern techniques. Notably, solvent extraction, microwave-assisted extraction, ultrasound-assisted extraction, and subcritical water extraction are distinguished by their effectiveness and efficiency (Kartik et al. 2021; Nam et al. 2024).

### 8.3.2.1 Solvent Extraction

Solvent extraction uses chemical agents to detach biopolymers from the cultivated algal biomass, creating polymer precipitates. This method is appreciated for its simplicity and generally demands less downstream processing compared to fermentation methods. The effectiveness of solvent extraction largely depends on fine-tuning chemical and physical parameters and can be improved by selecting algal strains exhibiting high productivity rates. Although this approach requires additional chemicals, it continues to be a fundamental technique in biopolymer isolation and is recognised for its directness and effectiveness (Kartik et al. 2021; Park and Lee 2022).

### 8.3.2.2 Microwave-Assisted Extraction

The microwave-assisted extraction method is a contemporary technique that harnesses microwave radiation to extract biopolymers from algal cells efficiently. This method has gained popularity because it improves extraction yields by affecting the ions and dipoles within the algae. This technique strengthens the biopolymers and reduces syneresis, making it an economically and environmentally sustainable choice for biopolymer isolation (Kartik et al. 2021; Nam et al. 2024).

### 8.3.2.3 Ultrasound-Assisted Extraction

Ultrasound-assisted extraction leverages the energy of ultrasound waves to create cavitation and turbulence within the algal biomass, which disrupts the cellular structure and facilitates the release of biopolymers. This technique presents numerous benefits over conventional methods, including shorter extraction times, the ability to conduct extractions at room temperature, and the avoidance of complex membrane separation processes. As a result, there is an increase in biopolymer yield, as well as an improvement in environmental sustainability (Kartik et al. 2021; Park and Lee 2022).

### 8.3.2.4 Subcritical Water Extraction

Subcritical water extraction is a novel technique employing pressurised water maintained below its critical pressure and heated beyond its boiling point to extract bioactive compounds from algal biomass. The main benefit of this approach is the use of water as the solvent, which circumvents the need for harmful chemicals, resulting in a higher quality and yield of the product while also reducing energy consumption. The efficiency of subcritical water extraction is greatly enhanced when combined with ionic liquid catalysts, markedly increasing the extraction efficiency and yield of biopolymers (Kartik et al. 2021; Park and Lee 2022).

In addition to the above methods, other extraction methods can be mentioned, such as alkaline extraction, enzymatic hydrolysis, acid hydrolysis, preparative high-performance liquid chromatography (HPLC), organic solvent precipitation, calcium chloride precipitation, chelating agents, activated carbon adsorption, and crossflow microfiltration (Sahu et al. 2024). Usually, bioplastics, which are alternatives to conventional petroleum-based plastics, fall into three main categories based on their origin and degradability:

#### (1) Bio-based Non-degradable Plastics:

This group includes plastics such as polyethylene (PE), polypropylene (PP), and polyethylene terephthalate (PET), which are made from renewable resources but are not biodegradable. Despite being derived from biological materials, these plastics share similar structural properties with their petroleum-based equivalents, making them resistant to natural decomposition.

## (2) Bio-based Biodegradable Plastics:

This category encompasses plastics like polylactic acid (PLA), polyhydroxyalkanoates (PHA) and PHB, as well as starch blends and cellulose. Originating from biological sources, these materials are capable of breaking down into water, carbon dioxide, and biomass with the assistance of microorganisms. Due to their ability to decompose and minimise environmental impact, these plastics are increasingly favoured in sustainable practices.

## (3) Fossil-based Biodegradable Plastics:

This last group includes plastics such as polybutylene adipate terephthalate (PBAT) that, although produced from petroleum-based resources, possess chemical structures enabling them to biodegrade. While these are derived from non-renewable sources, their biodegradable nature provides certain environmental advantages (Arora et al. 2023; Chia et al. 2020; Mal et al. 2022; Nanda and Bharadvaja 2022; Park and Lee 2022).

Additionally, various types of bioplastics derived from algae can be outlined as follows. These algae-based bioplastics present an environmentally friendly option compared to traditional plastics. They capitalise on the innate ability of algae to absorb carbon and thrive in diverse environments without encroaching upon agricultural land designated for food production (Table 8.1).

However, the sustainable harvesting of algae is essential to ensure its long-term availability as a resource for bioplastics and other uses. Sustainable practices entail responsible cultivation methods that avoid depleting natural resources, damaging aquatic ecosystems, or causing a loss in biodiversity. Additionally, these practices should aim to minimize waste and environmental impact throughout the extraction process. By adopting sustainable harvesting methods, the algae industry can aid in conservation while addressing the increasing demand for bio-based products. This strategy is in harmony with worldwide sustainability objectives and fosters the growth of a circular economy (Chia et al. 2020; Nanda and Bharadvaja 2022; Park and Lee 2022).

Traditional plastic production mainly depends on petroleum-based feedstocks, significantly adding to environmental pollution and greenhouse gas emissions. The process includes extracting crude oil or natural gas, refining them into monomers, and then polymerising these monomers to create plastics. This production method consumes a lot of energy and results in a considerable carbon footprint. Moreover, traditional plastics present waste management challenges because of their non-biodegradable nature, leading to persistent environmental pollution, especially in marine ecosystems (Arora et al. 2023; Chia et al. 2020; Nanda and Bharadvaja 2022; Park and Lee 2022). Comparing algae-based plastics to traditional ones underscores bio-based alternatives' environmental and economic benefits. Algae-based plastics provide a renewable and potentially carbon-neutral option, lessening dependence on fossil fuels and reducing greenhouse gas emissions (Arora et al. 2023; Chia et al. 2020).

**Table 8.1** Different types of bioplastics made from algae

Different types of bioplastics made from algae	Description	References
Poly(lactic acid) (PLA)	A thermoplastic derived from lactic acid, which can be produced through bacterial fermentation of algae biomass. PLA is known for its characteristics similar to conventional plastics such as polyethylene (PE), polystyrene (PS), and polypropylene (PP) but is biodegradable	Arora et al. (2023), Mal et al. (2022), and Nanda and Bharadvaja (2022)
Polyhydroxyalkanoates (PHAs)	A family of biodegradable polymers produced intracellularly by microalgae under specific conditions. Common types within this family include polyhydroxybutyrate (PHB) and poly(hydroxybutyrate-co-hydroxyvalerate) (PHBHV), which are made as a carbon and energy reserve in microbes and microalgae	Arora et al. (2023), Mal et al. (2022), Nanda and Bharadvaja (2022), and Park and Lee (2022)
Polyhydroxybutyrate (PHB)	A type of PHA synthesised by prokaryotes and some algae as an intracellular storage compound. PHB is biodegradable and possesses mechanical and thermal properties comparable to synthetic plastics	Arora et al. (2023), Mal et al. (2022), Nanda and Bharadvaja (2022), and Park and Lee (2022)
Algae-PLA composites	These are bio-composites created by blending algal biomass with polylactic acid. The composite material has been used for green packaging solutions due to its biodegradability and lower carbon footprint	Arora et al. (2023) and Sudhakar et al. (2024)
Algae-polymer blends	These bioplastics are produced by blending algae biomass with various other biodegradable polymers like PBS (polybutylene succinate) or biodegradable petroleum-derived polymers to improve specific properties like mechanical strength or biodegradability	Arora et al. (2023) and Kartik et al. (2021)
Algae-starch blends	Bioplastics created by mixing algal biomass with starch to produce biodegradable materials suitable for various applications including packaging	Arora et al. (2023) and Sudhakar et al. (2024)

Furthermore, algae-based bioplastics can be engineered to biodegrade, offering a solution to the waste management issues linked with traditional plastics. Nevertheless, challenges like scaling up algae-based production, refining extraction methods, and maintaining product performance still exist. Overcoming these obstacles will be essential in establishing algae-based bioplastics as a practical and sustainable alternative to conventional plastics, thereby contributing to a more eco-friendly and sustainable future.

### 8.3.3 Biochemical Composition of algae

The growing field of bio-based, biodegradable plastics is experiencing a significant shift towards using algal biomass, which includes both microalgae and macroalgae, as a key source of sustainable materials. Algae's distinct characteristics, such as their renewable nature, biodegradability, and low ecological footprint, make them an excellent alternative to traditional fossil-based plastics. Various components can be derived from algae, including polysaccharides, proteins, lipids, and other secondary metabolites, all playing significant roles in developing bioplastics. This underlines the potential for environmental sustainability (Arora et al. 2023; Sudhakar et al. 2023).

Cellulose is the most abundant natural polymer on Earth, offering endless raw materials for developing eco-friendly products without affecting the food supply. It consists of glucose units connected by  $\beta$ -1,4-glycosidic bonds, forming a structure with inter-chain solid hydrogen bonds. Due to its alternating side chains, this structure has a high crystalline nature, leading to characteristics such as brittleness and limited flexibility. However, when mixed with suitable plasticisers, cellulose derivatives like ethers and esters can be transformed into versatile bioplastics. Cellulose acetate, for example, is utilised in making products like eyeglass frames, combs, cigarette filters, and disposable jewellery due to its dimensional stability and printability. It has also been used in food packaging for items like baked goods. However, its popularity has waned due to poor moisture and gas barrier properties, and the risk of hydrolysis into acetic acid. The large-scale production of cellulose acetate is typically controlled, especially the temperature, which affects the degree of polymerisation; a low degree can compromise product quality. While there has been considerable research into producing cellulose acetate from plant sources, studies on its extraction from algal cell walls are ongoing. However, since algal cell walls are not entirely cellulose, the yield of cellulose-based polymers from algae may be low. Combining it with other biopolymers for large-scale production could be a sustainable approach to utilising the entire biomass (Sreenikethanam et al. 2021).

Polysaccharides such as alginate, carrageenan, agar, ulvan, fucoidans, porphyrin, xylan, mucopolysaccharides and laminarin play crucial roles in various industries. Alginate, obtained from brown algae, forms gels when interacting with divalent cations and is extensively utilised in the food and medical sectors for its biocompatibility. Carrageenan, derived from red algae, is valued for its thickening and gelling properties, making it a popular ingredient in food products and pharmaceuticals. Agar, sourced from red seaweed, is another gelling agent widely used in the microbiology and food industries and is renowned for its strong gelation ability. Ulvan, extracted from green seaweeds like *Ulva* sp., is recognised for its sulfated polysaccharides, contributing to its application in medical and environmental fields. Fucoidans, present in brown seaweed, are known for their various biological activities, including anticoagulant and anticancer effects, making them significant in pharmaceutical applications. Porphyrin, derived from *Porphyra* sp., has characteristic features as a gelling agent and emulsifier used in the food industry, whereas xylan is extracted from *C. reinhardtii*, *Chara* sp. and *Nitella flexilis* as a prebiotic

and dietary fibre, used in the food industry. Mucopolysaccharides extracted from brown algae are used as cell adhesives and immune responsiveness where those manufactures in pharmaceuticals. Lastly, laminarin, a storage glucan found in brown algae, is utilized in the production of biofuels and health supplements due to its energy content and health-promoting properties (Bin Abu Sofian et al. 2024; Bose et al. 2023; Chia et al. 2020; Kartik et al. 2021; Mohan et al. 2022; Sahu et al. 2024; Sudhakar et al. 2023, 2024).

Proteins extracted from algae, especially from microalgae such as *Spirulina* sp. and *Chlorella* sp., are highly nutritious and find applications in health supplements and as a basis for biodegradable materials (Kartik et al. 2021; Mohan et al. 2022; Park and Lee 2022; Zatta et al. 2023). Besides being a source of amino acids, these proteins also contribute to bioplastics' structural integrity and functional properties (Bose et al. 2023). Lipids, especially those from microalgae such as *Nannochloropsis* sp., *Scenedesmus* sp. and *Botryococcus braunii*, are essential in producing biopolymers like PHAs and PHBs. These biopolymers are distinguished by their biodegradability and resemblance to traditional plastics, rendering them outstanding substitutes for sustainable packaging and various other applications (Arora et al. 2023; Kartik et al. 2021; Park and Lee 2022; Sudhakar et al. 2023; Zatta et al. 2023).

Furthermore, biocomposite polymers are created by combining materials derived from algae with other biopolymers. For example, mixing algae with polymers such as polyvinyl alcohol (PVA) or PLA improves the mechanical and thermal properties of the resulting bioplastics, making them more durable and suitable for a broader spectrum of applications (Bin Abu Sofian et al. 2024; Park and Lee 2022; Sudhakar et al. 2023, 2024). These compounds, originating from the vast biodiversity of algae, offer an eco-friendly alternative to traditional plastic materials while showcasing a broad range of functionalities, such as biodegradability, biocompatibility, and renewability. Their use signifies an innovative step towards sustainable development, especially in reducing dependence on plastics derived from fossil fuels and in alleviating environmental pollution.

Algal biomass plays a crucial role in synthesising biopolymers, such as PHA and PHB, which are essential in shifting towards environmentally friendly material alternatives. These biopolymers possess characteristics similar to petrochemical-based plastics but have the added benefits of biodegradability and a lesser environmental footprint. Progress in biotechnological processes, including fermentation and metabolic engineering, has enabled the effective production of PHA and PHB from algal sources, driving advancements in the bioplastics industry (Nanda and Bharadvaja 2022; Sudhakar et al. 2024).

Polyurethane is a widely used commercial biopolymer found in products like adhesives, coatings, elastomers, and foams. It can be derived from various oils, with algal oils, particularly triglycerides, serving as sustainable sources. The fatty acid composition of these oils varies by species. For example, *Chlorella* sp. algae produces polyols through oxidation, achieving conversion rates comparable to those of other vegetable oils. The process includes epoxidation of algal oil and subsequent opening of the epoxide ring with ethylene glycol and lactic acid, producing rigid polyurethane foams with properties similar to commercial polyols. In separate

research (Patil et al. 2019), the researchers developed nanocomposite coatings by blending polyol from algal oil and ricinoleic acid with eggshell-based silver-doped nanoparticles. Compared to PU without nanoparticles, these polyurethane nanocomposite coatings displayed enhanced physico-mechanical, antibacterial, and anticorrosive properties (Sreenikethanam et al. 2021).

Combining materials derived from algae with traditional biopolymers has resulted in the creation of innovative biocomposite polymers. This blend has improved their mechanical, thermal, and biodegradable qualities. Mixing algal extracts with polymers like PLA and PVA has led to the emergence of new materials suitable for a wide array of uses, from biomedical devices to eco-friendly packaging solutions. This collaboration not only enhances the attributes of bioplastics but also broadens their use across different sectors, representing a considerable advance in the field of sustainable material science (Bose et al. 2023; Kartik et al. 2021; Mal et al. 2022; Nanda and Bharadvaja 2022; Park and Lee 2022). The exploration and integration of algal biomass into bioplastics represent a crucial development in the search for sustainable material alternatives. Algae's diverse properties and advances in biopolymer production technology offer a promising path to decrease dependency on fossil-based plastics and reduce environmental pollution. Ongoing research and development in this area are essential to fully realise the potential of algae as a renewable resource for the future of bioplastics, in line with worldwide environmental and sustainability objectives.

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## 8.4 Applications and Advantages of Marine Green Algae Bioplastics

Marine algae such as seaweeds have gained attention in recent years as a potential source for environment-friendly bioplastics production (Tennakoon et al. 2023). Bioplastics derived from marine algae offer several advantages over traditional petroleum-based plastics such as biodegradability, renewability, and reduced carbon footprint (Chia et al. 2020).

### 8.4.1 Potential Industrial Applications of Bioplastics

Marine algae-derived bioplastics have numerous potential applications across various industries due to their biodegradability, renewability, and versatility (Dang et al. 2022). These bioplastics offer similar properties to conventional plastics while being more environmentally friendly. Polyhydroxyalkanoates (PHAs) derived from microorganisms are a good sustainable alternative to conventional chemical plastics (El-malek et al. 2020). These bioplastics can be applied in various ways such as wood production, food packaging, 3D printing, cancer detection, and for treating ulcers as well as several agricultural and therapeutic applications. Biomedical applications of PHAs are vascular grafting, heart tissue engineering, skin tissue repairing, liver tissue engineering, nerve tissue engineering, bone tissue engineering,

cartilage tissue engineering, and therapeutic carrier (Shahid et al. 2021). Algae-based bioplastics can be used for packaging applications such as food packaging, single-use plastics (bags, cups and utensils), and packaging materials for consumer goods. For example, alginates, natural hydrophilic polysaccharide biopolymers have been utilized as a biodegradable packaging material in the food industry (Kontominas 2020). According to this study, these marine brown algae, alginates can be utilized as a multi-functional food packaging system.

Biodegradable mulch films made from algae-based bioplastics can be used in agriculture to suppress weeds, retain moisture, and enhance soil health (Bandopadhyay et al. 2018). These films can degrade naturally after use, eliminating the need for plastic film removal and disposal. Therefore, biodegradable mulch (BDM) films are largely used in eco-friendly agriculture practices concerning climate, soil, temperature, and weed management (Somanathan et al. 2022). Moreover, dark-coloured mulch can increase soil temperature and light-coloured mulch can reduce soil temperature (Tofanelli and Wortman 2020). In sustainable agriculture, biodegradable mulch can be utilized as a successful weed controller (Wang et al. 2021). Currently, the textile industry is becoming sustainable due to the utilization of bioplastic polymers (Friedrich 2021). Marine algae-based bioplastics can be processed into fibres and used in textile applications such as clothing, upholstery, and non-woven fabrics. These bioplastics offer a sustainable alternative to petroleum-based synthetic fibres like polyester and nylon (Manali et al. 2021). In the future, bioplastics will be the only option for a sustainable textile industry and hence there is a potential for culturing marine algae for extracting raw materials, and fibres.

Cosmetic industry is a huge business that uses plastic materials largely for packaging and storing products. Algae-based bioplastics can be incorporated into cosmetic formulations for packaging containers, applicators, and encapsulation of active ingredients (Ibrahim et al. 2021). These bioplastics offer a natural and sustainable option for cosmetic brands looking to reduce their environmental impact. Hence, cosmetic brands can be upgraded due to their sustainability. Biodegradable polymers such as poly(lactic acid), polyhydroxyalkanoates, polysaccharides and more can be utilized for cosmetic packaging (Cinelli et al. 2019). For example, chitosan-based bioplastics can be utilized as packaging materials (Jin et al. 2024). Moreover, algae-based bioplastics can be formulated into thin films and coatings for various applications in various industries such as paper coatings, food wraps, and biodegradable coatings for electronic devices such as chitosan (Tanpichai et al. 2022).

Algae-based bioplastics can be utilized as feedstock for 3D printing applications, allowing for the creation of biodegradable and environmentally friendly 3D printed products, prototypes, and components (Andanje et al. 2023). Accordingly, there are unfavourable characteristics of plant-based bioplastics to use as materials for 3D printing. Hence marine algae-based bioplastics may be an adaptive alteration for sustainable 3D printing; however, there is a research gap. Bioplastics and waste management have been discussed in various manners (Calabrò and Grosso 2018). Biodegradable films made from algae-based bioplastics can be used for wastewater treatment applications such as membrane filtration and adsorption of contaminants

(Lutzu et al. 2021). A study has been conducted to prepare bioplastic films using Taro starch (*Colocasia esculenta*) (Shanmathy et al. 2021); however, marine algae-based bioplastic film preparation for wastewater management is yet to be studied more. In a previous study, red seaweed (*Kappaphycus alvarezii*) was used for bioplastic film production (Sudhakar et al. 2021).

Algae-based bioplastics can be reinforced with natural fibres such as hemp, flax or bamboo to produce bio-based composite materials for automotive parts, construction materials, and consumer products. Algae biopolymers such as polyhydroxyalkanoates are aquatic natural fibres for a sustainable circular economy and moreover, carbon sequestration of 1 kg algae biomass integrates 1.83 kg atmospheric CO<sub>2</sub> (Devadas et al. 2021). Algae-based bioplastics biopolymers can be used to manufacture disposable products such as straws, cutlery, plates, and food containers, providing a sustainable alternative to single-use plastics. Also, algae-based biopolymers can be utilized for energy production in a sustainable manner (Joshi et al. 2024). These applications highlight the versatility and potential of marine algae-derived bioplastics in addressing environmental concerns and promoting sustainability across various industries. Continued research and development efforts are likely to expand the range of applications and improve the performance of algae-based bioplastics in the future.

Comparative analysis between conventional plastics and biodegradable plastics at a commercial scale can be conducted in various aspects. Raw materials of conventional plastics are from non-renewable resources (fossil fuels); however, bioplastics are produced from renewable biological resources. Non-renewable resources mainly cause environmental pollution compared to biological resources which affect the global economy. To produce conventional plastics, higher energy is used, and it produces large amounts of toxic and green house gases (Gironi and Piemonte 2011). Accordingly, conventional plastics have significant environmental impacts throughout their lifecycle, including resource depletion, pollution, and contribution to climate change. Their persistence in the environment poses long-term challenges for ecosystems and human health. However, bioplastics are mainly produced through environment-friendly methods such as fermentation, polymerization and extrusion. Biodegradable plastics offer the potential to mitigate some environmental impacts associated with conventional plastics, particularly in terms of reducing landfill waste and litter accumulation. However, their environmental benefits depend on factors such as material composition, disposal method, and end-of-life management practices. By the way, a recent study has revealed that any type of plastic (bio/conventional) has similar toxic effects (Zimmermann et al. 2020).

Conventional plastics have advanced characteristics such as durability, stability, and versatility that can offer a wide range of mechanical, thermal, and barrier properties suitable for various applications other than bioplastics. More research needs to be conducted to increase these properties in bioplastics in the future. Conventional plastics persist in the environment for extended periods that can contribute to pollution, and habitat degradation, and cause harm to wildlife. Some plastics can be recycled; however, recycling rates vary widely, and a significant portion still ends up in landfills, incineration facilities, or as litter. Biodegradable bioplastics are

designed to degrade into natural compounds under specific conditions, such as composting facilities or anaerobic digestion. Proper disposal and management are crucial to ensure efficient degradation, and biodegradable plastics may offer advantages in terms of reducing landfill waste and litter accumulation (Song et al. 2009). Moreover, long-term field experiments need to be carried out to study biodegradation of chemically modified biopolymers in the future (Polman et al. 2021).

Conventional plastics have dominated various industries due to their versatility, cost-effectiveness, and performance characteristics. They are widely used in packaging, construction, automotive, electronics, consumer goods, and medical applications (Abedsoltan 2024). Biodegradable plastics have mainly been used with disposability and environmental concerns such as single-use packaging, food service items, agricultural films, and disposable products. However, market adoption may be hindered by factors such as cost, performance, consumer awareness, and infrastructure limitations. Normally, conventional plastics continue to dominate many industries due to their performance, cost, and widespread availability. However, biodegradable plastics offer potential benefits in terms of reducing environmental impact and addressing concerns about plastic pollution (Thakur et al. 2018). There are challenges that still need to concern like technological advancement, market adoption, infrastructure development, and policy support to facilitate the transition towards more sustainable plastic alternatives. Continued research, innovation, and collaboration across stakeholders are essential to address these challenges and achieve a more sustainable plastics economy.

Economic viability and market trends play crucial roles in determining the adoption and growth of both conventional and biodegradable plastics. Conventional plastics are often favoured for their low production costs, driven by the abundance and relatively low cost of fossil fuel feedstocks (Bucknall 2020). The established infrastructure for extraction, refining, and polymerization further contributes to cost competitiveness. However, biodegradable plastics generally have higher production costs compared to conventional plastics due to the use of renewable feedstocks and potentially more complex manufacturing processes but sustainable. However, economies of scale, technological advancements, and shifts in market demand can influence cost competitiveness over time. Conventional plastics have historically dominated the market due to their versatility, performance, and cost-effectiveness. However, increasing awareness of environmental issues and concerns about plastic pollution are driving changes in consumer preferences and market demand for green industries. Bio-based and biodegradable plastics (BBBPs) are concerned with 12 principles of green chemistry that may enhance environment-friendly product development (Choudhary et al. 2021). Growing environmental consciousness among consumers, businesses, and policymakers has fuelled demand for biodegradable plastics, particularly in sectors where sustainability and disposability are prioritised. Market segments such as food packaging, single-use products, and agriculture are experiencing notable growth in demand for biodegradable alternatives.

Regulatory frameworks governing conventional plastics vary globally but generally focus on issues such as product safety, recycling, waste management, and

pollution control. Increasingly, regulations are being implemented to address plastic pollution and promote circular economy principles. Microplastics have become a serious environmental problem and therefore, incentives to replace certain microplastics must be concerned by policy makers (Mitrano and Wohlleben 2020). Regulatory support for biodegradable plastics varies across regions, with some governments incentivising their use through policies such as plastic bans, extended producer responsibility (EPR) schemes, composting infrastructure development, and green procurement initiatives. However, standards and certification processes for biodegradability and compostability remain areas of concern.

Ongoing research and development efforts in the conventional plastics industry focus on improving production processes, enhancing material properties, and exploring new applications. Innovations such as bio-based plastics derived from renewable feedstocks and advanced recycling technologies aim to address sustainability challenges. Technological advancements in biodegradable plastics encompass material development, processing techniques, and end-of-life solutions. Researchers are working on improving the performance, cost-effectiveness, and environmental compatibility of biodegradable materials to broaden their applicability and market acceptance. For example, a recent study has revealed that innovations in bioplastics can be useful in the medical sector such as drug delivery systems in the brain (Lamparelli et al. 2023). The conventional plastics market is highly competitive, with major multinational corporations dominating the industry. Established players benefit from economies of scale, extensive distribution networks, and strong brand recognition. Recently, the German and Australian governments have introduced several important plastic mitigation practices (Wurm et al. 2020). The biodegradable plastics market is characterised by a mix of established companies and newer entrants focused on innovation and sustainability. Market fragmentation, evolving consumer preferences, and regulatory dynamics contribute to a dynamic competitive landscape. Further, conventional plastics continue to dominate many sectors due to their cost competitiveness and established market presence while biodegradable plastics are gaining traction driven by increasing environmental concerns, regulatory support, and technological advancements. The economic viability and market trends for both types of plastics will be influenced by factors such as regulatory policies, consumer behaviour, industry innovation, and global sustainability initiatives. Continued collaboration among stakeholders across the plastics value chain is essential to drive sustainable solutions and address the complex challenges of plastic pollution and resource conservation.

#### **8.4.1.1 Sustainable Economy of Marine Green Algae-Based Bioplastics**

There is a growing interest for marine-based bioplastic innovations and a recent study has discussed about raw materials such as algae, animals, and microorganisms, as well as their extraction processes and properties (Tennakoon et al. 2023). Economic analysis of marine algae-based bioplastics involves assessing various factors such as production costs, market demand, regulatory considerations, technological feasibility, and potential revenue streams. The cost of sourcing marine algae

biomass as a feedstock, including cultivation, harvesting, and processing may be high. Several factors affect the cost of sourcing such as algae species, cultivation method (open pond vs. photobioreactor), nutrient requirements, water and land use, labour, and energy inputs impact production costs. The costs are also associated with extracting biopolymers from algae biomass, refining, polymerization, and forming into bioplastic products (Nanda and Bharadvaja 2022). Efficient extraction methods, scale of production, equipment costs, and energy requirements can influence the processing costs of marine algae into bioplastics. Hence, we need to assess the current and projected market demand for bioplastics, including consumer preferences, industry trends, regulatory drivers, and sustainability initiatives. For this, researchers need to understand market dynamics and identify potential niche markets or applications where marine algae bioplastics can offer unique value propositions.

We can compare the price of marine algae bioplastics with conventional plastics and other bioplastic alternatives. Factors such as performance, availability, and environmental attributes influence price competitiveness and market acceptance. Further, the policymakers need to understand regulatory requirements related to bioplastics production, labelling, certification, and end-of-life management. Therefore, standards must be adopted for bioplastics (Painuli et al. 2024). When we want to ensure compliance with standards such as biodegradability, compostability, food contact, and safety regulations, we may gain additional costs. Therefore, introducing government incentives, grants, subsidies, and tax credits available for renewable energy, sustainable materials, and circular economy initiatives can be considered for promoting bioplastic production.

For further development of the bioplastic sector, we need to evaluate advancements in algae cultivation techniques, biopolymer extraction methods, bioplastic processing technologies, and product innovations (Torres Lepe et al. 2024). Novel collaborations with research institutions, technology providers, and industry partners are suggested to enhance bioplastic production efficiency, product performance, and cost-effectiveness. Also, we need to assess the scalability of algae bioplastics production from lab-scale or pilot-scale to commercial-scale operations. For this, challenges related to infrastructure, logistics, supply chain optimisation, and economies of scale must be addressed. A diversified portfolio of marine algae bioplastic products can be tailored to target markets and applications. Hence, we need to explore opportunities in packaging, textiles, consumer goods, automotive, construction, and other industries. Genetic engineering can also be adopted into biopolymer production through microalgae (Onen Cinar et al. 2020). For example, diatoms like *P. tricornutum* are bioreactors for synthesising biotechnologically relevant polymers like PHB (Hempel et al. 2011).

For more sustainability, we can consider vertical integration opportunities along the bioplastics value chain, including algae cultivation, biopolymer extraction, compounding, manufacturing, distribution, and end-of-life solutions. Developers can collaborate with partners across the value chain to capture the value and optimise the costs of bioplastics. They can develop a strong brand identity, marketing strategy, and value proposition highlighting the environmental benefits, performance

attributes, and sustainable credentials of marine algae bioplastics (Hao et al. 2024). Therefore, customers can differentiate products based on quality, functionality, and price to target environmentally conscious consumers and corporate clients. Finally, we can understand that conducting a comprehensive economic analysis of marine green algae-based bioplastics requires a thorough understanding of production costs, market dynamics, regulatory requirements, technological feasibility, and business opportunities. By addressing these factors strategically, businesses can assess the viability of marine green algae-based bioplastics as a sustainable alternative to conventional plastics and capitalise on emerging opportunities in the circular economy.

Several emerging market trends and opportunities are shaping the landscape for marine algae bioplastics. These trends reflect growing consumer demand for sustainable alternatives to conventional plastics and evolving regulatory frameworks aimed at reducing plastic pollution. As consumers and businesses become more aware of the environmental impacts of conventional plastics, there is a growing demand for sustainable packaging solutions (Manali et al. 2021). Marine algae bioplastics offer a renewable and biodegradable alternative to petroleum-based plastics, making them well-suited for packaging applications. Opportunities exist to collaborate with food and beverage companies, consumer goods manufacturers, and retailers looking to adopt eco-friendly packaging solutions to meet consumer preferences and regulatory requirements.

There should be a proper regulatory support for sustaining bioplastics in the future. Hence, governments around the world need to implement regulations and policies to reduce conventional plastic wastes and need to promote the usage of biodegradable and compostable materials in each kind of industry. For example, a study has discussed the future of bioplastics in the food industry (Ghasemlou et al. 2024). Regulatory support for bioplastics, including marine algae bioplastics, creates opportunities for market growth and adoption. Companies can leverage regulatory incentives, such as tax credits, grants, and procurement preferences, to develop and commercialise marine algae bioplastics products in the future. Ongoing research and development efforts are leading to technological advancements in algae cultivation, biopolymer extraction, and bioplastic processing. A recent study has targeted production of polyhydroxyalkanoates (PHA) using food wastes (Tsang et al. 2019). Innovations in bioplastic formulations, additives, and processing techniques can improve the performance and properties of marine green algae bioplastics. This will serve as a good point to compete with conventional plastics. Hence, there should be more opportunities for companies to collaborate with research institutions, technology providers, and industry partners to accelerate innovation and scale up production of marine algae bioplastics. As a sustainable initiative, green technologies can be promoted for bioplastic production (Lim et al. 2021).

The transition towards a circular economy, where resources are kept in use for as long as possible, is driving demand for sustainable materials and waste reduction solutions. Marine algae bioplastics support the principles of the circular economy by offering renewable, biodegradable, and recyclable alternatives to conventional plastics (Rosenboom et al. 2022). There are opportunities to develop closed-loop

systems for algae cultivation, bioplastic production, and end-of-life management, creating value from waste streams and minimising environmental impacts. Growing consumer awareness of environmental issues, plastic pollution, and climate change is influencing purchasing decisions and driving demand for sustainable products in circular economy (Spierling et al. 2019). Some companies can offer transparent and eco-friendly products, including marine algae bioplastics, that appeal to environmentally conscious consumers and gain a competitive edge in the market. We can also aware consumers about the benefits of marine algae-based bioplastics and collaborate with retailers and brand owners to promote sustainable packaging and products. As an extended producer responsibility (EPR), single-used plastics need to manage well competing with “take, make, and dispose” model (Springle et al. 2022). In summary, emerging market trends and opportunities for marine algae bioplastics include increased demand for sustainable packaging, regulatory support for bioplastics, technological advancements, circular economy initiatives, and shifting consumer preferences. By capitalising on these trends and leveraging strategic partnerships, businesses can position themselves for growth and contribute to a more sustainable future.

### 8.4.2 Environmental Advantages

This section will review environmental benefits of marine green algae. Marine green algae-based bioplastics have a promising implication for environmental protection and sustainability (Fig. 8.2). Number of environmental issues and challenges can be overcome using biofibres, and biopolymers which are extracted from renewable,

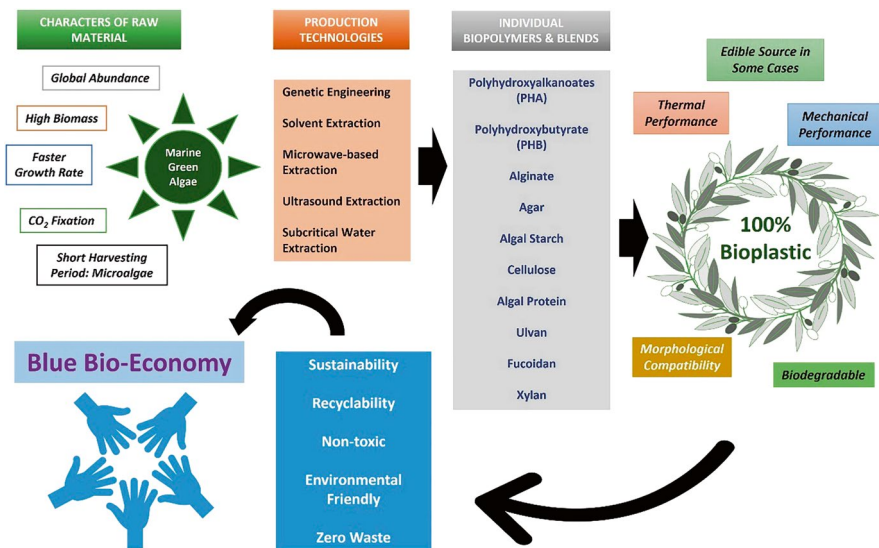


Fig. 8.2 Applications of marine green algae to combat the plastic pollution

and biological resources including marine, green algae (Soni et al. 2023). Biopolymer degradation covers four aspects as oxidative degradation, thermal degradation, photodegradation, and high energy degradation under biological, chemical or both mechanisms (Aswathi Mohan et al. 2022). Conventional plastics are widely used in different industrial sectors. Superior qualities of bioplastics: biodegradability and biocompatibility show potential industrial applications in biomedical, food packaging, non-food packaging, and other value-added products (Prasanth et al. 2021). As a result, these bio-based plastics do not generate waste and toxic, carcinogenic substances at the end of their life cycle. A previous study has revealed the application of macro green alga, *Ulva* sp. from the Arabian Gulf region and ground seeds: *Plantago ovata* as a filler and plasticiser for bioplastic production (El Semary et al. 2022).

All the algal biological products have been used for bioplastic processing considering bio-composting and biodegradation. Soil bio-compost of this algal bioplastic waste is enriched with antioxidants, vitamins, growth-promoting chemicals, minerals and other nutrients. Accordingly, this algal biomass mass can be used as an organic fertiliser in agriculture with zero-waste generation, and no treatment is required (El Semary et al. 2022). Similarly, ribbon sea lettuce: *Ulva reticulata*, from Allen, Northern Samar, Philippines have been used for seaweed-based bioplastic production (Bordeos et al. 2024). During soil biodegradation, approximately 82% of average weight loss was recorded after 21 days. This will result in minimum waste generation by *Ulva*-based bioplastics (Bordeos et al. 2024). So, *Ulva*-based bioplastic production seems cost-effective, a zero-waste, simple, and eco-friendly approach compared to conventional non-biodegradable plastic production. Seaweed-based bioplastics for large-scale economic, industrial, and agricultural applications have future implications for sustainable global development without environmental pollution. Moreover, cellulose bioplastic was successfully extracted from *Cladophora* sp. and recorded excellent properties in the derived product (Steven et al. 2022). As per this literature, degradability of cellulose bioplastic was over 40% in five days. Also, conventional plastic wastes are persistent in the environment for prolonged periods.

The accumulated environmental plastics could discharge the emerging contaminants (e.g. persistent organic pollutants) and form micro- and nano-plastic particles in the environment. This will result in increasing the non-biodegradable plastic waste input and pose a health risk. Additionally, bioplastics can be produced using seaweed-based wastes and this will reduce the usage of raw seaweed for other kinds of products and minimize accumulation of wastes in the environment (Liu et al. 2017). In the production line, bioplastics which process without chemicals, or extraction are considered as eco-friendly methods. It prevents further waste generation during bioplastic production (Lim et al. 2021). Expansion and promotion of marine algae-based bioplastics act as long-term waste management measures to avoid waste accumulation in the environment. Accordingly, green algae act as a promising environmentally friendly material for the formation of bioplastic products at the commercial scale by contributing to the blue bioeconomy.

Marine algae-based bioplastic products are also an alternative option for the mitigation of global climate change. The demand for petroleum-based, conventional plastic is continuously growing, and concurrently carbon discharge is also accelerating over the world. As per the estimations, around 90% of plastics are manufactured using fossil-based fuel feedstock and approximately 400 million tonnes of Green House Gases (global CO<sub>2</sub>) emissions were recorded by plastic production (Escobar et al. 2018). As a global warming mitigation and climate regulation measure, greenhouse gas emissions can be reduced or prevented by alternatives for conventional plastics. Microalgae act as carbon dioxide (CO<sub>2</sub>) capture system biologically and this biological system is involved in recycling of discharged CO<sub>2</sub> from diverse sources such as organic matter decaying, automobiles, volcanoes, forest fires, and power plant operations (Helen et al. 2021). Cyanobacteria and eukaryotic green algae could play a significant role in CO<sub>2</sub> storage through efficient photosynthesis, since these primary producers can acquire inorganic carbon even under lower levels of atmospheric CO<sub>2</sub> (Ward et al. 2012). In some cases, green algae (*Spirulina* sp.) are a carbon-neutral material with carbon-negative capacity.

As a bioplastic material, macroalgae can be used for plastic production, and large-scale farming is required for macroalgae production (Abdul-Latif et al. 2020). During bioplastic production, mass-scale marine green algae farming could induce the CO<sub>2</sub> capture system and reduce the carbon footprint as a mitigation measure for global climate change. For instance, the Sabah coast, Malaysia which covers around 388,500 ha (3885 km<sup>2</sup>) of area, has an annual potential production of seaweed up to ≈13.99 Mt./year by 2050 (Abdul-Latif et al. 2020). In this area, total assumed seaweed production with self-cultivation is <1Mt/year, and the total phenol level used for bioplastic formation is around 370 Mt. Based on the algae-based bioplastic requirement by 2050, it is predicted that over 0.6 million hectares of area is required to culture macroalgae for bioplastic production by reducing 100% CO<sub>2</sub> emission (Abdul-Latif et al. 2020). Further, biodegradation of bioplastics at the end of its life does not accelerate net CO<sub>2</sub> gas emission (Arora et al. 2023) and the quantity of produced CO<sub>2</sub> during biodegradation is equal to the absorbed quantity of gas by plants in growth (Atiweh et al. 2021). Moreover, an experimental study revealed that around 80% less discharge of CO<sub>2</sub> in bioplastics compared to the conventional petroleum-based plastics (Yu and Chen, 2008). The environmental opportunities and benefits ensure the future potential for expansion and development marine algae-based bioplastic sector to achieve the sustainable goals.

### 8.4.3 Social Benefits

Several sectors like food and textile industries are discussing about benefits from sustainable development using bioplastics (Friedrich 2021). Further, triple bottom line (TBL) approach to three distinct sustainability concepts (economic characteristics, environmental consequences, and social attitudes) has been discussed as a unique approach for the sustainability of bioplastics (Moshood et al. 2022). Marine

algae-based bioplastics offer several social benefits that contribute to sustainable development and address various societal challenges.

Directly or indirectly marine algae-based bioplastics can reduce plastic pollution. Marine algae-based bioplastics help to mitigate the environmental impacts associated with conventional plastics, such as littering, marine debris, and pollution. By providing a biodegradable alternative, these bioplastics reduce the accumulation of plastic waste in terrestrial and marine environments, protecting ecosystems, wildlife, and human health (Karpušenkaitė and Varžinskas 2014).

Marine algae-based bioplastics production utilises renewable resources derived from algae cultivation, which reduces dependence on finite fossil fuel reserves (Raschka et al. 2013; Tennakoon et al. 2023). By promoting the sustainable use of marine resources, these bioplastics contribute to resource conservation and support the long-term viability of coastal communities reliant on marine ecosystems. Hence, green bioplastic production can support the circular economy as well (Karan et al. 2019). Algae cultivation for bioplastics production can also sequester carbon dioxide from the atmosphere through photosynthesis. This helps to mitigate global warming and climate change (Nakanishi et al. 2020). Additionally, replacing fossil fuel-based plastics with algae-based bioplastics reduces greenhouse gas emissions associated with plastic production and disposal, contributing to climate change mitigation efforts (Karan et al. 2019).

Marine algae-based bioplastic production also provides opportunities for rural development and employment. Algae cultivation for bioplastics production can create employment opportunities in coastal and rural areas, particularly in regions where traditional livelihoods such as fishing or agriculture may be declining (Hiloidhari et al. 2020). Accordingly, agro-industrial waste can be utilized to produce bioplastics by diversifying economic activities, and providing income-generating opportunities. Hence, marine algae-based bioplastics can support rural growth, poverty alleviation and community empowerment. Marine algae-based bioplastics can empower local communities, including indigenous and coastal communities, by involving them in sustainable resource management and value-added activities. Community-based initiatives for algae cultivation and bioplastics production can foster local ownership, knowledge transfer, and capacity building, enhancing social cohesion and resilience.

Through bioplastic usage, we can enhance health and well-being of communities. Reduction of plastic pollution and environmental degradation associated with conventional plastics can benefit human health and well-being (Rajpoot et al. 2022). Marine algae-based bioplastics offer a safer and healthier alternative that is free from harmful additives and toxins commonly found in conventional plastics. Hence, these bioplastics can reduce exposure risks for consumers and workers along the supply chain. Marine algae-based bioplastics provide opportunities for education and awareness-raising on environmental sustainability, marine conservation, and circular economy principles (Bin Abu Sofian et al. 2024). By engaging stakeholders, including students, educators, scientists, policymakers, and the general public, these bioplastics production and supply chains can promote environmental literacy and foster a culture of responsible consumption and stewardship. Collaborative

research and development initiatives for marine algae-based bioplastics can foster international cooperation and knowledge exchange among nations. By sharing best practices, technologies, and expertise, countries can address common challenges related to plastic pollution, climate change, and sustainable development, leading to global benefits for present and future generations.

In summary, marine algae-based bioplastics offer a range of social benefits, including reduced plastic pollution, resource conservation, climate change mitigation, rural development, community empowerment, health and well-being, education and awareness, and international collaboration. By harnessing these social benefits, marine algae-based bioplastics contribute to building more resilient, inclusive, and sustainable societies.

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## 8.5 Challenges and Future Perspectives

### 8.5.1 Potential Challenges

The process of scaling up algal biomass for bioplastic production presents several considerable challenges. Key among these are the prohibitive costs related to the separation and harvesting of algal biomass, the potential for genetic and microbial contamination, and the need to select suitable strains for cultivation in non-sterile conditions (Arora et al. 2023). Addressing these issues requires a multifaceted approach that includes both innovative technological solutions and strategic planning.

One solution to alleviate the financial burden of algae biomass recovery is improving the efficiency of the harvesting process. Techniques like flocculation and bio-flocculation have become recognized as cost-effective and energy-efficient methods for recovering algae biomass. These methods use natural or synthetic flocculants to clump algal cells together, making it easier to separate them from the culture medium. This approach reduces operational costs and enhances the scalability of algal biomass production (Arora et al. 2023; Mal et al. 2022; Zatta et al. 2023).

In genetic engineering and bioengineering, gene-editing tools such as the CRISPR-Cas9 system offer significant potential. By utilizing these advanced techniques, scientists can create genetically enhanced algae strains that show higher productivity of biopolymer precursors and greater resilience to environmental stressors and contaminants. This genetic optimization can result in more robust strains better suited for large-scale cultivation under non-sterile conditions (Arora et al. 2023; Mal et al. 2022; Nanda and Bharadvaja 2022).

Moreover, the challenge of selecting strains for growth in non-sterile conditions can be tackled through dedicated research and development efforts. These efforts should focus on identifying microalgae species that naturally possess robustness and adaptability. Finding strains that can survive and flourish in open pond systems while resisting pathogens and contaminants is essential for achieving sustainable and cost-effective bioplastic production (Arora et al. 2023).

Metabolic and synthetic biology techniques present another method for boosting the bioplastic production capabilities of algae. Scientists aim to enhance the efficiency and yield of biopolymer precursor synthesis by modifying the metabolic pathways within algal cells. This process involves changing the genetic structure of the algae to optimise the production of specific compounds essential for bioplastic formulations (Kartik et al. 2021; Sudhakar et al. 2023, 2024).

The life cycle assessment (LCA) is crucial in the sustainable development of bioplastics. By conducting thorough LCA studies, researchers can assess the environmental impacts associated with each stage of the bioplastic lifecycle (Arora et al. 2023). This analysis aids in pinpointing areas where improvements can be implemented to reduce ecological footprints and ensure that bioplastic production aligns with principles of environmental sustainability and the circular economy.

### 8.5.2 Future Perspectives

The path to successfully introducing algae-based bioplastics into mainstream markets is complex, entailing a series of interconnected challenges across technological, economic, regulatory, and environmental domains. These challenges require careful navigation to facilitate the transition from traditional petroleum-based plastics to more sustainable alternatives. (Arora et al. 2023; Mal et al. 2022). Technologically, the development of algae-based bioplastics requires selecting the optimal algae species, a task complicated by the varied compositions of different algae strains. These variations influence the physical and chemical characteristics of the resulting bioplastics. Techniques for extracting biopolymers from algae, such as ultra-sonification, must be finely tuned and optimised for each specific species. Moreover, it is crucial to develop algae-based polymers that maintain structural integrity and performance while being environmentally sustainable. This includes addressing challenges related to biodegradability, moisture resistance, and the physical properties of the bioplastics (Bose et al. 2023; Park and Lee 2022; Pathak et al. 2014).

From an economic standpoint, the high costs involved in producing algae-based bioplastics represent a substantial challenge. These expenses can be traced back to several factors, including the early stage of the technology, limited economies of scale, and the lack of governmental incentives (Arora et al. 2023; Sudhakar et al. 2023). Additionally, competition for raw materials, especially those also utilized in food production, intensifies cost pressures and highlights the necessity of identifying alternative, cost-effective sources of raw materials (Arora et al. 2023; Bose et al. 2023; Kartik et al. 2021; Mal et al. 2022; Nanda and Bharadvaja 2022).

Environmentally, although algae-based bioplastics are praised for their potential to decrease carbon footprints and reliance on fossil fuels, it's essential to assess their life cycle impacts thoroughly. This includes examining aspects such as biodegradability and the emissions of greenhouse gases during decomposition (Arora et al. 2023; Chia et al. 2020; Nanda and Bharadvaja 2022; Sudhakar et al. 2023, 2024). Ensuring these materials can break down efficiently and harmlessly in diverse

environmental settings is essential to their sustainable credentialing. Regulatory aspects also pose challenges, as the lack of unified standards and transparent regulatory frameworks for the production and use of algae-based bioplastics can impede their development and adoption. It is crucial to establish coherent policies and international standards to ensure product safety, consistency, and environmental compliance (Arora et al. 2023; Chia et al. 2020; Nanda and Bharadvaja 2022; Park and Lee 2022). Looking towards the future, the prospects for algae-based bioplastics are undoubtedly promising but depend on overcoming the multifaceted challenges. Progress in genetic engineering, bioprocessing techniques, and the establishment of microalgal biorefineries could dramatically transform the economics of algae cultivation and bioplastic production (Kartik et al. 2021). By developing materials that are not only cost-effective but also perform well, meet consumer expectations, and align with environmental goals, the pathway to a sustainable bioplastic industry becomes more defined (Arora et al. 2023; Bose et al. 2023; Chia et al. 2020; Sudhakar et al. 2024).

Furthermore, increasing public awareness and understanding of bioplastics' advantages and strategic market positioning could boost consumer acceptance and demand (Bose et al. 2023; Chia et al. 2020). Complementing these initiatives, thorough environmental impact assessments, and the establishment of supportive regulatory frameworks are vital to ensure the sustainable integration of algae-based bioplastics into the global materials economy (Arora et al. 2023; Bose et al. 2023; Chia et al. 2020). In essence, while there are many obstacles, the combined efforts in scientific research, industry innovation, policy development, and consumer education are crucial to unlocking the significant potential of algae-based bioplastics as a fundamental component of sustainable material management in the future. The future of algae-based bioplastics is being sculpted by a landscape filled with innovation, regulatory changes, and an increasing awareness of environmental issues. As we address the current challenges, we are greeted by transformative opportunities that promise to redefine the materials economy, focusing on sustainability and circularity (Arora et al. 2023; Chia et al. 2020). Here, various other strategies can be employed to overcome future challenges and to find solutions while addressing these issues.

### **8.5.2.1 Innovative Breakthroughs in Biotechnology and Engineering**

Technological advancements, especially in genetic and metabolic engineering, are poised to revolutionise the algae-based bioplastic industry (Arora et al. 2023; Nanda and Bharadvaja 2022). We can anticipate a significant decrease in production costs by optimising algae strains for higher yield and more efficient biopolymer production. Techniques like CRISPR-Cas9 provide promising paths for enhancing specific characteristics in algae, such as accelerated growth rates and increased biopolymer content (Mal et al. 2022; Nanda and Bharadvaja 2022). At the same time, advancements in bioprocessing technologies and algae cultivation systems, such as photobioreactors and integrated biorefinery approaches, are expected to enhance scalability and minimize environmental impacts (Mal et al. 2022).

### **8.5.2.2 Regulatory Frameworks and International Standards**

Developing comprehensive regulatory frameworks and international standards for the production, use, and disposal of algae-based bioplastics is essential (Arora et al. 2023; Park and Lee 2022). These regulations are expected to cover guidelines on biodegradability, compostability, and the ecological footprint of bioplastics. The industry can ensure product safety, environmental protection, and market transparency by establishing clear, strict, and uniform standards. This will aid consumer acceptance and facilitate integration into the global market (Arora et al. 2023; Bose et al. 2023; Chia et al. 2020).

### **8.5.2.3 Environmental and Economic Sustainability**

As the global community becomes increasingly aware of environmental issues, the demand for sustainable materials is expected to rise (Bose et al. 2023; Sudhakar et al. 2024). Algae-based bioplastics align closely with these sustainability goals with their renewable nature and potential for carbon neutrality. Furthermore, as the technology matures and scales up, the economic feasibility of algae-based bioplastics is expected to improve, making them competitive with conventional plastics and more attractive to investors and consumers alike (Kartik et al. 2021; Nanda and Bharadvaja 2022; Sudhakar et al. 2024).

### **8.5.2.4 Market Development and Consumer Awareness**

Educating consumers about bioplastics' benefits and proper disposal will be crucial to their acceptance and successful market penetration. Marketing strategies highlighting the environmental benefits, such as reduced carbon footprint and decreased dependency on fossil fuels, can drive consumer preference towards algae-based bioplastics. Additionally, demonstrating bioplastics' practical applications and performance in packaging, agriculture, automotive, and other industries will further validate their utility and foster market growth (Arora et al. 2023; Chia et al. 2020).

### **8.5.2.5 Integration into the Circular Economy**

The integration of algae-based bioplastics into the circular economy is a promising prospect. We can create a closed-loop system that minimises waste and resource consumption by designing bioplastics for recyclability and compostability and establishing effective waste management and recycling systems. This approach enhances bioplastics' environmental credentials and contributes to broader sustainability goals (Arora et al. 2023; Bin Abu Sofian et al. 2024; Bose et al. 2023; Chia et al. 2020).

### **8.5.2.6 Collaboration and Cross-Sector Partnerships**

The future development of algae-based bioplastics will likely be driven by collaborative efforts across various sectors, including academia, industry, government, and non-profit organisations. Partnerships focused on research and development, commercialisation, and public policy can accelerate innovation, address market barriers, and promote the widespread adoption of bioplastics (Chia et al. 2020). The prospects for algae-based bioplastics are marked by potential and promise. As we

advance in technology, regulatory clarity, and market readiness, algae-based bioplastics stand at the forefront of sustainable material solutions, offering a path towards reducing environmental impacts, enhancing resource efficiency, and contributing to a greener, more sustainable future.

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## 8.6 Conclusion

Marine green algae are a key photosynthetic component in the coastal and marine ecosystems and represent both microalgae and macroalgae: seaweed. Both groups share general characteristics, but size and morphological traits are different in them. Algae-based bioplastic extraction corresponds with the characteristic biopolymer composition in marine algae. For instance, marine green algae are enriched with algae protein, lipids, cellulose, PHAs, and polysaccharides (e.g., agar, carrageenan, alginate, fucoidan, cellulose, and ulvan) and these biopolymers' extraction involves in bioplastic production using green algae as a sustainable raw material. This chapter reviewed multiple techniques and recent advances in the production line with the effective bioplastic extraction potential in future context. The biological, degradable, physical, and chemical properties of algae-based bioplastics show promising implications in socio-economic, ecological, and industrial perspectives. Accordingly, marine algae-based bioplastic products have a tendency to improve and expand the global market and production sector as a low cost, efficient alternative by replacing petroleum-based conventional plastics. Furthermore, algae-based bioplastics make a significant contribution to the blue bioeconomy to achieve sustainable economic development goals. As an emerging sector, the algae-based bioplastic sector is encountering different technological and financial challenges, and other risks. However, there is future potential in the development of this sector through identified opportunities and strengths. This chapter further discussed and suggested the feasible solutions, technologies, resources, alternatives and expansions required in the algae-based bioplastic sector at farming, production, and market scale. In conclusion, marine green-algae-based bioplastics are considered a novel, eco-friendly, sustainable, viable alternative to combat environmental plastic pollution and emerging threats toward a zero-waste, green environment.

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# Production of Bioethanol and Biobutanol from Seaweed Biomass

# 9

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## Abstract

The excellent higher calorific value and various combustion benefits like gasoline provide a strong potential for bioethanol and biobutanol as green fuel blends for drop-in fuels. Presently, the global interest in seaweed or macroalgae, as the likely wellspring of third-age biofuels is tremendously attracting attention. Seaweed has weak concentrations of lignin and other refractory components. Hence, enzymatic hydrolysis of the material is considered with imperceptible pretreatment. This chapter focuses on the potential of seaweeds for the production of bioethanol and biobutanol. Various aspects of the characteristics and properties of seaweeds, bioethanol, biobutanol and generation of biofuels have been covered to explore the potential of seawater for production of green fuel alternatives. Continued advancements in genetic engineering can lead to the development of microorganisms or enzymes that are more efficient in fermenting complex sugars present in third-generation feedstocks, improving yield and reducing processing costs. An in-detailed overview of different processes for cultivation, harvesting and pretreatment of seaweed biomass is provided. Various aspects of the fermentation process are also covered to produce bioethanol and biobutanol specifically from seaweed-derived sugars. In the last segment challenges, drawbacks, advantages, and future perspectives are also covered to provide a guide for the upcoming researchers.

## Keywords

Seaweed · Biobutanol · Bioethanol · Pretreatment · Hydrolysis and Fermentation (SHF) · Distillation · Low Heating Value (LHV)

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## 9.1 Introduction

Globally principal sources of fuel are running out quickly and capriciously due to expanding population demands in the renewable energy sector, which is mostly brought on by fast urbanisation and industrialisation (Godvin Sharmila et al. 2021). Fossil fuels are the primary nonrenewable source of energy. The careless use of fossil fuels has negative effects on the ecosystem, bad air quality and worldwide climate fluctuation, all of which are major contributors to ecological unbalance and its effect on health. Between 2010 and 2040, there will likely be a 40% increase in the demand for fossil fuels. Thus, supplying a distinctive sustainable energy source is a top priority. Different biomasses have made great strides and have the potential to be base products that are environmentally friendly, making them one of the most promising fossil fuel substitutes (Kapoor and Rafatullah 2022). The process of transforming biomass through conversion processes into a range of commercial products, such as chemicals and fuels, is known as biorefinery (Bhatia et al. n.d.). One such biorefinery energy product made from biomass is biofuel (Godvin Sharmila et al. 2021). Worldwide, there is right now a push for biofuels, for example, bioethanol, biogas, bio-butanol, and biodiesel as practical and ecologically helpful energy sources.

The biofuels are classified as first-, second-, or third-generation fuels on the basis of feedstocks used. The process of turning primary food crops like corn or sugarcane into ethanol is known as first-generation biofuels. By utilising just the inedible portions of food crops (like rice husk), second-generation biofuels enhance this by lessening competition for food supply. The high production costs of first- and second-generation biofuels as well as the damage caused by biofuel expansion to natural habitats pose significant obstacles. The worldwide food ultimatum crisis of 2007–2008 made it more vital for crops used to produce biofuel to be used as food, sparking the ongoing argument “food contrary to fuel” (Cavelius et al. 2023). In addition, a rise in the market price of those foods resulted from greater demand for commodities (like maize) for the manufacturing of fuel (Bhatia et al. n.d.). Seaweed, or algae, has been utilised as an energy feedstock since the 1950s, but it is currently regarded as the most practical and scalable source of third-generation biofuel. Seaweed has weak concentrations of lignin and other refractory components. Hence, enzymatic hydrolysis of the material is considered with imperceptible pretreatment (Taherzadeh and Karimi 2008). Contrasted with terrestrial biomass, photosynthetic proficiency which is 6–8% is substantially greater for seaweed. Carbon neutrality is another significant benefit of seaweed bioethanol production by minimising greenhouse gas emissions, optimising production processes, utilising co-products, sourcing sustainable feedstocks, and conducting lifecycle analysis. (Zidanšek et al. 2009). These benefits suggest that seaweed has a great deal of potential as a sustainable and environmentally acceptable feedstock for the synthesis of bioethanol and biobutanol. The production of bioethanol fuel reached 26.1 billion gallons worldwide in 2017, with the US (58.8%), Brazil (28.0%) Europe (5.3%), China (3.2%), and Canada (1.7%) contributing significantly to the production (Tan et al. 2020). The

top two nations that produce the most bioethanol are still the United States and Brazil. Brazil generated 7.1 billion gallons of bioethanol in 2017, compared to 15.8 billion gallons in the United States.

Red, brown, and green macroalgae typically have carbohydrate concentrations of 30% to 60%, 30% to 50%, and 25% to 50% dry mass, respectively (Offei et al. 2018). To effectively create bioethanol and other related bio-products, it is vital to determine the carbohydrate compositions of the various species of macroalgae, as these vary greatly in terms of their makeup. Glucan, galactan, and cellulose make up red macroalgae in general. Sulfated galactans, or long-chain polysaccharides like agar and carrageenan, predominate in the amorphous matrix of red macroalgae and are crucial for their capacity to produce gels (Khambhaty et al. 2012). Laminarin and mannitol carbohydrates may make up 55% of the dry mass of the major carbohydrates found in brown macroalgae. Some green macroalgae are rich in cellulose up to 70 weights% and contain pectin as the main structural cell wall content. Furthermore, as food reserves, green macroalgae contain carbohydrates in the form of starch. It is made up of polymerised glucose molecules that are deposited as rewards in chloroplasts (Offei et al. 2018). *Palmaria palmata* had the highest yield of bioethanol among 20 macroalgae varieties as it contains carrageenan ( $354 \text{ mg}\cdot\text{g}^{-1}$ ). Hence, on a comparison of bioethanol yield, it is the most suitable variety for the large-scale synthesis of bioethanol and biobutanol (Godvin Sharmila et al. 2021). According to the report (Godvin Sharmila et al. 2021), the anticipated yields of bioethanol produced from *Eucheuma* spp. as a feedstock could reach up to 110,000 t per year. Every one of the three seaweed species needed a pre-treatment phase, and it was discovered that the pre-treatment circumstances varied depending on the species. Aqueous or water-based pre-treatments were more effective for producing *Dilsea carnosa* (125.0 mg glucose/g) and *U. lactuca* (360.0 mg glucose/g). However, it is noteworthy that *D. carnosa* which was not pre-treated produced 106.4 g g<sup>-1</sup> glucose. For *Laminaria digitata* to release the highest amounts of glucose, a diluted acid thermochemical pre-treatment was necessary.

It is shown that the low heating value (LHV) of biobutanol is more comparable to the LHV of petrol when comparing the LHV of bioethanol, petrol, and biobutanol. While the LHV of bioethanol is 21.3 MJ/L, which is just 66% of the energy density of petrol or a 34% reduction in energy density, the LHV of petrol is 32.3 MJ/L and the LHV of biobutanol is 27.8 MJ/L or approximately 90% of the energy density of petrol (Swana et al. 2011). It is clear that biobutanol is a more promising biofuel than bioethanol, as it has been shown to have several benefits and mitigate some of the disadvantages of bioethanol.

In this regard, this chapter will provide a thorough analysis of the possible uses of macroalgae cultivation and suggest a method for producing biobutanol and bioethanol on an industrial scale which is a sustainable movement towards carbon neutrality and circular economy. This chapter describes the potential for producing biofuels (bioethanol and biobutanol) from seaweed, with a focus on third-generation biofuel production. It also details the pre-treatment procedures that must be followed, such as washing, drying, hydrolysis, and fermentation types.

## 9.2 Potential of Biobutanol and Bioethanol

### 9.2.1 Biobased Fuel and Biomass Conversion Routes

Marine seaweeds are employed all around the world to make renewable biofuels, or third-generation fuels, in addition to colloidal chemicals. By preparing all land and ocean spaces, the actual capability of French biogas age from all cultivable kelp biomass in 2030 is roughly nine Terawatt hours LHV per year; this is over two times the biogas delivered in France in 2011 (Zhao et al. 2022) as France is surrounded by the North Sea in the north, the English Channel in the northwest, the Atlantic Ocean in the west and the Mediterranean Sea in the southeast.

The transformation of biomass into biofuels includes three distinct courses; thermochemical, aqueous and biochemical separately which prompted the development of various items following different innovations. Thermochemical change of biomass incorporates both immediate and backhanded approaches. In the immediate ignition process, biomass is changed over into intensity and power. The roundabout cycles incorporate pyrolysis and gasification that produce bio-oils and union gas ( $\text{CO} + \text{H}_2$ ) (Zabed et al. 2019). Syngas in this manner delivered can additionally be changed over into biofuels, for example, bioethanol. Aqueous pathway essentially involves supercritical water as the vehicle for changing biomass into sugars and syngas. The biochemical course incorporates a few stages for biomass transformation, like pretreatment, hydrolysis, and maturation. Maturation is a typical and last step where solvent sugars obtained in the upstream cycles are changed over into biofuels like bioethanol, biobutanol, biogas and biohydrogen.

#### 9.2.1.1 Bioethanol

Generally, the method of producing bioethanol involves either enzymatic or acid hydrolysis to convert polysaccharides into simple sugars. Pretreatment, enzymatic hydrolysis/saccharification, and fermentation are its three primary phases. The latter two steps can be carried out in tandem. Dehydration and distillation are used to recover the produced ethanol (Zhao et al. 2022).

Seaweeds are among the greatest raw materials for the synthesis of bioethanol because they have the benefit of having very few lignocellulosic components. However various sugar types present necessitate the addition of particular and suitable enzymes; therefore, this must be taken into account when selecting the pretreatment techniques. The potential of producing ethanol from ocean growth by *Sargassum* is restricted because of the great water content of algal biomass; it is assessed to be 29.6 kg per tonne of unrefined substance, which is equivalent to that of sugarcane yet not exactly that of many edible crops whose creation rate is around 400 kg per tonne.

#### 9.2.1.2 Biobutanol

With the help of *Clostridium* strains, a variety of carbohydrates, including hexoses and pentoses, can be converted into simple alcohols during the acetone-butanol-ethanol fermentation process (ABE) to produce biobutanol (Ibrahim et al.

2018). Acidogenesis and Solventogenesis are the two distinctive phases of this process. The capability of earthy coloured green growth *Saccharina* species for *C. acetobutylicum*'s biochemical transformation to butanol was inspected. The kelp separate had yield of 0.12 g/g eventhough there are multiple carbon sources (Obergruber et al. 2021b). They discovered that resistant alginates were limiting product yields and came to the conclusion that considerable improvements are still required for the industrial scale ABE process of seaweed to be commercially viable.

### 9.2.1.3 Bio-Oil

It can be obtained through the high-temperature, oxygen-limited process of pyrolysis of seaweeds (thermochemical conversion). The biomass needs to be dried in order to maximise the yield. Three primary conventional pyrolysis varieties exist because of variations in temperature and retention time: conventional pyrolysis, fast pyrolysis, and flash pyrolysis. Hydrothermal Liquefaction (HTL), a potential method for producing biofuels, can also be used for it. It operates in subcritical conditions—that is, at pressures between 2 and 28 MPa and temperatures between 200 and 380 °C—and uses less energy (Machado et al. 2022). The bio-oil generated by this method is more stable than pyrolysis because it contains less oxygen and moisture. Other side products include biochar, soil conditioner, and chemicals.

### 9.2.1.4 Biodiesel

By means of transesterification, biodiesel which is comprised of long-chain carbon molecules along with esters functional group of long-chain unsaturated fats obtained from bio-oils, can be created. It is truly eco-friendly and has various positive natural impacts. In the evaluation of the production of biodiesel from seaweeds, it was found that *Enteromorpha compressa* (about 11%) and *Ulva lactuca* (about 10%) had low oil extraction yield values (Atadashi et al. 2010). Because of their low lipid content, seaweeds consequently appear to be less appropriate for this production.

### 9.2.1.5 Biogas

Biogas is a blend of gases primarily made up of carbon dioxide (CO<sub>2</sub>), methane (CH<sub>4</sub>), traces of hydrogen sulfide (H<sub>2</sub>S) and water vapours. Anaerobic digestion is a typical method used to produce biogas as a sustainable energy source from abundantly available raw materials like waste food/vegetables, municipal trash, agricultural waste etc. A typical Anaerobic digestion scheme consists of four steps: hydrolysis, acidogenesis, acetogenesis, and methanogenesis. Hydrolysis is the limiting step allowing the decomposition of complex organic matter. At the end of this step, simple materials such as amino acids and fatty acids are formed. In the acidogenesis stage, H<sub>2</sub>, alcohol, ammonia, and volatile fatty acids (VFA) (acetic acid, propionic acid, butyric acid, and isobutyric acid) are produced. Then, comes the acetogenesis which produces acetate, CO<sub>2</sub>, and H<sub>2</sub>. These are the main substrates of methane formation. Finally, the production

of methane is done either from acetate by acetoclastic methanogenic bacteria, or by the reduction in  $\text{CO}_2$ . Seaweeds are considered a suitable substrate for biogas production owing to their high carbon-nitrogen ratio, low lipid content and lack of lignin. The huge amounts of stranded biomass represent an attractive feedstock for energy production and could be integrated into a biorefinery scheme.

## 9.2.2 Characteristics and Properties of Biobutanol and Bioethanol

Both bioethanol and biobutanol are biofuels that come from renewable resources and are essential to the search for environmentally friendly energy sources. These biofuels contribute to the ongoing efforts to lessen reliance on fossil fuels and decrease environmental problems by offering unique qualities and advantages.

### 9.2.2.1 Properties of Biobutanol

Compared to bioethanol, the structure of biobutanol is more complex, with four carbon atoms, ten hydrogen atoms, and one oxygen atom ( $\text{C}_4\text{H}_9\text{OH}$ ). According to (Ezeji et al. 2007), biobutanol has two distinct qualities: (1) higher energy content and (2) less volatility. When compared to bioethanol, biobutanol has a number of benefits, such as reduced water content, higher energy density, and compatibility with current infrastructure (Obergruber et al. 2021b). Compared to petrol and ethanol, butanol has a greater kinematic viscosity value. When butanol is added, the liquid becomes more viscous.

### 9.2.2.2 Properties of Bioethanol

The basic chemical structure of bioethanol is made up of one oxygen atom, six hydrogen atoms, and two carbon atoms ( $\text{C}_2\text{H}_5\text{OH}$ ). The characteristics of bioethanol, such as its high oxygen content and octane number, make it a desirable fuel choice for internal combustion engines. When it comes to greenhouse gas emissions, bioethanol is thought to burn cleaner than conventional petrol. Some properties of bioethanol and biobutanol are given in Table 9.1 that makes them efficient fuel for future generations.

**Table 9.1** Properties of bioethanol and biobutanol

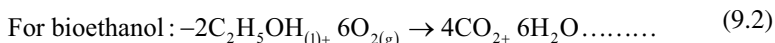
Property	Bioethanol	Biobutanol	References
Molecular weight	46.07	74.11	Yusoff et al. (2015)
Cetan number	5–8	12–5.6	Liu et al. (2022)
Heating value (kcal/g)	25.22	32.5	Liu et al. (2022)
Flashpoint ( $^{\circ}\text{C}$ )	8	35	Yusoff et al. (2015)
Viscosity ( $\text{mm}^2/\text{sec}$ )	1.13	3.64	Liu et al. (2022)
Flammability (v/v%)	3.3–19	1.4–11.2	Obergruber et al. (2021b)

### 9.2.3 Carbon Footprint of Biobutanol and Bioethanol Combustion

An important consideration for assessing the environmental sustainability of biofuels made from seaweed, such as biobutanol and bioethanol, is their carbon footprint. Compared to traditional fossil fuels, biofuels that are seaweed-based have the capacity to lower gas emissions responsible for global warming. When compared to conventional fossil fuels, the burning of bioethanol derived from seaweed has the potential to drastically lower carbon emissions. Bioethanol demonstrates a decreased impact on the environment and carbon emissions. Improved process optimisation and cutting-edge conversion technologies are essential for improving the environmental performance of seaweed-based bioethanol. In conclusion, burning seaweed to produce bioethanol and biobutanol has a carbon footprint that offers a promising way to cut greenhouse gas emissions if we compare wood combustion with biobutanol and bioethanol combustion. Wood is primarily composed of cellulose, hemicellulose, and lignin, which are primarily composed of carbon, hydrogen, and oxygen. When combusted, the carbon in wood combines with oxygen to form  $\text{CO}_2$ . The exact composition of wood can vary, but for simplicity, we can assume an average composition.

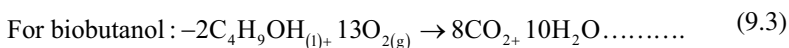


Here 1 mole of carbon gives 1 mole of  $\text{CO}_2$ , which means 12 kg of carbon gives 44 kg of  $\text{CO}_2$ . So, the amount of  $\text{CO}_2$  produced per kg of wood is 3.66 kg of  $\text{CO}_2$ .



For each molecule of bioethanol, 2 molecules of carbon dioxide are produced. Now, the amount of  $\text{CO}_2$  that is produced per kg of ethanol is as follows:

Mass of ethanol / molar mass of ethanol. 2 molar mass of  $\text{CO}_2 = 1 \text{ kg} / 46 \text{ g mol}^{-1} (2 \cdot 44 \text{ g mol}^{-1}) = 1.913 \text{ kg CO}_2 \text{ produced/kg of ethanol}$ .



Similarly, for biobutanol, the amount of  $\text{CO}_2$  that is produced per kg of butanol is 2.38 kg  $\text{CO}_2$  produced / kg of butanol.

Hence, for wood, the amount of  $\text{CO}_2$  produced is greater than that of biobutanol and bioethanol.

### 9.2.4 Advantage of Fuel Blending

The various chemical natures of biobutanol and hydrocarbon fuel, such as their calorific value, density, and octane number, are the reasons behind blends. The primary issue is the low cetane number, or reactivity, which needs to be raised with specific additions. There are several ways to incorporate alcohol into fuels. For instance, E95 gasoline, which is made up of 95% bioethanol and 5% additives, increases lubricity and reactivity. The commercialisation of isobutanol for petrol

blends is the main focus of current efforts. Fuel can be blended with up to 12.5% biobutanol by volume according to two Clean Air Act rules. Additionally, a 16% blend of biobutanol is an approved fuel that is comparable to E10 (10% ethanol, 90% petrol) according to a waiver from the U.S. Environmental Protection Agency (EPA). The ASTM D7862 fuel quality standard for petrol and butanol mixtures up to 12.5% applies to butanol(Saini [n.d.](#)).

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## 9.3 Generation of Biofuels

### 9.3.1 First Generations

Ethanol and biodiesel are examples of first-generation biofuels, which are derived from biomass that is frequently edible. Typically, the fermentation of C6 sugars—mostly glucose—using conventional or genetically modified yeast strains, like *Saccharomyces cerevisiae*, yields ethanol. In reality, just a few distinct feedstocks—mostly corn or sugarcane—are utilised in the synthesis of first-generation bioethanol. In addition to these more marginal feedstocks, whey, barley, potato wastes, and sugar beets are either utilized or being investigated for the production of the above-mentioned stage of bioethanol. When producing first-generation bioethanol, the USA and Brazil—which are recognised as global leaders in this regard—use feedstocks that are high in starch (corn and wheat) and sugar (sugarcane), respectively. While sucrose, a disaccharide made up of hexoses, fructose and glucose, is easily fermented by yeast, starch is easily degraded into glucose. The classic process for producing bioethanol is fermentation, which has been done for millennia. Other nations that produce a significant amount of bioethanol worldwide, including China and Canada, do it by using grains like maize, cassava, wheat, and rice. Bioethanol is made from sugarcane, beetroot, and wheat in Australia, France, Germany, and India. The global food demand crisis of 2007–2008 made it more vital for crops used to produce biofuel to be used as food, sparking the ongoing argument “food versus fuel.” In addition, a rise in the market price of those foods resulted from a greater demand for commodities (like maize) for the manufacturing of fuel (Guimarães et al. [2023](#)).

### 9.3.2 Second Generations

Fuels made from a variety of diverse feedstocks, particularly but not exclusively non-edible lignocellulosic biomass, are referred to as second-generation biofuels. Potentially addressing the drawbacks of first-generation biofuels, second-generation biofuels made from crop and forest residues, energy crops, and waste from building and municipal projects could lower net carbon emissions, improve energy efficiency, and lessen reliance on fossil fuels. Therefore, second-generation biofuels do not compete with food supplies and do not require a change in agricultural land use.

On the other hand, second-generation waste streams are frequently more complicated feedstocks than sugarcane or palm oil, and they may contain substances like lignin that might lower the efficiency of fermentation. As a result, adding more pretreatment processes is typical, which lengthens the process and raises expenses.

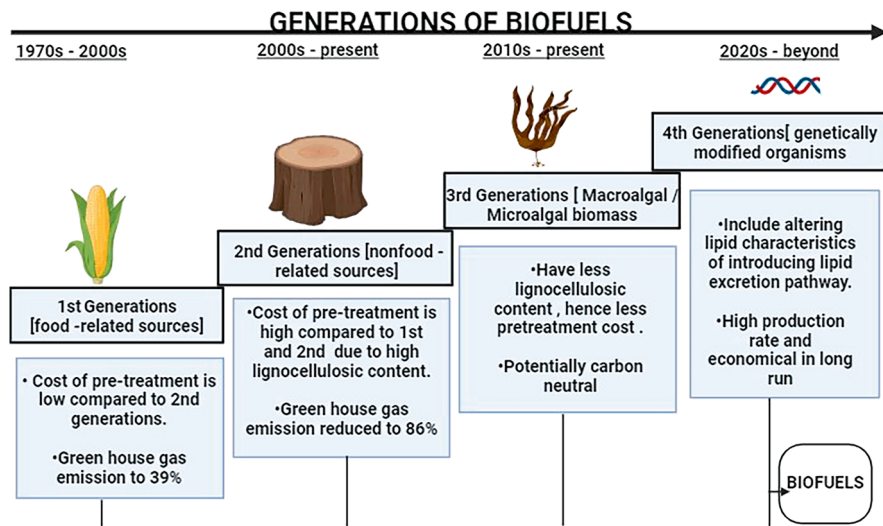
### 9.3.3 Third Generations

Third-generation biofuels are generally defined as fuels derived from algal biomass, which has a substantially different growth yield than traditional lignocellulosic biomass. The lipid content of the microorganisms is often what determines the production of biofuels from algae. Typically, species like *Chlorella* are chosen because of their high productivity (7.4 g/L/d for *Chlorella protothecoides*) and high lipid content (between 60 and 70%; Liang et al. 2009). Algal biomass presents a number of difficulties, both technical and geographic. Under optimal development circumstances, algae typically produce 1 to 7 g/L/d of biomass (Lee and Lavoie 2013).

Third-generation bioethanol derived from micro- and macroalgae has been viewed as a possible substitute for dwindling petroleum fuels because it does not have the disadvantages of its predecessor. Macroalgae has drawn a lot of attention lately as a potential substitute feedstock for the synthesis of bioethanol. Over 70% of the Earth's surface is made up of oceans and seas, which presents a potential for the sustainable development of macroalgae biomass feedstock. This is so because growing macroalgae does not conflict with the usage of agricultural land and does not need fresh water. Furthermore, compared to crops grown on land, macroalgae develop at a far faster rate. Although more than 10,000 species of macroalgae have been identified worldwide to date, only a dozen of these are grown for profit; the remainder are taken from their natural habitats. Nonetheless, the global production of macroalgae has been steadily rising at an average annual growth rate of 10% for the past 10 years.

### 9.3.4 Fourth Generation

Genetically modified (GM) algae are used in fourth-generation biofuel (FGB) to increase biofuel production. Despite becoming a well-known substitute for fossil fuels, genetically modified algal biofuel still poses significant concerns to human health and the environment. In addition to reducing the number of steps required in the absorption and transformation of solar energy into the corresponding biofuel, genetic and metabolic alterations in microorganisms capable of producing biofuel also collect CO<sub>2</sub> to reduce emissions into the environment (Guimarães et al. 2023). A reduction in the number of steps could speed up the reaction and improve the efficiency of producing biofuels, saving a significant amount of money on capital and running costs (Fig. 9.1).



**Fig. 9.1** Generations of biofuels

## 9.4 Seaweed Feedstock and Potential for Biofuel Production

Based on their pigmentation, seaweeds are classified into three groups: Rhodophyceae (red seaweeds), Phaeophyceae (brown seaweeds), and Chlorophyceae (green seaweeds). In seaweed groups, r-phycoerythrin, chlorophyll, and xanthophyll are the predominant pigments found in red, green, and brown seaweeds, respectively (Liao et al. 2021). Minerals, lipids, proteins, and carbohydrates make up seaweeds. Large volumes of complex sulfated carbohydrates, or polysaccharides, are typically found in seaweeds and are frequently extracted for use primarily in the hydrocolloid industry. Each group of seaweed is made up of distinct kinds of complex polysaccharides that support and store structural tissue like the cell wall.

### 9.4.1 Red Seaweed/Macroalgae

Glucan, galactan and cellulose make up red macroalgae in general. The macroalgal cell wall is composed of three domains: the glycoprotein domain, the amorphous matrix, and the fibrillar wall, and it can make up as much as 65 weight percent of the dry matter. Long-chain polysaccharides called sulfated galactans, which include carrageenan and agar, predominate in the amorphous matrix of red macroalgae and are crucial for their capacity to produce gels. Agarose, which comprises D-galactose and 3, 6-anhydro-L galactose (AHG) with alternate  $\alpha$ -1, 3- and  $\beta$ -1, 4-linkages, is the primary gelling component of agar. While carrageenan is a sulfated polygalactan made of D-galactose and 3, 6-anhydro-D-galactose units with a 15%–49%

ester-sulfate concentration, agar is easily hydrolysed to generate galactose monomers. Based on their ability to form a gel, carrageenan is further divided into lambda ( $\lambda$ ), kappa ( $\kappa$ ), and iota ( $\iota$ ) (Liao et al. 2021). Red macroalgae can be used to extract carrageenan by dissolving it in an aqueous solution. With a carrageenan concentration of  $354 \text{ mg}\cdot\text{g}^{-1}$ , *Palmaria palmata* had the highest yield of bioethanol among 20 macroalgae varieties. Based on a comparison of bioethanol yield, *P. palmata* is the most suitable variety for large-scale bioethanol production.

### 9.4.2 Brown Macroalgae

Laminarin and mannitol carbohydrates may make up 55% of the dry mass of the major carbohydrates found in brown macroalgae. Laminarin is a  $\beta$ -1, 3-linked glucan that has a reducing end bonded to either glucose (G-chain) or mannitol (M-chains). Laminarase (endo-1, 3 (4)- $\beta$ glucanase) has the ability to hydrolyse brown macroalgae and yield glucose monomers. D-mannose, which is made up of six carbon sugars, can be converted into mannitol, which has osmoregulatory qualities. In addition, mannitol is a sugar alcohol that ferments readily to produce bioethanol (Zhao et al. 2022). The primary structural polysaccharides found in the cell walls of brown macroalgae are cellulose and alginate, which serve as structural support to avoid ruptures during currents and tidal oscillations.

### 9.4.3 Green Seaweed

As the primary structural polysaccharides in the cell wall, cellulose (up to 70 weight percent) and pectin are abundant in green macroalgae like *Valonia* sp. Furthermore, green macroalgae store carbohydrates as starch for sustenance. It is found in chloroplasts as gains and is made from polymerised glucose molecules. Sucrose and other carbohydrates, including ulvan, are also present in green macroalgae. *Ulva* sp. contains up to 29% dry mass of Ulvan, a sulphated polysaccharide that is soluble in water. According to reports, ulvanobiouronic acid 3-sulfate types comprising either glucuronic or iduronic acid are the most common repeating disaccharide units (Offei et al. 2018). Furthermore, it was observed that minor repeat units on O-2 of rhamnose-3-sulfate included sulfated xylose instead of uronic acid or glucuronic acid (Table 9.2).

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## 9.5 Seaweed Biomass Pretreatment and Handling

After seaweed biomass is harvested, it is crucial to handle it carefully since improper handling can cause seaweed to degrade while being transported and stored. Additionally, the biomass composition may alter as a result of contamination by contaminants such as sand, aquatic plants, and animals. Thus, washing, drying, and

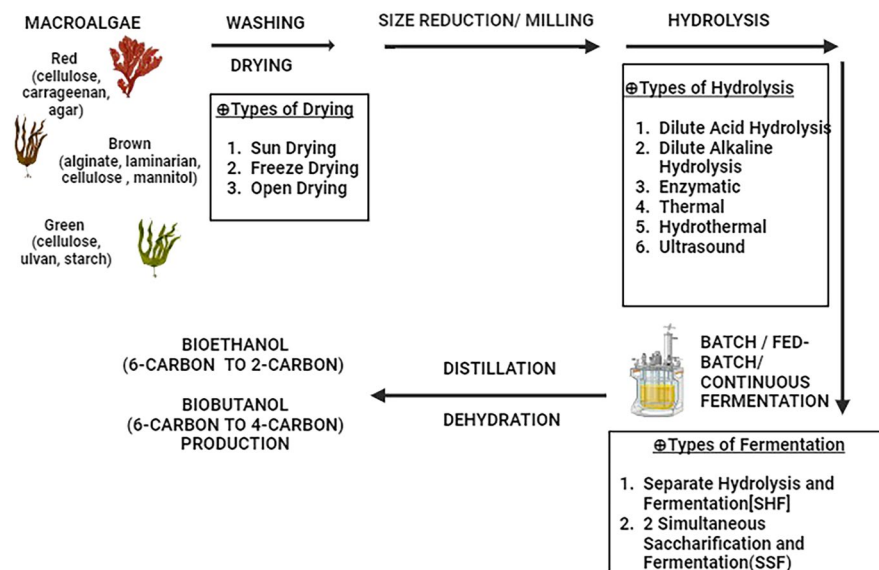
**Table 9.2** Chemical composition profile of three representative seaweeds

Seaweed type	Species	Carbohydrate	Protein (% dry biomass)	Lipid	Ash	References
Green	Ulva	43–53	14–23	1.2–1.8	16–22	del Río et al. (2020)
Red	Gelidium amansii	66	20.5	0.3	13.3	Offei et al. (2018)
Brown	Sargassum sp	33–69	5–13.6	0.3–4.9	46–19.4	Offei et al. (2018)

grinding are the main handling and pre-treatment procedures employed following seaweed harvesting (Fig. 9.2).

### 9.5.1 Washing

Following collection, seaweed is commonly rinsed with water to eliminate undesirable contaminants such as sand and rock. Washing *L. digitata* under tap water rapidly can result in a considerable loss of carbohydrates, up to 49% of laminarin, according to a study that examined the effect of washing (Offei et al. 2018). However, despite these losses, it is unfavourable for debris to be present in process streams, especially during large-scale bioethanol production. To save fresh water, it could be better to wash at the source with seawater. This makes it a more sensible and long-term choice.

**Fig. 9.2** Steps involved in bioethanol and biobutanol production from seaweed

### 9.5.2 Drying

Because fresh seaweed has a high moisture content (85–90%), this process is significant and requires high energy content in the manufacture of bioethanol and biobutanol. Seaweeds can be dried using a variety of techniques, such as freeze-drying, sun-drying, and oven-drying. Laminarin, the main carbohydrate percentage in brown seaweeds, was found to be present around 11% in oven-dried as well as frozen-oven-dried and around 15% in freeze-dried seaweed in the form of g/100 g dry solids, respectively, through a study comparing the effects of different drying techniques on the compositional profile of the *L. digitata* species (Offei et al. 2018). These findings support freeze-drying as a feasible option; nevertheless, in order to determine whether or not it is a sustainable choice, a comparison of its economic benefits must be made. Furthermore, because of the high energy costs involved, seaweed farmers—the majority of whom come from impoverished coastal communities—might not be able to apply freeze drying. Hence, sun drying, which is in trend is the most preferable and economical for seaweed producers. Its impact on the substrate chemical profile composition has still yet not been explored. In contrast with oven drying, sun drying cannot be well-controlled but its inexpensive cost is still a crucial factor. Commercial bioethanol and biobutanol output can only be endured if the substrate is stockpiled and fetched to processing mills in the withered form to minimise bacteriological or fungal contamination and conveying expenses. The use of non-dried seaweed is not currently in trend. However, the drying stage can be skipped if the culturing site can sufficiently contribute to a nearby bioethanol and biobutanol plant, harmonizing with the feed rate.

### 9.5.3 Grinding

Milling or size reduction of seaweed biomass not only elevates its exposure but also improves the efficiency of catalysts during further steps, but it also reduces the bulk volume of the biomass, making stockpiling and freight more efficient. Furthermore, milling seaweed biomass can initiate some hydrolytic effects, breaking down complex carbohydrates into simpler sugars, which can facilitate subsequent fermentation processes.

In essence, size reduction plays a critical role in preparing seaweed biomass for ethanol production by enhancing its accessibility to enzymes and catalysts, reducing logistical challenges associated with handling and transportation, and initiating initial hydrolysis processes that can streamline downstream fermentation steps (Maneein et al. 2018).

### 9.5.4 Hydrolysis

The breakdown of complicated sugars (starches) in ocean growth, for example, laminarin, cellulose, mannitol, alginate, ulvan, carrageenan, and agar, into basic

sugars, like glucose, galactose, mannose, fucose, xylose, and arabinose, for maturation into ethanol, is known as the hydrolysis cycle of bioethanol creation. Kelp has been hydrolyzed utilizing different methods to create bioethanol. These medicines incorporate ball processing, aqueous (HTT) (Edeh 2021), ultrasonic, enzymatic, weaken corrosive warm, weaken basic warm, and warm. Physical, synthetic, warm, and enzymatic medicines are ordinarily used to arrange them.

#### **9.5.4.1 Dilute Acid Thermal Hydrolysis**

Weakened corrosive warm hydrolysis is the treatment most normally used in ocean growth bioethanol research since it is accepted to be more financially savvy and has a quicker response time than the hydrolysis methods right now being used. Solid acids like HCl and H<sub>2</sub>SO<sub>4</sub> have been the most frequently involved compound impetuses for the hydrolysis of ocean growth. One significant disadvantage of utilizing corrosive impetuses is the creation of inhibitors like furfural, levulinic corrosive, and 5-hydroxymethylfurfural (5-HMF). These inhibitors are framed when hexoses (C6 lessening sugars) and pentoses (C5 diminishing sugars) dry out because of high corrosive fixations and delayed maintenance terms. The inhibitors can stop the aging of lessening sugars by harming DNA and forestalling the blend of proteins and RNA in maturing creatures like yeast. By utilizing initiated carbon to channel hydrolysates before aging, inhibitors have been successfully wiped out. Corrosive hydrolysates from *G. amansii* were separated through an initiated carbon bed to diminish the 5-HMF level from 30 g/L to 5 g/L. In contrast with different techniques or the utilisation of chemicals, the weakened corrosive hydrolysis approach is viewed as more efficient on the grounds that strong corrosive impetuses are produced and used in a laid-out industry. Costs are additionally diminished on the grounds that the impetuses are utilized at low convergences of 0.01–0.90 M (Kuhad and Singh 2016). Factors including impetus focus, response temperature, response time, and substrate fixation are frequently considered for enhancing the hydrolysis of weakened acids. In general, corrosive impetus-catalyzed ocean growth hydrolysis appears to be a profoundly encouraging innovation as a result of its noteworthy economy and productivity. Nonetheless, it is less practical, for the most part as a result of the corrosive impetuses' poisonousness and how the recuperated salts from refining are discarded.

#### **9.5.4.2 Dilute Alkaline Thermal Hydrolysis**

The immediate substitute for weakened corrosive hydrolysis is weakened soluble warm hydrolysis. Rather than involving a corrosive as an impetus in this case, a base is utilized. Furthermore, hydroxide particles in bases consolidate with the agarophytes and carrageenophytes in ocean growth to produce thickened structures that are gooey to even consider maturing at high temperatures and expanded response periods. This is an issue for the soluble hydrolysis process, especially concerning red ocean growth. Notwithstanding, this can be decreased by utilizing the

technique, which involves separating the gel-like hydrocolloid followed by applying weakened antacid hydrolysis to the buildup. In a review contrasting corrosive and base impetuses and enzymatic hydrolysis on the profile composition of carrageenan extraction buildup of *E. cottonii*, the biorefinery method was utilized (Kumar et al. 2013). Glucose yields of 92% approx. Dry matter were obtained through treatment with 1% strong acid and base, individually. However, the impact of inhibitors, formed as a result of acidic treatment, on successive fermentation has not been documented, despite the higher glucose production observed for the acidic treatment. Additionally, degradation products or fermentation inhibitors (2,5-dimethyl-4-hydroxy-3(2H)-furanone) are also produced by dilute alkaline hydrolysis. Nevertheless, the impact of these remains unclear. If proven to be less harmful than dilute acid hydrolysis, it could present a significant advantage. As of right now, there isn't much of a benefit to using base catalysts instead of acid catalysts while hydrolysing seaweed.

#### 9.5.4.3 Other Methods of Hydrolysis

The pre-treatment and hydrolysis of seaweeds have also been done using a number of non-traditional techniques. These consist of ball milling, hot water washing, ultrasound therapy, and HTT. They are frequently employed in conjunction with conventional chemical and enzymatic procedures to optimise the output of reducing sugar, or as alternatives to help address the many issues related to them. The most extreme yield of glucose, or 0.45 g/g biomass, is acquired via autoclave (warm) treatment rather than 0.20 g/g biomass for untreated (Edeh n.d.). This shows that when joined with enzymatic hydrolysis, autoclave treatment is a successful method for diminishing the arrival of galactan and raising the general centralisation of glucose. As how much gamma illumination developed, so did the convergence of diminishing sugars. The convergence of decreasing sugar at zero illumination was 0.017 g/L; at 500 kilo Greys, the focus rose to approximately 0.050 g/L (Edeh n.d.). This shows that the most ideal way to limit bringing down the arrival of sugar is to consolidate gamma light with weakened corrosive hydrolysis. The profoundly receptive free revolutionaries known as hydroxyl extremists (HR) created in vivo by the Fenton or Haber-Weiss response can deliver basic sugars by breaking the hydrogen securities in lignin and carbs. It is notable that the ultrasound procedure can burst cells, delivering intracellular items rapidly, moderately, and with next to zero poisonousness. In a concentrate on *S. japonica*, aqueous circumstances with subcritical water were utilized to dispose of issues such as the utilisation of harmful synthetic compounds, long response times, and significant expenses related to the utilization of acids and proteins during hydrolysis. Fluid water under tension at temperatures between the edge of boiling over (373 Kelvin) and the basic temperature (647 Kelvin) of water is alluded to as subcritical water. To safeguard the fluid state while adjusting its actual attributes, like dissolvable thickness, surface strain, and dielectric consistency, this technique utilises heated water under high tension.

## 9.6 Fermentation Mode and Strategies

Macroalgae are fermented by bacteria or yeast to produce bioethanol and biobutanol. Different macroalgae species have unique physical and chemical properties, necessitating the use of certain treatment settings. Therefore, before producing bioethanol, it is crucial to comprehend their properties. Cell growth profile, the pace at which microorganisms consume reducing sugar, and the synthesis of bioethanol are typically used to provide a comprehensive evaluation of the fermentation process. The reducing sugar from macroalgae can be fermented in a variety of ways to make bioethanol.

### 9.6.1 Separate Hydrolysis and Fermentation (SHF)

It is possible to fully convert the reducing sugars from biomass into bioethanol by a process that uses chemicals (in the case of acid hydrolysis and fermentation) or enzymes (in the case of enzymatic hydrolysis and fermentation). Generally, the process of saccharification/hydrolysis (either enzymatic or diluted acid hydrolysis) is done in a different vessel and then the hydrolysate is fermented into bioethanol in a different vessel under different conditions.

### 9.6.2 Simultaneous Saccharification and Fermentation (SSF)

Another method for producing bioethanol from biomass is simultaneous saccharification and fermentation (SSF), which combines fermentation and enzymatic hydrolysis into a single stage. Since cellulase inhibition can be reduced and a high bioethanol production rate can be attained due to yeast's quick conversion of glucose to bioethanol, the SSF process is typically preferred over the SHF process. Furthermore, there were a number of benefits associated with the SSF method, including reduced contamination risk, low initial osmotic stress of the fermenting agent, and good energy efficiency (Qureshi et al. 2008).

### 9.6.3 Simultaneous Saccharification and Co-Fermentation (SSCF)

Macroalgae, in contrast to lignocellulosic biomass, include cellulose and galactan/carrageenan, which, upon hydrolysis, can be converted to glucose and galactose, respectively. The microbes involved in the fermentation process must be able to efficiently and concurrently consume all reducing sugars in order to produce a more cost-effective method of producing a macroalgae-based biorefinery. On the other hand, microorganisms' carbon catabolite repression (CCR) aids in striking the right balance between their maximum capacity for up taking sugar and their metabolic capacity. In general, glucose is the preferred carbon source, and until the glucose

concentration is exhausted, the use of other carbon sources may be prevented. Consequently, during the fermentation of mixed sugar, sequential utilization or diauxic growth was noted, leading to low bioethanol production and productivity (Thang et al. 2010). To address these issues, scientists have recently shown that cellulose and galactose may be synthesised using SSCF (Thang et al. 2010). Before being subjected to 24-hour enzymatic hydrolysis, the cellulosic residue and the galactose liquid fraction were combined at a concentration of 18% (w/v). Afterwards, *S. cerevisiae* CBS1782, which had first been chosen based on its capacity to ferment galactose, was added to the medium in order to produce bioethanol. The outcome demonstrated a notable increase in galactose consumption throughout the fermentation process.

#### **9.6.4 Direct Microbial Conversion (DMC) or Consolidated Bioprocessing (CBP)**

In the process known as direct microbial conversion (DMC), a single microbial population is responsible for producing all the necessary enzymes and bioethanol within a single reactor. The key feature distinguishing DMC from other fermentation processes is that this microbial community produces cellulase enzymes and conducts fermentation simultaneously (Banner et al. 2021).

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### **9.7 Recovery Process of Bioethanol and Biobutanol**

Since distillation is the most cost-effective and dependable method for large-scale industrial production, it is frequently used to recover bioethanol and biobutanol from fermentation broth. In order to minimise energy consumption, low-content bioethanol was pre-processed using solvent extraction rather than traditional distillation. Extractive distillation was used to make the product concentrated, and a deep eutectic solvent was used to overcome the azeotrope mixture (ethanol/water). As a result, an energy-efficient bioethanol recovery process was created by combining extractive distillation with choline chloride/ethylene glycol (1:2) extraction pre-treatment. The created process's energy usage was 25% lower. In addition, the suggested procedure is more economical than the ones in use at the moment. While bigger equipment like distillation columns is utilized for commercial processes, analytical and litre-scale research work can extract bioethanol and biobutanol with modest distillation units and rotary evaporators (Obergruber et al. 2021a). To separate ethanol from water beyond the ethanol-water azeotrope, industrial processes often employ a combination of distillation columns and ethanol dewatering techniques, such as molecular sieves. This approach enables the recovery of ethanol with higher purity levels than what can be achieved through simple distillation alone. By utilizing molecular sieves, which are highly selective adsorbents capable of removing water molecules from the ethanol-water mixture, it becomes possible to further concentrate ethanol and obtain it in a purer form. This integrated method

is commonly employed in various industries where the production of high-purity ethanol is essential, including pharmaceuticals, beverages, and fuel ethanol production. Fermentation broths can be distilled using distillation columns and can give up to 95.6% ethanol concentration (ethanol-water azeotrope). To get >99% grade ethanol, dehydration strategy including vacuum distillation, pressure swing adsorption, membrane separation, and molecular sieves. By combining these techniques, industries can meet the stringent purity requirements for applications such as pharmaceuticals, beverages, and fuel ethanol production, ensuring the desired quality and performance of the final product. Molecular sieves are able to selectively adsorb water by taking advantage of the size difference between ethanol and water molecules. Due to their capability for continuous regeneration through drying, these dehydration techniques are preferred for ethanol purification, ensuring their cost-effectiveness and sustainability in industrial applications. One type of material used as a molecular sieve is zeolite.

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## 9.8 Technological Challenges, Limitations, and Advantages

Because of the different environmental conditions, efficiently producing and collecting seaweed on a wide scale might provide technical challenges. Seaweed's fermentable sugars can be difficult and expensive to extract. It is difficult to create and optimise microbes or enzymes that effectively digest seaweed sugars into butanol or ethanol. Large-scale seaweed farming, processing, and conversion technologies must be affordable in comparison to conventional fuel sources. It is crucial but difficult to establish a dependable and long-lasting supply chain for seaweed feedstock.

When compared to other biofuel sources, seaweed may have less sugar, which could have an impact on the total yield of bioethanol or biobutanol per unit. Certain technologies for converting seaweed into biofuels are however in the early phases of growth since they are neither cost-effective nor scalable. Seaweed farming on a large scale may have an impact on marine ecosystems, so environmental concerns must be carefully considered.

Seaweed does not compete with food crops for land resources because it is abundant and renewable. When compared to fossil fuels, bioethanol and biobutanol made from seaweed have the potential to drastically lower greenhouse gas emissions. These biofuels can be combined with traditional fuels or used as a drop-in substitute for petrol. Because seaweed grows without freshwater or fertile soil, it provides a sustainable substitute for fossil fuels. The generation of biofuel from seaweed can also provide useful byproducts like antioxidants, proteins, or fertiliser.

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## 9.9 Future Scope

Continued advancements in genetic engineering can lead to the development of microorganisms or enzymes that are more efficient in fermenting complex sugars present in third-generation feedstocks, improving yield and reducing processing

costs. Innovations in bioreactor design, fermentation techniques, and downstream processing could streamline production, making it more cost-effective and environmentally friendly.

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## 9.10 Conclusion

Research on macroalgae-based bioethanol and biobutanol technologies has increased with the goal of competing with or even replacing fossil fuels, given the commitment of macroalgae biomass as a feasible, perfect and inexhaustible biofuel source on a worldwide scale. Macroalgal biomass is still being developed for use in the synthesis of bioethanol, and the majority of the literature has only examined this topic in lab-scale studies. Future studies could concentrate on technological unfolding for genetic engineering, which will greatly increase the carbohydrate content and hence unwrap new options for productive industrial use. Furthermore, a high substrate-loading hydrolysis process and effective microbial utilization of reducing sugars are needed. Because it has intrinsic benefits over earlier generations, macroalgae biomass is currently a desirable renewable source for the creation of 3G bioethanol. The primary obstacle that could delay the market's adoption of macroalgae bioethanol and biobutanol longer than anticipated is its high cost of conversion. Consequently, increasing the efficiency of the bioethanol conversion process will be essential to establishing this new bioenergy source for commercial use. The synthesis of bioethanol and biobutanol from macroalgae may soon be one of the feasible methods if these technologies are further refined.

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# Harvesting Potential: Unlocking Value from Unexplored Biomass Resources

# 10

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## Abstract

This book chapter explores the frontier of using unexplored biomass resources to create value-added goods, explaining the opportunities and difficulties that come with this undertaking. The chapter looks at various biomass sources with an emphasis on optimising the potential of renewable resources. This chapter reviews the landscape of available biomass, ranging from agricultural leftovers to atypical sources like seaweed, and looks at new methods for turning these materials, especially seaweed into high-value products such as bioethanol and biobutanol. Exploring the intriguing field of bioethanol and biobutanol synthesis from seaweed biomass, this book chapter highlights the various production procedures, pretreatment techniques, and cost analyses. Seaweed biomass is a promising resource for the generation of sustainable biofuels due to its high carbohydrate content and quick growth. A range of methods are investigated for their potential to effectively convert seaweed components into sugars, which in turn produce bioethanol and biobutanol. These methods include enzymatic hydrolysis and fermentation. The chapter also examines the technological, environmental, and economic aspects influencing the feasibility of developing value-added products from unexplored biomass resources. This chapter provides researchers, policymakers, and industry stakeholders with a path for realising the full potential of renewable biomass for sustainable development by offering a thorough review of opportunities and obstacles.

## Keywords

Energy · Biomass · Biofuel · Circular economy

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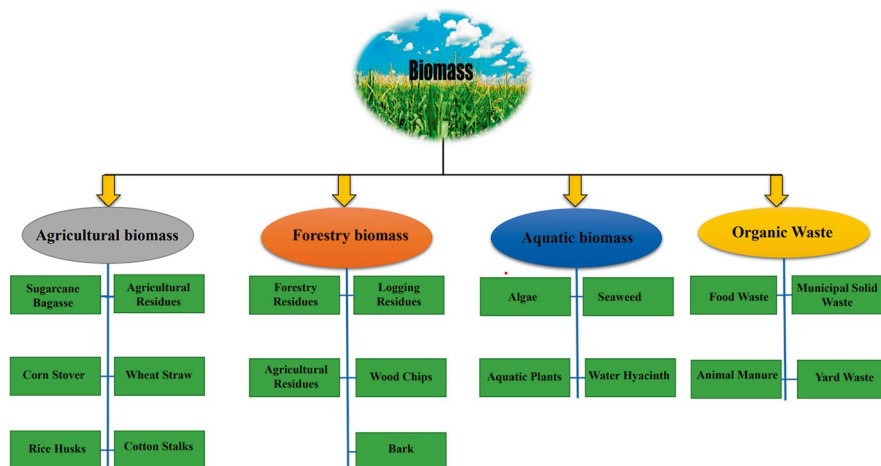
## 10.1 Introduction

Energy is a vital component of human civilisation that powers several economic sectors as well as our daily activities. Energy is necessary for the operation of modern society's homes, workplaces, transit networks, and several other technical advancements. It is the engine of social advancement, economic expansion, and rising living standards. The availability and effective use of energy resources have a significant influence on the prosperity and development of countries all over the world. It is difficult to exaggerate the significance of energy. It makes it possible for us to cook our food, light up our houses, and maintain our electronic connections. Energy is essential to industries to produce commodities, run machinery, and enable the production and distribution of goods and services. It is also regarded as an indicator of a nation's progress toward improved health and economic independence (Gong et al. 2023). Conventional energy and renewable energy are the two main types of energy sources that power our contemporary society. The term "conventional energy" describes the historical energy sources that have been in use for many years. Among these are fossil fuels, which include coal, oil, and natural gas. The remnants of extinct plants and animals that underwent millions of years of geological processes are what gave rise to them. Although conventional energy sources are essential for driving industrialisation and technological advancements, they have several serious disadvantages. It is generally accepted that fossil fuel is running out and cannot be replaced, even though the precise amount in existence at any given time is unclear. It makes sense to search for more renewable energy sources in light of these facts. One of the drawbacks of utilising fossil fuels is the release of carbon dioxide into the atmosphere from stored carbon in them, which has sparked worries about global warming. Furthermore, not all countries have equal access to fossil fuels, which makes many of them extremely dependent on imports (Luo et al. 2024). Renewable energy, on the other hand, is a cleaner and more sustainable substitute for traditional energy sources. On human timescales, naturally regenerating resources that are essentially limitless provide the basis for sustainable and renewable energy. Examples of renewable energy sources include geothermal, biomass, hydropower, wind, and solar energy. Renewable energy systems have a significantly lower environmental impact and produce nearly no greenhouse gases as compared to conventional energy sources. The growing worldwide need for energy, which is being caused by urbanisation, population expansion, and rising living standards in developing nations, is exacerbating the energy issue. As a result, there is an increasing need to diversify our energy sources and use sustainable substitutes that can fulfil demand without endangering the environment further.

Making the switch to renewable energy sources is essential to addressing these issues. Energy sources that naturally replenish themselves regularly are referred to as renewable energies. Thermal, photochemical, and photoelectric energy are among the sources that can be obtained straight from the sun. Alternatively, hydropower, wind, and the photosynthetic energy found in biomass can be used to indirectly extract solar energy. Further harming the globe are instances of other environmental motions and systems that can be utilised to generate renewable

energy, such as geothermal and tidal energy. Recent years have witnessed notable progress in the efficiency and cost-effectiveness of renewable energy systems. In addition to promoting energy security and independence, they may reduce greenhouse gas emissions and mitigate the consequences of climate change. We will examine the traits, advantages, difficulties, and potential applications of conventional and renewable energy sources in this investigation of energy. We will look at how conventional energy sources shaped our industrial civilisation and how urgently we must switch to renewable energy sources to slow down global warming and secure a sustainable future. Biomass energy is a substantial renewable resource that has the potential to make a major contribution to supplying the world's energy demands in a sustainable and ecologically friendly manner. The term "biomass renewable energy" describes energy produced from organic materials, including wood, plants, crop residues, and agricultural waste. Currently, 10–14% of the world's primary energy supply comes from renewable sources, with the transportation sector receiving about 3% of this total. But by 2050, it's expected that renewable energy will have contributed up to 30–40% (Kumar and Reddy 2022). Biomass is a resource that is both sustainable and adaptable, providing multiple pathways for conversion into energy that may be used (Kapoor et al. 2022). Renewable organic material derived from plants and animals is called biomass. The chemical energy that plants make during photosynthesis is stored in biomass. Various techniques can be used to convert biomass into liquid and gaseous fuels, or it can be burned directly for heating. The application of biomass provides a multitude of products with added value, benefiting the energy, chemical, materials, and agricultural sectors, among others. We may lessen our reliance on limited resources, promote economic growth, and lessen our negative environmental effects by turning biomass into biofuels, bio-based chemicals, bioplastics, and soil amendments. Let's now explore the wide range of biomass sources that support this sustainable paradigm. Waste management, industrial waste, animal waste, municipal solid waste, and sewage disposal are important biomass feedstocks that can be processed using the right technology to produce useful goods. These biomass sources offer distinct chances for resource recovery and exploitation, supporting the objectives of sustainable development and the circular economy.

The depicted Fig. 10.1 represents an array of unexplored biomass resources, each strand holding the potential for advancement and metamorphosis. In "Agricultural Biomass," the divided canvas, we see the golden tones of agricultural wastes, such as sugarcane bagasse, corn stover, rice husks, wheat straw, and cotton stalks. These materials are all set to become biofuels, biochar, and bioplastics, bringing significant value to what was previously considered waste. Next door, the world of "Forestry Biomass" mutters about forest floors covered in bark, sawdust, and wood chips, all of which are waiting to be alchemically reborn as wood pellets, biofuels, and raw materials for pulp and paper goods that will improve our lives and respect the forests from which they originate. Furthermore, promises of nutraceuticals, biofuels, and bioplastics abound in the aquatic depths of "Aquatic Biomass," where algae, seaweed, aquatic plants, and water hyacinth call, each wave carrying the potential to completely transform ecosystems and industries alike. Finally, food



**Fig. 10.1** Classification of untapped biomass resources

waste, yard waste, animal manure, and municipal solid waste congregates within the urban sprawl of “Organic Waste,” ready to transform into biogas, biofertilisers, and bioethanol, turning the tide of waste into a river of opportunity. The figure is a map and a muse in this complex dance of resource utilisation, pointing the way toward a future in which the untapped biomass richness not only maintains but also enhances our planet.

In recent years, the global demand for sustainable biofuels has surged, driven by concerns over climate change, energy security, and environmental sustainability. The reliance on fossil fuels, with its associated carbon emissions and environmental degradation, has spurred the search for renewable and environmentally friendly alternatives (Eloka-Eboka and Maroa 2023). Biofuels, derived from biomass sources such as crops, algae, and organic waste, have emerged as promising solutions to mitigate these challenges. However, the widespread adoption of biofuels faces hurdles, including competition with food production, land use conflicts, and limited feedstock availability (Sukhikh et al. 2023).

Traditional biofuel feedstocks, such as corn, sugarcane, and soybean, have limitations that hinder their scalability and sustainability. These limitations include the displacement of food crops, intensive land and water requirements, and concerns about deforestation and biodiversity loss (Kooren et al. 2023). As a result, there is a pressing need to explore alternative biomass sources that offer higher productivity, lower environmental impact, and reduced competition with food production. Seaweed, also known as macroalgae, has emerged as a promising alternative feedstock for biofuel production due to its unique characteristics and environmental benefits. Unlike terrestrial crops, seaweed cultivation does not require arable land or freshwater resources, as it can be grown in marine environments, including oceans, seas, and coastal areas (Dave et al. 2019). This aspect of seaweed cultivation

alleviates concerns about land use conflicts and competition with food crops, making it an attractive option for sustainable biofuel production (Sukhikh et al. 2023).

One of the most compelling features of seaweed biomass is its rapid growth and high productivity (Elshobary et al. 2021). Macroalgae are among the fastest-growing organisms on the planet, with growth rates that far surpass those of terrestrial crops. Some species of seaweed can double their biomass in a matter of days under optimal growing conditions, making them highly efficient carbon capture and biomass production systems (Elkatory et al. 2022). This rapid growth rate enables continuous harvesting and replenishment of seaweed biomass, ensuring a sustainable and renewable source of feedstock for biofuel production (Zakaria et al. 2023).

Moreover, seaweed biomass is rich in carbohydrates, particularly polysaccharides such as cellulose, hemicellulose, and alginates, which can be converted into fermentable sugars for biofuel production (Sunwoo et al. 2023). These polysaccharides serve as energy reserves for the seaweed and can be enzymatically hydrolysed into simple sugars suitable for fermentation (Zakaria et al. 2023). This abundance of fermentable sugars makes seaweed an attractive feedstock for the production of bioethanol and biobutanol, two promising biofuels with potential applications in transportation, energy generation, and industrial processes (Moenaert et al. 2023).

The environmental benefits of seaweed cultivation further enhance its appeal as a biofuel feedstock. Macroalgae play a crucial role in marine ecosystems, serving as habitat and food for various marine organisms, as well as contributing to nutrient cycling and carbon sequestration (Llano et al. 2023). Seaweed cultivation can also help mitigate ocean acidification by absorbing carbon dioxide from seawater during photosynthesis, thereby reducing carbon emissions and mitigating the impacts of climate change (Timung et al. 2021). In addition to its environmental benefits, seaweed cultivation offers opportunities for sustainable economic development and job creation, particularly in coastal communities and regions with limited arable land. The cultivation, harvesting, and processing of seaweed biomass can generate income and employment opportunities, while also promoting sustainable resource management practices and supporting local economies (Zakaria et al. 2023).

Overall, the production of bioethanol and biobutanol from seaweed biomass holds immense potential to address the growing demand for sustainable biofuels while mitigating environmental impacts associated with conventional fuel sources. By harnessing the rapid growth, high carbohydrate content, and environmental benefits of seaweed biomass, researchers, policymakers, and industry stakeholders can work together to develop a robust and sustainable biofuel sector that contributes to a cleaner, greener, and more sustainable energy future.

### **Agricultural Biomass**

Agricultural biomass is cultivated through a series of practices encompassing crop cultivation and livestock farming. After a period of seed sowing, plant maintenance including fertiliser, irrigation, pest control, and mature crop harvesting, crop cultivation culminates in the harvesting of finished products. The rearing of animals for meat, milk, eggs, or wool, on the other hand, is known as livestock farming, and it calls for meeting the needs of the animals' housing, well-being, and diet. Animal

dung, food processing byproducts, crop leftovers such as straw, husks, and stems, and organic wastes are among the several organic materials that make up agricultural biomass in agricultural operations. Various conversion techniques, such as biochemical or thermochemical conversion, biorefining, or biomaterial synthesis, are methods that can be applied to increase the value of agricultural biomass that is underutilised. These processes help turn agricultural biomass in its basic form into high-value products like biofuels, biobased products, renewable energy, and bioproducts (Kapoor and Rafatullah 2022). Increasing the value of untapped agricultural biomass is important because it can increase farmers' income, cut down on waste and dependence on limited resources, lessen the impact on the environment, and promote rural development by generating new jobs and industries.

A crucial step in adding value to agricultural products is converting raw materials into more usable forms. Even though many raw materials are valuable in their natural condition, processing, and refinement are usually necessary to add value. For example, field maize adds value when it is processed and fed to livestock because it becomes meat or animal protein. In a similar vein, wheat turned into flour is a product with additional value. To optimise the potential advantages from agricultural goods, value-added initiatives must be identified and implemented with careful consideration of the necessary investments in processing, marketing, and research.

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## 10.2 Sugarcane Bagasse

A byproduct of the sugarcane industry, sugarcane bagasse is created when the stalks are crushed to release the juice needed to generate sugar. Bagasse is the term for the fibrous material that remains after the juice has been extracted. Because of its relatively high energy content, biodegradability, and abundance, this substance has drawn a lot of interest as a biomass source for the production of renewable energy, among other applications.

The main components of sugarcane bagasse are cellulose, hemicellulose, and lignin, the amounts of which might differ depending on the type of sugarcane, the environment in which it is grown, and the methods used for processing. About 45–55% cellulose, 20–25% hemicellulose, and 18–24% lignin is often found in bagasse. Bagasse is a good option for a variety of bio-based goods and bioenergy because of these factors:

*Cellulose:* Useful for making paper, bioethanol, and other items made from cellulose.

*Hemicellulose:* It can be transformed into various biochemicals or into xylitol, a sugar alcohol that is sweetened.

*Lignin:* Can be used as a combustible ingredient to generate heat and power or as a binder in the manufacturing of biodegradable plastics.

### 10.3 Thermochemical Conversation

Various techniques are available for utilising biomass resources' energy potential through thermochemical conversion processes. Gasification is a process that produces a synthesis gas that is high in carbon monoxide, hydrogen, and methane by carefully breaking down biomass at high temperatures and low oxygen levels. Using high temperatures and pressures in an aqueous environment, hydrothermal carbonisation transforms biomass into hydrocar, a solid carbonaceous substance that can be used as a soil amendment and to produce sustainable fuel. A sustainable substitute for fossil fuels, hydrothermal liquefaction turns wet biomass into bio-crude oil by applying pressure and heat. By burning biomass at high temperatures and with an abundance of oxygen, incinerators produce thermal energy and reduce the volume of waste produced. High-temperature, oxygen-free pyrolysis produces bio-oil, syngas, and char that can be used as biofuel. The thermochemical conversation is described in Fig. 10.2.

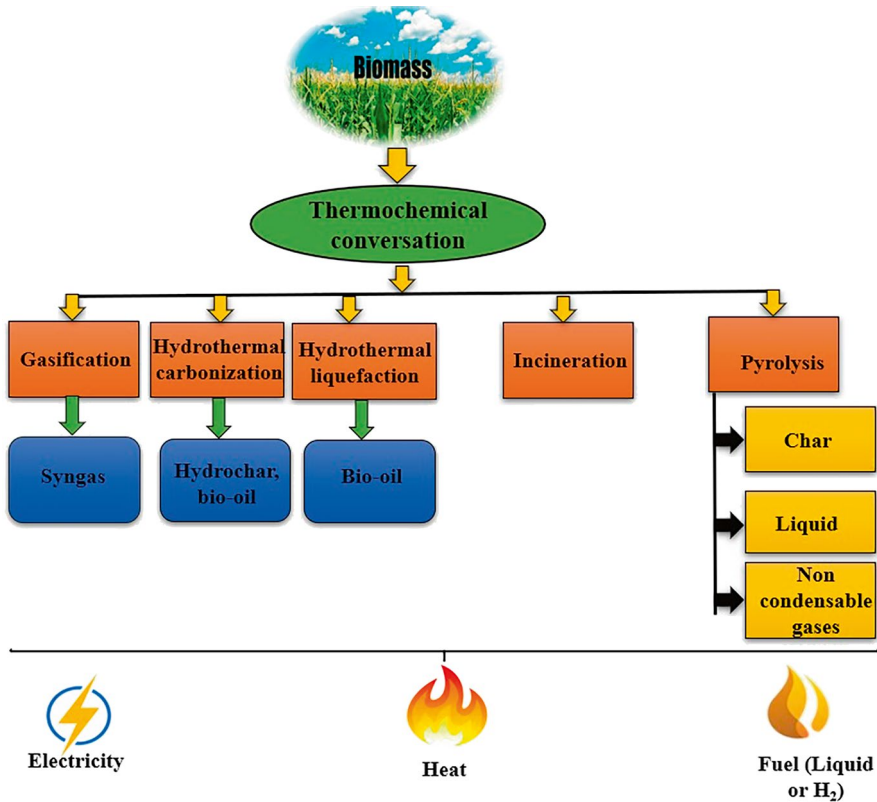
**Gasification** Gasification is a thermochemical process that produces syngas from biomass in a regulated atmosphere with a low oxygen content. At high temperatures, biomass undergoes chemical processes that produce gases like methane ( $\text{CH}_4$ ), hydrogen ( $\text{H}_2$ ), and carbon monoxide ( $\text{CO}$ ). Syngas is used as a fuel for factories, and power plants.

**Hydrothermal Carbonisation** Hydrothermal Carbonization (HTC) is a process that converts biomass into hydrocar at moderate temperatures and high pressure in an aqueous environment. Biomass produces hydrocar through processes including hydrolysis, dehydration, decarboxylation, and polymerisation. Hydrocar can be used as a solid fuel, soil amendment, or to produce activated carbon.

**Hydrothermal Liquefaction** Using a catalyst, hydrothermal liquefaction (HTL) transforms wet biomass into bio-crude oil at high temperatures and pressures. Transportation fuels like biodiesel or sustainable diesel can be produced from this crude through refinement.

**Incineration** *Incineration* is a common waste management technique that reduces biomass to ash, flue gases, and heat energy by burning it at high temperatures with extra oxygen.

**Pyrolysis** Biomass is pyrolysed at high temperatures without oxygen to produce gaseous products, liquid bio-oil, and solid char. Although char and syngas are utilised for energy or additional processing and provide a variety of conversion choices



**Fig. 10.2** Thermochemical conversion of biomass

while reducing emissions, bio-oil is a lucrative biofuel and feedstock for chemicals and materials.

## 10.4 Types of Seaweed

### 10.4.1 Red Seaweed (Rhodophyceae)

Red seaweeds, classified under the class Rhodophyceae, are renowned for their bioactive compounds, including polysaccharides like carrageenan, agar, and cellulose. In almost all red algae, the heteroside floridoside [-D-galactopyranosyl-(1–2)-glycerol], the sugar component that builds the florid starch(semi-amylopectin), is their primary photosynthetic storage molecules(Kongjan et al. 2021). Apart from floridoside, some species also contain other carbohydrates such as mannitol (Caloglossa,Ceramiales), sorbitol, digeneaside (Osman et al. 2023). The carbohydrate content in red seaweeds varies widely, ranging from 27% for *E. cottonii* to 66% for *G. amansii* (Offei et al. 2018). However, the most significant

polysaccharides in red macroalgae from a commercial standpoint are galactans, which include carrageenan (up to 75% dw) or agar (up to 52% dw) (Osman et al. 2023). Carrageenan, a linear sulfated galactan, and agar, composed of hydrophilic galactans, are extracted from carrageenophytes and agarophytes, respectively (Gottumukkala et al. 2019; Offei et al. 2018). As another major constituent, agar is made up of alternating D-galactose and L-galactose with scarce sulfations (Hong et al. 2020).

#### 10.4.2 Brown Seaweed (Phaeophyceae)

Brown seaweeds, belonging to the class Phaeophyceae, are characterised by their carbohydrate-rich composition, which includes polysaccharides such as laminarin, mannitol, cellulose, alginate, and fucoidan. The carbohydrate content in brown seaweeds varies from 40% to 64%, with species like *S. fulvellum* and *L. digitata* (Offei et al. 2018). Laminarin, a  $\beta$ -1,3 glucan, serves as the primary storage polysaccharide in brown seaweeds, while mannitol, derived from mannose, functions in osmoregulation (Sudhakar et al. 2020). Laminarin ( $-1, 3$ -glucans) is the unique polysaccharide in brown algae, with mannitol (M-chains) or glucose (G-chains) attached to the reduction end (Osman et al. 2023). This polysaccharide accounts for up to 30–35% dw in brown algal biomass and serves as the primary storage polysaccharide in brown seaweeds, while mannitol, derived from mannose, functions in osmoregulation (Offei et al. 2018). Alginate, a major component of the cell wall, comprises linear co-polymers of guluronic and mannuronic acids, essential for maximising bioethanol recovery during fermentation (Sudhakar et al. 2020). Fucoidans, rich in L-fucose and sulfated ester groups, exhibit various beneficial biological and pharmacological properties, including antioxidant and anticoagulant activities. Brown seaweeds also contain cellulose, contributing to their structural integrity (Nagula et al. 2022).

#### 10.4.3 Green Seaweed (Chlorophyceae)

Green seaweeds, belonging to the class Chlorophyceae, encompass a diverse group of macroalgae rich in carbohydrates, polysaccharides, and other bioactive compounds. The carbohydrate content in green seaweeds varies, with species such as *C. lentillifera* containing approximately 45% and *C. fragile* containing up to 59% carbohydrates (Offei et al. 2018). Starch ( $-1,4$ -glucan) is a polysaccharide found in green algae as a storage molecule in a relatively sparse amount of 1–4%, while the content of lipids is up to 6% (Kongjan et al. 2021). Green macroalgae also contain cellulose and sucrose (Nagula et al. 2022; Kongjan et al. 2021) and may also contain other carbohydrates such as ulvan. The latter is a water-soluble polysaccharide composed of various oligosaccharide units, including L-rhamnose-3-sulfate and D-xylose-2-sulfate, along with uronic acids, found in relatively high amounts in *Ulva* (8–29% dw) (Offei et al. 2018). Starch and cellulose, also abundant in green

seaweeds, differ in their configuration, with cellulose featuring  $\beta$ -1,4-glycosidic linkages and forming a stable crystalline structure, while starch exhibits an open, helical configuration, making it more susceptible to enzymatic breakdown (Offei et al. 2018).

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## 10.5 Pretreatment of the Feed Materials

The pretreatment of macroalgae is a crucial step in bioprocessing for bioethanol production. The macroalgal cell wall comprises two layers: external (primary) and internal (secondary). Pretreatment aims to break down the outer cell wall, releasing biomolecules like cellulose and complex sugar polymers, making them accessible for bioethanol production. The internal cell wall mainly consists of hemicellulose, pectin, and sulfated sugar polymers (Dave et al. 2019). Pretreatment involves physical, chemical, biological, or integrated processes to expose the cell constituents and cell wall materials of feedstock (Ramachandra and Hebbale 2020). Physical pretreatment involves washing, drying, and milling steps to remove impurities, reduce water content, and achieve size reduction for the size of feedstock to increase surface area for better transport of acid/base catalysts, enzymes, and steam to the fibres (cellulose) (Dave et al. 2019). Chemical pretreatment includes methods like diluting acid, alkaline, ammonia, organic solvent, and other chemicals to solubilise hemicellulose and expose cellulose fibres. Mild alkali treatment with hydroxyl derivatives of sodium and potassium salts is commonly used for red algae. Acid pretreatment typically uses dilute sulfuric acid for all classes of macroalgae (Ramachandra and Hebbale 2020). Biological pretreatment involves microorganisms rich in cellulase enzymes to degrade biomass and release sugars. Enzymatic pretreatment utilizes commercial enzymes like cellulase, amylase, and agarase to hydrolyse complex macroalgal polysaccharides into monomeric reducing sugars (Ramachandra and Hebbale 2020). Integrated pretreatment combines various processes like an acid-catalysed steam explosion, ammonium fibre explosion (AFEX), and acid-pretreated enzyme hydrolysis (Ramachandra and Hebbale 2020). The efficiency of pretreatment processes depends on factors such as cellulose crystallinity, hemicellulose fraction, and accessible surface area for enzymatic hydrolysis (Ramachandra and Hebbale 2020).

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## 10.6 Production Process

### 10.6.1 Hydrolysis Techniques

Various hydrolysis techniques have been explored for the efficient conversion of seaweed biomass into fermentable sugars, including dilute alkaline thermal hydrolysis, enzymatic hydrolysis, and dilute acid thermal hydrolysis.

**Enzymatic Hydrolysis** Enzymatic hydrolysis, employing cellulases and other enzymes, offers high conversion efficiency and minimal byproduct formation. Cellulases, including endoglucanases, exoglucanases, and  $\beta$ -glucosidases, target cellulose and other polysaccharides in seaweed biomass, yielding simple sugars suitable for fermentation (Moenaert et al. 2023). Enzymatic hydrolysis presents advantages in high sugar yields but requires pH optimisation and entails high production costs and long reaction times (Offei et al. 2018). Enzymatic hydrolysis, compared to acid hydrolysis, offers the advantages of lower energy requirements and milder environmental conditions. Optimum conditions for cellulase and xylanase enzymes, key players in saccharification, include temperatures of 40–50 °C and pH 4–5 (Offei et al. 2018). Enzymatic hydrolysis boasts low toxicity, utility costs, and corrosion, with no inhibitory by-products formed. However, cellulase enzymes exhibit high substrate specificity, targeting cellulose and hemicellulose bonds (Elshobary et al. 2021; Osman et al. 2023). Various microbial species, including bacteria like *Clostridium* and fungi like *Trichoderma* and *Aspergillus*, produce cellulase and hemicellulose enzymes. *Trichoderma*, known for its cellulase production, lacks the  $\beta$ -glucosidase activity efficiently provided by *Aspergillus*. Combining *Trichoderma* cellulase with *Aspergillus*  $\beta$ -glucosidase has shown improved hydrolysis yields (Sarkar et al. 2012).

**Dilute Acid Thermal Hydrolysis** Dilute acid thermal hydrolysis, utilizing strong acids like  $H_2SO_4$  and HCl, is extensively used in seaweed bioethanol research due to its effectiveness, speed, applicability, and cost-efficiency compared to enzymatic (Dave et al. 2019). Previous research has suggested acid hydrolysis as an effective method for breaking down carbohydrates in seaweeds such as *Sargassum* sp. and *Laminaria japonica*. The hydrolysis conditions used resulted in a maximum hydrolysis efficiency of 57.3% (Hong et al. 2020). Furthermore, higher levels of reducing sugars were observed after hydrolysis of lipid-free biomass compared to whole biomass, likely due to increased cell wall permeability following lipid extraction. This finding is supported by previous research indicating higher reduced sugar content in spent seaweeds after agar and alginate production compared to whole biomass, suggesting that lipid extraction enhances sugar release (Elshobary et al. 2021). However, it produces inhibitors such as 5-HMF, furfural, and levulinic acid, which can hinder fermentation. Methods, like activated carbon filtration and yeast strains capable of metabolising inhibitors, mitigate these effects to some extent. Despite its efficiency and economics, challenges remain regarding the toxicity of acid catalysts and the sustainability of the process (Offei et al. 2018).

**Dilute Alkaline Thermal Hydrolysis** Dilute alkaline thermal hydrolysis serves as an alternative to dilute acid hydrolysis, employing a base catalyst instead of acid. However, challenges arise due to the requirement for higher base concentrations and the formation of gel-like structures at elevated temperatures, hindering fermentation. The biorefinery approach, involving the extraction of hydrocolloids before

hydrolysis, mitigates these challenges to some extent. Despite potential advantages, dilute alkaline hydrolysis yields degradation products and fermentation inhibitors, necessitating further investigation for its viability (Offei et al. 2018).

### 10.6.2 Fermentation Strategies

Two primary fermentation strategies are commonly employed in seaweed bioethanol production: Separate Hydrolysis and Fermentation (SHF) and Simultaneous Saccharification and Fermentation (SSF).

**Separate Hydrolysis and Fermentation (SHF)** SHF involves completing the hydrolysis process before introducing fermenting organisms. This approach allows for optimisation of conditions for both hydrolysis and fermentation. SHF has been applied effectively in various studies, yielding significant ethanol concentrations from seaweed biomass (Kongjan et al. 2021). Macroalgal biomass contains various types of polysaccharides, primarily composed of glucose, such as cellulose, starch, floridean starch, and laminarin, depending on the type of seaweed. Additionally, non-glucans like agar, carrageenan, and alginate are present. To enhance ethanol production, both glucans and non-glucans need to be hydrolyzed, followed by fermentation of the resulting sugars (Sunwoo et al. 2023). Various microorganisms, including yeast, bacteria, and fungi, ferment these sugars to produce ethanol.

The fermentation process for bioethanol production from macroalgal biomass relies on selecting appropriate yeast strains and operational conditions, influenced by factors like the Crabtree effect and strain growth kinetics (Moenaert et al. 2023). Engineered strains of bacteria and yeast are developed to enhance bioethanol yield, with some strains capable of switching between semi-anaerobic and aerobic conditions. New methods like SSF and SSCF are utilized alongside conventional SHF to improve bioconversion (Dave et al. 2019). *Saccharomyces cerevisiae* is commonly used due to its ability to readily ferment glucose, although it cannot utilize xylose efficiently (Melendez et al. 2022). Research focuses on isolating wild yeast strains capable of fermenting both hexose and pentose sugars. Bacteria and yeast are preferred for xylose fermentation over fungi due to their faster fermentation rates (Gottumukkala et al. 2019). Common yeast strains include *Saccharomyces cerevisiae*, *Pichia angophorae*, and *Pichia stipitis*, with a growing focus on halotolerant marine yeast strains to eliminate desalination steps. Studies aim to isolate wild-type or genetically modified yeast strains capable of fermenting various monomeric sugars from macroalgal hydrolysate (Dave et al. 2019). Fermentation of laminarin and mannitol from *Laminaria hyperborea* using specific microorganisms like *Pichia angophorae* and *Zymobacter palmae* has shown promising ethanol yields. Additionally, mannitol fermentation by *E. coli* KO11 and glucuronic acid fermentation by *Pachysolen tannophilus* and *E. coli* have been attempted. Bioethanol

production from various forms of macroalgal biomass, including wet, dried, and residues after hydrocolloid extraction, has been explored, with residues rich in cellulose being utilized for ethanol production (Ramachandra and Hebbale 2020).

**Simultaneous Saccharification and Fermentation (SSF)** SSF integrates hydrolysis and fermentation processes, utilizing enzymes and fermenting organisms simultaneously. Although cost-effective and time-saving, SSF requires careful optimization of conditions due to differences in temperature requirements for hydrolysis and fermentation. SSF has demonstrated higher efficiency compared to SHF in some studies (Nagula et al. 2022).

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## 10.7 Bioethanol and Biobutanol Recovery

Bioethanol recovery processes are crucial for its utilisation as fuel, primarily in engines and as a fuel additive. Following fermentation, bioethanol is refined through distillation and dehydration methods. Distillation, the main recovery process, involves separating ethanol from the fermentation broth, which comprises ethanol, solid biomass residue, residual sugars, enzymes, and fermenting organisms (Melendez et al. 2022). Distillation can be conducted using simple units like rotary evaporators for small-scale research or larger distillation columns for commercial purposes. Commercial processes often combine distillation columns with ethanol dewatering techniques, such as molecular sieves, to surpass the ethanol-water azeotrope. Distillation columns can achieve ethanol concentrations of up to 95.6%, after which dehydration methods like vacuum distillation, pressure swing, membranes, or molecular sieves are employed to obtain >99% pure ethanol (Cooper et al. 2020). Molecular sieves, such as zeolite, selectively adsorb water over ethanol based on molecular size, offering advantages in dehydration and continuous regeneration for reuse (Offei et al. 2018). Muhammad conducted a study comparing different ethanol production methods and found that fermenting food waste without enzymes and employing a two-step distillation system yielded the most economical results. This method achieved the lowest ethanol minimum selling price of \$2.41 per gallon (\$0.64 per litre). Although the two-column distillation used in this process is a common practice in the ethanol industry, it is considered energy-intensive, accounting for at least 40% of total energy consumption in ethanol production. To address this, alternative methods like reverse osmosis and membrane distillation have been proposed (Cooper et al. 2020). Membrane distillation (MD) has gained attention as an emerging technology for ethanol separation due to its efficiency, ease of operation, and low energy requirements. MD allows separation below the average boiling point of the solution and offers flexibility based on membrane selectivity and operational conditions. Previous studies have shown MD as a viable alternative for ethanol separation from various feedstocks, suggesting its potential to enhance process economics (Muhammad and Rosentrater 2020).

## 10.8 Prospects and Challenges of Bioethanol and Biobutanol Production from Seaweed

### Renewable Energy Source

Bioethanol and biobutanol derived from seaweed offer a renewable alternative to fossil fuels, presenting a significant opportunity to mitigate climate change and reduce dependence on finite resources. Unlike fossil fuels, which release carbon dioxide stored underground into the atmosphere when burned, seaweed-based biofuels recycle atmospheric carbon dioxide through photosynthesis, resulting in a closed carbon cycle. This carbon-neutral characteristic makes bioethanol and biobutanol from seaweed an attractive option for reducing greenhouse gas emissions and combating climate change. Additionally, seaweed cultivation for biofuel production can play a role in carbon sequestration, as seaweed absorbs CO<sub>2</sub> from seawater during growth, effectively removing carbon from the environment and storing it in biomass. Furthermore, bioethanol and biobutanol derived from seaweed offer a sustainable solution to meet energy demands while reducing reliance on finite fossil fuel reserves. Seaweed is a renewable resource that can be cultivated in marine environments using minimal land and freshwater resources. Its rapid growth rates, high biomass yields, and ability to thrive in diverse aquatic ecosystems make seaweed a promising feedstock for biofuel production. By harnessing the energy potential of seaweed, bioethanol and biobutanol production can contribute to energy security, resilience, and sustainability on a global scale (Kurniawan et al. 2023).

### Diversification of Energy Feedstocks

Seaweed-based biofuel production presents an opportunity to diversify energy feedstocks, reducing dependence on traditional crops such as corn or sugarcane for biofuel production. Unlike conventional biofuel feedstocks, which compete with food crops for arable land and freshwater resources, seaweed cultivation can occur in marine environments using seawater and coastal areas unsuitable for agriculture. This diversification enhances energy security by reducing the vulnerability of biofuel supply chains to factors such as weather-related crop failures, price volatility, and geopolitical tensions. Moreover, seaweed cultivation offers a sustainable alternative to land-based biomass feedstocks, helping to alleviate pressure on terrestrial ecosystems and promote land conservation. Additionally, seaweed-based biofuels can contribute to the development of a more sustainable and resilient economy by utilizing underutilised marine resources for energy production. Seaweed cultivation has the potential to create new opportunities for coastal communities and industries, stimulating economic growth, job creation, and innovation. By tapping into the vast potential of seaweed biomass, bioethanol, and biobutanol production can diversify the biofuel market, improve resource efficiency, and promote the transition to a more sustainable and environmentally responsible energy system (Tawfik et al. 2022).

### **Carbon Sequestration and Environmental Benefits**

Seaweed cultivation for biofuel production offers significant environmental benefits beyond renewable energy generation, including carbon sequestration and ecosystem restoration. Seaweed has a remarkable capacity to absorb carbon dioxide (CO<sub>2</sub>) from seawater during photosynthesis, effectively sequestering carbon in its biomass. As a result, large-scale seaweed cultivation can help mitigate ocean acidification, a process driven by the absorption of excess atmospheric CO<sub>2</sub> by the oceans, which poses threats to marine ecosystems and biodiversity. By removing CO<sub>2</sub> from seawater, seaweed cultivation not only reduces the acidity of marine environments but also enhances water quality and promotes the growth of calcifying organisms such as corals, shellfish, and phytoplankton. Furthermore, seaweed cultivation can provide additional ecosystem services such as nutrient cycling, habitat creation, and coastal protection. Seaweed acts as a natural biofilter, absorbing excess nutrients such as nitrogen and phosphorus from seawater, thereby reducing nutrient pollution and preventing harmful algal blooms. Additionally, seaweed beds serve as vital habitats and nursery grounds for a diverse array of marine species, including fish, invertebrates, and marine mammals. The presence of seaweed can stabilise coastal sediments, mitigate shoreline erosion, and provide coastal protection against storm surges and wave action, enhancing the resilience of coastal ecosystems and communities to climate change impacts (Duan et al. 2022).

### **Value-Added Products and Circular Economy**

Seaweed-based biofuel production can be integrated into a circular economy model, where waste streams and byproducts from biofuel production are valorised to generate additional revenue streams and minimise waste generation. Seaweed biomass contains valuable components such as proteins, lipids, carbohydrates, and bioactive compounds, which can be extracted and utilized for various applications in food, feed, pharmaceuticals, cosmetics, and bioplastics industries. For example, protein-rich seaweed biomass can be processed into animal feed or human food products such as seaweed snacks, supplements, or plant-based meat alternatives. Similarly, seaweed oils can be extracted and refined for use in cosmetics, nutraceuticals, or bio-based lubricants and chemicals (Duan et al. 2022). Moreover, seaweed-derived biofuel production generates co-products and byproducts such as biochar, biofertilisers, and biogas, which can be utilized to enhance soil health, agricultural productivity, and waste management practices. Biochar produced from seaweed residues can improve soil fertility, water retention, and carbon sequestration in agricultural soils, contributing to climate change mitigation and sustainable land management. Likewise, biofertilizers derived from seaweed biomass can provide essential nutrients and beneficial microorganisms to enhance crop yields and soil health, reducing reliance on synthetic fertilisers and minimising nutrient runoff into waterways. By maximising the value of seaweed biomass and byproducts, seaweed-based biofuel production can create a closed-loop system that promotes resource efficiency, environmental sustainability, and economic prosperity within coastal communities and beyond (Kumar and Verma 2021).

### **Rural Development and Job Creation**

Seaweed cultivation and biofuel production have the potential to stimulate rural economies and create job opportunities, particularly in coastal communities where traditional industries such as fishing or agriculture may be declining. Establishing seaweed farms and biofuel processing facilities generates employment along the entire value chain, from farm workers and harvesters to technicians, engineers, and managers involved in processing, logistics, and marketing. The labour-intensive nature of seaweed cultivation, particularly in small-scale or artisanal farming operations, provides job opportunities for residents, including women, youth, and marginalised communities, thereby contributing to poverty alleviation and social inclusion. Additionally, the development of seaweed-based biofuel industries can diversify local economies, reduce dependence on single industries or income sources, and enhance socioeconomic resilience to external shocks such as climate change, market fluctuations, or natural disasters. Furthermore, seaweed cultivation can provide alternative livelihoods for coastal communities facing challenges such as overfishing, declining fish stocks, or environmental degradation. By tapping into the potential of marine resources for sustainable energy production, seaweed-based biofuel projects can empower communities to utilize their natural assets in innovative and environmentally responsible ways. Engaging local stakeholders in the planning, implementation, and management of seaweed cultivation and biofuel production initiatives fosters community ownership, builds social capital, and strengthens resilience to external pressures. Overall, the development of seaweed-based biofuel industries holds promise for promoting rural development, creating green jobs, and improving livelihoods in coastal areas around the world (Duan et al. 2022).

### **Technological Innovation and Collaboration**

The development of seaweed-based biofuel technologies fosters innovation and collaboration among researchers, industry stakeholders, and government agencies, driving technological advancements and knowledge transfer across sectors. Research and development initiatives aimed at improving seaweed cultivation techniques, biomass conversion processes, and product development strategies stimulate innovation and create opportunities for technology transfer and commercialisation. Interdisciplinary collaborations between biologists, engineers, chemists, and economists facilitate the integration of diverse expertise and perspectives, leading to holistic solutions to complex challenges in seaweed-based biofuel production. Moreover, public-private partnerships, industry-academic collaborations, and knowledge-sharing platforms promote the exchange of best practices, data, and resources, accelerating the development and deployment of seaweed-based biofuel technologies. Additionally, the development of seaweed-based biofuel industries can drive demand for innovative technologies and equipment, spurring investment in research, development, and manufacturing of new technologies. For example, advancements in seaweed cultivation systems, bioreactor design, algae harvesting techniques, and biomass processing technologies contribute to increased efficiency, scalability, and cost-effectiveness of seaweed-based biofuel

production. Furthermore, collaborative research projects and technology transfer initiatives facilitate the transfer of knowledge and expertise from research institutions to industry stakeholders, supporting the scaling up and commercialisation of seaweed-based biofuel technologies. By fostering a culture of innovation, collaboration, and knowledge exchange, the development of seaweed-based biofuel industries can catalyse technological progress, economic growth, and sustainability in the bioenergy sector (Velvizhi et al. 2022).

### **Complexity of Seaweed Biomass**

Seaweed biomass is made up of a wide variety of polysaccharides, proteins, lipids, colours, and minerals, making it a very complex and heterogeneous substance. Because each component has unique chemical structures and characteristics, processing seaweed biomass is difficult. Biochemical makeup might vary throughout seaweed species and even within the same species, making biomass conversion plans more difficult to implement. Furthermore, the complexity is increased by the structural elements found in seaweed cell walls, such as cellulose, hemicellulose, and alginate, which need certain pretreatment techniques to release sugar for fermentation. Furthermore, a variety of factors, including species, geographic location, seasonal variations, and growing strategies, can have a substantial impact on the biochemical composition of seaweed biomass. Because of this heterogeneity, choosing and characterising seaweed feedstocks carefully is necessary to maximise the generation of biofuels. The challenge for researchers is to create customised processing plans that can manage the varied composition of seaweed biomass while optimising biofuel output and preserving process efficiency (Awasthi et al. 2023; Duan et al. 2022; Kurniawan et al. 2023; Naveen et al. 2023; Song et al. 2021; Tawfik et al. 2022; Velvizhi et al. 2022).

### **Pretreatment Limitations**

Scholars are examining diverse methodologies to enhance the efficiency of fermentation in the manufacture of biofuel derived from seaweed. Microbial strain engineering is one tactic used to improve substrate consumption and inhibitor tolerance. Microbial strains can be modified genetically or through adaptive evolution to create enzymes that are more resistant to inhibitors or to use metabolic pathways that avoid stages that are vulnerable to inhibitors. Additionally, by utilizing the synergistic interactions between several microorganisms to increase fermentation robustness and productivity, mixed microbial cultures or consortia may provide benefits over single-strain fermentations. To clarify complicated microbial dynamics, modern analytical approaches and computer modelling are necessary for comprehending and optimizing microbial interactions within these coalitions. To get over these restrictions, scientists and engineers are investigating cutting-edge pretreatment techniques including enzyme treatments, microwave-assisted pretreatment, and ultrasonic pretreatment. With the least amount of energy and environmental impact possible, these techniques seek to increase the effectiveness of the carbohydrate extraction process from seaweed biomass. Optimizing pretreatment conditions for seaweed biomass is still a difficult task, nevertheless, because different seaweed

species and processing conditions call for distinct techniques due to the complex structure and varied content of seaweed cell walls. In addition, it is imperative to thoroughly assess the scalability and cost-effectiveness of innovative pretreatment techniques to guarantee their pragmatic use in extensive biofuel manufacturing operations.

### **Fermentation Efficiency**

Microorganisms that can metabolise seaweed-derived sugars must be active for these sugars to be fermented into biofuels like bioethanol and biobutanol. On the other hand, inhibitory substances that can obstruct microbial development and fermentation efficiency are frequently present in seaweed hydrolysates. Furfurals, phenolics, organic acids, and salts are examples of these inhibitors; they can cause cellular disruption, stop the functioning of certain enzymes, and lessen the survival of microorganisms that ferment. Therefore, methods to lessen the impact of these inhibitors and improve microbial tolerance are needed to achieve high fermentation yields and productivity from seaweed hydrolysates. Scholars are examining diverse methodologies to enhance the efficiency of fermentation in the manufacture of biofuel derived from seaweed. Microbial strain engineering is one tactic used to improve substrate consumption and inhibitor tolerance. Microbial strains can be modified genetically or through adaptive evolution to create enzymes that are more resistant to inhibitors or to use metabolic pathways that avoid stages that are vulnerable to inhibitors. Additionally, by utilizing the synergistic interactions between several microorganisms to increase fermentation robustness and productivity, mixed microbial cultures or consortia may provide benefits over single-strain fermentations. To clarify complicated microbial dynamics, modern analytical approaches and computer modelling are necessary for comprehending and optimizing microbial interactions within these coalitions.

### **Microbial Tolerance to Inhibitors**

Creating microbial strains that are more resistant to the inhibitors found in seaweed hydrolysates is essential to increasing the yields of biofuel and the efficiency of fermentation. Finding or creating microbes with strong resistance to a variety of inhibitors; however, it is a difficult task. Microorganisms have intricate and diverse methods for tolerance to inhibitors, which include modifications to membrane composition, efflux pump activity, metabolic pathways, and stress response systems. Furthermore, the presence of certain inhibitors in seaweed hydrolysates may affect the efficacy of microbial tolerance mechanisms, emphasising the necessity for customised strategies to improve tolerance in various fermentation circumstances. To create microbial strains with improved inhibitor tolerance, scientists are combining techniques from systems biology, adaptive laboratory evolution, and genetic engineering. To increase the expression of stress response genes or metabolic pathways involved in detoxification and inhibitor tolerance, genetic manipulation approaches such as gene deletion, gene overexpression, and pathway optimization can be applied. By exposing microbial populations to extended selective pressure in the presence of inhibitors, adaptive laboratory evolution enables natural selection to

prefer mutants with increased tolerance. Furthermore, the rational design of modified microbial strains can be guided by systems biology techniques like transcriptomics, metabolomics, and flux analysis, which can shed light on the molecular pathways behind inhibitor tolerance. To overcome obstacles to fermentation efficiency in the manufacture of seaweed-based biofuel, interdisciplinary cooperation, and creative approaches are necessary to achieve broad-spectrum inhibitor tolerance in microbial hosts, which continues to be a tough task.

### **High Production Costs**

The commercial viability of producing biofuel from seaweed is severely hampered by the production expenses related to seaweed cultivation, harvesting, and processing. Seaweed farming necessitates large initial infrastructure expenditures, such as those in anchoring systems, floating platforms, and offshore cultivation facilities, in addition to continuous operating costs for manpower, upkeep, and monitoring. The labour-intensive process of harvesting biomass from seaweed may call for specific tools and vessels, which raises the cost of production. Moreover, energy-intensive processes including pretreatment, hydrolysis, fermentation, and product separation are included in the processing of seaweed, which raises the cost of production overall. Furthermore, production efficiency and cost-effectiveness may be impacted by the variability in seaweed biomass output and quality, which is determined by variables like species selection, culture conditions, and seasonal fluctuations. Researchers and business participants are investigating ways to lower the cost of producing seaweed-based biofuel and increase the overall viability of the project economically. These include advancements in farming practices including offshore farming, integrated multi-trophic aquaculture (IMTA), and automated harvesting technology that raise biomass yield and quality while lowering operating costs. Furthermore, the goal of advances in biomass processing technologies is to lower energy consumption and increase process efficiency. Examples of these technologies include integrated biorefinery concepts, enzymatic pretreatment, and fermentation process optimization. Additionally, techno-economic evaluations and cost-benefit studies can provide light on the viability of seaweed-based biofuel initiatives financially, assisting in the selection of appropriate investments and pointing out opportunities for savings and efficiency.

### **Scale-Up Challenges**

The process of converting seaweed cultivation and biofuel production from pilot or laboratory settings to commercial operations poses a multitude of logistical, technological, and financial obstacles. Optimizing processes and ensuring consistency in products can become more challenging when dealing with variations in seaweed growth rates, biomass production, and biochemical composition among various cultivation sites or seasons. Furthermore, there may be financial risks and uncertainties associated with the enormous capital investments in infrastructure, machinery, and facilities that come with expanding cultivation and processing processes to bigger sizes. Moreover, increasing the production of biofuel from seaweed could worsen environmental effects such as nutrient runoff, habitat modification, and rivalry with

other marine operations, therefore mitigation and cautious planning are needed. Innovative ideas and interdisciplinary cooperation are being employed by researchers and industry stakeholders to tackle the issues associated with scaling up seaweed-based biofuel production. Studies on process optimization and pilot-scale experiments can yield important information on the viability and scalability of methods for processing and growing seaweed. Moreover, improvements in automation, monitoring, and bioreactor design are meant to boost output and efficiency on a bigger scale. Additionally, cooperation between government, business, and academic institutions can aid in the creation of laws, rules, and other incentives that will assist the expansion of the seaweed-based biofuel sectors. To fully utilize seaweed's potential as a renewable biomass resource for biofuel production, scaling up difficulties necessitates an integrated approach that incorporates technological innovation, economic analysis, environmental sustainability, and stakeholder engagement.

### **Environmental Sustainability**

When developing systems for producing biofuel from seaweed, environmental sustainability is a crucial factor to take into account to prevent environmental deterioration from outweighing the advantages of biofuel production. Carbon sequestration, nitrogen cycling, and habitat formation are just a few of the ecosystem services that could be produced by large-scale seaweed farming. However, improper management of seaweed farming could have negative effects on the ecosystem, including competition with native species, nutrient runoff, and habitat modification. Seaweed-based biofuel production is therefore dependent on sustainable growing techniques that reduce environmental risks and enhance ecosystem health to be viable over the long run. Sustainable production methods are being investigated by academics and industry participants to lessen the negative environmental effects of seaweed farming. Seaweed can be grown offshore, for instance, in deeper waters, which lessens its impact on shorelines and reduces competition with coastal habitats. By using waste products from aquaculture operations, integrated multi-trophic aquaculture (IMTA) systems, which combine seaweed farming with clam or finfish farming, can improve nutrient cycling and lessen environmental consequences. Furthermore, to identify and mitigate any dangers related to seaweed farming and maintain the environmental sustainability of biofuel production, monitoring programmes, and environmental impact evaluations are crucial.

### **Regulatory Hurdles**

Different countries have different regulatory frameworks that control the production of biofuel and seaweed, which can provide substantial obstacles to market access and commercialization. It can be difficult for businesses to navigate the regulatory environment and adhere to relevant regulations because permit requirements, environmental regulations, and quality standards might differ significantly between locations. In addition, the absence of clear legal frameworks for the manufacture of biofuel derived from seaweed could impede the sector's growth and development by delaying investment and innovation. To overcome regulatory obstacles and create transparent, uniform regulatory frameworks that promote the expansion of the

seaweed-based biofuel industries, legislators, industry stakeholders, and regulatory authorities must work together. Engaging stakeholders and advocating for their needs can help spread the word about the possible advantages of biofuels derived from seaweed and encourage the creation of laws and other incentives that will favour their use. Furthermore, research and development programmes targeted at meeting legal requirements—like product quality standards and environmental impact assessments—can offer insightful information and useful data to support regulatory decision-making. In general, overcoming regulatory obstacles calls for a proactive, cooperative strategy that involves all pertinent parties and establishes a supportive regulatory framework for the long-term growth of the seaweed-based biofuel industry.

### **Market Acceptance and Competition**

Key factors for the successful commercialization of seaweed-based biofuels in the larger energy market are competitiveness and market acceptability. The adoption of seaweed-based biofuels is contingent upon various aspects, including fuel performance, cost competitiveness, and governmental support, even though they present several potential benefits such as carbon neutrality, reduced greenhouse gas emissions, and the possibility of sustainable production. To be accepted by customers, fuel distributors, and regulatory bodies, biofuels made from seaweed must perform on par with or better than traditional fossil fuels in terms of energy content, combustion efficiency, and emissions characteristics. Furthermore, for seaweed-based biofuels to compete with other renewable energy sources and traditional fossil fuels, they must be economically competitive. The manufacture of seaweed-based biofuel from it is not always cost-competitive because of high production costs, fluctuations in biomass supply, and unpredictability in market demand. Therefore, to lower production costs and increase the viability of seaweed-based biofuels from an economic standpoint, technological breakthroughs, process optimization, and economies of scale are crucial.

### **Technological Uncertainties**

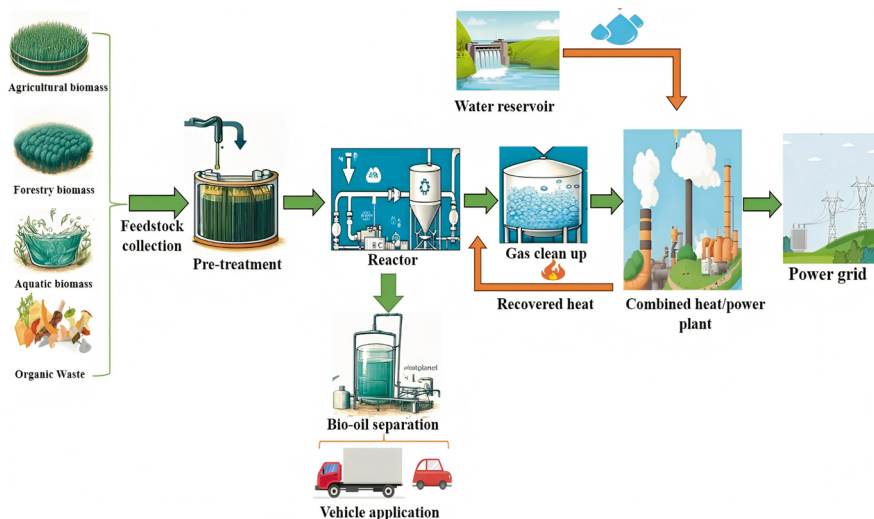
It is necessary to handle the inherent risks and uncertainties associated with the development and commercialization of seaweed-based biofuel technologies to ensure their effective deployment. Technological uncertainty can be attributed to various factors, including but not limited to process scalability, product quality, equipment dependability, and technological readiness. Technical obstacles about biomass output variability, cultivation logistics, and process optimization must be overcome to scale up seaweed cultivation and biofuel production from laboratory or pilot-scale operations to commercial-scale operations. Additionally, the overall efficacy and financial viability of producing biofuel from seaweed may be impacted by uncertainties in biomass conversion technologies, such as pretreatment strategies, fermentation procedures, and downstream separation techniques. The economic viability and adoption of seaweed-based biofuel technologies can also be impacted by legislative changes, geopolitical circumstances, and market uncertainty, which complicates the process of developing new technologies and making investment

decisions. To develop robust, dependable, and affordable seaweed-based biofuel production methods, interdisciplinary knowledge, collaborative research efforts, and strategic partnerships between academia, business, and government agencies are needed to address technological uncertainties. Furthermore, to reduce risks and hasten the adoption of new technologies, pilot-scale demonstrations, techno-economic evaluations, and market analyses can offer insightful information on the viability and scalability of seaweed-based biofuel technologies.

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## 10.9 Proposed Sustainable Biomass Management Model

Large amounts are produced when it comes to biomass production, yet there is a great deal of energy lost because of poor management. To unlock the latent energy potential of biomass resources, a sustainable model has developed, opening the door to a more effective and ecologically friendly energy paradigm. The complex process that starts with the gathering of biomass from diverse sources, such as forestry byproducts or agricultural residues, is the basis of this concept. Following their transportation to a sustainable power plant, these various biomass feedstocks go through a carefully planned set of processes that are meant to maximise energy extraction and minimise waste. In this sustainable paradigm, the biomass journey begins with an important stage called pre-treatment. Here, a variety of procedures are applied to the biomass to improve its appropriateness for further conversion stages, such as separation and the addition of required chemicals. This initial phase of preparation guarantees that the biomass is ready for maximum usage in the future. The prepared biomass is fed into the reactor unit after pretreatment. A transformative process takes place inside this reactor, producing a range of useful outputs. Notably, a valuable byproduct called bio-oil is produced along with a variety of gases like methane ( $\text{CH}_4$ ), carbon dioxide ( $\text{CO}_2$ ), and carbon monoxide ( $\text{CO}$ ). This high-energy bio-oil is meticulously recovered using specialised separation techniques and is used as a sustainable substitute fuel, especially in the transportation sector. In the meantime, the generated gases go through a rigorous purification procedure to guarantee their cleanliness and suitability for the environment. These cleaned gases are then directed into a combined heat and power (CHP) facility. Here, the reactor's functioning is effectively supported by the recovered heat produced during the creation of electricity, creating a closed-loop energy system that requires little outside energy. Furthermore, the CHP plant strengthens the total energy supply by generating surplus power for the grid in addition to producing electricity for local consumption. Crucially, the surrounding flora efficiently absorbs the greenhouse gases released during the biomass conversion process, reducing the impact on the environment and creating a self-sustaining energy-generating loop. Figure 10.3, which captures the essence of the sustainable biomass consumption model, demonstrates this complex process. This paradigm, which combines cutting-edge technology with careful resource management and environmental stewardship, ushers in a new era of green energy generation that is well-positioned to meet the twin demands of energy security and sustainability.



**Fig. 10.3** A sustainable biomass utilization model

## 10.10 Conclusion

The research and usage of untapped biomass, such as seaweed, present a prospective path for the development of value-added products like bioethanol and biobutanol, as the need for sustainable and environmentally friendly resources continues to rise globally. This chapter's thorough research explores the complex processes of pretreatment, fermentation, and hydrolysis that are necessary to transform this material into useful biofuels, in addition to highlighting seaweed's promise as a sustainable resource. To properly utilize seaweed, nevertheless, several technological and financial obstacles must be overcome. These obstacles must be carefully managed despite the abundance of prospects.

Because seaweed is widely available and requires little land, it is one of the most underutilized resources in the bioproducts industry. The variety of seaweed varieties, which include brown, red, and green varieties, each has a distinct chemical composition that makes it appropriate for a range of biotechnological uses. Pretreatment techniques are the first step in the procedures that turn seaweed into bioethanol and biobutanol, as explained in detail in this chapter. These are essential for dissolving the strong cellulose structures and making the ensuing biochemical reactions possible. Technologies that have demonstrated promise in increasing the yield of fermentable sugars include steam explosion, acid hydrolysis, and enzymatic treatment. After pretreatment, microorganisms are used in the fermentation process to transform the extracted sugars into bioethanol and biobutanol. This stage highlights the significance of choosing suitable microbial strains and the environments in which they flourish in order to effectively create the intended outputs. Furthermore, hydrolysis is essential for guaranteeing that the complex

carbohydrates found in seaweed are converted into simpler sugars that are subsequently fermented. Even though it presents a technological challenge, integrating these processes is essential to maximizing production and ensuring commercial viability.

The path from lab to market is not without difficulties, though. Significant obstacles include the high setup costs, the scalability of manufacturing techniques, and the viability of economically obtaining value-added goods from seaweed. Scaling up activities also has an environmental impact that needs to be carefully managed, including possible implications on water quality and marine biodiversity. The potential for exploiting seaweed as a source for biofuels and other bioproducts seems promising despite these obstacles. Technological developments in genetic engineering and biotechnology hold the potential to improve seaweed processing yields while cutting expenses. Seaweed is becoming a more appealing option for the generation of biofuel due to the possibility of increased biomass yield and quality through innovative breeding procedures and farming practices. Moreover, the creation of integrated biorefineries that can generate other bioproducts in addition to biofuels has the potential to greatly enhance the economic analysis of seaweed use. The evolution of companies based on seaweed will also be greatly aided by the state of policy. Investment and innovation in the field can be stimulated by favourable legislative frameworks and financial incentives for renewable energy sources. Furthermore, promoting cooperation between government agencies, businesses, and academia can quicken the pace of research and development, simplify the commercialization procedure, and eventually result in the sustainable utilization of seaweed biomass.

In conclusion, the advantages for sustainability and the environment are in line with the global goals for renewable energy, even though there are a number of technical and financial obstacles in the way of creating value-added products from seaweed. In the domains of environmental engineering and bioprocessing, continuous research and technological developments are opening the door to more effective and financially feasible solutions. Seaweed has the potential to become a key component of the economy, providing a sustainable substitute for traditional fossil fuels and helping to create a more environmentally friendly future, with sustained multidisciplinary efforts and supportive policies.

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## 10.11 Future Recommendations

### Exploration of Novel Seaweed Species

- Investigating lesser-known seaweed species should be the main focus of research, particularly those with unusual biochemical compositions and characteristics that could improve the efficiency of biofuel generation.
- To determine which seaweed species, have the greatest potential for producing biofuel, characterisation studies should look into the protein, lipid, and carbohydrate composition of the different species.

- Screening tests based on growth rate, biomass yield, and biochemical composition can be created to assess the suitability of various seaweed species for the production of biofuel.

### **Optimization of Pretreatment Methods**

- To enhance sugar release from seaweed biomass, more studies are required to optimise currently used pretreatment methods, such as steam explosion, acid hydrolysis, and enzymatic treatment.
- New pretreatment techniques that have the potential to improve pretreatment effectiveness and lower energy consumption include biological pretreatment utilizing microbial or enzymatic agents, ultrasonic pretreatment, and microwave-assisted pretreatment.
- To increase sugar output while minimising chemical and energy inputs, it should be examined whether to integrate multiple pretreatment procedures sequentially or simultaneously.

### **Microbial Strain Development**

- By using genetic engineering techniques, it is possible to improve the fermentative potential of bacteria and yeast to produce biofuel from sugars produced from seaweed.
- To increase microbial tolerance to inhibitors such as salt, heavy metals, and organic acids found in seaweed hydrolysates, directed evolution and metabolic engineering techniques can be employed.
- Custom microbial strains with specific metabolic pathways can be created using synthetic biology techniques, such as genome editing and pathway optimization, to effectively convert seaweed sugars into biofuels.

### **Integration of Biorefinery Concepts**

- The development of integrated biorefinery systems that can use seaweed biomass to produce a variety of products with added value, such as biofuels, biochemicals, biopolymers, and nutraceuticals, should be the main goal of research efforts.
- Research on process integration and optimization has to be carried out in biorefinery systems to optimize resource efficiency and reduce waste production.
- When comparing integrated biorefinery concepts to standalone biofuel production facilities, techno-economic evaluations should be carried out to assess the integrated biorefinery concepts' economic feasibility and environmental sustainability.

### **Sustainable Cultivation Practices**

- To reduce environmental impacts and increase resource efficiency, sustainable seaweed growing techniques such as land-based closed-loop systems, offshore farming, and integrated multi-trophic aquaculture (IMTA) should be investigated.
- Creating seaweed strains with better growth traits—such as quicker growth rates, larger biomass yields, and increased stress tolerance—should be the main goal of research. To analyse the ecological footprint of seaweed growing methods and determine ways to mitigate any harm to marine ecosystems, environmental impact assessments ought to be carried out.

### **Economic and Techno-Economic Analysis**

- In-depth techno-economic studies ought to be carried out to evaluate the economic viability of producing biofuel from seaweed at various sizes and in various market circumstances.
- Sensitivity analyses should be carried out to assess the influence of important criteria on the overall profitability of seaweed-based biofuel production, such as biomass yield, feedstock cost, and product market price.
- Lifecycle assessments should be conducted to quantify the environmental impacts of seaweed-based biofuel production and compare them to conventional fossil fuel-based alternatives.

### **Policy Support and Regulatory Frameworks**

- To promote investment in seaweed farming and biofuel production, policymakers should put in place favourable regulatory frameworks and incentives, such as tax breaks, grants, and requirements for renewable energy.
- Grants and funding opportunities for research and development initiatives centred on seaweed-based biofuel technologies and sustainable production practices should be given top priority by research funding agencies.
- To standardise laws, share best practices, and expedite knowledge transfer in the worldwide seaweed biofuel industry, international cooperation and partnerships ought to be encouraged.

### **Collaborative Research and Knowledge Exchange**

- To promote information sharing and cooperation between researchers, industry stakeholders, and governmental and non-governmental organisations, collaborative research networks and consortia should be formed.

- Seaweed-based biofuel research findings, best practices, and technological breakthroughs should be shared through knowledge-sharing venues like conferences, seminars, and online forums.
- The creation of capacity-building programmes, technical seminars, and instructional materials is necessary to provide the knowledge and abilities required to promote seaweed biofuel research and technology development on a worldwide scale.

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# Harnessing the Potential of Macroalgae Biomass as Alternative Feedstocks to Grain Legumes: A Step Towards Food Security

# 11

Phetole Mangena

## Abstract

Macroalgae predominantly grow in aquatic ecosystems and constitute an extensive group of microscopic to giant marine organisms serving as direct evolutionary ancestors to all advanced fungal, animal and plant life forms. Organic remains of these marine organisms continue to help provide the food we eat, oil deposits and natural gas extracted from underground reservoirs. Currently, macroalgae has also been utilised as a source of wide-ranging industrial products, including raw materials for livestock feed and food resources that remain underexploited. The different algal species possess unique chemical properties due to their high content of nutrients such as fatty acids, polysaccharides, vitamins, sterols, phenols, flavonoids and tocopherols. Due to these characteristics, they are suitable candidates for use as alternative livestock feed to legumes which play a significant role in symbiosis with microbes, soil structure, biotechnology and food security. This chapter discusses the importance of macroalgae as a sustainable source of dietary energy and proteins for livestock and comparatively analyses against leguminous crops such as alfalfa, fava bean, pea and soybean. It briefly explores the chemical properties and biotechnology of both legumes and algae targeted for processing into feed protein and other high-value products. This evaluation of macroalgae biomass as potential alternative feedstocks to grain legumes can expand our understanding relative to their benefits in improving the growth of animals, genetic modification, processing challenges and the environment, as well as impact on agriculture, globally.

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**Keywords**Macroalgae · Feedstocks · Food security · Nutritional value

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**Abbreviations**

AEE	Acid hydrolysed ether extract
ATTD	Apparent total tract digestibility
CO <sub>2</sub>	Carbon dioxide
DNA	Deoxyribonucleic acid
GE	Gross energy
Kcal/kg	Kilocalorie per kilogram
NE	Net energy
UN	United Nations
US	United States Census Bureau

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**11.1 Introduction**

Algae, classified in the kingdom Protista are photosynthetic organisms predominantly growing in aquatic ecosystems. Algae form an extensive group of microscopic to giant marine organisms that serve as direct evolutionary ancestors to all advanced life forms such as fungi, plants and animals. These non-vascular, non-embryo-forming eukaryotes comprise a large variety of morphologies and different degrees of complexity. Amongst the variety of life forms and components found within algal cells are layers of photosynthetic lamellae, ribosomes, protein granules, nucleoids (circular deoxyribonucleic acid (DNA)) and phycobilisomes. Some of their features exist among plants and animals, and they were earlier confirmed through electron microscopy by Komarek and Ludvik (1982), as well as Chapman (2013). Algae exist as fairly simple, unicellular or large multicellular organisms consisting of wide-ranging morphological structures such as the giant seaweeds, from which many ecological services that we receive directly or indirectly depend on (Shalaby 2011).

Most importantly, these organisms provide us with the air we breathe, the food we eat, feed for our animals and oil deposits that we extract from marine ecosystems for the manufacturing of biofuel. However, of major interest to the feed industry are the oil pockets or lipid droplets, protein granules, carbohydrates and many other bioactive compounds that are extracted from algal biomass. Likewise, marine resources are also important in driving the global feed market, especially like the rest of the legumes and cereal grains. Currently, soybean and corn serve as the main sources of feedstuffs utilised for dietary energy and proteins for livestock feed (Iyu et al. 2020; Parrini et al. 2023). Both crops are processed first by grinding them into powder before incorporating into the diets of livestock. Corn oil and soybean oil are preferable due to their greater apparent total tract digestibility (ATTD) of acid

hydrolysed ether extract (AEE) than most fat/lipid-containing feedstuffs of the same crops (Kim et al. 2013; Zhou et al. 2017; Iyu et al. 2020).

Although macroalgal bioresources are presently underutilised, their protein, lipid and carbohydrate composition have been used as fertilisers, foodstuff, animal feed ingredients and for manufacturing of consumables such as agar used in plant tissue culture and biostimulants for agricultural research purposes (Su et al. 2023). However, the utilisation of marine algae biomass as alternative feed resources for livestock, and the development of macroalgae variants via genetic engineering have been scantily explored, despite the potential for these marine organisms to substitute conventional legume feedstuffs as the main environmentally friendly source of animal feed. While genetic engineering in macroalgae has been avoided due to low efficiencies and a range of unique challenges that it presents, this remains a crucial toolkit for the establishment of reliable and effective transgenic variants, performing better even under adverse climatic conditions (Mosey et al. 2021). This chapter, therefore, discusses the importance of marine algae (seaweeds/macroalgae) as sustainable sources of dietary energy and protein for livestock and comparatively evaluates them against sensorial or feed quality palatability of leguminous crops such as soybean (*Glycine max* L. Merr.), alfalfa (*Medicago sativa*), fava bean (*Vicia faba*) and pea (*Pisum sativum*).

Additionally, the chapter briefly explores the chemical ingredients of both genetically improved macroalgae and legumes that are targeted in the biorefinery processing of high-quality feed proteins and other active phytochemicals such as fatty acids, polysaccharides, vitamins, sterols and tocopherol. Many of these chemical compounds possess important biological activities and have demonstrated great potential for agricultural feed applications. Subsequently, the contribution of macroalgae-formulated diets in improving the growth and overall health of livestock, compared to legume-based feed is also discussed. Finally, genetic engineering to improve algal yield and quality, processing challenges and the environmental impacts associated with the production and consumption of macroalgal feedstuffs and other forms of feed will also be incorporated into these discussions.

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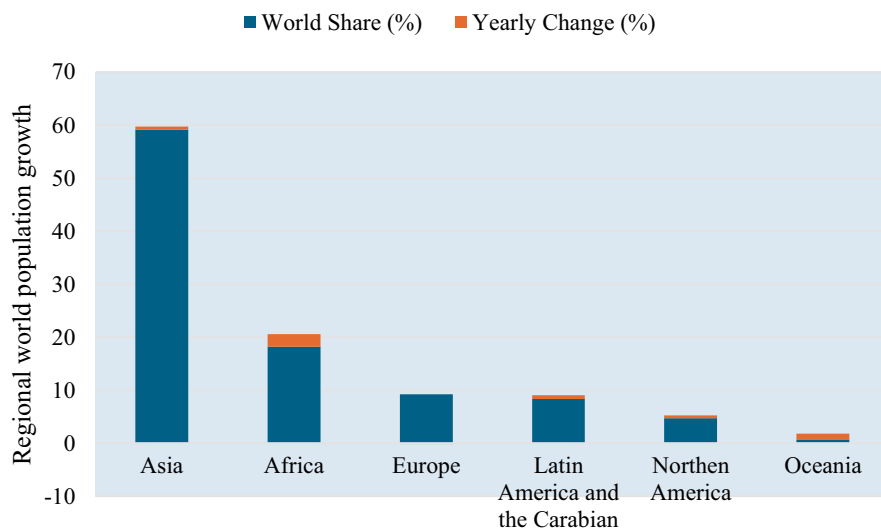
## 11.2 Current and Prominent Feed Bioresources

The production and feeding patterns of livestock are persistently changing and will continue doing so over the coming years, especially amid the alarming increases in global human population and the changing climate. According to the worldometer (<https://www.worldometers.info/>) projections that are informed by the United Nations and the United States Census Bureau data, the current world population is sitting at 8.1 billion, and it is estimated to reach 8.5 billion by the year 2030 (Sadigov 2022). Climate change, on the other hand, causes serious instabilities in marine, terrestrial and freshwater ecosystems, reducing species diversity and making them redundant, as well as driving some to near extinction. The increase in world population, however, raises many problems, including the mismatch between rapid growth rates and the socio-economic security of the human population. The main social and

economic challenges that society will continue to face include poverty, food insecurity and environmental degradation (Washington and Kopnina 2022; Miladinov 2023).

As such, the attention to addressing possible severe increases in future food insecurity and undernourishment already occurring in many parts of the world, particularly, in low- and middle-income countries must focus on livestock feeding and production. Figure 11.1 demonstrates the increases in the number of individuals in the world population, typically due to higher birth rates expressed in regions such as Asia, Africa and Europe. The rapid growth of the population escalates the overall demand for food, which necessitates the production of sufficient nutrition for survival. As the demand for food grows, many farmers and researchers continue to explore the use of grain legumes (pods and seeds), together with cereal crops, that are processed as value-added feed products. Largely, grain legumes are preferred for balancing amino acids in livestock due to their amount of crude protein concentration of 20–30%, considerable levels of carbohydrates, anti-nutritive factors and sulphur-containing amino acids (Puppo and Felker 2022). Amongst the leguminous crop species that are utilised in the manufacturing of feeds are alfalfa, soybean, species of clover (*Melilotus* spp. and *Trifolium* spp.), *Vicia* spp. and pea (Kulkarni et al. 2018).

Legumes not only contribute nutritionally to livestock production but also play a key role in improving soil fertility. They have been recognised and valued as soil-building crops, improving soil fertility through the symbiotic association with nitrogen-fixing microorganisms such as rhizobia (Kebede 2021). Factors that make legumes important sources of feed for livestock with a great potential to provide a sustainable solution for food and feed security, particularly, in addition to



**Fig. 11.1** Regional world population and growth, current estimates based on the UN and USCB data (<https://www.worldometers.info/>)

macroalgae will be discussed in the subsequent sections. At present, legumes remain the most preferred source of commercially grown forage and feed source in many countries for livestock production (Muoni et al. 2019). The major boost in this regard is the ability to use biotechnology to identify and incorporate new DNA sequences (genes) through various direct and indirect gene transfer methods to increase genetic diversity and nutrient compositions of feed-targeted pulses and cereals, predominantly soybean and corn, as well as other forage leguminous crops.

Inevitably, a large proportion of grain crop production is then used for livestock feeding than human consumption. Thus, this consequently creates a major problem of balancing food availability for malnourished human populations and livestock production, while rapid population growth also drives fast depletion of the limited bioresources due to threats of poor food security as reported by Osoro (1991) and Maja and Ayano (2021). However, it should be noted that as the most preferable source of feed, many livestock producers inadvertently make use of grain legumes rather than forage species for livestock feeding. This constitutes a threat to food security since some of the species relied upon for the production of livestock feed are required or are in demand as food for human beings. There are ongoing debates as to how the demand for meat and dairy products will be met without having major implications on poverty alleviation and food security efforts. To date, the transformation of the livestock and feed manufacturing sector has occurred without thoroughly considering the inclusion of marine bioresources to ensure that the industry contributes to equitable and sustainable development.

Grote et al. (2021) reported an overall contribution of 61% to feed production by maize (*Zea mays* L.) while only 13% is used for human consumption. With ongoing debates on how to best feed the growing population, reducing the overuse of stable crops as feedstocks by incorporating marine bioresources will not only disentangle their effects on food security but will also make macroalgae a sustainable feedstock and abundant alternative to grain legumes. As already mentioned, some of the genetically enhanced characteristics that make farmers incorporate legumes in their agricultural production practice will be compared with those of macroalgae and their long-term benefits briefly discussed in this chapter.

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### 11.3 Composition and Specific Properties of Feedstocks

Traditionally, grain legumes have been used for the manufacturing of livestock feed. Leguminous grain seeds and pods, whether non-transgenic or transgenic crops, are prepared by simply mixing the ground plant materials from pulses and other different crop species with a common salt or mineral mixture, normally at a 1:1 ratio (Puppo and Felker 2022). However, algal biomass, especially green, red and brown seaweeds have also been used as fertilisers, various food products and ingredients to produce animal feed at least at a 30% rate (Zhou et al. 2017; Arioli et al. 2023). Some of the widely consumed species of algae worldwide include *Spirulina*, *Dunaliella*, *Haematococcus* and *Chlorella* (Su et al. 2023). Apart from their high growth rate, high biomass productivity and yield, macroalgae contain excellent

nutritional composition and content of proteins, lipids as well as carbohydrates required for efficient production of high-quality feed. Furthermore, macroalgae contain sterols, vitamins, pigments and functional proteins used in the pharmaceutical industry as therapeutic products (Su et al. 2023; Fernandez et al. 2018).

The market demands and expects high-quality unprocessed and processed feedstocks, along with whole algal biomass or dried powder used as food sources and applications even in human health. The good composition and specific nutritional properties of feed are not merely a matter of the total amount of hay, per grain, per dry roots but rather the amount of nutrients needed, including water, starch, gluten etc. Moreover, a good feedstock should be a rarely optionally used food/non-food source for humans, offering higher product yield and market value (Bhaska et al. 2016). Most importantly, the big question should be what is the chemical composition of algal biomass. What proportion is digestible and consequently nutritious? Which properties does it contain that could play a critical part in livestock production and animal economy? Answers to the above questions could emanate from the knowledge of the composition and specific properties found in macroalgae, compared to other forms of feed such as *Glycine*, *Vigna* and *Phaseolus* species.

The questions can furthermore be answered by interrogating whether genetically modified macroalgal biomass could contain higher yields of nutritive chemicals and bioactive content than wild-type species. In addition, more feedstuff alternatives are highly required, particularly due to the intensification of livestock farming to meet meat protein demands for the growing human population. This means that increased feed manufacturing and livestock production could rely on massive imports of legumes as the main feedstock source in many developing countries. Many farmers currently rely on transgenic varieties characterised by high protein content and their ability to meet their own nitrogen demand by biological nitrogen fixation for feedstuff production (Rubiales et al., 2021). Research-wise enhanced macroalgal or legume feed production will also depend on the genetic improvement of both macroalgae and legume species in order to increase their biomass. However, the potential use of any plant-based feedstock should not involve crops whose use threatens food security by not being in a more sustainable position. Therefore, this will intensify the utilisation of algal biomass, including genetic modification, as a great opportunity for enhancing their value, particularly for the feed industry.

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## 11.4 Role of Biotechnology on Feed Production

The impact of biotechnology on agriculture and food security is well documented and includes bioprospecting and biosafety assessments of genetically modified organisms before field applications. Amongst the tools, genetic engineering has been one of the techniques developed to explore biochemical and genetic information for establishing commercially valuable DNA sequences for agricultural and other applications (Kapoor 2023). By manipulating the genetic materials of organisms, scientists have the ability to enhance desired traits and introduce novel characteristics into plants, animals and macroalgae, as well as other living organisms. In

the feed industry, genetic engineering has opened new possibilities, providing enhanced nutritional value of proteins and ideal digestibility of amino acids constituting the feeding materials. Genetic engineering has simultaneously offered the opportunity to improve genetic diversity and provide innovative solutions to global challenges such as food security and environmental sustainability (Tekeda and Matsuoka 2008; Begna 2020).

### 11.4.1 Improvement of Prominent Feedstuffs via Genetic Engineering

Grain and forage legumes as well as grasses are the most important sources of livestock feed globally. However, a variety of feedstuffs is available based on what is cultivated in a particular region. According to Sapkota et al. (2007), the United States was the largest feed producer in the world, mixing feed grains, mill by-products, animal proteins and micro-ingredient formulations such as vitamins, minerals and antibiotics. Currently, according to the statistics by World Grains' (<https://www.world-grain.com/articles/18016-world-feed-output-holds-firm-in-2022>) grain and milling animal report findings, the entire global feed supply chain was steady in 2022, falling at 0.42% to 1.266 billion tonnes compared to 2021 with Europe enduring a significant drop of 12.882 million tonnes (4.67%). This drop was followed by the African continent and Asia-Pacific region with 3.86 and 0.51%, respectively (Alltech Agri-Food Outlook 2023).

Contributory factors attributed to this fall were disease challenges, severe weather conditions and the impact of war between Russia and Ukraine (El Bilali and Ben Hassen 2023). Numerous studies are available that attempt to uncover the trends and technologies that are impacting the global feed production industry. Some of these studies clearly highlight opportunities for improvement and gauge expectations following adequate and sustainable application of modern technologies. Although narrow reductions were experienced, China remained the largest feed-producing country globally, followed by the United States and Brazil (Table 11.1). Among the technologies making the biggest impact are nutritional solutions. These are concentrates of high-energy value that constitute fats, cereal grains and by-products of barley (*Hordeum vulgare*), corn (*Zea mays*), oats (*Avena sativa*), rye (*Secale cereale*), wheat (*Triticum* sp.), including high-protein sources such as soybean, canola (*Brassica napus*), cottonseed (*Gossypium herbaceum*), peanut (*Arachis hypogaea*) and processed sugar beets (*Beta vulgaris* subsp. *vulgaris*), animals and fish.

Roughages like pasture grasses, hays, silage, root crops, straw and stover (corn-stalks) are also included (Babic and Peric 2011; Moorby and Fraser 2021; Bayissa et al. 2022). However, the use of genetically improved cereal and pulse grains to improve the production of feed remains less significant to the market. According to the Alltech Agri-Food Outlook (2023), genetic technologies only contributed 3% to the feed industry (Table 11.1) also accounting for a very small fraction of transgenic cereal and legume crops used globally. Nonetheless, the environmental impact of

**Table 11.1** Top 10 livestock feed-producing countries over the 2022/2023 outlook period with their 2023 total feed tonnage and technologies making the biggest impact

Country	Feed (million tonnes)
China	260.739
United States	240.403
Brazil	81.948
India	43.360
Mexico	40.138
Russia	34.147
Spain	31.234
Vietnam	26.720
Argentina	25.736
Germany	24.396
Technologies	Impact (%)
Nutritional solutions	33
Biosecurity	13
Automation/robotics	13
Renewable energy	9
Smart agriculture	7
Data collection and analysis	7
Traceability tools	3
Biogas	3
Genetics	3
Irrigation technologies	2
Soil health	2
Artificial intelligence	1
Aerial imagery	1
Camera systems	1

agriculture has significant negative effects and requires genetic technologies as stated above to increase efficiency and enhance the sustainability of feed production. Genetic technologies hold the biggest potential for growth and reductions in production costs since they involve research and development for more durable and productive agricultural products. One example reported by Zhao et al. (2019) is the use of *mAppA* transgenic soybean as a source of phytase supplements for livestock feed manufacturing.

The incorporation of a modified *appA* gene (*mAppA*) into soybean under the control of a seed-specific promoter from *Phaseolus vulgaris* (common bean) increased phytase activity at pH 4.5 and 70 °C serving as an effective feed additive by increasing nutrient availability by catalysing the hydrolysis of phytic acid (Zhao et al. 2019). In this case, transgenic crops could improve the dietary availability of phosphorus and other minerals emerging as some of the best alternative feed additives. Therefore, improved use of macroalgae through the development of transgenic variants could represent another effective way to deal with climate-related agricultural challenges and eliminate the need for fertilisers as well as other environmental hazards. The above approach could also go beyond the utilisation of prominent and widely used cereal and grain crops to seaweeds which remain the most underutilised marine bioresources. As such, genetic engineering can also be

applied to these important marine organisms to provide an effective macroalgae feed value chain. Like the focus given to enhance economic profitability by targeting high-value metabolite products for biofuel, energy and food (Sudhakar et al. 2019; Liu et al. 2023; Healy et al. 2023), macroalgae could be exploited as a promising source of nutrition for livestock, and a sustainable food production system for humans.

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## 11.5 Use of Macroalgal Biomass as a Sustainable Feed Source

Since the birth of civilisation, biologists have used forage legumes and cereals as the main sources of feed. For various reasons, soybean remains the most widely used leguminous crop as a feedstock, in addition to barley (*Hordeum vulgare*), corn, oats (*Avena sativa*) and sorghum (*Sorghum bicolor* (L.) Moench) as reported by Gonzalez-Garcia et al. (2016) and Fushai et al. (2019). Still, the growing demand for food and increased reductions in environmental sustainability continue to attract attention towards finding new sources of feed. Although macroalgae have been utilised for decades as feedstock materials found in marine and freshwater ecosystems, these organisms partly opened space in the animal feed market. Their minimal use in this industry emanates from the fact that they were found to possess unique and interesting biochemical properties. Unlike crop plants, they reproduce quickly, grow rapidly and may be harvested during any season and are renewable.

Many seaweed species, for instance, allow cultivation for constant harvesting year-round even though Ahmed et al. (2022) reported that seasonal dynamics of seaweed production in commercial farming is higher only during the summer season. Currently, reports indicate that macroalgae are gaining worldwide popularity and continue to grow in many parts of the globe as a well-established industry (Froehlich et al. 2019; Rosa et al. 2020; Mosey et al. 2021; Ahmed et al. 2022; Hasnain et al. 2013). Noticeably, such interest is growing without what appears to be a biotechnological lockdown wherein there seems to be a lower exploration of genetically engineered algal species for use in the value chain. According to Froehlich et al. (2019), several seaweed farmers started to record high economic returns while the industry is only starting to create interesting opportunities to serve as a sustainable climate change mitigation strategy through carbon sequestration. Recent analyses from macroalgae farming showed that about 0 to 8.1 tonnes of carbon dioxide (CO<sub>2</sub>) get sequestered into organic carbon and biomass from seawater. As such many role players in the industry, including law and policy makers believe that seaweed farming could significantly contribute to sustainable food and feed production from aquatic life.

Additionally, macroalgae offer essential fish habitat sufficient for fish reproduction, growth and feeding, which may serve as an additional or alternative stream of income in aquaculture (Hedberg et al. 2018). Furthermore, they are also sustainably responsible for sequestration of nutrients by both CO<sub>2</sub> sequestration via photosynthesis and elimination of inorganic contaminants which also maintain nutrient flux.

It was reported by Hasnain et al. (2013) that several macroalgal species have the capability to absorb and convert heavy metals and metalloids present in their vicinity into proteins, oil and carbohydrates processed into livestock feed. Such capabilities are an additional role played by all green, red and brown macroalgae in avoiding threats of pollutants to the environment, ecosystem functionality, diversity and the safety of humans as well as animals (Hasnain et al. 2013). Therefore, macroalgae not only serve as a sustainable, low cost and environmentally friendly source of feedstock but also need no fertilisers or pesticides contributing to a safer environment.

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## 11.6 Macroalgae Improvement Through Biotechnology

Presently, many eastern and south-eastern Asian countries continue to be key role players and major producers of algae biomass production globally. The statistics by FAO (2020) recorded an estimated 99.6% of global macroalgae production from these regions with China contributing about 58% of the global production. Other emerging and significant role players include Indonesia, Japan, North Korea, South Korea and the Philippines (Ahmed et al. 2022). As interest grows in a variety of algal species due to climate change and instability in crop productivity, genetic improvement of macroalgae as feedstock resources has also come to light. Several species have already shown higher production rates that are greater than those of terrestrial legume plants (Radakovits et al. 2010). As previously mentioned, macroalgae farming now has been rejuvenated for a variety of industrial purposes, including petroleum resource acquisition due to their storage amounts of triacylglycerols and starch required for processing into biodiesel and ethanol.

In fact, it is believed that a large portion of crude oil deposits in oceans are derived from ancient algae (Dismukes et al. 2008). Consequently, if ancient algae are responsible for naturally creating substantial crude oil deposits, therefore, they can potentially be further investigated for the development of new products and amenability to genetic engineering to improve their metabolites (lipids, proteins, oil and carbohydrates) profile and productivity. As such, genetic manipulation can be used to investigate the potential of these organisms for enhanced feedstocks should be a priority. In many cases, leguminous crops have been manipulated to express transgenes, subsequently leading to the production of transgenic plants. Su et al. (2023) reported higher levels of miR156b expression which increased the number of branches and yield in soybean. This optimisation of the plant's architecture to increase the yield of crops remains a vital goal for researchers, both in legumes and algae production. Like numerous genes that control shoot architecture in legumes, the molecular mechanisms underlying these effects can also be explored and introgressed in macroalgae species.

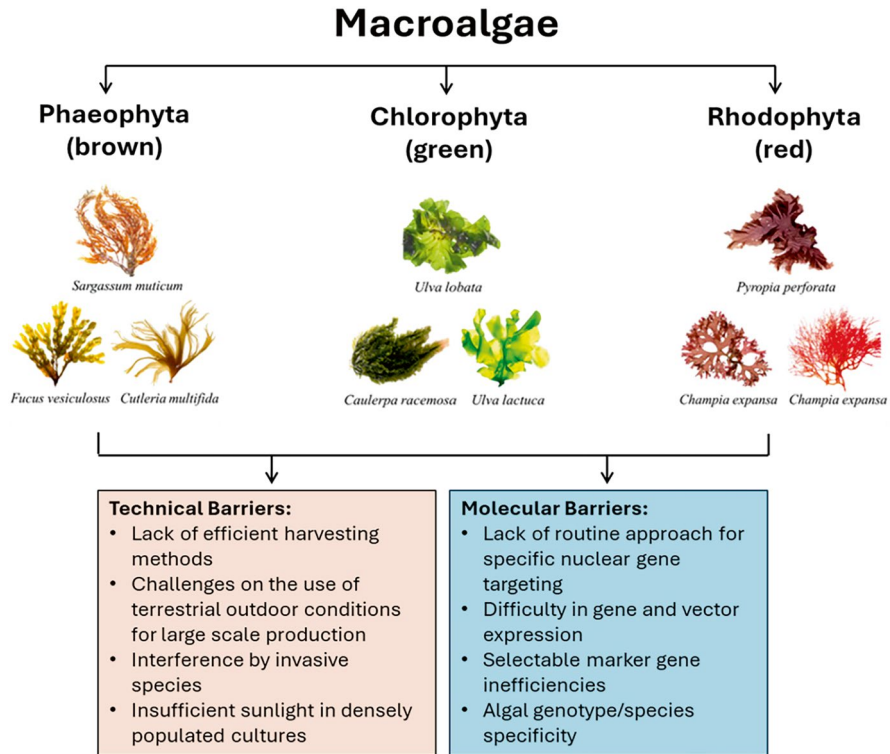
Substantial improvement of magnanimous amount of functional and nutritional ingredients such as albumins, prolamins, glutelins and globulins that constitutes 1.41–3.01, 1.83–3.57, 12.0–18.4 and 69.5–78.1% of total proteins in fava beans were also reported (Gantait and Mukherjee 2022). The distributions of these protein

fractions depend on the species and environmental conditions. Similarly, macroalgae can also be genetically improved to leverage the metabolic pathways to produce a wide variety of lipids, proteins and polysaccharides. Genetic engineering can further increase the amounts of secondary metabolites produced in algal tissues that include phenolic compounds, halogenated compounds, sterols, terpenes and small peptides (Rosa et al. 2020). Furthermore, the successful use of macroalgae in feedstock production, globally, will help mitigate some of the potential deleterious environmental and agricultural consequences that are associated with current land-based feed manufacturing (Dismukes et al. 2008). Therefore, it is encouraged that researchers in many parts of the world focus considerable attention on developing genetic engineering strategies for improving macroalgae as a stable renewable and sustainable approach to mitigating the impact of climate change.

### 11.6.1 Molecular Barriers Impeding Genetic Improvements in Macroalgae

Like legumes, macroalgae face several barriers to genetic transformation (Fig. 11.2) that need to be overcome before they can be used as economically viable feedstocks. Grain legumes such as soybean, mung bean and lentil (*Lens culinaris*) are well known for their recalcitrance to most of the *in vitro* genetic improvement approaches. They possess a great variability wherein particular species may have the lowest responsiveness to *in vitro* regeneration and genetic transformation compared to their counterparts such as cereal grains. Leguminous crops are rich in proteins and, thus, serve as the favoured source of livestock feed and plant proteins for the human diet in most countries. However, legume plant transformation frequently succumbs to genetic recalcitrance due to genotype-specificity, choice of explants, lack of efficient regeneration protocol and type of direct/indirect gene transfer tools used, together with the strain of *Agrobacterium tumefaciens* used for transgene expression and integration in host genomes (Mundhara and Rashid 2006; Navya and Shah 2023; Wu et al. 2023).

However, macroalgae's technical barriers to livestock feed improvement via genetic engineering include the lack of efficient methods to harvest algal cells, inconsistency challenges in producing biomass at large scale under outdoor conditions, interference by invasive species and low-light penetrance in dense macroalgal cultures (Rudakovits et al. 2010). Presently, most genetic tools explored for transgene expression and integration have been developed for *Chlamydomonas reinhardtii*, green Chlorophytum, red Rhodophyta and brown Phaeophyta algae species (Fig. 11.2). Although an efficient genetic transformation has been reported, most of these species reported on, such as diatoms, euglenoids and dinoflagellate algae demonstrated nuclear and plastid transformation with only transient gene expression observed in some cases (Qin et al. 1999; Teng et al. 2002; Poulsen and Kroger 2005; Zorin et al. 2009). Furthermore, the studies also indicated that the outcomes of transformation frequency specifically targeting nuclear genes were not always routinely possible. For a while, the specific targeting and modification of nuclear



**Fig. 11.2** A variety of technical and molecular barriers involved in trait and quality improvement of red, brown and green macroalgae using biotechnological tools such as direct and indirect genetic engineering

genomes instead of plastid genes have hampered functional and biotechnological studies for most green species.

Since then, efforts have been made towards establishing transformation protocols for seaweeds, including eliminating the difficulties in introducing foreign DNA, vector expression of exogenous genes and the use of selectable marker gene sequences to screen transgenic algae (Qin et al. 1999; Radakovits et al. 2010; Mosey et al. 2021). Mosey et al. (2021) reported the most significant challenge to macroalgae genetic engineering to be the complex and resilient nature of the cell wall. Surprisingly, the application of genetic transformation to modulate and engineer algae metabolite profile with the aim to increase the quality and quantity of biomass productivity results from the complications associated with protective barriers and other internal defence mechanisms that reportedly led to the loss of foreign DNA and silencing. Therefore, there is still a great need to gather new insights into mechanisms and approaches that could eliminate these technical and molecular barriers observed in brown, red and green macroalgae, thus helping in the development of efficient genetic engineering strategies in model and non-model algae species.

### 11.6.2 Anatomical and Physiological Impediments on Genetic Engineering

In addition to the molecular barriers discussed above, genetic engineering also faces a number of anatomical and physiological challenges that render this technology inefficient. A major anatomical obstacle to applying this technique in several different species to benefit livestock, humans and the environment using renewable macroalgae biomass-based feed is the difficulty in algal cells and tissues to take up foreign DNA. In *A. tumefaciens*-mediated genetic transformation, specific properties of cells and tissues interfere with the transfer of tumour-inducing plasmid-carrying genes responsible for delivering the T-DNA for integration into the macroalgal genome (Ahmad and Mukhtar 2017). Even when the T-DNA finds itself inside the cells it may then be physiologically recognised as foreign particles. However, as macroalgae are considered promising feedstocks to produce livestock feed and numerous valuable commercial products, genetic tools such as particle bombardment, electroporation and genome agitation with silicon carbide whiskers should be explored for their capability to genetically enhance marine species (Munoz et al. 2019).

Most of these technologies have proved to be reliable toolboxes for most grain and cereal crops. However, some have worked with great success in alleviating some of the anatomical and physiological bottlenecks in model strains such as *Chlorella* sp., *Phaeodactylum tricornutum* and *Chlamydomonas reinhardtii*. The great diversity of species with a variety of cell sizes, cell wall structures and cell wall composition was reported by Gimpel et al. (2015) as some of the critical obstacles to genetic engineering. The delivery of DNA through the cell wall, plasma membrane and nuclear membrane creates serious resistance, including cellular damage that occurs during DNA transfer which significantly reduces the transformation efficiencies (Munoz et al. 2019). Like plants, macroalgae possess carbohydrate-rich cell walls which are integral and important in many physiological processes. As earlier alluded by Ochs et al. (2014), these cell walls consist of a complex and dynamic composite of polymers and enzymes that serve as barriers to pathogens and any breaching of the cell membrane, including the transfer of foreign DNA during genetic engineering.

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## 11.7 Conversion of Non-transgenic and Transgenic Algal Biomass to Value-Added Products

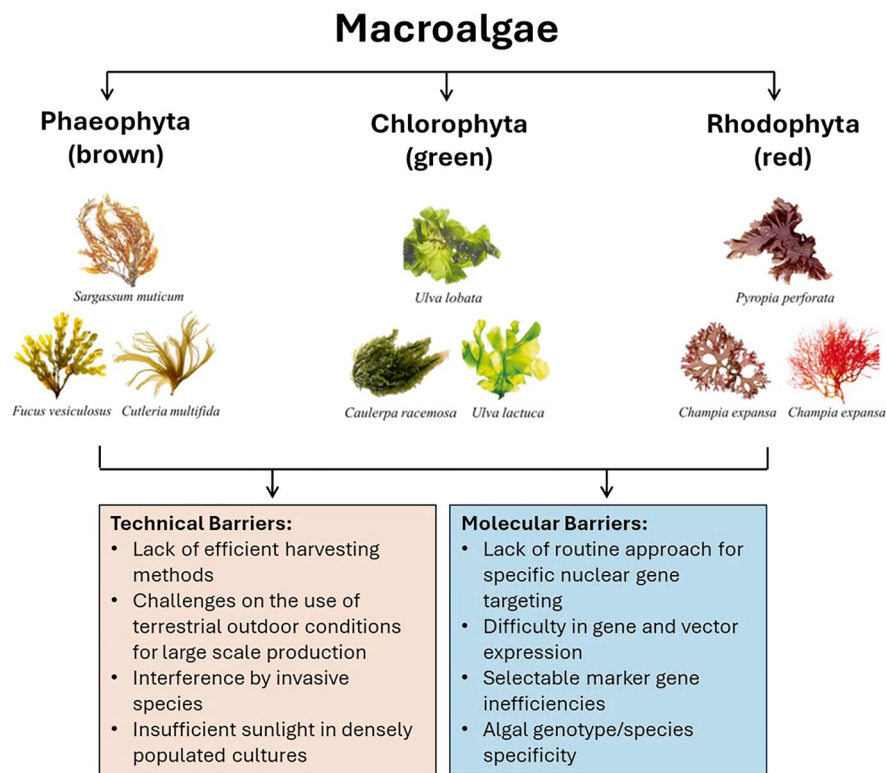
As already mentioned, the incorporation of macroalgae in livestock diets can improve the growth and quality of livestock and, subsequently, the quality of food produced for human consumption, especially based on algal species composition and dietary levels. The composition of seaweed-derived feedstuff has a major role to play in livestock growth parameters. In more common feeds, such as grain legumes, forage and cereals, reliable nutritional data is widely available that highlights the actual energy and elements of matter which analytically characterise the

feed by its chemical composition and dietary value (Sauvant et al. 2004). Such data in seaweed is a subject of continuing research by many laboratories across the globe. Costa et al. (2021) identified Laminarin, Codium and Palmaria species as some of the most commonly brown, green and red algae, respectively, used as critical sources of reliable feedstuff based on their chemical composition. The chemical profiles of these algae species are still collated, summarised and included in tables describing animal feed materials.

This information on the chemical composition and nutritional value of livestock feed will be beneficial for farm animals and the rationalisation and improvement of agricultural techniques and practices. The abovementioned algal species are also believed to contain higher amounts of nutrients even though many of the genetic resources still need tremendous improvement genetically to meet the nutritional requirements of livestock without having negative impacts on the safety and quality of livestock products (Lin and Qin 2014). Currently, as the world is experiencing energy deficiencies and depletion in bioresources, transgenic seaweeds can be used to complement non-transgenic seaweeds to increase global scale cultivation that remains small. The rapid development of seaweed genetic engineering will not only help meet the demand for industrial and biomedical fields, but will also improve the genotype, phenotype and nutritional value (Purnick and Weiss 2009; Lin and Qin 2014). If the genetic expression of transgenes is achieved, both nutritional profile and value-added dietary formulation for livestock feeding can be improved. Furthermore, seaweed compounds highlighted in Fig. 11.3 also exhibited anticancer, antimicrobial, antiviral, antioxidant, probiotic and anti-inflammatory properties.

Studies have demonstrated that incorporating novel DNA sequences into their genomes can positively impact the valorisation of macroalgae biomass, and as the biomass is used as feedstuff instead of their utilisation for direct human consumption, both transgenic and non-transgenic materials could be applied without stringent regulatory setbacks. However, the preferred types of nutritive chemical contents required from both transgenic and non-transgenic seaweed are briefly demonstrated in Fig. 11.3. Such critical objectives require the development of, if at all possible, new transgenic lines that consistently express high levels of phytochemicals, in addition to the contents of nutrients. Unfortunately, algae, as crucial marine bioresources remain underutilised due to their inconsistent and varying levels of bioactive content emanating from their genetic variations in the amounts of carbohydrates, proteins and lipids (Van Hal et al. 2014). Expressively, the higher the amounts of carbohydrates, lipids and amino acids, then the higher the amounts of secondary metabolites that can be produced by these organisms.

However, it is clear that genetic variations also have an impact on the nutritional, functional and biological properties of seaweed, which also depends on the species or genotype specificity. As such, chemical composition and element characterisation must be representative of actual feed materials, particularly from the nutritional point of view (Fig. 11.3). For instance, the legume-based feed gets sufficiently individualised in terms of its different compositions like in the amounts of soluble polysaccharides, n-3 and n-6 polyunsaturated fatty acids as provided in the feed market. Furthermore, algal species should also enhance livestock quality and growth up to



**Fig. 11.3** Summary of nutritive chemical compounds of carbohydrates, fatty acids, vitamins and minerals required for the manufacturing of high-quality livestock feed from both transgenic and non-transgenic macroalgae

at least 10% in addition to the livestock’s genetic potential based on ATTD indices. The compounds indicated in Fig. 11.3 also contribute immensely to the diet and digestion-related properties that help to increase nutrient bioavailability (Costa et al., 2021).

### 11.7.1 Nutritional Value and Energy Yield of Algal Biomass

Generally, animals use the gross energy (GE) contained in the ingested feed from the chemicals as illustrated in Fig. 11.3. However, the best way to measure the nutritional value of feed energy content is by net energy (NE), starting with GE and considering the predicted value of energy digestibility and energy lost as methane, urine and heat. Compared to legumes, as well as other oilseed crops, digestibility, metabolisable and net energy are based on the cell constituents of plant materials (Table 11.2) which are similarly expected to be observed in seaweeds. Chlorophyta (green algae), Rhodophyta (red seaweed) and Phaeophyceae (brown algae) also

**Table 11.2** Comparison of composition and nutritional value of feed materials from leguminous and seaweed species (Olsson et al. 2020; Azizi et al. 2021; Xu et al. 2023)

Content	Faba bean	Pea	Soybean	Lupin	Green alga	Red alga	Brown alga
Dry matter (%)	91.5	91.6	88.1	90.3	96.2	96.2	96.8
Crude protein (%)	20.9	21.9	34.8	22.6	76	55.9	59.8
Crude fibre (%)	8.3	5.5	5.2	9.2	2.93	5.19	5.78
Ash (%)	17.2	16.7	26.4	19.8	12.5	9.17	9.58
Gross energy (kcal/kg)	836.5	764.8	1242.8	764.8	6150.3	6150.3	6171.5

hold the potential to become an important raw material for feed production. Olsson et al. (2020) reported the carbohydrate, ash, protein, water and metal contents of the earlier mentioned seaweeds to gather details of their biorefining potential and to benchmark with already industrially and commercially produced feedstuffs such as leguminous crop species.

As indicated in Table 11.2, some of the constituents were higher than those found in grain legumes suggesting that several species within these taxa must be further explored for industrial processing (Azizi et al. 2021; Xu et al. 2023). Clearly, the amounts of the chemical nutritional composition further require detailed studies to provide more biomass for the production of feeds, as well as other forms of high-value products. More evidence is also emerging (Azizi et al. 2021) illustrating that enhanced nutritional properties, apparent digestibility and metabolisable/gross energy were improved in broiler chickens fed with both brown and green seaweed. Findings further revealed significant differences in crude protein, fibre and metabolisable energy, implying that these form part of essential factors to be considered for genetic engineering.

## 11.8 Final Considerations

Macroalgae are one of the main potential marine resources used as the right feeding stock for animals. They are rich in various chemicals that are required for agro-processing (Fig. 11.3), biofuel and bioactive compound production. To date, more than 20 million tonnes of macroalgae have been harvested wherein 70% is used as food and only 30% as processed feed, fertilisers, bioactive chemicals and energy (Poblete-Castro et al., 2020). This chapter reviewed applications in the feed industry, including genetic improvement of macroalgae to enhance their cultivation and biosynthesis of primary as well as secondary metabolites. As the threats of climate change, environmental pollution and food insecurity exacerbate, many eyes turn to the sea because these bioresources remain underexploited. According to Abdel-Kareem and ElSaied (2022), a huge diversity of seaweeds constituting more than 100,000 different plant-like macroalgae can be found in the sea. These species fall into three groups: Rhodophyta, Chlorophyta and Ochrophyta, and contain large amounts of carbohydrates (4–7%), lipids (1–20%), proteins (7–47%) and many other valuable chemical substances in terms of their dry matter.

However, the production of genetically modified macroalgae variants should also be envisaged by intensifying *Agrobacterium*-mediated genetic transformation, biolistic bombardment and electroporation for the recovery of high-value transgenic products. These are already proven techniques that work well in plants but currently only need to be scaled up to develop industrially relevant variants of green, brown and red macroalgae for commercial feed processing. These approaches can be efficiently used to improve the seaweed value chain in terms of novel cultivation and expression of new genes that increase the extraction of industrially useful compounds from these marine organisms. Sulistiani et al. (2019) reported *A. tumefaciens*-based genetic manipulation of *Kappaphycus alvarezii* Doty using the *Ga* gene encoding heterotrimeric G protein  $\alpha$  subunit playing a role in the tolerance of biotic and abiotic stress. *K. alvarezii* is a commercial source of carrageenans widely used in pharmaceuticals and the feed industry but is highly sensitive to ice-ice disease caused by extreme changes in temperature and seawater salinity.

Moenaert et al. (2023) also reported the involvement of strain AK17 in the successful production of renewable biomass from brown seaweed, *Laminaria digitata*. These studies, including other genetic engineering reports in brown and green macroalgae, illustrate the potential to replace fossil and grain-based feedstocks with sustainable renewable marine biomass to produce feed, food and chemicals of industrial interest. Many strides have already been made in red and green macroalgae (Charrier et al. 2015), necessitating further transgenic studies in brown algae, plus other species of red algae which both trail behind those of green algae (Ramessur et al. 2018). Although, the current stage of genetic engineering knowledge still lags behind cereal and pulse crops widely used as feedstocks, advances already made allow access to new and more efficient strategies for generating improved quality and quantity of feed materials from altered macroalgae. Using both conventional and modern breeding techniques to create macroalgal variants with specific, precise and predictable phenotypes could significantly increase seaweed harvesting and processing into highly nutritional forms of feed products.

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## 11.9 Conclusion

The utilisation of marine algal biomass as an alternative feed resource for livestock has been scantily explored. However, its use as a valuable food source for livestock may potentially play a leading role in the global food industry as a substitute for the conventional legume feedstuff that are widely utilised as the main source of animal feed. This chapter, therefore, concludes that the importance of marine algae (seaweed/macroalgae) as sustainable sources of dietary energy and protein for livestock needs to be further explored. Comparatively, the nutritional value and feed quality palatability of macroalgae are also similar to that of leguminous crops such as soybean, alfalfa, fava bean and pea. In addition, the chemical ingredients of both macroalgae and legumes that are targeted in the biorefinery processing of high-quality feed proteins and other active phytochemicals such as fatty acids, polysaccharides, vitamins, sterols and tocopherol can be enhanced using tools such as genetic engineering.

Many of these chemical compounds possess crucial biological activities and have demonstrated great potential for agricultural and industrial applications. Subsequently, this suggests that the contribution of macroalgae-formulated diets in improving the growth and overall health of livestock, compared to legume-based feed, should also be thoroughly considered as a major and alternative sustainable feedstock. Finally, more reported evidence suggests that the negative environmental impacts associated with the emission of greenhouse gases as observed in ruminants fed with plant-based feed remain or heavy use of chemical fertilisers can be minimised by the use of processed marine organisms as feed as they do not cause emissions and are also involved in CO<sub>2</sub> sequestration.

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# Transforming Food Waste into Nutrient-Rich Fertilizer: A Sustainable Path Towards Carbon Neutrality and Circular Economy

# 12

Siti Suraya Munirah Normi and Siti Baidurah

## Abstract

The rising trend of world population growth has contributed to the increase of municipal solid wastes, especially food waste because of several factors which are increased consumption, changes in eating habits, supply chain challenges, urbanization growth, and changes in consumer behavior. Food wastes contain various beneficial elements that are required for plants such as nitrogen (N), phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg), iron (Fe), inorganic salts, and other micronutrients. With suitable biological treatment such as anaerobic digestion, composting, landfill treatment, and incineration, the food wastes can be valorized into fertilizer, soil amendment, and animal feed. The main objective of this chapter is to highlight the current valorization method of food waste in Malaysia into nutrient-rich fertilizer via the biological approaches to achieve carbon neutrality and circular economy. By using some case studies as an example, in-depth advantages, disadvantages, and challenges of each biological approach are discussed.

## Keywords

Carbon neutrality · Circular economy · Fertilizer · Food waste

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## 12.1 Introduction

According to the Department of Statistics Malaysia (DOSM), Malaysia's population in the last quarter of 2023 has been reported to be 33.7 million and is expected to continuously increase from 2024 onwards (DOSM 2024). The rising population has contributed to the increase of food waste (FW) at an alarming rate because of several factors which are increased consumption, changes in eating habits, supply chain challenges, urbanization growth, and changes in consumer behavior. As a result, it will contribute to overloaded solid waste municipal transportation and landfills. Statistics from the Solid Waste Management and Public Cleansing Corporation (SWCorp) showed that Malaysians dispose of approximately 39,078 tonnes of solid waste per day and approximately 1.17 kg per person (Zainal 2024). This observation indicates that food waste is a common issue in Malaysia, and it will keep increasing, especially during festive seasons, birthday celebrations, and other formal occasions within the government and private sectors.

Poor management of FW throughout household, commercial, institutional, and industrial areas presents complex and diverse dilemmas that will result in enduring environmental, financial, and social impacts. The source separation and recycling practices in Malaysia are still at a lower rate as many people lack understanding, awareness, and correct perception of recycling (Mohammad et al. 2021; Sen & Baidurah 2021). They cannot turn the knowledge into behaviour as well as connect the benefits of the practice and the consequences of not practising, thus leading to a low recycling rate in Malaysia. Therefore, the community tends to put all the responsibility on the local authorities and municipal waste collectors to deal with the waste problems. In addition, the treatment of food waste involving incineration is also a bit tough to implement in Malaysia due to its higher moisture content, complex composition, and high amount of organic matter.

Thus, an efficient and sustainable alternative to transform food waste into value-added products should be implemented. Many researchers suggest biological treatment of anaerobic digestion and composting methods to improve food waste management (Yaser et al. 2022). The similarity product from both methods is basically organic fertilizer or soil amendment because FW is a main source of organic matter containing various chemical elements that are required for plants such as nitrogen (N), phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg), iron (Fe), inorganic salts, and other micronutrients depending on the type of waste disposed of. All these elements have their own functions for the growth of plants. Moreover, the benefits of utilizing food waste as fertilizer are to improve the soil's sustainability, reduce soil erosion, and improve water quality.

This chapter highlights the situation of the food waste disposal system in Malaysia and provides a brief explanation of its composition in municipal solid waste (MSW), focusing on the types and characteristics of FW. Then, the impacts of FW accumulation in terms of environmental, economy and social will be explained when improper management of food waste occurs, followed by the current valorization and treatment method to reduce FW using biological treatment such as anaerobic digestion, composting, incineration, and landfill. The final part of

this chapter discusses the application of FW after treatment which is the production of organic fertilizer and animal feed and its correlation with carbon neutrality and circular economy for a sustainable future via the biological approach.

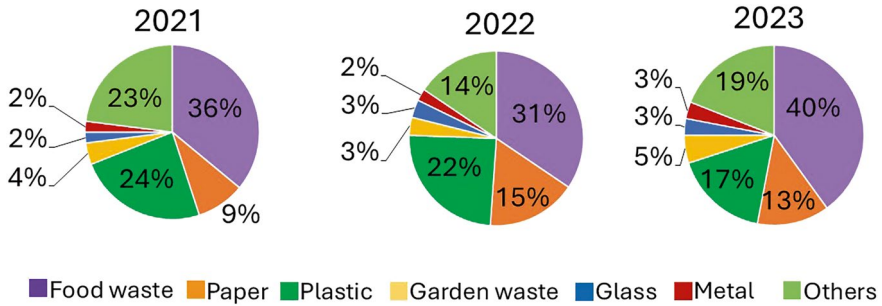
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## 12.2 Biomass Food Waste Generation in Malaysia

### 12.2.1 Overview of Food Waste

The United Nations Food and Agriculture Organization (FAO) defines FW as food appropriate for human consumption being discarded, whether after it is left to spoil or kept beyond its expiry date (Ishangulyyev et al. 2019). Basically, this occurs at different stages in the food supply chain, beginning with production and moving forward through manufacturing, distribution of resources, retail, and finally consumer consumption. This is frequently due to spoiled foods and many other reasons, such as oversupply, depending on market conditions, or individual consumer eating and shopping habits (Ishangulyyev et al. 2019). It is a major global issue that will threaten the economy, and lead to environmental, and social consequences, such as high costs to manage the variety of waste, resource depletion, greenhouse gas emissions, and food insecurity. Many countries subsequently identify and execute crucial solid waste management duties, such as prevention, recycling, and disposal, to avoid food waste management becoming worse in the future. United Nations Educational, Scientific and Cultural Organization (UNESCO) implemented “Sustainable Development Goals” (SDGs) specifically SDG 2 (Zero Hunger) and SDG 12 (Responsible Consumption and Production) addressing the initiative to reduce wasting of food, food loss, and ending of poverty.

FW can be classified as MSW which can be segregated, and categories based on their physical compositions which are organic or inorganic waste. MSW usually will be discarded by households, commercial, institutions, and industries with various forms of waste. Therefore, there are several wastes that can be included in organic waste which are FW, crop residue, paper waste, textile, and rubber waste while inorganic wastes are plastic, metal, and glass waste. In addition, FW presents as the largest fraction of waste which contains a high concentration of protein, carbohydrate, and lipid constituents, indicating a significantly higher degradability compared to other types of organic waste (Yukesh et al. 2020). FW is currently being disposed of in unhygienic landfills and could be environmentally harmful if not systematically controlled. There are 2.5 kg of greenhouse gases (GHGs) released for every 1 kg of food dumped in a landfill (Hani 2022). The environmental effects of FW are undeniable, as every meal that ends up in a landfill produces carbon dioxide gas (CO<sub>2</sub>) that contributes to pollution. Additionally, approximately 11% of the release of GHGs is derived from landfills and the solid waste industry, which is attributed to the presence of methane gas (CH<sub>4</sub>) due to the decomposition process of organic matter in MSW. In turn, this leads to more serious problems including climate change, air pollution, and water contamination. Figure 12.1 shows the distribution of MSW in Malaysia from the year 2021 until 2023 (Zainal 2023).



**Fig. 12.1** Distribution of municipal solid waste (MSW) in Malaysia from the year 2021 until 2023. \*Others refer to diapers, textiles, tetra pax, rubber or leather, and wood

Referring to Fig. 12.1, the MSW in Malaysia is increasing especially for the FW from the year 2021 until 2023. The percentage of FW is the highest portion which is in a range of 31–40% for each year (Zainal 2023;), followed by the composition of plastic (17–24%) and other types of waste (14–23%). The highest portion of FW in MSW is due to the variety of Malaysian cuisine frequently employs large quantities of raw and edible ingredients, increasing the chance of food leftovers at various levels of production, distribution, and consumption (Zainal 2023). Furthermore, societal norms such as generous hospitality and large family events encourage food over-purchasing and preparation, which leads to increased waste. In terms of economic factors, the rise in wealth has led the increased consumption by consumers with higher levels of food waste. Furthermore, inefficient and insufficient waste management systems facilities to compost and recycle the waste have exacerbated the problem by having limitations to remove the disposal of food waste from landfills.

Plastics which are made from petroleum-based rank as the second highest waste component (17–24%) (Zainal 2023) in MSW in Malaysia due to a multitude of interconnected factors. Initially, the common utilization of disposable plastics in a variety of industries, such as retail, food and beverage, household products, packaging material, and containers. The characteristics of non-degradable plastics which are convenient to use, longevity and cost-effectiveness have made the lives of consumers easier without demonstrating that it will lead to negative impacts if the utilization of non-degradable plastics increases. Furthermore, Malaysia's rapid economic growth and urbanization caused an increase in consumption habits and lifestyles, leading to greater demand for packaged products and convenience foods, which generates more plastic waste. A total 40% of plastics produced globally are commonly used for single-use packaging purposes. In Malaysia's market segment, packaging stood the highest (48%) in the plastic market share as compared to plastic use in other industries. It was reported that Malaysia still relies heavily upon plastic packaging as part of its economic support. Boey et al. (2021) reported that the advancement of biopolymer research has made polyhydroxyalkanoate (PHA) and polylactic acid (PLA) viable alternatives to replace petroleum-based plastics.

Other waste, also known as excess waste, includes a wide range of materials that are not recyclable, that do not fit into specific recycling or organic waste categories and that are widely used in the construction and manufacturing sectors. In Malaysia, other waste ranks as the third highest component (14–23%) (Zainal 2023) in MSW due to rapid urbanization and industrialization have led to an increase in consumption and production of non-biodegradable items such as diapers, textile, tetra pax, rubber or leather and wood. By addressing these underlying factors, Malaysia can work towards reducing the amount of other waste generated and mitigating its undesired environmental impact on landfills and ecosystems.

### 12.2.2 Types of Food Waste

Food waste can be comprehensively understood by categorizing it based on its origin. Kitchen waste, originating primarily from households, encompasses food scraps, peelings, leftovers, and expired items discarded during meal preparation, cooking, and consumption. Kitchen food waste can occur through various channels and scenarios, reflecting both intentional and unintentional actions within household food management practices. Firstly, over-purchasing or bulk buying of perishable items without considering consumption needs often leads to excess food that eventually goes unused and spoils, contributing to waste. Additionally, a lack of meal planning and organization may result in forgotten items in the refrigerator or pantry, eventually becoming expired or spoiled. Inefficient food storage practices, such as improper sealing or refrigeration, can accelerate food deterioration and waste. Furthermore, food preparation habits, such as peeling excessively or trimming excessively, may discard edible portions unnecessarily. Plate waste, in which leftover portions of meals are not consumed and approximately 11% are discarded, is another common source of kitchen food waste. Lastly, misunderstanding or misinterpretation of expiration dates can lead to premature disposal of food items that are still safe for consumption.

Commercial food waste involves business sectors such as restaurants, hotels, and grocery stores and can be generated through various mechanisms within the food service industry. A primary cause is overproduction and over-ordering, often driven by uncertain customer demand, seasonal fluctuations, or inaccurate forecasting. Restaurants, hotels, and other establishments may prepare or purchase excessive quantities of ingredients, leading to surplus food that ultimately goes unused and ends up as waste. Additionally, inefficient inventory management practices, such as inadequate stock rotation or poor storage conditions, can contribute to food spoilage and expiration before items are consumed. Plate waste is another significant contributor to commercial food waste, where customers may leave uneaten portions of their meals due to oversized servings, changing preferences, or dietary restrictions. Furthermore, the prevalence of strict food safety regulations and quality standards may lead to the discarding of perfectly edible food deemed unsuitable for sale due to cosmetic imperfections or nearing expiration dates. Inefficient food preparation processes, such as excessive trimming or peeling, also contribute to waste generation.

FW in Malaysia occurs in a variety of institutions, including schools, universities, hospitals, hotels, and corporate canteens (Ghafar 2017). Food waste arises from many factors within institutional settings. Firstly, large-scale food preparation in institutions often leads to overproduction and excess food, resulting in a surplus that is ultimately discarded. Additionally, menu planning and portion control may not always align with actual consumption patterns, leading to uneaten or leftover food. Moreover, food safety regulations and quality standards may prompt institutions to discard food that is still edible but nearing expiration or not meeting aesthetic standards. Furthermore, cultural norms and social expectations around hospitality in Malaysia may lead to generous servings and buffets, further exacerbating food waste. Addressing institutional food waste in Malaysia requires comprehensive strategies that focus on improved planning and forecasting, portion control, staff training on food handling and storage, as well as implementing food waste reduction initiatives such as food donation programs and composting.

Industrial FW emerges from food production, processing, and manufacturing operations, comprising by-products, trimmings, and offcuts discarded in processing facilities and manufacturing plants (Ghafar 2017). Several factors influence the occurrence of industrial food waste. For example, crops may remain unharvested during agricultural production because of factors such as weather, market demand changes, or shortages of workers, leading to waste of resources and nutrient losses in the field. Furthermore, post-harvest storage and transportation practices can spoil, damage, or degrade edible crops and increase agricultural food waste. In food processing and manufacturing facilities, various operations such as cleaning, peeling, cutting, and packaging generate by-products and trimmings that are often discarded as waste. For example, vegetable peels, fruit cores, and meat trimmings are commonly produced during processing activities. Furthermore, the production of cheese and yoghurt in the dairy sector frequently produces by-products that are then be disposed of via landfilling or incineration. In addition, inefficient operations in production processes, such as excessive manufacturing, problems with machinery, or quality control issues, can result in the production of extra or low-quality goods that do not meet market standards and are then discarded as waste. Similarly, in the packaging industry, excess packaging materials or packaging errors can result in the rejection of products and contribute to industrial food waste.

### 12.2.3 Characteristics of Food Waste

Food waste exhibits various physical and chemical characteristics that contribute to its composition and behaviour within the waste stream. Food waste can vary in form and texture, nature of volatile solids, pH, and moisture content (Yukesh et al. 2020). Food waste can exist in various forms and textures, including solid, semi-solid, and liquid. Solid food waste includes fruit and vegetable peels, uneaten bread, and meat remnants. These solid components frequently consist of known food items that retain their original structure to some extent, despite potential changes caused by

decomposition or processing. Semi-solid organic waste includes cooked remains, condiments to food, and mashed foods. These substances are frequently generated during the processing or arrangement of edibles and may have a more uniform consistency than solid refuse. Dealing with and managing semi-solid organic waste can be more difficult due to its adhesive or thick nature. Liquid organic waste includes soups, infusions, and liquids used in food preparation. These solutions are frequently a by-product of food preparation activities, food arrangement, or food manufacturing processes and can vary in thickness and composition. Liquid organic waste presents unique challenges in terms of storage and processing due to its tendency to overflow or contaminate other waste streams (Yukesh et al. 2020).

Food waste contains high concentrations of volatile solids, including a wide variety of organic compounds like carbohydrates, proteins, and fats. These volatile solids are important constituents of the organic material found in food waste, increasing its calorific value and biodegradability. Carbohydrates, including starches and sugars, are abundant in many types of food waste, including fruits, vegetables, grains, and baked goods. These substances serve as a readily available energy source for microorganisms in processes such as composting or anaerobic digestion, whereby they are broken down into simpler compounds like carbon dioxide and methane. Proteins, which can be found in meat, dairy products, legumes, and grains, are another major contributor to food waste. Proteins degrade into amino acids and other nitrogenous compounds, improving the nutrient quality of compost and generating biogas in anaerobic digestion. Fats and oils, which can be found in animal products, dairy products, cooking oils, and processed foods, are also considered volatile solids. These lipid compounds are made up of energy-rich carbon and hydrogen molecules, which microorganisms can metabolize to produce biogas or heat during composting (Slopiecka et al. 2022).

The pH of food waste can also differ depending on the type of food disposed of, varying from acidic to alkaline and the moisture content is critical in the decomposition process. Fruits such as oranges, tomatoes, and vinegar-based products, are acidic in the range of 4.1 to 7.4 and may reduce the pH of food waste (Yaser et al. 2022). Acidic foods contain organic acids such as citric acid, acetic acid, and lactic acid, which are accountable for the sour flavour profile and acidic pH level. These acidic foodstuffs, when disposed of, can reduce the overall pH of the sewage. On the contrary, foods such as vegetables, grains, and proteins have a more neutral or slightly alkaline pH in the range of 7.0 to 8.0 (Ameen et al. 2016). These specific food types contain essential minerals and proteins that can counterbalance acidity and contribute to a more neutral pH level. Nonetheless, the pH level of food waste varies depending on culinary techniques, processing methodologies, and additives used during food preparation. The pH value of food waste is an important consideration in waste management strategies because it influences the effectiveness of composting, anaerobic digestion, and other organic waste treatment techniques. Notably, acidic conditions can impede microbial processes and slow the breakdown of organic materials in compost heaps. In contrast, alkaline conditions can affect the stability and odour-handling aspects of the anaerobic digestion process.

Food waste with higher moisture levels ranging from 50% to 60% increases microbial activity and decomposition rates (Palaniveloo et al. 2020). Moisture content plays an important role in promoting the growth and metabolism functions of microorganisms responsible for decomposing organic matter in food waste. Microorganisms such as bacteria, fungi and actinomycetes thrive in moist, rich water environments. Food waste with high moisture content creates an ideal environment for these microorganisms to thrive and multiply. As a result, microbial populations grow rapidly, accelerating the decomposition of organic matter. Increased microbial activity, fuelled by higher moisture levels, leads to the rapid breakdown of organic matter in food waste. Microorganisms use enzymatic reactions to convert complex organic molecules into simpler compounds, producing energy, CO<sub>2</sub>, and water as metabolic by-products. This decomposition process produces heat, which stimulates microbial activity and fosters thermophilic conditions in compost piles or anaerobic digesters. Nonetheless, excessive moisture, while increasing microbial activity and decomposition rates, can also lead to anaerobic conditions, unpleasant odours, and leachate production in waste management systems. As a result, maintaining optimal moisture levels is critical for maximizing microbial activity and avoiding problems such as compaction, odour emissions, and process instability.

### 12.2.4 Impact of Food Waste Without Proper Management

As Malaysia is a fast-developing country, improper management of food waste at the landfills can have a significant outcome that affects various aspects such as the environment, economy, public health, and social well-being. Furthermore, Malaysia's MSW is commonly disposed of directly in landfills approximately 89% with limited processing, with only 1% receiving appropriate treatment (Yong et al. 2019). It is imperative to address this issue promptly to mitigate future adverse consequences for our country.

First, food waste negatively impacts the environment by increasing GHGs, polluting soil and water reservoirs, and exhausting natural ecosystems due to land use for waste disposal. The unregulated breakdown of food waste in the atmosphere produces GHG emissions, specifically methane gas. Globally, 7% of total GHG emissions come from food dumps. Approximately 1 kg of food waste can emit 2.5 kg of CO<sub>2</sub> and produce 0.0602 kg of CH<sub>4</sub> (Woon et al. 2021). This is very harmful as methane exists in the air continuously and contributes to climate change. Furthermore, the process of food waste decomposition produces leachate, a hazardous liquid that flows through the soil and has the potential to contaminate underground water sources by introducing pollutants such as heavy metals, pathogens, and organic substances. This contamination poses risks to ecosystems jeopardizing the availability of clean drinking water and compromising soil quality for agricultural productivity.

Furthermore, improper food waste disposal can lead to soil erosion and nutrient imbalances, affecting soil fertility and ecosystem function. Food waste can indirectly contribute to the depletion of natural habitats through the land use associated

with disposal sites such as landfills. Landfills frequently require large areas of land for both construction and operation. As the volume of food waste increases, the demand for land to store these disposal sites also increases. As a result, natural habitats such as forests, wetlands, and wildlife refuges may be converted into landfills, resulting in habitat loss and slowly leading to animal extinction. Then, landfill construction and operation can disrupt ecosystems which will alter the hydrological patterns and pollute soil and water resources through leachate run-off and greenhouse gas emissions such as methane. These findings could have far-reaching consequences for biodiversity, ecosystem services, and the overall health and resilience of natural habitats.

Second, the economic impact results from a major depletion of natural resources along the food supply chain. Food waste refers to spent investments in agricultural inputs, labour, energy, and transportation costs incurred during the stages of manufacturing, processing, and distribution. This depletion of resources reduces profitability for farmers, producers, and businesses, affecting the overall efficiency and competitiveness of Malaysia's agricultural and food industries. Furthermore, the economic costs will be affected when there is inadequate food waste management at the waste disposal. Landfilling food waste requires land, infrastructure, and ongoing maintenance, imposing financial costs on local governments and taxpayers. Furthermore, food waste causes inefficiencies in resource allocation and utilization and will impact economic sectors such as tourism, public health, and industries that rely on natural resources.

Improper disposal of food waste also poses health risks. Food waste degradation encourages pests such as rodents, flies, and cockroaches, which can act as disease vectors and pollute food and water sources, leading to the transmission of food-borne and waterborne illnesses. These pests can exacerbate pre-existing health conditions like asthma and allergies, particularly in vulnerable populations. Furthermore, improper food waste disposal can emit unpleasant odours and airborne contaminants, contributing to respiratory problems and other health concerns in nearby communities. Landfills and other waste disposal sites may further pollute soil and groundwater with toxic substances and pathogens, putting public health at risk through routes such as ingestion, inhalation, and skin contact. Furthermore, the presence of food waste in public areas may lead to unsanitary conditions and breeding grounds for bacteria and parasites, increasing the risk of infectious diseases and gastrointestinal infections. Socially, the prevalence of food waste reflects inefficient and unsustainable consumption patterns, highlighting the need for cultural shifts towards responsible consumption and waste reduction practices.

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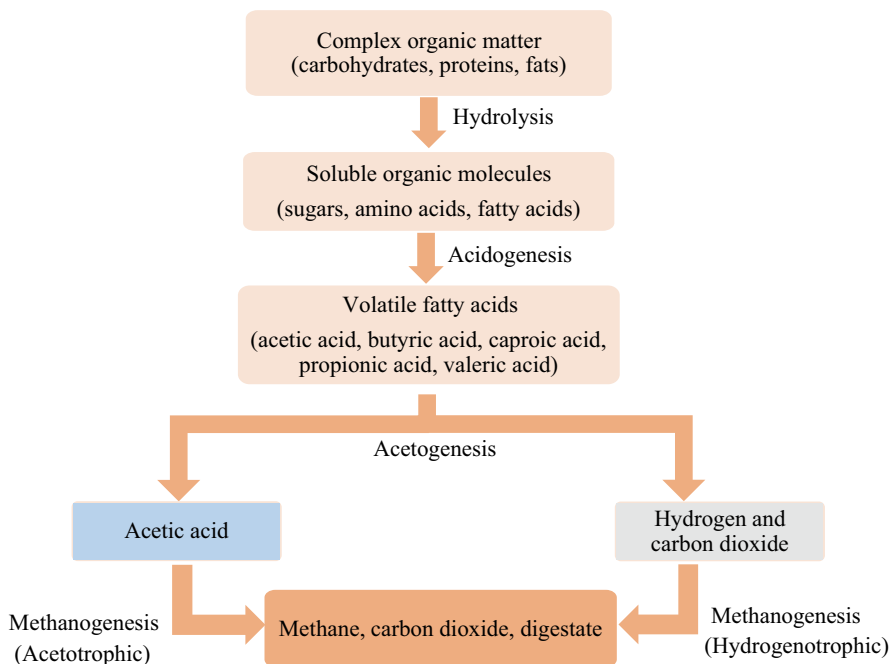
## **12.3 Valorization and Treatment Methods for Food Waste**

### **12.3.1 Anaerobic Digestion**

Anaerobic digestion (AD) is considered a prominent biological treatment method that degrades organic waste including food waste, without the oxygen supply. This method is recommended due to the minimum land area required and less energy

consumption as compared to landfilling, composting, and incineration with the merit of an environmentally sustainable approach to managing food waste. Basically, AD involves existing microorganisms undergoing the decomposition process of organic matter such as fruits, vegetables, and leftovers. Fig. 12.2 shows the anaerobic process with four significant processes of anaerobic digestion which are hydrolysis, acidogenesis, acetogenesis, and methanogenesis (Korbag et al. 2021).

Figure 12.2 shows that the first stage involves hydrolysis, in which bacterial enzymes disintegrate biopolymers such as proteins, carbohydrates, and lipids into soluble monosaccharides, amino acids, and fatty acids. During the acidogenesis period, the hydrolyzed components and dissolved chemicals undergo a conversion process that produces volatile fatty acids such as acetic acid, butyric acid, caproic acid, propionic acid, and valeric acid. Afterwards, it is the crucial phase known as acetogenesis, in which volatile fatty acids are converted into acetic acid, carbon dioxide, and hydrogen via two different pathways. The final step in the process is the methanogenesis phase, which produces primarily  $\text{CH}_4$  at levels that vary between 50% to 70% and carbon dioxide  $\text{CO}_2$  at levels ranging from 25% to 50%, as well as small amounts of other secondary products such as digestate. Methane production, commonly referred to as biogas, can be collected and used as a sustainable energy supply for electricity, heating, and transportation. Additionally, the residual material known as digestate, which results from the digestion process, boasts a high nutrient



**Fig. 12.2** The process of anaerobic digestion (AD)

content and can serve as a biofertilizer or a soil enhancer within the context of landscape architecture, plant nurseries, and the agricultural sector.

In the study conducted by Woon et al. (2021), AD is used as an essential technique for the management of sustainable food waste in Malaysia, with major environmental advantages. The method described in the study transforms 80% of daily food waste into electricity, reducing carbon emissions by 0.4% and contributing 1.1% to the country's total electricity consumption. Woon et al. presented an innovative framework that includes an optical sorting system to improve source segregation. This system allows for the categorization of food waste using distinct green optic bags, avoiding the need for extensive behavioural modifications in the population. This system's effectiveness is highlighted through a life cycle assessment, demonstrating that electricity production from food waste through AD is the most environmentally friendly scenario, mitigating 4.92104 disability-adjusted life years (DALY) and 6.30 potentially disappeared fraction of species over a square metre per year (PDF.m<sup>2</sup>.y) impacts on human health and ecosystem quality.

AD has several environmental benefits, including lowering GHG emissions, reducing the odours and pathogens associated with food waste decomposition, and diverting organic waste from landfills. Furthermore, it offers the potential to generate renewable energy and valuable resources from food waste, thereby contributing to a more sustainable and circular approach to waste management. The AD method has a lot of qualitative benefits such as reducing the amount of municipal solid waste, transportation cost of carrying waste to landfill, emissions and leachate of landfill, increasing the life span of landfills and reducing land use. The utilization of AD for energy production presents noteworthy environmental benefits. The biogas generated serves as a sustainable and eco-friendly energy alternative capable of displacing traditional fossil fuels in the realm of power and heat generation. This substitution plays a pivotal role in the global initiative to diminish dependence on finite energy resources and address climate change. Furthermore, the emission levels associated with the biogas production process via anaerobic digestion are comparatively minimal, thereby amplifying its environmental allure.

AD offers various economic and environmental benefits. It generates income by selling biogas and digestate. This feature makes it a desirable choice for waste management and agricultural operations. Using digestate as a fertilizer reduces the need for chemical-based fertilizers, resulting in cost savings and environmental benefits. The adaptability of AD is also significant. AD can process a variety of organic materials, such as waste from agriculture, food waste, and sewage waste. The approach's flexibility makes it applicable in various settings, including rural farms and urban waste management systems.

Yong et al. (2019) studied the process of turning MSW of Malaysia into biogas using AD, demonstrating the economic and environmental benefits of this renewable energy source. The study reported that 45% of MSW is composed of organic materials, which can be converted into 3,274,812.51 m<sup>3</sup>/day of biogas with 56.62% methane production. This production could yield 7494.08 MWh/day of electricity and 13,013.73 tonnes/day of bio-fertilizer. This strategy not only addresses the financial challenges associated with landfill disposal's current average operational

cost of RM148/tonne/day, but it also transforms it into a profitable revenue-generating enterprise. This approach's viability evinced its ability to significantly reduce carbon emissions while achieving an economic profit from the sale of electricity and bio-fertilizers. The electricity can be sold back to the grid at RM 0.3997/kWh under the feed-in-tariff mechanism, while the fertilizer can be sold for an average of RM 515/tonne. This study demonstrates AD's transformative potential in modifying organic waste management from a financial burden to a sustainable and profitable model that promotes both environmental responsibility and energy production.

However, AD also faces challenges in economic, technological, and social aspects. The accumulation of harmful intermediate products is basically the effect of inadequate optimization and process control which is resulting in a decrease in biogas yield. The AD can rapidly convert putrescible food waste into volatile free acids (VFAs), resulting in a decrease in pH without a proper buffer system. Food waste contains nitrogen, which prevents acetolactic methanogens and produces ammonia (NH<sub>3</sub>) during digestion. Hydrogenotrophic methanogens continue to produce biogas. However, food waste lacks trace elements required for the accumulation of volatile fatty acids (VFAs).

### 12.3.2 Composting

Composting is the aerobic thermophilic decomposition of organic waste by microorganisms such as bacteria, fungi, and other decomposers into a sanitary, humus-rich product which is compost, and the by-products are carbon dioxide, water, and heat. Some of the bacteria, namely *Lactobacillus* sp. and *Acetobacter* sp. (mesophilic phase) and *Bacillus* sp. and Actinobacteria (thermophilic phase) widely utilized for composting (Palaniveloo et al. 2020). The resultant compost product may be used as a soil supplement and organic fertilizer. The process is typically done in an aerobic condition, an oxygen-rich environment, aided by a proper balance of carbon-rich and nitrogen-rich from the food waste, and adequate moisture and oxygen levels. The rate and extent of the transformations depend on available food waste and the parameters used to control composting.

For example, the study by Al Mussa Ugak et al. (2022) utilized 0.61 kg Sabah ragi in the presence of *Saccharomyces cerevisiae* and *Saccharomycetales* sp. on 128 kg of food waste and dry leaves composting. The composting process was conducted using an in-vessel passive aerated bioreactor with turning every 3 days for 40 days. Several parameters such as temperature, total organic carbon, moisture content, pH, conductivity, and carbon-nitrogen ratio (C: N) were monitored. During the composting process, the highest temperature of 54.2 °C and the highest heat generation rate per initial mass of compost dry matter of 4098 kJ/kg/day was achieved on day 7. Furthermore, when compared to other similar studies, the study by Al Mussa Ugak et al. achieved a faster thermophilic phase which is more than 45 °C, a longer thermophilic period (4 days), and a higher cumulative temperature which improved the stability and maturity of the composting materials.

Food waste composting is commonly carried out using two distinct methods, namely the in-vessel system and the windrow system (Lim et al. 2017). The in-vessel system entails enclosing food waste in a sealed environment such as a silo, drum, agitated bed, closed container, or batch container for composting. The in-vessel system proves to be a more efficient composting system compared to the windrow system as it requires less space and provides superior management of gas and leachate discharge. Moreover, the in-vessel system aids in reducing the retention time of food waste during the mesophilic and thermophilic phases. On the other hand, the windrow system represents an open composting system structured like a triangular pile. The ideal size of this pile is largely affected by the constraints imposed by weather conditions and the physical characteristics of substrates. Normally, for the optimal conditions for composting, the base of the pile can vary in length from 2 to 6 meters in width and 1–3 meters in height (Hamid et al. 2019).

Keng et al. applied an open pile composting, consisting of a mixture of food waste and leaves with a ratio of 4:1, as this weight ratio is equivalent to an initial C: N of approximately 30:1 (Keng et al. 2020,). One complete compost pile on average consists of approximately 3900 kg of food waste and 975 kg of leaves. This process is repeated for the entire month and each day the food waste and leaves are added to the previous layers. The successful composting comes from the right ratios of food waste and the bulking agent which gives the initial C: N ratio of approximately 30:1 and a moisture content of 50–60%. For a community-level composting system with the capacity of treating 6 tonnes of food waste per month, the process requires 7 months to obtain a mature compost and yields approximately 11% wet basis (or 30% dry basis) of compost product with respect to the total organic waste input. The success of this community-scale composting method is validated by the quality of the resultant compost, which meets the Malaysian SIRIM MS 1517:2012 organic fertilizer standard, with organic matter (52.5%), C:N ratio (12:1), moisture level (21%), total Kjeldahl nitrogen (2.62%), phosphorus as  $P_2O_5$  (P) (3.39%), and potassium as  $K_2O$  (K) (0.58%).

Compost can impact environmental benefits such as improving soil fertility, structure, and water retention in agriculture, landscaping, and gardening. Moreover, composting makes diverting organic waste from landfills easier, lowering GHGs, and applying a close-loop system by closing nutrient cycles by reintroducing valuable organic matter into the soil. Additionally, composting promotes sustainable waste management practices and fosters a stronger connection to the natural cycles of life and decomposition. Furthermore, composting is a cost-effective waste management method as compared to incineration due to lower operating and investment costs because it relies on the natural activity of microorganisms for the decomposition process and utilizes a simple technique with minimal space requirement.

Several factors must be considered while conducting the composting method, including oxygen saturation, temperature, pH, moisture content, C: N, porosity, and particle size. Firstly, the presence of oxygen plays a crucial role in enhancing various processes during composting by controlling the temperature, and moisture, and ensuring the smooth advancement of biological activities under aerobic conditions. The ideal oxygen level required for aeration rate typically ranges from 15% to 20%

(Palaniveloo et al. 2020) and good aeration is important for the maturity of the compost. The indication of compost maturity can be observed in its colour which is black and has smells like earthy aroma. However, increasing oxygen above the ideal oxygen level will lead to adverse effects such as releasing GHG emissions into the atmosphere.

Temperature regulation is also important due to the potential inhibition of the composting process and reduction in decomposition rate when thermophilic bacteria's tolerance limits are surpassed. The range of temperature most conducive for composting is within 40–65 °C and various essential techniques can be employed to regulate temperature during composting. For example, the maintenance of adequate moisture levels and oxygen concentration plays a crucial role in fostering the desired temperature. Moreover, the composition of compost materials holds significant importance. Turning or mixing the compost materials aids in the uniform distribution of heat and moisture, thereby preserving the optimum temperature. Furthermore, insulation and the selection of appropriate bioreactor sizes are key factors in ensuring temperature control.

The pH level changes during the composting process, which influences the biological process and final resultant products. The pH influences the activity of the microorganisms that decompose organic matter in compost. The values of pH below 5.5 can inhibit their activity, resulting in a longer composting time. Controlling pH is crucial in reducing GHGs, as exceeding the optimal range (more than 9) can release harmful substances such as ammonia and nitrogen dioxide (Palaniveloo et al. 2020). GHGs may contribute to global warming and climate change which can trigger other side effects to all living organisms. The optimum pH range suggested by many researchers at the end of the composting process is 7.0–8.5.

Moisture content is vital for composting and affects microbial interactions. Inadequate moisture can cause nutrient loss and secondary pollution. For optimum results, feedstock materials should have a moisture content of 40–65% during the first phase of the process. Microorganisms require water to function and survive. A lack of moisture impedes the effective decomposition of organic matter. The levels of moisture content less than 40% have been shown to reduce microbial activity while the excess moisture in compost can reduce oxygen levels, resulting in anaerobic conditions. This leads to inefficient processes and the release of unpleasant odours and toxic substances. The ideal moisture content for the final compost product is approximately 30% and higher moisture levels which are around 70% lead to the release of hydrogen sulphide.

Compost quality will be influenced by the C:N ratio to balance and promote the optimal conditions for microbial activity. The suggested ideal ratio of C:N is between 20 and 30:1 (Azis et al. 2023). Carbon content will serve as an energy source for microbes whilst nitrogen is required for protein, amino acid, and nucleic acid synthesis. Aerobic microbes require a higher C:N ratio because they decompose at a faster rate. Higher C:N ratios, beginning at 40:1, cause slower degradation because excess carbon and insufficient nitrogen slow aerobic microbe growth (Azis et al. 2023). In contrast, C:N ratios below the recommended level result in nitrogen under-utilization, with the extra nitrogen released into the environment as ammonia

or nitrous oxide, which can cause odour issues. In addition, to achieve the optimal C:N ratio, a technique of mixing organic materials is used. The substances that represent the carbon content are added to the compost to increase the carbon value, and nitrogen-rich content is supplied to lower the carbon ratio.

Compost porosity and particle size are also important factors to consider. Porosity, or the amount of pore space filled with air in compost, is critical for temperature control. Allows air to flow freely through the compost, ensuring optimal temperatures. Low porosity in compost can cause overheating. The composting process will occur under anaerobic conditions, which are less efficient and produce unpleasant odours to the environment when there is improper circulation of airflow. The optimal porosity range is usually between 35% and 60% (Azis et al. 2023). Particle size and porosity are related. Smaller particles clog the compost's small pores, reducing airflow. Controlling particle size prevents the compost from overheating and ensures adequate oxygen supply and the study by Ho et al. suggested a particle size range of 5.0–20.0 cm.

### 12.3.3 Landfill

A landfill is a general facility whereby food waste and other solid waste materials are deposited and stored in the ground as it is cost-effective and simple to apply. This is due to the landfilling requires less high-technological equipment and machinery to operate. At present, 80% of food waste generated in Malaysia is disposed of at landfill sites (Ghafar 2017). The selection of a suitable landfill site based on the site's location, geology, and hydrogeology with depth evaluation can minimize risks to public health, protect natural resources, and comply with regulatory requirements. Also, the planning for landfill construction includes strategies to minimize leachate and gas generation and measures to prevent flooding and manage waste covering or capping.

From the study of Malakahmad et al. 2017, Jeram Sanitary Landfill (JSL), which is located at Mukim Jeram, Selangor, has an expected lifespan of 16 years, reported by Worldwide Landfills Sdn Bhd. The JSL had an initial design capacity of 1250 tonnes per day and over 2500 tonnes of waste are disposed of in the landfill. For instance, in 2015, the landfill received 925,139 tonnes of waste at a daily average rate of 2535 tonnes. Data on dumped solid waste (SW) in the landfill between 2007 and 2015 was provided by Worldwide Landfills Sdn Bhd, while estimated future waste quantities that will be dumped in the landfill up to 2023 have been projected at an annual growth rate of 3.3% as reported by Fazeli et al. for waste generation growth rate in Malaysia (Fazeli et al. 2016). The JSL received over 1,160,000 tonnes of waste in the year 2022. At the end of its lifespan, approximately 14,495,000 tons of waste will be dumped at the landfill over its 16-year life span and it mainly comprises approximately 45–60% of CH<sub>4</sub> and 40–60% of CO<sub>2</sub>.

As a result, the continuation of site monitoring is required to ensure operational safety, and this practice continues even after the site has been shut down. Food waste landfills are typically made up of lined cells or pits where waste is deposited

and compacted to maximize space efficiency. Protective liners and leachate collection systems are installed to prevent soil and groundwater from being contaminated by leachate, a liquid formed when water filters through waste. The landfill system is subject to strict guidelines and evaluations to ensure that its sustainability objectives are met while lowering potential negative effects on public health and the environment.

There are two types of classification systems for landfills based on decomposition processes and level of landfills. For the decomposition process, the system is anaerobic landfill, anaerobic sanitary with daily cover, improved anaerobic sanitary with buried leachate collection pipes, semi-aerobic with natural ventilation and leachate collection facilities, and aerobic with forced aeration. Then, there are five levels of landfills such as open dumping, controlled tipping, sanitary landfills with a bund (embankment and daily soil covering), sanitary landfills with a leachate recirculation system, and sanitary landfills with leachate treatment systems. Malaysia has applied the second classification system for landfilling.

Landfill could be environmentally harmful if not controlled. Food waste at the landfill goes through several processes before being converted into methane. The first step in the process is the breakdown of food waste using microorganisms or called the hydrolysis process. Through the hydrolysis process, the compound elements will undergo chemical breakdown because of a reaction with water. The hydrolysis-degraded compounds are then further metabolized in the acidogenesis phase by using Acidogenic bacteria such as *Clostridium* (*Firmicutes*), *Peptococcus* (*Firmicutes*), *Bifidobacterium* (*Actinobacteria*), *Desulfovibrio* (*Proteobacteria*), *Corynebacterium* (*Actinobacteria*), *Bacillus* (*Firmicutes*), *Pseudomonas* (*Proteobacteria*), and *Desulfobacter* (*Proteobacteria*) (Laiq Ur Rehman et al. 2019). They will degrade these compounds, producing fatty acids, alcohols, and other organic acids. The bacterium is further metabolized during the next step, which is the acetogenesis phase, to produce acetic acid; it is followed by the methanogenesis process which generates methane from food waste using methanogenic archaea will convert acetate, hydrogen, and carbon dioxide into methane gas.

The production of methane emissions has strong heat-trapping properties that can trap the radiation of solar in the atmosphere and again will lead to global warming and climate change (Bong et al. 2017). The study by Kurniawan et al. stated that by 2025, CO<sub>2</sub> and CH<sub>4</sub> emitted from landfills worldwide would reach 1000 and 16,000 Gg, respectively (Kurniawan et al. 2023). Although CH<sub>4</sub> consists of 18% GHG emissions, the gas has a 21-fold higher global warming potential (GWP) than CO<sub>2</sub>. While biogas can be captured and utilized as renewable energy, CH<sub>4</sub> emissions from landfills reflect landfill implications on climate change. Within 10 years, open dumping could be responsible for a tenth of man-made GHGs. As a result, the developing world is under pressure to responsibly dispose of large amounts of waste to decrease CO<sub>2</sub> emissions by 45% by 2030 and achieve carbon neutrality by 2050. Despite being a common waste management option in Malaysia, landfills are widely considered unsustainable in the long term due to their negative environmental impact and limited waste disposal capacity. When landfills meet their maximum capacity, it becomes more difficult to build a new landfill due to an insufficient

amount of available land, increasing costs of land, and high demand, particularly in urban areas where the population is growing. Currently, there are 141 operational landfills and 182 closed landfills in Malaysia based on Table 12.1 (MHLG 2021). Table 12.1 shows that the operating landfill in Malaysia is decreasing and several agencies and environmental activists, including Alam Flora and Malaysian Green Technology and Climate Change Corporation, have previously warned that there would be no space available by 2050 if no immediate initiative is taken to reduce waste.

### 12.3.4 Incineration

The incineration method involves the combustion at high temperatures of organic materials in specially designed incineration facilities. The mechanism requires a furnace or boiler with a high-pressure combustion process and the range of temperatures is 850–1100 °C, which generates hot combusted gas containing N<sub>2</sub>, CO<sub>2</sub>, H<sub>2</sub>O, flue gas, O<sub>2</sub> and non-combustible residue (United Nations Environment Programme 2017). When the hot flue gases enter the heat exchanger, they act as a hot stream, generating steam from the water. The high-temperature combustion converts organic matter into ash, gases, and heat energy. Various applications can use the heat that has been recovered such as generation of electricity, heating and industrial sectors, and it helps to reduce the volume of food waste, making it easier to dispose of and reducing the amount of landfill space required. In Malaysia, there are four small-scale incinerators in Langkawi (with a capacity of 100 tonnes per day operated by Drizzle Engineering Sdn. Bhd.), Tioman (15 tonnes per day operated by Drizzle Engineering Sdn. Bhd.), Pulau Pangkor (20 tonnes per day operated by DRB-Hicom

**Table 12.1** Distribution of operating and closed landfills across states in Malaysia (MHLG 2021)

States in Malaysia	Total of landfill site	Operating	Closed
Perlis	3	1	2
Kedah	15	4	11
Pulau Pinang	6	2	4
Perak	31	16	15
Selangor	20	8	12
Wilayah Persekutuan	11	1	10
Negeri Sembilan	19	3	16
Melaka	8	1	7
Johor	37	8	29
Kelantan	20	10	10
Terengganu	18	9	9
Pahang	32	10	22
Sabah	42	22	20
Sarawak	61	46	15
Total	323	141	182

Environmental Services), and Cameron Highlands (40 tonnes per day operated by DRB-Hicom Environmental Services) (MHLG 2021).

The incineration procedure comprises the following phases which are combustion, energy recovery, stack emissions, and cleaning system. The initial phase of combustion is accelerated by consistently introducing the feed into a furnace and subjecting it to combustion at elevated temperatures which is 850 °C for more than 2 s, with an adequate air supply to ensure thorough feed combustion. However, without sufficient air supply, carbon monoxide and dioxins are generated. The second phase of energy recovery generates power in the steam turbines, which use the heat energy from the combusted feed. This phenomenon occurs when steam propels a turbine that is linked to an electrical generator. The heat can also be used for other purposes, such as heating the boiler's feed water. Several sub-processes support the cleaning system, the third stage. The exhaust gas cleaning, in which the exhaust gas is purified in accordance with the protocols of advanced pollution control systems; after that, scrubbers are employed to neutralize and eliminate any potentially acidic gases, including hydrogen chloride and sulphur dioxide, by spraying lime powder onto the hot exhaust gas. Activated carbon injection is used to absorb organic and heavy metal pollutants, including dioxins, that may be present in the exhaust gas. The bag house filter removes any dust particles from the exhaust gas and the nitrogen oxide, which is a common contributor to urban smog, will be removed via selective non-catalytic reduction by reacting it with ammonia or urea.

There are many benefits from the incineration method, which is a decrease in waste volume and mass. Research indicates that this approach can result in a reduction of overall waste quantity by as much as 95% and a decrease in the solid volume of the original waste by approximately 80–85%. Other evidence suggests that incineration can lead to a reduction in waste mass of approximately 70% and a volume can decrease by up to 90%. Furthermore, incineration serves as a primary means for generating energy which involves elevated temperatures ranging between 750 and 1100 °C, to burn the waste in the presence of oxygen. As a result, heat and energy are generated, thereby establishing incineration as a traditional thermal technology for converting waste into energy, functioning optimally within the temperature range of 850–1200 °C. The residual products of incineration also possess significant utility. When agricultural waste is burned, the resulting ash contains valuable elements such as silica and aluminium which can be utilized in engineering applications to improve the quality of products. Specifically, fly ash can improve acidic soils by enriching them with essential nutrients, thereby enhancing agricultural productivity.

Yong et al. (2019) have described the Kajang Waste-to-Energy (WTE) facility, which includes a refuse-derived fuel (RDF) plant and is said to be Malaysia's most comprehensive incineration system because it incorporates the RDF process. WTE and RDF technologies are emerging energy recovery strategies in Malaysia, particularly in solid waste management. However, existing RDF technology can only recover 77% of the energy contained in MSW as fuel. To improve efficiency, the operational framework will include biogas produced from organic waste via AD, which is expected to increase energy extraction from MSW to 83%. From 2010 to 2030, MSW production increased from 6.37 to 13.38 million metric tonnes,

significantly increasing the potential for WTE applications. The calorific value of MSW in Malaysia falls within the range of 1500–2600 kcal/kg, indicating substantial energy prospects for the incineration plant in Malaysia, which is poised to generate approximately 640 kilowatts per day based on the specified calorific value.

According to the study of Yong et al. (2019), XCN Technology Sdn. Bhd., in Malaysia established an incineration facility in June 2011 situated on a land area of 0.8 hectares at Teluk Cempedak, Pangkor Island. Employing the Autogenous Combustion Technology (ACT), the facility has the capacity to decrease the incoming waste volume by as much as 94%. The facility began operations in January 2012 and was later handed over to the Ministry of Housing and Local Government. Capable of incinerating up to 20 tonnes of MSW daily, the facility at Tioman Island also hosts two additional mini incinerators with the capacity to combust 3221 tonnes of MSW annually. In Cameron Highland and Labuan, two more mini-incinerators were constructed, each capable of combusting 15 and 60 tonnes of MSW per day, respectively. The incineration plant in Langkawi stands out as the most extensive facility, pioneering the WTE technology concept in Malaysia and constructed at a cost of RM68 million. The Langkawi plant is projected to process 100 tons of waste per day to generate 1 MW of electricity.

Despite the apparent benefits associated with incineration, a variety of challenges have been identified. These challenges must be considered to conduct a thorough assessment and direct efforts towards improving the technology. One potential hindrance that may arise is the production of harmful gases. In situations where combustion takes place without a sufficient air supply, harmful by-products such as carbon monoxide and dioxins could be generated. The dioxins have been recognized as dangerous pollutants, emphasizing the importance of reducing their emission. Another significant issue concerns the purification of flue gas. Clusters of solid ash particles carried by the flue gas pose risks to the environment and human health if not adequately removed through filtration. Although the purification system is advanced, it is intricate and demands meticulous maintenance. Apart from purifying exhaust gases, the use of scrubbers and activated carbon injection, as well as several other sub-processes, are essential to ensure compliance with environmental standards. Any malfunction in these systems could lead to increased emissions of pollutants. Moreover, residues like bottom ash, boiler and economizer ash, fly ash, and others are produced post-incineration. Managing these residues poses logistical and environmental challenges.

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## **12.4 Application of Food Waste After Valorization and Treatment**

### **12.4.1 Fertilizer**

The agricultural sectors in Malaysia, particularly farmers, extensively utilize fertilizers for the cultivation of their crops. Malaysia relies extensively on fertilizer imports from China, India, Vietnam, the United States, Indonesia, Canada, and Russia. Malaysian imports of nitrogen (N), phosphate (P), and potassium (K) in

huge amounts of approximately RM4.3 billion. China emerged as the primary nitrogen importer, accounting for 54.2% of Malaysia's total nitrogen import value, while Egypt and Canada held the top positions for phosphate and potassium imports to Malaysia, respectively. The escalating prices of fertilizers in Malaysia have emerged as a significant issue of concern. Consequently, farmers and producers find themselves grappling with increased cost burdens, leading to a surge in production expenses and a subsequent reduction in farmers' incomes (Department of Statistics Malaysia 2022).

Conversely, consumers are compelled to bear the brunt of higher prices for food and fresh produce. Mostly, the importation of fertilizers is derived from inorganic (chemical) fertilizers and farmers have been introduced by the governments to these fertilizers a long time ago. So, the usage of organic fertilizers has rarely been used by modern farmers nowadays as they lack knowledge and are not aware of the benefits of the usage of organic fertilizers in agriculture sectors. Thus, the valorization of food waste into fertilizer is a sustainable solution to promote agricultural sustainability and manage organic waste disposed of. Organic fertilizer presents itself as an environmentally friendly replacement for conventional inorganic (chemical) fertilizer, with the goal of reducing reliance on chemical fertilizers in agriculture. This alternative nutrient source improves the sustainability of the soil, and plant development, and minimizes environmental contamination.

Generally, organic fertilizers are characterized by their specific chemical composition and high analytical value, providing plant nutrients in an accessible form. Organic waste for utilization as agricultural fertilizers can be classified into several categories which are animal-based organic waste (manure), compost (plant sources and food waste), and urban waste (sewage sludge and household waste) (He et al. 2023). Organic fertilizers differ from chemical fertilizers as they consist of materials derived as by-products of vegetables, animals, or minerals. The decomposing matter sourced from these origins naturally breaks down, enriching the soil with nutrients and minerals. These fertilizers can deliver a balanced and adequate supply of nutrients to plants, thereby supporting their health and vitality through proper lawn care practices.

Moreover, the stimulation of crop growth and enhancement of yield necessitate the presence of three key nutrients, namely NPK while there are some micronutrients such as iron, chlorine, copper, manganese, zinc, molybdenum, and boron are essential in small quantities to facilitate plant growth and serve as essential components in various enzymatic processes. The primary inorganic nutrient crucial for protein synthesis is nitrogen. Its significance stems from its ability to facilitate critical biological processes, most notably photosynthesis in plants, as well as its presence in amino acids, the basic building blocks of proteins. Nitrogen is also involved in catalyzing enzymatic reactions, given that enzymes are categorized as a subset of globular proteins. The initial indication of nitrogen deficiency is manifested through chlorosis, observed in the older foliage of plants, where the colour transitions from a subdued green to a vibrant yellow (Lee-Ann Ataikiru and Ajuzieogu 2023).

Phosphorus is regarded as an essential nutrient for optimal plant growth and for the successful completion of a plant's development cycle. Adequate levels of

phosphorus are crucial in promoting root proliferation, strengthening stalks and stems, and increasing the yield of flowers and seeds. In contrast, phosphorus deficiency can cause delayed maturation, poor quality of fruit, and disrupted seed development. As a result, potassium is required for photosynthesis, protein synthesis, and enzymatic reactions that can boost photosynthetic efficiency and nutrient production. Additionally, potassium contributes to cellulose synthesis and facilitates the movement of sugars and starches throughout the plant. Potassium, known as the “quality nutrient,” has a significant impact on characteristics such as size, shape, colour, taste, shelf life, and fibre content. It also promotes root growth and improves a plant’s resilience to drought conditions (Hamid et al. 2019).

From the study of Kadir et al. (2016), the objective of the research is to transform food waste produced by Makanan Ringan Mas, a medium-scale enterprise situated in Parit Kuari Darat, Batu Pahat, through the implementation of a composting technique with controlled parameters such as temperature and pH level. Banana peels of 250 g are used as the fermentation liquid for 7 days, while soil and coconut husks serve as composting materials. The findings from the composting process indicate that the pH levels in most reactors exceed 5, reaching a nearly neutral state. This observation suggests that microbial respiration in the meticulously controlled composting reactor was impeded, signalling the onset of the maturation phase. During the composting process, the temperature fluctuated between 25 and 47 °C, indicating active composting. The NPK content ranges from 35,325 mg/L to 78,775 mg/L for nitrogen, 195.83 mg/L to 471 mg/L for phosphorus, and 422.3 mg/L to 2046 mg/L for potassium, all of which are considered adequate for agricultural purposes. A comparison was drawn against commercially available organic compost, revealing only minor discrepancies. Nevertheless, when contrasted with standard fertilizers, the NPK content in organic compost is considerably reduced.

The study of Malakahmad et al. 2017 investigated the mixing of food waste and yard waste with the addition of effective microorganisms (EM) and Shimamoto enzyme (SE) for the quality of compost. Four compositions of feedstock with different yard waste (YW) and food waste (FW) ratios were tested. The compositions were 70% YW, 30% FW, 80 FW, 20% FW, 90% YW 10% FW, and 100% YW. The physicochemical properties of compost including pH, moisture content and C:N ratio were monitored throughout the experiment. Furthermore, the quality of compost and its potential for direct application after production were evaluated based on germination index (GI) and nutrient content (NPK). The compost samples had a pH ranging from 7 to 9 and a moisture content of 15.45–32.13%. The initial C: N ratio of all feedstocks was decreased throughout the composting process by more than 50%. The seed germination test showed that only 70%YW 30%FW feedstock produced immature compost with GI 80%. The highest GI of 130% was obtained when FW represented 10% of the feedstock with the addition of EM. Average concentrations of nitrogen, phosphorus and potassium were 1.73, 1.21 and 1.66% in the case of EM additive and 1.47, 0.56 and 1.74% in the case of SE additive. Maturity tests of germination index and NPK value indicated better quality of compost with EM additives compared to those with SE additives. Composts produced in this study have shown superior quality compared to the ones produced in the window method.

The biological transformation of yard waste instead of landfilling is a promising solution to overcome growing problems of solid waste management and reduce air and water pollution. Vessel composting of yard waste instead of its windrow or aerated pile composting in Cameron Highlands, where the lands are in great demand, is an environmentally friendly and sustainable approach for solid waste management.

The advantage of utilizing organic fertilizer is the gradual release of nutrients compared to chemical fertilizers. This gradual nutrient release process enables plants to effectively absorb the fertilizer in a more organic manner, thereby preventing the risk of over-fertilization that could potentially harm the plant. Moreover, organic fertilizers can improve soil absorption, and air circulation and do not have side impacts to the soil. The harmful chemicals present in synthetic fertilizers tend to seep into the soil, eventually contaminating water sources and being ingested by various wildlife species. Conversely, organic fertilizers lack these detrimental compounds, eliminating the associated risks even with frequent usage. Furthermore, the immediate hazards posed by chemical fertilizers to children and pets playing in gardens or on lawns are not an issue with organic fertilizers. Unlike their synthetic counterparts, organic fertilizers contribute to reducing soil acidity without causing leaching and without harming beneficial soil microorganisms. Overall, organic fertilizer is the preferred fertilizer to be used as they have more advantages compared to disadvantages based on Table 12.2. To achieve sustainability in Malaysia, agriculture sectors supposedly moving towards eco-friendly practices to ensure food security, land and environmental sustainability from now on until the next future.

#### **12.4.2 Animal Feed**

Malaysia's livestock population includes both ruminants (buffalo, cattle, goat, and sheep) and non-ruminants (swine and poultry, particularly chicken and duck). Malaysia's ruminant livestock industry is dominated by small-scale farmers, while the non-ruminant sector is made up of large-scale commercial businesses. Currently, Malaysia heavily relies on imported corn, soybean and barley grains for poultry and ruminant feed. According to World Grain, in 2018, Malaysia imported 4 million tonnes of grain corn, mainly from Argentina and Brazil, while various grains are sourced from the United States, Ukraine, Russia, Canada, India and Australia. Farmers, in the year 2023 were experiencing the necessity to allocate up to RM 80 for the procurement of a 50 kg sack of cattle feed, a notable increase from the RM 45 price point observed in January 2022, owing to the surge in imported livestock feed materials. So, the valorization of food waste can be one of the alternatives to minimize the imported animal feed into our country and help farmers enhance their income by reducing the cost of animal feed. In addition, the production of animal feed from food waste should be considered with Malaysia laws which is the Feed Act 2009 (Act 698) as it is established to regulate the feed quality by controlling the importation, manufacture, sale and use of feed and feed additive and also to ensure that feed satisfies the nutritional requirement of animals, is not harmful to animals

**Table 12.2** Characteristics comparison of organic fertilizer and chemical fertilizer

No.	Characteristic	Organic fertilizer	Chemical fertilizer	References
1.	Sources	Food waste, plant waste and animal manure	Human-made, chemical substances	Dhiman et al. (2021)
2.	Cost of production	Cheaper (RM4.75–30.00 per day)	Expensive (more than RM 30.00)	Hadi Ishak et al. (2021)
3.	Nutrient concentration	Less rich in plant nutrients	Rich in plant nutrients	Dhiman et al. (2021)
4.	Duration of nutrient release	Balanced, slow and easily available	Soluble and easily available	Dhiman et al. (2021)
5.	Absorption	Slowly absorbed by plants	Quickly absorbed by plants	Dhiman et al. (2021)
6.	Composition of N:P:K	N: 0.60–10.10% P: 0.10–6.00% K: 0.40–4.00%	N: 13.00–46.00% P: 6.00–54.00% K: 37.00–60.00%	Patel (2010)
7.	Presence of humus	Provide humus for the health and fertility of soil	Does not provide humus to the soil	Dhiman et al. (2021)
8.	Side effects	No side effects. Improve the physical condition of the soil, water retention and microbial activity	Causes harm to living organisms, disturbs soil ecology, pollutes groundwater and emissions of GHGs such as methane, carbon dioxide and nitrous oxide.	Dhiman et al. (2021)
9.	Longevity	Sustainable	Non-sustainable	Dhiman et al. (2021)
10.	Safety	Safe	Harmful	Dhiman et al. (2021)

and is not contaminated. From this law, the processing of animal feed should be in the right way as it will affect human consumption as well.

From the research of Betchem et al., solid state fermentation (SSF) has been extensively researched as one of the prominent methods employed in the conversion of food waste into high-value products for poultry animals among various approaches (Betchem et al. 2024). This method involves fermenting food waste in a bioreactor with a standardized carbon-to-nitrogen ratio of 2:1. The fermentation process will be run with the selected microorganisms for about 120 h. The ratio of C:N, the pH level, the aeration, the intensity of agitation, the temperature conditions, the application of antiseptic methods, and the effectiveness of sterilization were systematically regulated during the entirety of the fermentation procedure. The resulting outputs, specifically the poultry feed, exhibited a uniform standard in both quality and nutritional content. The crude protein, crude fat, crude fibre, total ash, and total energy content of chicken feed have adhered to the standards specified by Malaysian regulations. Conversely, in accordance with international regulations, the chicken feed has complied with the stipulated 18% crude protein content. This compliance is of utmost importance as it allows for the utilization of chicken feed in both domestic and international markets.

Whilst for ruminant animals, corn silage presents itself as a viable option due to its numerous benefits for utilization in ruminant nutrition. Indigenously cultivated maize offers a reliable source of premium feedstuff that can be ensiled for extended periods. During the ensiling process, the primary focus lies on the impact of plant nutritional composition on the ensuing fermentation process. Inadequate fermentation may result in substantial dry matter (DM) losses, diminished aerobic stability, and compromised overall quality of the silage intended for livestock consumption. Additionally, the diverse genetic makeup of different corn cultivars can exert a substantial influence on both yield and nutritional composition. Corn is cut into small fragments before being deposited into a hermetically sealed storage receptacle, such as a silo. It has been articulated that the fodder elements experience anaerobic fermentation for about 21 days facilitated by microorganisms, predominantly lactic acid bacteria, within the confines of the silo. Throughout this anaerobic fermentation process, the lactic acid microorganisms transform the carbohydrates present in the fodder elements into organic acids, predominantly lactic acid. This series of events engenders an acidic milieu characterized by a diminished pH level, thereby inhibiting the proliferation of deleterious microorganisms and the decay of ensiled fodder elements, thereby contributing to the retention of the nutritional integrity of the fodder elements.

A significant benefit of both methods is the mitigation of environmental challenges stemming from the decay of such residues. The adoption of more circular systems to recycle nutrients for feed can aid in diminishing the substantial environmental repercussions associated with cultivating feed crops, including land, energy, and water usage, while concurrently enhancing food security through waste reduction and heightened food production. Diverse processing techniques such as dehydration, drying, pelleting, extrusion, fermentation, and silage production are feasible options for transforming food scraps into animal feed to boost the nutritional value, digestibility, feeding efficacy, toxin elimination, pathogen sterilization, removal of inedible constituents, suitability for long-term storage, ease of transport, and market appeal of food waste. Recycling food waste into livestock feed necessitates careful consideration due to the potential spread of transmissible diseases resulting from improper food waste handling. It is essential to subject food waste to processing before integrating it into animal diets, given its inherent undesirable properties such as nutrient variability. The variability in nutrient composition of food waste can be mitigated through appropriate measures. Rigorous monitoring of the origin of food waste designated for animal nutrition, and/or the blending of food waste with other feed ingredients during processing to achieve a well-balanced diet, is crucial.

Okara is an insoluble portion of the soybean that contains high moisture (8.4–22.9%); on a dry matter basis, it contains high metabolizable energy (9.0–14.2 MJ/kg) and other components that include crude protein (20.9–39.1%), crude fibre (12.2–61.3%), crude fat (4.9–21.5%), and ash (3.4–5.3%), according to a study of Rahman et al. 2021. Fermentation of okara improves its nutritional quality and reduces its anti-nutrient contents. Due to animals' palatability, okara can be used to replace the soybean meal/concentrate feed partially or completely in ruminant diets and partially in nonruminant diets. Okara feeding does not depress the

intake, digestibility, growth, milk production, blood metabolic profiles, and meat quality of animals. Okara can be fed to animals in fresh, dried, and ensiled forms. It can be used as a sole source of concentration or incorporated with other feed ingredients such as corn, rice bran and forage crops when being fed to animals (Rahman et al. 2021). But preservation of okara into silage is the best method by sundry it or mixing it with other dry feed ingredients before making it into silage, as this can reduce the moisture content of the okara up to 75%, and then storing it in an air-tight silo for at least 21 days. The benefit of using this method is that okara will not have to be delivered frequently to farms in fear of the okara rotting and, therefore, being rendered useless. Ensiling may be a practical alternative and it can improve the nutritive value of okara. There are several nutritive values provided from okara which are crude protein (ranges of 15.2% to 39.1%) on a DM basis, fibre (range of 12.1 to 61.3% and neutral detergent fibre (NDF) with a range of 12.7–72.6% on a DM basis), crude fat (range from 4.9% to 21.5% of DM) and minerals (the concentrations of calcium (Ca) and phosphorus (P) were 0.7% and 0.6%, respectively, based on the DM basis).

The study reported by Muin et al. discusses the use of mushroom stalk and soybean meal as a partial and complete replacement for fishmeal (FM) in tilapia fingerling diets and the experiment was conducted for 56 days (Muin et al. 2015). The diets were processed into sinking pellets. The experimental diets were formulated to replace fish meal protein at 0, 33, 67, and 100% (diets 4, 3, 2 and 1). In this experiment, Nile tilapia fingerlings weighing about 1.00 g were fed each of four isonitrogenous diets. They were randomly distributed into 12 plastic tanks with each tank stocking 20 fish and experiments were conducted in three replicates for each treatment. All the diets were well accepted by the fish. No physical abnormalities were observed in all treatments. Good growth performance was shown in 33% replacement (diet 3) of the FM diet. However, diet 1 (100% replacement) gave the highest increment in crude protein level and the best result of feed conversion ratio (FCR) and protein efficiency ratio (PER). Furthermore, the 100% replacement of FM (diet 1) was the best with a production cost of RM2.61/kg. Hence, the mushroom stalk has the potential to partially replace fishmeal in combination with soybean meal and should be seriously considered as an alternative protein source to replace fishmeal in the making of cheaper fish feed.

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## 12.5 Carbon Neutrality and Circular Economy

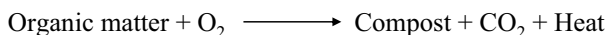
In 2019, the global GHG emissions reached a historic peak of 49.76 billion tonnes, which has potentially caused a climate crisis. Regrettably, the natural environment can only assimilate a fraction of these emissions, approximately 19 billion tonnes of CO<sub>2</sub> annually, necessitating immediate actions to mitigate our carbon footprint. The excessive emission of GHGs, notably CO<sub>2</sub>, results in the retention of heat within the atmosphere, contributing to the escalation of worldwide temperatures, which have already ascended by 1 °C. Failure to alter our current trajectory may lead to a disastrous 2 °C temperature surge that could be irreversible, resulting in extensive

destruction and devastation. Thus, Malaysia has implemented substantial measures to address GHG emissions by making a commitment to the global community. The government has pledged to achieve net-zero emissions by 2050 and reduce CO<sub>2</sub> intensity relative to GDP by 45% by 2030, as presented in the nationally determined contribution (NDC) pledge made during COP26 and reaffirmed at COP27 (United Nations Environment Programme 2017).

The concepts of carbon neutrality and the circular economy are intricately linked and serve as pivotal components in the realm of sustainable management of food waste. Carbon neutrality refers to an equal proportion between CO<sub>2</sub> emissions and removal, which results in a net-zero level of CO<sub>2</sub> to reduce its accumulation in the atmosphere and mitigate global warming. Thus, the GHG emissions will have to be counterbalanced by carbon sequestration (removing carbon oxide from the atmosphere and storing it) to achieve net zero emissions. Although it is impossible to achieve fully zero-carbon emissions, offsetting is a viable approach to becoming carbon neutral. Achieving carbon neutrality will effectively mitigate the progression of global warming and address the ongoing energy crisis, yielding additional advantages for air quality, ecological restoration, and enhancement of landscapes. Consequently, this achievement can be perceived as an industrial transformation that signifies a significant advancement in human progress.

To solve the economic, environmental, and societal challenges associated with current linear resource usage, the circular economy concept will focus on transitioning the linear chain system to a closed-loop system and improving resource utilization efficiency. The circular economy's main objective in food waste management is to restore substances into the economic cycle while preventing waste from being disposed of in landfills or incinerated, thereby increasing material value and reducing losses. The circular economy's objective is to address waste within a closed-loop system, necessitating an understanding of the loop's extent and potential expansion. One effective strategy involves developing internal loops that prioritize resource recovery and preservation. It is essential to consider that different types of food waste may necessitate different approaches by identifying the specific type for effective management. Food waste is increasingly being reused for resource recovery and the creation of high-value products that provide economic benefits while also addressing environmental concerns. The adoption of circular economy frameworks for handling food waste presents opportunities for diverse stakeholders, fostering new businesses and societal and environmental benefits.

There are two efficient methods for valorizing and treating food waste which will be highlighted which are AD and composting and the simple conversion of both methods as shown in Fig. 12.3 (Yap and Hadibarata 2022). In this case, anaerobic digestion and composting emerge as the most promising biotechnologies method for food waste management, with significant potential to reduce reliance on incineration and landfill disposal. The utilization of anaerobic digestate and compost as a fertilizer and soil enhancement can diminish the use of synthetic fertilizers, thus fostering a circular economy. This practice aids in closing nutrient cycles, endorsing resource efficiency, and reducing wastage. Anaerobic digestate, a by-product of the anaerobic breakdown of organic substances like food waste, is abundant in nutrients

**Anaerobic Digestion:****Aerobic Composting:**

**Fig. 12.3** The conversion of organic matter in anaerobic digestion and aerobic composting. (Yap and Hadibarata 2022)

and organic content. It acts as a valuable soil conditioner or fertilizer, furnishing crucial elements such as nitrogen, phosphorus, and potassium for sustaining plant development and soil vitality. Through the application of anaerobic digestate as a fertilizer, agricultural systems can curtail the requirement for synthetic fertilizers, lessen reliance on finite mineral reservoirs, and alleviate environmental contamination linked to nutrient leakage. Likewise, compost, derived from the aerobic decomposition of organic refuse, confers various advantages as a soil enhancement and fertilizing agent. Compost comprises organic substances, humus, and advantageous microorganisms that enhance soil composition, moisture retention, and nutrient circulation. By infusing compost into agricultural lands, cultivators can enrich soil fertility, output, and resistance to environmental pressures. Furthermore, compost aids in carbon sequestration within the soil, thereby bolstering endeavours to combat climate change.

Anaerobic digestate and compost, when used as fertilizers, help to achieve carbon neutrality by aiding in carbon sequestration in soils and lowering greenhouse gas emissions associated with traditional fertilizer production and organic waste decomposition. Anaerobic digestate, derived from the anaerobic breakdown of organic waste, is abundant in organic material and essential nutrients. The use of anaerobic digestate as a fertilizer improves soil amendment, enhancing soil composition, moisture retention, and nutrient accessibility. Similarly, compost can be produced through the aerobic decomposition of organic waste which can be an excellent soil improver and fertilizer due to it contains organic matter, nutrients, and beneficial microorganisms that help plants grow and improve soil health. Upon application to soils, compost elevates soil carbon levels and microbial activity, fostering the sequestration of carbon dioxide from the atmosphere. In addition, compost enhances soil structure, moisture retention, and nutrient circulation, thereby diminishing the necessity for synthetic fertilizers and alleviating greenhouse gas emissions linked to their production and utilization.

In addition, a Life Cycle Assessment (LCA) approach can be used following the international standards of ISO 14040 and 14044 for the sustainability assessment in terms of environment, economy and energy aspects. In environmental assessment, LCA determines the environmental losses over the life of a product all in or commercial and various environmental indicators associated with sustainable operations using the LCA method are carbon footprints, which currently include carbon

dioxide emissions, acidification potential (AP), eutrophication potential (EP), and global warming potential (GWP) mean.

According to LCA research, AD is deemed more favourable compared to incineration, composting, and landfilling as it exhibits lower environmental repercussions in contrast to incineration and other traditional techniques. AD presents opportunities for influencing climate change, terrestrial acidification (TA), marine eutrophication, and particulate matter formation (PMF). Despite the primary advantage of AD lying in resource recuperation, there remains significant room for enhancing the rate of resource recovery through the AD process, thereby reducing environmental consequences. Enhanced production of renewable energy can be achieved through AD of food waste containing moisture levels below 5% (Bakar & Baidurah 2013; Bakar et al. 2022).

Composting is the process of combining food waste with other organic waste, such as yard waste or agricultural residues, in a controlled composting system to provide an ideal environment for a wide range of microbial organisms, including fungi, bacteria, and worms, to decompose organic materials. The examination of various methods indicates that windrow composting has more pronounced environmental impacts. Several studies (Bhatia et al. 2023) have identified composting as having the greatest environmental impact due to the emissions produced during decomposition, which contributes to acidification, eutrophication, and global warming potential.

These investigations underscore the necessity for a global consensus on emission standards within the realm of composting, emphasizing the importance of mitigating emissions like  $\text{CH}_4$ ,  $\text{N}_2\text{O}$ , and  $\text{NH}_3$  during the decomposition process. The integration of anaerobic digestion after composting can alleviate environmental pressures compared to standalone composting practices. A research endeavour conducted at the University of Nottingham Malaysia indicated that utilizing in-house compost could serve as a financially viable alternative to chemical fertilizers. Comprehensive life-cycle assessments demonstrate that this transition yields significant environmental advantages, including the reduction of  $\text{CH}_4$  emissions and mitigation of fossil fuel depletion (Keng et al. 2020).

The study conducted by (Batool et al. 2024) focuses on the AD of the organic fraction of MSW within a biogas digester hosting specialized microorganisms working at mesophilic temperatures (around 35 °C). At this point, the complex organic material in FW is broken down and converted into short-chain organic compounds then decomposed by methanogens to produce biogas. Biogas production includes 62%  $\text{CH}_4$ , 32% biogenic  $\text{CO}_2$ , and 6% other gas components such as  $\text{NH}_3$ , volatile organic compounds (VOCs),  $\text{O}_2$ , and  $\text{N}_2$ . Following this, the biogas is withdrawn utilizing a 12-kW blower and transmitted to a gas turbine. Within this context, three specific sub-scenarios are outlined where biogas is utilized for generating electricity, cooking gas, and vehicle fuel. It is crucial to stress that the biogas must undergo a refining procedure called biogas upgrading, utilizing water scrubbing, to elevate the  $\text{CH}_4$  concentration to 98% before its utilization as cooking gas and vehicle fuel. Furthermore, the analysis conducted indicated that to decrease the moisture content of food waste, it is blended with sawdust in a 0.179:1 weight proportion.

The amalgamation is then preserved and aerobically treated. The CO<sub>2</sub> generated during the process is viewed as biogenic and falls outside the research's scope. Other gases, such as CH<sub>4</sub>, N<sub>2</sub>O, CO, K, and P, are also considered. Meanwhile, wastewater discharges from leachate encompass heavy metals such as Cd, Cr, and Cu, BOD<sub>5</sub>, and COD. It is presumed that one metric tonne of food waste can yield 0.33 metric tonnes of organic fertilizer.

The LCA provides important insights into the environmental consequences of chemical treatment methods (the use of alkaline and acid chemicals) for food waste. Hydrolysis, fermentation and pyrolysis are chemical treatment processes that convert organic waste into value-added products like biofuels, biochemicals, and platform chemicals. However, the environmental consequences of chemical food waste treatment can be significant at various stages of the product life cycle, necessitating the use of highly energy-intensive operations, chemical reagents, and specialized equipment, resulting in high energy consumption, resource depletion, and greenhouse gas and air pollutant emissions. The extraction and processing of raw materials for chemical inputs, such as catalysts and solvents, will have environmental consequences, including habitat destruction, water pollution, and ecosystem degradation. During operation, chemical treatment facilities may emit air pollutants and hazardous waste, endangering human health and the environment. Depending on the process and technology used, chemical treatment methods may produce by-products or residues that must be disposed of or treated, adding to environmental burdens such as waste generation, land use impacts, and ecosystem disruption. Chemical treatment residues can be difficult to dispose of or recycle at the end of their useful life due to waste management and environmental impact concerns. Some by-products or residues from chemical treatment processes may be classified as hazardous waste and require specialized handling, treatment, or disposal measures to prevent environmental contamination and human exposure to harmful substances.

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## 12.6 Conclusion

In conclusion, this chapter aimed to study the utilization of food waste into nutrient-rich fertilizer to achieve carbon neutrality and a circular economy. Food waste, which is the highest fraction in MSW increased every year due to the impact of urbanization and the growth of population. Thus, it is a concern that serious measures should be taken to move forward into a more sustainable method for proper food waste management.

The impacts of food waste generation in terms of environmental, economic and social aspects can be minimized through an efficient method other than landfill which is a traditional method for the decomposition process. From this study, the suggested treatment methods for food waste are anaerobic digestion and composting, a biological approach that naturally uses microorganisms as decomposers and then produces organic fertilizer.

By applying these methods, carbon neutrality and a circular economy can be achieved. The production of organic fertilizer can give many benefits to Malaysia. Malaysia has remained dependent on some expensive chemical fertilizers from the neighbouring countries. As Malaysia is a developing country, the reliance on imported fertilizer should be decreased and then managed to produce an efficient organic fertilizer for plant growth and yield. So the usage of chemical fertilizer can be minimized to ensure soil fertility, reduce GHG emissions and improve public health.

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# Potential of Marine Resources for Generation of Clean and Green Energy: A Path Towards Sustainable Future

# 13

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**Abstract**

With the rising challenges associated with climate change and global warming, various countries of the world are witnessing a rapid transition from conventional energy sources to cleaner and environmentally friendly energy. In this regard, various sources of green energy are being explored by researchers across the globe due to their renewability and sustainability. More recently, scientists are considering the marine environment as a potential medium that can provide vast resources that can be utilized in the generation of sustainable and green energy that would mitigate or reduce significantly the current challenges of climate change and global warming. Ocean has been identified as one of the largest sources of renewable energy; this marine energy generation occurs through the harnessing of the chemical and physical state of the ocean. Various resources from the marine environment have been considered promising in this regard, some of which include undercurrent and surface currents, tides, wave movement, variation in water temperature and the salinity of water. This chapter presents the application of marine resources for the generation of green energy. It gives a general overview of marine resources and their sources. It further discusses the principles involved in the generation of energy from marine resources. The merits and limitations of marine energy sources are also highlighted. Finally, a future perspective in this regard is also provided.

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**Keywords**

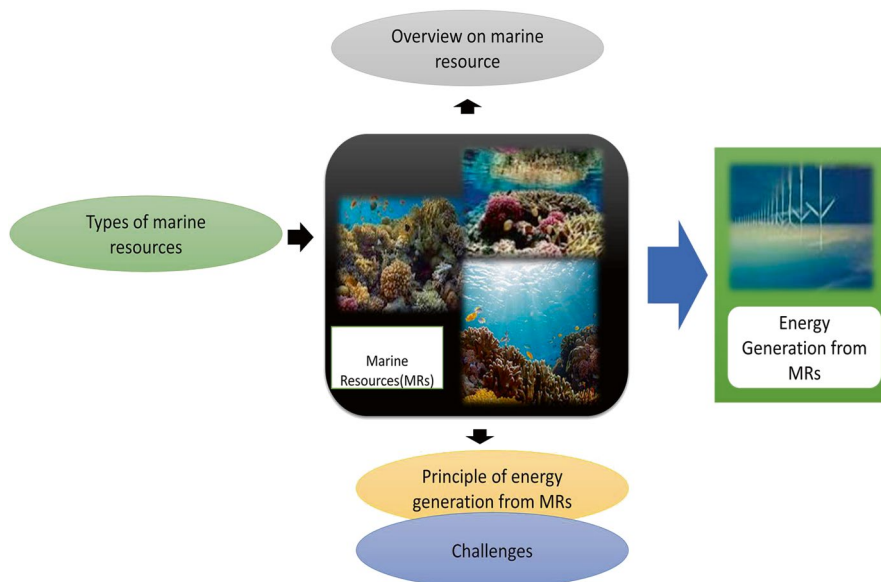
Cell · Disease · Inflammatory · Future · Sickle · Therapeutic

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## 13.1 Introduction

Marine resources encompass a vast array of biological, mineral, and energy sources found in Earth's oceans and seas. These resources play crucial roles in sustaining life, supporting ecosystems, and driving economic activities worldwide (Fig. 13.1). From fisheries to renewable energy, marine resources offer a diverse range of opportunities and challenges that shape both environmental and socio-economic landscapes. This overview provides insight into the significance, utilization, and conservation of marine resources (Chu and Karr 2017).

**Fisheries:** Fisheries are essential marine resources, supplying a primary protein source for billions globally. Commercial fisheries harvest various fish, shellfish, and crustaceans for consumption, pharmaceuticals, and industry. Yet, overfishing, illegal practices and habitat destruction imperil marine biodiversity and ecosystems. Sustainable management is vital for fisheries' long-term sustainability. Measures like marine protected areas and catch quotas promote responsible harvesting, allowing fish populations to replenish and ecosystems to thrive. Additionally, combating illegal fishing through monitoring and enforcement is crucial. Collaboration among governments, scientists, and stakeholders is key to implementing effective management strategies that balance economic interests with environmental conservation.



**Fig. 13.1** Schematic representation of chapter

By prioritizing sustainability, we can safeguard marine ecosystems, ensure food security, and support livelihoods dependent on fisheries for generations to come (Viana et al. 2023).

**Aquaculture:** Aquaculture, or fish farming, plays a vital role in marine resource utilization by cultivating aquatic organisms in controlled environments for food production. It serves to supplement wild fisheries while alleviating pressure on natural ecosystems. However, environmental concerns surrounding aquaculture include pollution, disease transmission, and potential genetic impacts on wild populations. Sustainable aquaculture practices are imperative to address these challenges. These practices may involve implementing efficient waste management systems to minimize pollution, employing disease prevention measures such as biosecurity protocols, and adopting selective breeding techniques to mitigate genetic impacts. Additionally, promoting ecosystem-based approaches and certification programmes like the Aquaculture Stewardship Council (ASC) can encourage responsible aquaculture practices. By prioritizing sustainability in aquaculture operations, we can ensure the continued provision of seafood while safeguarding marine ecosystems and biodiversity for future generations (Arshad et al. 2022).

**Marine energy:** Marine energy resources, comprising wave, tidal, and ocean thermal energy, offer promising avenues for renewable electricity generation by tapping into the kinetic and thermal energy of the oceans. These sources present clean and sustainable alternatives to fossil fuels, aiding in mitigating climate change. However, their widespread adoption faces hurdles such as technological constraints, environmental impacts, and regulatory challenges. Developing efficient and

cost-effective technologies, addressing concerns about habitat disturbance and marine life impacts, and navigating complex regulatory frameworks are critical steps to overcoming these barriers. Collaborative research efforts, innovative solutions, and supportive policies are essential to unlocking the full potential of marine energy resources. By surmounting these challenges, marine energy can play a significant role in transitioning towards a more sustainable and resilient energy future, reducing dependence on fossil fuels and mitigating environmental degradation (Pérez-Vigueras et al. 2023).

**Minerals and metals:** The ocean floor harbours extensive reserves of minerals and metals like manganese nodules, polymetallic sulphides, and cobalt-rich crusts, coveted for their utility in electronics, renewable energy, and infrastructure. Yet, the pursuit of these resources through deep-sea mining poses grave ecological risks, including habitat disturbance, biodiversity decline, and pollution release. Sustainable mining practices and robust international regulations are imperative to reconcile economic aspirations with environmental imperatives. Implementing technologies for minimal environmental impact, such as remotely operated vehicles and seabed mapping, can mitigate ecosystem disruption. Additionally, establishing marine protected areas and rigorous monitoring mechanisms can safeguard vulnerable habitats and species. By fostering cooperation among stakeholders and prioritizing environmental stewardship, we can ensure that deep-sea mining activities are conducted responsibly, preserving the integrity of marine ecosystems for future generations (Inobeme et al. 2023a).

**Marine biotechnology:** Marine organisms offer a rich source of bioactive compounds with diverse applications in pharmaceuticals, nutrition, and industry. Marine biotechnology harnesses these compounds for drug discovery, bioremediation, and biomaterials. Examples include anti-cancer agents from sponges, biocatalytic enzymes from marine bacteria, and biofuels from algae. However, sustainable harvesting practices and conservation efforts are imperative to prevent overexploitation and safeguard marine biodiversity. By implementing responsible harvesting techniques, such as aquaculture and selective extraction methods, we can ensure the continued availability of marine resources for biotechnological applications while preserving the delicate balance of marine ecosystems. These measures are essential for maximizing the benefits of marine biotechnology while minimizing negative environmental impacts (Senadheera et al. 2023).

**Marine tourism:** Coastal and marine tourism is a major contributor to local economies globally, offering recreational activities like snorkelling, diving, boating and beachcombing. While these activities generate revenue for coastal communities, unregulated tourism can harm marine ecosystems through habitat degradation, pollution, and disturbance to wildlife. Implementing sustainable tourism practices is crucial to balance environmental preservation with economic benefits. This includes setting carrying capacity limits to manage visitor numbers and educating tourists about responsible behaviour. By adopting these measures, we can minimize negative impacts on marine environments while maximizing socio-economic benefits for coastal communities. Sustainable tourism not only preserves the natural beauty of

coastal areas but also ensures their long-term viability as tourist destinations for future generations (Adetuyi et al. 2024).

**Conservation and management:** Effective conservation and management strategies are essential for preserving marine resources and ecosystem health. This involves establishing marine protected areas, implementing sustainable fisheries management plans, and controlling pollution. International cooperation is crucial for addressing transboundary issues. Furthermore, public awareness campaigns and community engagement are vital for fostering stewardship and promoting sustainable marine resource use. By combining these approaches, we can work towards safeguarding marine environments and ensuring their long-term sustainability for current and future generations (Dong and Guo 2022).

In addition, marine resources offer a wealth of opportunities for human well-being and economic development. However, their sustainable utilization requires careful management, conservation, and international cooperation to balance economic interests with environmental protection. By adopting holistic and science-based approaches, we can ensure the long-term viability of marine ecosystems and secure the benefits they provide for current and future generations (Hariram et al. 2023).

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## 13.2 Types of Marine Resources

Table 13.1 outlines different types of marine resources, including fisheries, aquaculture, marine energy, minerals and metals, and marine biotechnology. It provides a brief description of each resource type, examples, challenges associated with their exploitation, and management strategies to address these challenges and ensure sustainability.

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## 13.3 Principles of Green Energy Generation from Marine Resource

Green energy generation from marine resources harnesses the power of the ocean's renewable energy potential to produce electricity while minimizing environmental impact. This innovative approach holds promise for sustainable energy production, offering numerous benefits over traditional fossil fuels. Here are some key principles guiding this endeavour:

**Utilization of renewable resources:** Marine energy encompasses a spectrum of renewable resources, including tidal currents, waves, and ocean thermal energy. These sources are perpetually replenished by natural processes, ensuring their sustainability in the long term. Unlike finite fossil fuels, which are non-renewable and subject to depletion, marine energy offers a consistent and reliable power source that can be harnessed without depleting the Earth's resources. By tapping into the immense power of the ocean's renewable energy potential, we can reduce

**Table 13.1** Types of marine resources

Type of marine resource	Description	Examples	Challenges	Management strategies	References
Fisheries	Provide protein source for billions; target fish, shellfish, and crustaceans; face threats like overfishing and habitat destruction	Fish, shrimp, crabs	Overfishing, illegal practices, habitat destruction	Marine protected areas, catch quotas, monitoring/enforcement	Szuwalski et al. (2020)
Aquaculture	Cultivation of aquatic organisms in controlled environments; supplements wild fisheries; environmental concerns include pollution and disease transmission	Fish, mollusks, seaweed	Pollution, disease transmission, genetic impacts	Efficient waste management, disease prevention measures, selective breeding	Araujo et al. (2022)
Marine energy	Harness kinetic and thermal energy of oceans for renewable electricity; includes wave, tidal, and ocean thermal energy	Wave, tidal, ocean thermal	Technological limitations, environmental impacts, regulatory hurdles	Research and development, environmental impact assessments, supportive policies	Shadman et al. (2023)
Minerals and metals	Vast deposits on ocean floor; used in electronics, renewable energy, and infrastructure; concerns over ecosystem disruption and pollution	Manganese nodules, polymetallic sulphides, cobalt-rich crusts	Ecosystem disruption, biodiversity loss, pollution	Sustainable mining practices, international regulations, monitoring	Seijmonsbergen et al. (2022)
Marine biotechnology	Explores bioactive compounds from marine organisms for pharmaceutical, nutritional, and industrial applications	Anti-cancer agents, enzymes, biofuels	Overexploitation, conservation	Sustainable harvesting, conservation measures, certification programs	Karthikeyan et al. (2022)

dependence on fossil fuels, mitigate climate change, and transition towards a more sustainable energy future (Mathew et al. 2024a).

**Tidal energy:** Tidal energy harnesses the gravitational forces between the Earth, moon, and sun to generate electricity. Tidal currents, driven by the gravitational pull of these celestial bodies, exhibit predictability and consistency, rendering them a reliable energy source. Deploying technologies like tidal turbines, akin to underwater wind turbines, in regions with robust tidal flows enables the capture of kinetic energy from moving water masses. As tidal currents ebb and flow, these turbines spin, converting mechanical energy into electrical power through generators. The scalability and modularity of tidal energy systems allow for deployment in various marine environments, from coastal regions to estuaries. By tapping into the inexhaustible power of tidal forces, we can diversify our energy mix, reduce greenhouse gas emissions, and advance towards a more sustainable energy future (Inobeme et al. 2024a).

**Wave energy:** Wave energy technology utilizes the energy inherent in ocean waves to produce electricity. Wave energy converters (WECs) are designed in diverse configurations, such as oscillating water columns, point absorbers, and attenuators. Each type of WEC is tailored to capture different aspects of wave motion. Oscillating water columns, for instance, exploit the movement of air within a chamber as waves enter and exit, driving a turbine to generate electricity. Point absorbers harness the up-and-down motion of waves through buoyant structures connected to generators. Attenuators, on the other hand, utilize the horizontal movement of waves along their length to drive hydraulic pumps or turbines. By converting wave motion into mechanical or electrical energy, these WECs offer a promising avenue for sustainable power generation. Despite challenges such as device durability and deployment logistics, ongoing research and development efforts aim to enhance the efficiency and viability of wave energy systems for widespread deployment (Guo et al. 2022).

**Ocean thermal energy conversion (OTEC):** Ocean thermal energy conversion (OTEC) is a renewable energy technology that leverages the temperature contrast between warm surface waters and cold deep waters to produce electricity. This temperature gradient is harnessed through a closed-loop system using a working fluid, such as ammonia or a similar compound with a low boiling point. As warm surface water vaporizes the working fluid, it expands and drives a turbine connected to a generator, producing electricity. The vapour is then condensed using cold deep seawater, completing the cycle. OTEC systems are particularly suitable for tropical regions with substantial temperature differentials between surface and deep waters. By tapping into this abundant energy resource, OTEC offers a sustainable alternative to fossil fuels while minimizing greenhouse gas emissions. Research and development efforts continue to enhance OTEC technology for widespread commercial deployment, aiming to capitalize on the vast potential of ocean thermal energy (Mathew et al. 2024b).

**Environmental considerations:** Marine energy offers significant environmental advantages over fossil fuel-based power generation. Unlike coal or oil extraction and combustion, which emit greenhouse gases and pollutants, marine energy

projects produce minimal atmospheric emissions, contributing to climate change mitigation efforts. Furthermore, marine energy systems have a low visual and acoustic footprint, reducing their impact on marine ecosystems and coastal communities. Unlike offshore oil rigs or coal-fired power plants, marine energy devices are often submerged or located offshore, minimizing visual intrusion and noise pollution. This characteristic makes marine energy particularly suitable for coexistence with marine life and coastal activities such as fishing and tourism. By harnessing the renewable energy potential of the ocean while mitigating environmental impacts, marine energy plays a vital role in transitioning towards a more sustainable and resilient energy future. Continued research and development efforts aim to further optimize marine energy technologies for enhanced environmental performance and widespread adoption (Manisalidis et al. 2020).

**Site selection and resource assessment:** The successful deployment of marine energy projects hinges on meticulous site selection and resource assessment studies. Various factors, including tidal patterns, wave height, water depth, and seabed conditions, must be carefully evaluated to identify optimal locations for energy extraction. Advanced modeling techniques and remote sensing technologies play a crucial role in this process, enabling accurate assessment of resource potential and optimization of energy yield. These tools allow developers to analyse oceanographic data, predict energy fluxes, and simulate the performance of marine energy devices under different environmental conditions. By leveraging these insights, stakeholders can make informed decisions about project siting, design, and operation, maximizing energy production while minimizing risks and environmental impacts. Thorough site characterization and resource assessment are essential steps in the development of marine energy projects, ensuring their long-term viability and success (Hosseinzadeh et al. 2023).

**Technological innovation:** Continued research and development (R&D) efforts are vital for the advancement of marine energy technologies and the reduction of associated costs. Innovations in turbine design, materials, and control systems are key areas of focus, aiming to enhance the efficiency, reliability, and durability of marine energy systems. Through collaborative initiatives involving industry, academia, and government institutions, knowledge sharing and technology transfer are facilitated, driving progress in the field. These partnerships enable researchers to leverage expertise from diverse disciplines, access funding opportunities, and share resources and infrastructure. Furthermore, collaboration fosters innovation through the exchange of ideas, data, and best practices, accelerating the development and commercialization of marine energy technologies. By fostering a collaborative ecosystem, stakeholders can overcome technical challenges, optimize performance, and ultimately realize the full potential of marine energy as a sustainable and scalable renewable energy source (Pérez-Caballero et al. 2023).

**Integration with existing infrastructure:** Integrating marine energy systems into existing energy infrastructure is crucial for ensuring their effective deployment and contribution to the overall energy grid. Interconnection standards and grid stability measures are implemented to accommodate the inherent variability of renewable energy output, including fluctuations in tidal currents, wave heights, and ocean

thermal gradients. These measures help maintain grid reliability by balancing supply and demand and managing intermittent energy generation from marine sources. Smart grid technologies play a pivotal role in this integration process, enabling real-time monitoring, control, and optimization of energy flows. By leveraging advanced sensors, communication networks, and control algorithms, smart grids facilitate the seamless integration of marine energy into the broader energy landscape. This integration enhances grid flexibility, resilience, and efficiency while supporting the transition towards a more sustainable and diversified energy mix (Benti et al. 2023).

**Economic viability and policy support:** The commercial viability of marine energy technologies hinges on various factors, including capital costs, operational efficiency, maintenance expenses, market dynamics, and regulatory frameworks. High upfront investment costs and ongoing operational and maintenance expenses can present challenges to widespread adoption. However, government incentives, subsidies, and supportive policies are instrumental in mitigating these barriers and fostering market growth. Incentive programmes, such as feed-in tariffs, tax credits, and grants, provide financial incentives for investors and developers, reducing the financial risks associated with marine energy projects. Additionally, supportive regulatory frameworks and streamlined permitting processes help streamline project development and deployment. By creating a favourable investment climate and reducing market uncertainties, government intervention stimulates private sector involvement, accelerates technology innovation, and drives down costs, ultimately unlocking the full potential of marine energy as a reliable and sustainable energy source (Allioui and Mourdi 2023; Agyekum et al. 2024).

**Community engagement and stakeholder consultation:** Effective stakeholder engagement and community consultation are critical components of successful marine energy project development. Engaging local communities, indigenous groups, and other stakeholders at the outset fosters transparency, builds trust, and promotes social acceptance of proposed projects. By actively involving stakeholders in the decision-making process, developers can identify and address concerns related to environmental impact, cultural heritage, fishing activities, and other socio-economic factors. Furthermore, inclusive stakeholder engagement enables the co-creation of project plans that align with community needs and values, maximizing socio-economic benefits and minimizing potential conflicts. Through meaningful dialogue, consultation, and collaboration, developers can establish mutually beneficial partnerships with stakeholders, enhance project credibility, and ensure the long-term sustainability and acceptance of marine energy initiatives within the communities they serve (Spadaro et al. 2023).

Green energy generation from marine resources presents a promising pathway to a sustainable and resilient energy future. Adhering to principles such as renewable resource utilization, environmental stewardship, technological innovation, and stakeholder engagement, marine energy holds the potential to substantially reduce carbon emissions, enhance energy security, and foster economic development. By harnessing the vast and renewable power of the ocean, marine energy can diversify the energy mix, reduce reliance on fossil fuels, and mitigate climate change impacts. Moreover, advancements in marine energy technologies can create new

opportunities for innovation, job creation, and economic growth in coastal communities. Through collaborative efforts and strategic investments, marine energy can play a pivotal role in transitioning towards a cleaner, more sustainable energy landscape, while simultaneously addressing pressing environmental challenges and supporting socio-economic prosperity (Mathew et al. 2024c).

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### 13.4 Advantages of Utilization of Marine Resources for Green Energy Generation

Utilizing marine resources for green energy generation offers a multitude of advantages that contribute to a sustainable and resilient energy future. Here are some key advantages:

**Abundance and renewability:** Marine resources like tidal currents, waves, and ocean thermal energy are globally abundant. Unlike finite fossil fuels, they are continually replenished by natural processes, ensuring long-term sustainability. This abundance mitigates concerns about resource depletion and offers a reliable and continuous source of energy. With the potential for harnessing these renewable resources across various regions, marine energy contributes to energy security and resilience. Additionally, the predictability of tides and wave patterns enhances reliability, making marine energy an attractive option for sustainable power generation. As the world seeks alternatives to fossil fuels, the inexhaustible nature of marine resources positions them as vital components of a cleaner and more sustainable energy future (Strielkowski et al. 2021).

**Low environmental impact:** Marine energy generation offers significant environmental benefits compared to fossil fuel-based power generation. With minimal greenhouse gas emissions and pollutants, marine energy projects contribute to climate change mitigation and reduce environmental harm. Moreover, the visual and acoustic footprints of marine energy infrastructure are relatively low, minimizing disruption to marine habitats and coastal communities. This eco-friendly approach aligns with global efforts to transition towards cleaner energy sources while preserving marine ecosystems. By harnessing the renewable energy potential of the ocean in a sustainable manner, marine energy represents a vital component of the broader strategy to combat climate change and achieve environmental sustainability. Continued investment and development in marine energy technologies can further enhance its environmental performance, paving the way for a greener and more resilient energy future (Liu et al. 2023).

**Predictable and consistent energy source:** Tidal currents and wave patterns exhibit predictability and consistency, making marine energy a reliable source of power generation. Unlike wind and solar energy, which are subject to weather variability, marine energy provides a more predictable output. This reliability facilitates grid integration and ensures stability in meeting demand fluctuations. With the ability to forecast tidal and wave patterns accurately, operators can optimize energy production and synchronize it with grid requirements. Additionally, the predictability of marine energy enhances its attractiveness for energy planners and investors,

as it offers greater confidence in meeting energy needs consistently. By providing a stable and dependable energy source, marine energy contributes to energy security and grid stability, supporting the transition towards a more sustainable and resilient energy system (Chen et al. 2023).

**Diversification of energy mix:** Harnessing marine resources enables countries to diversify their energy mix, reducing reliance on imported fossil fuels and enhancing energy security. Diversification promotes energy independence and resilience by mitigating risks associated with over-reliance on a single energy source or volatile fuel markets. By incorporating marine energy into their energy portfolios, nations can decrease their vulnerability to disruptions in fossil fuel supplies and price fluctuations, thereby ensuring a more stable and secure energy supply. Furthermore, diversifying the energy mix can bolster economic stability and stimulate domestic industries, such as manufacturing and technology development, associated with marine energy production. Overall, the integration of marine resources into the energy mix offers countries a strategic advantage in managing energy-related risks and achieving greater energy self-sufficiency, ultimately contributing to a more resilient and sustainable energy future (Nwokolo et al. 2023).

**Job creation and economic development:** Developing marine energy projects not only provides job opportunities but also stimulates economic growth, especially in coastal regions abundant in these resources. The construction, operation, and maintenance of marine energy infrastructure demand a skilled workforce, fostering employment across sectors like engineering, manufacturing, and marine services. Moreover, these projects attract investment and inject vitality into local economies, generating revenue and supporting small businesses. From supply chain logistics to research and development, marine energy initiatives create a ripple effect of economic activity, benefiting communities and industries alike. Additionally, the establishment of marine energy hubs can catalyse regional development by nurturing clusters of expertise and fostering innovation. Overall, the socioeconomic benefits of marine energy projects extend beyond job creation, contributing to economic diversification, resilience, and prosperity in coastal areas (Du et al. 2022).

**Technological innovation:** Research and development (R&D) in marine energy technologies are catalysts for innovation, driving advancements in turbine design, materials, and control systems. These innovations enhance the efficiency and reliability of marine energy systems while reducing costs, making them increasingly competitive with conventional energy sources. Improved technology enables marine energy projects to achieve higher energy yields and lower operational expenses, bolstering their commercial viability. Additionally, R&D efforts open up new possibilities for hybrid energy systems, combining marine energy with other renewable sources like wind or solar, to maximize energy production and grid stability. Furthermore, innovations in energy storage solutions complement marine energy generation by addressing intermittency issues and ensuring a consistent power supply. By continually pushing the boundaries of technological innovation, R&D in marine energy contributes to the ongoing evolution of the renewable energy landscape, driving sustainability and resilience in the global energy sector (Fan et al. 2022).

Community engagement and stakeholder consultation: Effective stakeholder engagement is vital for the successful development of marine energy projects. Involving local communities, Indigenous groups, and other stakeholders from the project's inception fosters social acceptance, addresses concerns, and maximises socio-economic benefits for affected regions. Meaningful dialogue and collaboration build trust, promote transparency, and ensure that projects align with community needs and values. By actively involving stakeholders, developers gain valuable insights into local contexts, environmental sensitivities, and cultural considerations, leading to more informed decision-making and project designs that minimize negative impacts. Moreover, engaging stakeholders early on can help identify opportunities for local employment, capacity-building, and community investment, enhancing the project's long-term sustainability and positive legacy. Ultimately, effective stakeholder engagement is essential for building strong partnerships, fostering mutual respect, and achieving shared goals in the development of marine energy projects (Azeh et al. 2022).

Climate resilience and adaptation: Marine energy holds significant potential to bolster climate resilience and adaptation efforts, especially in coastal areas susceptible to sea-level rise and extreme weather events. By offering a locally sourced and sustainable energy supply, marine energy projects enhance the resilience of critical infrastructure and reduce reliance on centralized power grids. This decentralized energy source helps mitigate risks associated with climate-induced disruptions and strengthens community resilience planning. Furthermore, by diversifying the energy mix and incorporating renewable resources, marine energy contributes to reducing greenhouse gas emissions and mitigating the drivers of climate change. In the face of increasing climate-related challenges, marine energy emerges as a strategic asset, providing coastal communities with a reliable and resilient energy solution that supports their long-term sustainability and adaptability to changing environmental conditions. Through proactive investment and integration, marine energy can play a pivotal role in building climate-resilient infrastructure and safeguarding coastal communities against future risks (Kara and Şahin 2023).

Energy access and equity: Marine energy represents a transformative opportunity to enhance energy access and equity, especially in remote or island communities facing challenges with traditional energy sources. By providing a decentralized and renewable energy source, marine energy projects empower these communities to meet their energy needs sustainably. This reduces reliance on expensive imported fuels and mitigates the environmental and economic vulnerabilities associated with fossil fuel dependency. Moreover, marine energy offers a reliable and continuous power supply, addressing energy access gaps and promoting socio-economic development in underserved areas. By investing in marine energy infrastructure and capacity-building initiatives, governments and stakeholders can unlock the potential for energy independence and resilience in remote communities, fostering local empowerment and supporting sustainable development goals. Ultimately, marine energy has the capacity to catalyse positive change by democratizing access to clean and affordable energy, thereby advancing energy equity and fostering inclusive growth (Ambole et al. 2021).

International collaboration and cooperation: Marine energy offers compelling opportunities for international collaboration and cooperation due to the shared nature of marine resources across borders. Given the interconnectedness of oceans and the need for coordinated management, collaborative efforts are essential for maximizing the potential of marine energy as a sustainable energy solution. Through collaborative research initiatives, knowledge sharing, and technology transfer, countries can leverage each other's expertise and resources to accelerate progress in the field. By pooling resources and expertise, nations can overcome common challenges, drive innovation, and advance the development of marine energy technologies on a global scale. Moreover, international collaboration fosters the exchange of best practices, harmonizes regulatory frameworks, and facilitates market growth, promoting the widespread adoption of marine energy as a viable renewable energy source. Ultimately, by working together, countries can unlock the full potential of marine energy and address shared energy and climate challenges in a collective and coordinated manner (Bilawal et al. 2023).

In general, the utilization of marine resources for green energy generation offers numerous advantages, including abundance, sustainability, low environmental impact, and socio-economic benefits. By harnessing the power of the ocean's renewable energy potential, marine energy contributes to climate change mitigation, enhances energy security, and fosters economic development. Continued investment in research, technology development, and supportive policies is essential to realizing the full potential of marine energy and accelerating the transition towards a cleaner, more sustainable energy future (Olabi et al. 2023).

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### 13.5 Challenges in Green Energy Generation from Marine Resources

Marine resources offer vast potential for green energy generation, harnessing the power of ocean currents, waves, tides, and thermal gradients. However, despite this promise, several challenges hinder the widespread adoption of marine energy technologies. From technological limitations to environmental concerns and regulatory hurdles, addressing these challenges is crucial for unlocking the full potential of marine renewable energy (Agoundedemba et al. 2023). In this article, we explore some of the key challenges faced in green energy generation from marine resources.

Environmental impact: Marine energy projects, notably tidal turbines and wave energy converters, can disrupt marine ecosystems and habitats during installation and operation. Construction activities and operational machinery contribute to noise pollution, disturbing marine life such as mammals, fish, and seabirds. Moreover, alterations in water flow patterns and sediment transport induced by these devices can exacerbate environmental impacts, jeopardizing biodiversity and essential ecosystem services. Balancing the benefits of marine renewable energy with environmental preservation necessitates rigorous assessment and mitigation measures to minimize these adverse effects and ensure sustainable deployment of marine energy technologies (Copping et al. 2020; Ogundolie et al. 2023).

**Technology maturity:** Marine energy technologies are in nascent stages, encountering hurdles in technological maturity, reliability, efficiency, and scalability. Unlike wind and solar, marine systems demand specialized engineering to endure harsh marine conditions, encompassing corrosion, biofouling, and extreme weather. Furthermore, the diverse array of marine resources—waves, tides, and currents—mandates varied technological solutions, each with distinct technical challenges and uncertainties. Overcoming these obstacles demands sustained research, innovation, and collaboration across interdisciplinary fields to advance marine energy technologies towards commercial viability and widespread adoption, unlocking the vast potential of ocean-based renewable energy sources (Agyekum et al. 2024).

**Maintenance and durability:** Maintaining and ensuring the durability of marine energy devices pose significant challenges due to the corrosive nature of seawater, biofouling, and the dynamic forces exerted by waves, tides, and currents. Regular maintenance and inspection of underwater equipment often require specialized vessels, remotely operated vehicles (ROVs), or divers, adding to operational costs and logistical complexities. Furthermore, the harsh marine environment can accelerate wear and tear on mechanical components, leading to reduced device lifespan and increased downtime for repairs and replacements (Rubino et al. 2020).

**Resource variability and predictability:** Unlike conventional energy sources, such as fossil fuels or nuclear power, marine renewable energy resources exhibit high variability and limited predictability. Ocean currents, wave heights, and tidal patterns are influenced by complex interactions between oceanographic, meteorological, and geographical factors, making accurate resource assessment and energy forecasting challenging. Variations in resource availability can affect the reliability and stability of marine energy systems, impacting their ability to integrate with existing power grids and meet energy demand fluctuations (Chowdhury et al. 2021).

**Infrastructure and grid integration:** Integrating marine energy into existing power infrastructure and electricity grids presents technical and logistical challenges. Marine energy projects are often located in remote or offshore areas, requiring the development of new transmission infrastructure to deliver electricity to onshore grid connections. Additionally, the intermittent nature of marine renewable energy sources necessitates advanced grid management strategies, energy storage solutions, and demand-side management techniques to ensure grid stability and reliability (Shadman et al. 2023).

**Cost competitiveness:** Despite advancements in technology and decreasing costs over time, marine energy generation remains more expensive compared to conventional energy sources such as fossil fuels and mature renewable technologies like wind and solar. High upfront capital costs, limited economies of scale, and uncertainties surrounding project financing and revenue streams contribute to the overall cost competitiveness of marine energy projects. Achieving cost parity with conventional energy sources will require continued innovation, research, and supportive policy frameworks (Hoang et al. 2021; Mathew et al. 2023b).

**Regulatory and permitting challenges:** Regulatory frameworks for marine energy projects vary widely between regions and jurisdictions, often posing significant hurdles for project development, permitting, and licensing. Environmental impact

assessments, stakeholder consultations, and compliance with marine spatial planning regulations are essential components of the permitting process. Delays and uncertainties in regulatory approval can increase project development timelines and costs, affecting investor confidence and hindering market growth (Peplinski et al. 2021).

Generally, while marine renewable energy holds immense potential for clean, sustainable power generation, overcoming the numerous challenges outlined above is essential for realizing this potential. Collaboration between governments, industry stakeholders, research institutions, and environmental organizations is needed to address these challenges and accelerate the deployment of marine energy technologies on a global scale. By fostering innovation, supporting research and development, and implementing effective policies, we can harness the power of the oceans to transition towards a more sustainable energy future (Falcone 2023).

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### 13.6 Recent Reports on Green Energy Generation from Marine Resources

In recent years, there has been a significant surge in interest and investment in green energy generation from marine resources. This trend is driven by the urgent need to transition towards sustainable energy sources to combat climate change and reduce dependence on fossil fuels. Harnessing the power of the ocean offers immense potential for clean and renewable energy production. Let us delve into some recent developments in this burgeoning field (Olujobi et al. 2023).

One of the most promising technologies for marine energy generation is tidal energy. Tidal power plants utilize the natural ebb and flow of ocean tides to generate electricity. Recent advancements in tidal energy technology have focused on improving efficiency and reducing costs. For example, innovative tidal turbine designs with enhanced blade efficiency and durability have been developed, allowing for more reliable and cost-effective energy production. Moreover, projects such as the MeyGen tidal array in Scotland have demonstrated the feasibility of large-scale tidal energy deployment, paving the way for further expansion of this technology (Khan et al. 2022).

Another area of focus in marine energy generation is wave energy. Waves carry a tremendous amount of kinetic energy, which can be converted into electricity using wave energy converters (WECs). Recent developments in WEC technology have led to the creation of more efficient and robust devices capable of capturing energy from a wide range of wave conditions. Furthermore, research efforts have been directed towards optimizing WEC deployment strategies to maximize energy yield while minimizing environmental impact. Projects like the WaveRoller in Finland and the Wave Hub test site in the UK are showcasing the potential of wave energy as a reliable source of renewable power (Shadmani et al. 2022).

Beyond tidal and wave energy, there is growing interest in other forms of marine energy, such as ocean thermal energy conversion (OTEC) and salinity gradient power. OTEC utilizes temperature differences between warm surface water and

cold deep water to drive a power-generating cycle, while salinity gradient power exploits the difference in salt concentration between freshwater and seawater to produce electricity. Although these technologies are still in the early stages of development, recent research efforts have focused on improving efficiency and scalability to unlock their full potential (Rivera et al. 2020; Inobeme et al. 2024b).

In addition to technological advancements, there has been increasing recognition of the importance of ecosystem-based approaches in marine energy development. By considering the ecological impacts of energy projects and incorporating measures to minimize harm to marine habitats and species, stakeholders aim to ensure that green energy generation from marine resources remains truly sustainable. Initiatives such as environmental impact assessments and stakeholder engagement processes play a crucial role in balancing energy needs with environmental conservation objectives (Liu et al. 2023).

Furthermore, policy support and financial incentives have been instrumental in driving the growth of the marine energy sector. Governments around the world are implementing measures to promote the development and deployment of marine renewable energy technologies through subsidies, feed-in tariffs, and regulatory frameworks. These initiatives create a favourable environment for investment and innovation, stimulating growth and driving down costs (Agyekum et al. 2024).

Despite the progress made in marine energy generation, significant challenges remain, including technological limitations, regulatory hurdles, and economic viability concerns. However, with continued research, innovation, and collaboration, the potential of marine resources to contribute to a sustainable energy future is immense. As the world strives to transition towards a low-carbon economy, marine energy stands poised to play a pivotal role in meeting growing energy demands while mitigating the impacts of climate change (Dhali et al. 2023).

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## 13.7 Future Perspectives

Looking ahead, the potential of marine resources for clean energy remains promising, thereby offering a sustainable pathway for the future. Advances in technology, coupled with growing environmental awareness, will likely drive further exploration and development in this field. As renewable energy becomes increasingly imperative, marine resources stand out for their reliability, scalability, and low environmental impact. However, future success hinges on addressing technical challenges, enhancing regulatory frameworks, and fostering international collaboration. With concerted efforts, marine energy has the potential to play a significant role in achieving global sustainability goals, powering a cleaner, greener future for generations to come. Each of these marine resources offers unique advantages and faces distinct challenges in harnessing their energy potential (Holechek et al. 2022). Despite these challenges, continued research, innovation, and collaboration can unlock the full potential of marine resources for clean and green energy generation, paving the way towards a sustainable future (Table 13.2).

**Table 13.2** Outlining the future perspectives

Marine resource	Energy generation technology	Potential benefits	Challenges	References
Tidal energy	Tidal turbines	Predictable energy source, low carbon footprint	High upfront costs, environmental impact on marine ecosystems	Coles et al. (2021), Mathew et al. (2023c)
Wave energy	Wave energy converters (WECs)	Abundant resource, high energy density	Device reliability, cost-effectiveness	Giglio et al. (2023)
Ocean thermal energy conversion (OTEC)	Heat exchangers, turbines	Continuous energy production, low operating costs	Limited deployment areas, technological complexity	Xiao and Gulfam (2023)
Salinity gradient power	Pressure exchange systems	Scalable technology, minimal environmental impact	Efficiency optimization, site-specific requirements	Hsu et al. (2021)
Underwater currents	Underwater turbines	Consistent energy output, low visual impact	Turbine maintenance, grid connection challenges	Wang et al. (2022)
Algae biofuel	Algae cultivation, conversion	Renewable fuel source, carbon sequestration	Production scalability, competition with food production	Inobeme et al. (2023b)
Ocean biomass	Macroalgae farming, conversion	High growth rates, carbon sequestration	Nutrient availability, harvesting logistics	Khan et al. (2024)
Deep Sea geothermal	Geothermal heat extraction	Abundant resource, baseload power generation	Technical complexity, drilling costs	Mathew et al. (2023a)
Floating solar	Photovoltaic panels	Utilizes unoccupied ocean space, synergistic with marine life	Material degradation, wave and wind forces	
Marine hydrokinetics	Kinetic energy harvesting	Diverse energy sources, low visual impact	Efficiency optimization, environmental impact assessment	Chao et al. (2024)

## 13.8 Conclusion

The exploration of marine resources for clean and green energy presents a promising pathway toward a sustainable future. With escalating concerns over climate change and the depletion of finite fossil fuels, leveraging the power of the ocean offers a renewable and abundant alternative. From tidal and wave energy to offshore

wind farms and ocean thermal energy conversion, various technologies demonstrate immense potential for generating electricity while minimizing environmental impact. Harnessing marine resources for energy production also aligns with global efforts to transition to cleaner energy sources, reducing greenhouse gas emissions and mitigating environmental degradation. Moreover, investing in marine energy contributes to economic growth, job creation, and technological innovation, particularly in coastal regions. However, realizing this potential requires overcoming technical, financial, and regulatory challenges. Collaborative efforts among governments, industries, and research institutions are crucial for advancing research, development, and deployment of marine energy technologies. Additionally, robust environmental monitoring and mitigation strategies must accompany deployment to safeguard marine ecosystems. In essence, tapping into the vast energy potential of our oceans holds great promise for achieving a sustainable future. Through continued investment, innovation, and international cooperation, we can unlock the full benefits of marine resources while safeguarding our planet for future generations.

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# Potential Seaweed-Derived Bioactive Compounds for Pharmaceutical Applications

# 14

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**Abstract**

The quest for various nutraceuticals has risen recently due to their invaluable bioactive ingredients and therapeutic properties. To this end, experts have sourced various species of plants that have high contents of bioactive compounds for their potential exploration in pharmaceutical applications. More recently, seaweeds have proven to be highly promising, hence their wide application in medicinal usage. They have been documented to contain a high amount of numerous biologically active molecules which are accountable for their antioxidant, antiviral, and antimicrobial properties. They have also been well explored in food, and cosmetic production, as well as in nutraceuticals industries. In some current investigations, seaweeds have been considered a suitable and reliable alternative to various synthetic compounds used in pharmaceutical industries. Seaweeds have varying compositions of bioactive compounds, which are dependent on factors such as the type of algae, period of harvesting, and environmental conditions. The consumption of seaweeds as a source of nutrients is due to their high mineral, vitamins, and protein compositions. This work focuses on the bioactive compounds that are derived from seaweeds and their applications in pharmaceutical industries. It discusses various bioactive compounds present in seaweeds. It highlights the antimicrobial, antiviral, and antioxidant potentials of these active ingredients. Furthermore, some recent studies on their exploration of these applications are also presented. Future perspectives in the exploration of bioactive compounds from seaweeds for pharmaceutical applications are also attempted.

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**Keywords**

Bioactive · Compounds · Pharmaceutical · Seaweeds

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## 14.1 Introduction

Seaweeds, also known as marine macroalgae, have long been recognized for their rich bioactive compound content and diverse pharmacological properties. This review explores the potential of seaweed-derived bioactive compounds for pharmaceutical applications. Seaweeds encompass a vast array of species with unique chemical compositions, making them a valuable resource for drug discovery and development (Jaworowska and Murtaza 2022). Polysaccharides, proteins, peptides, polyphenols, lipids, and pigments are among the bioactive compounds found in seaweeds, each exhibiting a range of beneficial effects such as antioxidant, anti-inflammatory, antimicrobial, anticancer, and wound healing properties. However, harnessing these bioactives for pharmaceutical use presents challenges, including sustainable sourcing, extraction optimization, and regulatory compliance. Nevertheless, recent advancements in extraction techniques, coupled with growing interest in natural products-based therapies, have spurred research and development efforts in this field. Case studies highlighting the successful utilization of seaweed-derived bioactives in pharmaceutical products underscore their potential as valuable



**Fig. 14.1** Schematic representation of chapter

therapeutic agents (Gomez-Zavaglia et al. 2019). Addressing sustainability concerns and navigating regulatory pathways are crucial steps towards realizing the full pharmaceutical potential of seaweed bioactive. In conclusion, seaweed-derived bioactive compounds offer promising avenues for the development of novel pharmaceuticals, with implications for both human health and environmental sustainability (Afzal et al. 2023). This chapter presents potential seaweed-derived bioactive compounds for pharmaceutical applications. It starts with a general overview of seaweeds, their classes, and bioactive compositions. It discusses the various methods of extraction and characterization of their active ingredients (Fig. 14.1). It also highlights the applications of these biochemical compositions in the pharmaceutical industry. Finally, recent reports in this regard are also presented.

## 14.2 General Overview of Seaweeds

Seaweeds, also known as marine macroalgae, are a diverse group of photosynthetic organisms that inhabit the world's oceans and other bodies of water. Despite their name, seaweeds are not weeds at all but rather complex multicellular algae that play vital ecological roles and have significant economic and cultural importance worldwide. Seaweeds belong to the kingdom Protista within the broader classification of algae. They are classified into three main groups based on their pigmentation and cell structure: red algae (Rhodophyta), brown algae (Phaeophyceae), and green algae (Chlorophyta). Each group exhibits distinct characteristics, including coloration, size, and habitat preferences (El-Beltagi et al. 2022).

Seaweeds are found in a wide range of marine environments, from the rocky intertidal zones along coastlines to the depths of the open ocean. They can thrive in diverse conditions, including cold polar waters, temperate coastal areas, and tropical coral reefs. Seaweeds are also adapted to various substrate types, such as rocks, sand, mud, and even other organisms like corals and shells. The morphology of seaweeds varies greatly among species but typically consists of thallus structures, which may be filamentous, sheet-like, or branched, depending on the species. Seaweeds reproduce through both sexual and asexual means. Sexual reproduction involves the release of gametes (eggs and sperm) into the water, where fertilization

occurs, leading to the formation of zygotes that develop into new individuals. Asexual reproduction occurs through fragmentation, where pieces of the seaweed break off and grow into new plants, or through the production of spores that germinate into new individuals (Takao et al. 2015; Inobeme et al. 2024a).

Seaweeds play crucial roles in marine ecosystems and contribute to global biogeochemical cycles. They provide habitat and food for a diverse array of marine organisms, including fish, invertebrates, and marine mammals. Seaweeds also contribute to primary production through photosynthesis, converting carbon dioxide and sunlight into organic matter, which supports marine food webs and influences nutrient cycling in coastal ecosystems. Seaweeds have been utilized by humans for thousands of years, with cultural and economic significance in many coastal communities worldwide. They are harvested for various purposes, including food, agriculture, cosmetics, pharmaceuticals, and industrial applications. In many Asian countries, seaweeds are integral components of traditional cuisines, valued for their nutritional properties and unique flavors. Additionally, seaweeds are cultivated commercially for the production of hydrocolloids such as agar, carrageenan, and alginate, which are used as gelling agents, stabilizers, and thickeners in food, pharmaceutical, and other industries (Menaar et al. 2020; Adetuyi et al. 2024).

Despite their ecological and economic importance, seaweeds face numerous challenges and threats in today's rapidly changing world. Anthropogenic activities such as overharvesting, pollution, habitat destruction, and climate change pose significant risks to seaweed populations and marine ecosystems. In particular, rising sea temperatures, ocean acidification, and changing ocean currents can disrupt seaweed growth and distribution, leading to shifts in marine biodiversity and ecosystem dynamics. Efforts to conserve and sustainably manage seaweed resources are increasingly important in mitigating these threats and preserving the ecological integrity of marine ecosystems. Conservation strategies may include the establishment of marine protected areas, implementation of sustainable harvesting practices, regulation of coastal development, and promotion of seaweed aquaculture as an alternative to wild harvesting. Additionally, public awareness and education campaigns can help foster appreciation for the value of seaweeds and the need for their conservation (Banach et al. 2022).

Looking ahead, seaweeds are likely to play an increasingly important role in addressing global challenges such as food security, climate change mitigation, and sustainable development. Advances in seaweed cultivation techniques, biotechnology, and industrial processing hold promise for expanding the range of seaweed-derived products and applications. Furthermore, continued research into the ecological functions of seaweeds and their interactions with marine ecosystems will deepen our understanding of their importance and inform conservation and management efforts in the years to come (Pereira et al. 2024).

### 14.3 Classes of Seaweeds and the Bioactive Components

Seaweeds, also known as marine macroalgae, encompass a diverse array of species classified into three main groups: red algae (Rhodophyta), brown algae (Phaeophyceae), and green algae (Chlorophyta). Each class exhibits unique morphological characteristics and biochemical compositions, giving rise to a wide variety of bioactive compounds with potential pharmaceutical applications (Menaar et al. 2021).

**Red algae (Rhodophyta):** Red algae are characterized by their distinctive red pigmentation, which results from the presence of phycoerythrin and phycocyanin pigments, masking the green chlorophyll. They are predominantly found in marine environments, ranging from intertidal zones to deep-sea habitats. Red algae are rich sources of bioactive compounds, including polysaccharides, polyphenols, peptides, and pigments, which exhibit a range of pharmacological activities (Chen et al. 2022).

**Bioactive components, polysaccharides:** Red algae are renowned for their sulfated polysaccharides, such as carrageenans and agar, which possess various biological activities, including antiviral, anti-inflammatory, and anticoagulant properties. Carrageenans, extracted from species like *Chondrus crispus* and *Gigartina skottsbergii*, have been investigated for their potential as antiviral agents against herpes simplex virus and human immunodeficiency virus (HIV) (Hans et al. 2021; Inobeme et al. 2023a).

**Polyphenols:** Red algae contain phenolic compounds with antioxidant and anti-inflammatory properties, such as phlorotannins and flavonoids. These compounds are derived from the phenylpropanoid pathway and contribute to the defense mechanisms of red algae against environmental stressors. Phlorotannins, found in species like *Ecklonia cava* and *Sargassum* spp., have shown promise as potential therapeutic agents for various diseases, including cancer and cardiovascular disorders (Pereira and Cotas 2023).

**Peptides:** Red algae produce bioactive peptides with diverse physiological effects, including antimicrobial, antihypertensive, and immunomodulatory activities. Peptides derived from red algae proteins exhibit inhibitory effects against pathogens such as bacteria, fungi and viruses, making them valuable candidates for pharmaceutical applications (Elbandy 2022).

**Brown algae (Phaeophyceae):** Brown algae are characterized by their brownish coloration, which results from the presence of fucoxanthin pigments, masking the chlorophyll. They are primarily marine organisms, commonly found in coastal regions and cold-water habitats. Brown algae are renowned for their large size and complex thallus structures, which harbour a rich diversity of bioactive compounds with potential pharmacological benefits (El-Beltagi et al. 2022).

**Bioactive components, fucoxanthin:** Brown algae are the primary sources of fucoxanthin, a carotenoid pigment with potent antioxidant and anticancer properties. Fucoxanthin has attracted significant attention due to its ability to modulate various cellular pathways involved in cancer development, including apoptosis, cell cycle regulation, and angiogenesis inhibition (Mohibullah et al. 2022).

**Fucoidans:** Brown algae produce fucoidan polysaccharides, sulfated polymers with diverse biological activities, including anticoagulant, antithrombotic, anti-inflammatory, and antiviral properties. Fucoidans extracted from species like *Fucus vesiculosus* and *Undaria pinnatifida* have demonstrated potential therapeutic effects in various preclinical and clinical studies, suggesting their utility in the treatment of cardiovascular diseases, cancer, and viral infections (Usov et al. 2022).

**Laminarins:** Brown algae synthesize laminarin polysaccharides,  $\beta$ -glucans with immunomodulatory properties that enhance the immune response and stimulate the production of pro-inflammatory cytokines. Laminarins have been investigated for their potential as adjuvants in vaccines and immunotherapies for infectious diseases and cancer (Caseiro et al. 2022).

**Green algae (Chlorophyta):** Green algae are characterized by their green coloration, resulting from the predominant presence of chlorophyll pigments. They inhabit various aquatic environments, including freshwater lakes, rivers, and marine habitats. Green algae exhibit diverse morphologies, ranging from unicellular organisms to multicellular macroalgae, and contain a wide range of bioactive compounds with pharmaceutical potential (Pierre et al. 2019; Adetunji et al. 2024a).

**Bioactive components: Chlorophylls—**Green algae are rich sources of chlorophyll pigments, which possess antioxidant properties and contribute to photosynthesis. Chlorophylls have been investigated for their potential therapeutic effects, including detoxification, wound healing, and anticancer activity, although further research is needed to elucidate their mechanisms of action and clinical applications (Martins et al. 2023).

**$\beta$ -Glucans:** Green algae produce  $\beta$ -glucan polysaccharides, complex carbohydrates with immunomodulatory properties that enhance the activity of immune cells and stimulate the production of cytokines and antibodies.  $\beta$ -Glucans derived from green algae species like chlorella and spirulina have shown promise as immunotherapeutic agents for enhancing immune function and combating infections and tumors (Zhong et al. 2023).

**Pigments:** In addition to chlorophylls, green algae produce other pigments, such as lutein, zeaxanthin, and astaxanthin, which possess antioxidant and anti-inflammatory properties. These pigments contribute to the coloration of green algae and may confer various health benefits when consumed as dietary supplements or incorporated into pharmaceutical formulations (Generalić Mekinić et al. 2023).

Generally, seaweeds represent valuable sources of bioactive compounds with diverse pharmacological activities, offering promising avenues for drug discovery and development. The classes of seaweeds—red, brown, and green—each harbour unique bioactive components that hold the potential for addressing a wide range of human health conditions, from infectious diseases to chronic disorders. Continued research into the identification, isolation, and characterization of seaweed-derived bioactives is essential for unlocking their full therapeutic potential and harnessing the benefits of these marine resources for pharmaceutical applications (Lomartire and Gonçalves 2022).

## 14.4 Extraction and Characterization of Bioactive Compounds from Seaweeds

Seaweeds, also known as marine macroalgae, are abundant sources of bioactive compounds with diverse pharmacological properties. The extraction and characterization of these compounds are crucial steps in harnessing their potential for pharmaceutical applications. This overview discusses the methods used for extracting bioactive compounds from seaweeds and the techniques employed for their characterization (Cotas et al. 2024).

## 14.5 Extraction Methods

Several extraction techniques are employed to isolate bioactive compounds from seaweeds, including conventional methods and modern approaches utilizing advanced technologies. The choice of extraction method depends on factors such as the type of bioactive compound, seaweed species, desired yield, and purity requirements. Common extraction techniques include (Sosa-Hernández et al. 2018).

**Solvent extraction:** Solvent extraction involves the use of organic solvents such as ethanol, methanol, acetone, or water to dissolve and extract bioactive compounds from seaweed biomass. This method is widely used for extracting a broad range of compounds, including polysaccharides, polyphenols, lipids, and pigments (Wang et al. 2024).

**Supercritical fluid extraction (SFE):** SFE utilizes supercritical fluids such as carbon dioxide (CO<sub>2</sub>) to extract bioactive compounds from seaweeds under high pressure and temperature conditions. Supercritical CO<sub>2</sub> offers several advantages, including its non-toxic nature, selectivity, and ability to extract heat-sensitive compounds without leaving solvent residues (Uwineza and Waśkiewicz 2020).

**Ultrasound-assisted extraction (UAE):** UAE utilizes ultrasound waves to disrupt cell walls and enhance the extraction efficiency of bioactive compounds from seaweeds. Ultrasound energy promotes the release of intracellular components into the solvent, resulting in higher extraction yields and reduced extraction times compared to conventional methods (Kumar et al. 2021; Mathew et al. 2024a).

**Microwave-assisted extraction (MAE):** MAE employs microwave radiation to accelerate the extraction of bioactive compounds from seaweeds by promoting heat transfer and mass transfer processes. Microwave energy penetrates the seaweed matrix, causing rapid heating and vaporization of solvent molecules, leading to enhanced extraction efficiency (Quitério et al. 2022).

**Enzyme-assisted extraction (EAE):** EAE involves the use of enzymes such as carbohydrases, proteases, or lipases to hydrolyze cell wall components and release bioactive compounds from seaweed biomass. Enzymes can improve extraction yields and facilitate the recovery of specific compounds by targeting specific bonds or structural components (Lemes et al. 2022).

## 14.6 Characterization Techniques

Once bioactive compounds are extracted from seaweeds, they undergo characterization to identify their chemical composition, structural properties, and biological activities. Characterization techniques provide valuable insights into the nature and functionality of seaweed-derived bioactives, guiding further research and development efforts (Inobeme et al. 2023b). Common characterization techniques include:

**HPLC (high-performance liquid chromatography):** HPLC is a powerful analytical technique used to separate, identify, and quantify individual components within complex mixtures of bioactive compounds. HPLC systems employ a mobile phase, stationary phase, and detector to elute and detect compounds based on their retention times and absorbance properties (Kumar 2017).

**GC-MS (gas chromatography-mass spectrometry):** GC-MS combines gas chromatography with mass spectrometry to analyze volatile and semi-volatile compounds present in seaweed extracts. GC separates compounds based on their volatility, while MS identifies and quantifies compounds based on their mass-to-charge ratios and fragmentation patterns (Yamamoto et al. 2014; Adetunji et al. 2024b).

**FTIR (Fourier transform infrared spectroscopy):** FTIR spectroscopy measures the absorption and transmission of infrared light by functional groups present in bioactive compounds, providing information about their chemical structure and composition. FTIR spectra can be used to identify specific bonds and characterize molecular structures (Damto et al. 2023).

**NMR (nuclear magnetic resonance spectroscopy):** NMR spectroscopy analyzes the nuclear magnetic properties of atoms within bioactive compounds, yielding information about their molecular structure, conformation, and dynamics. NMR spectra provide valuable data on chemical shifts, coupling constants, and connectivity within molecules.

**Mass spectrometry (MS):** MS analyzes the mass-to-charge ratios of ions generated from bioactive compounds, allowing for their identification, quantification, and structural elucidation. MS techniques such as MALDI-TOF (Matrix-Assisted Laser Desorption/Ionization Time-of-Flight) and ESI (Electrospray Ionization) are commonly used for analyzing seaweed-derived compounds (Pintér et al. 2021).

The extraction and characterization of bioactive compounds from seaweeds represent essential steps in harnessing their pharmaceutical potential. Various extraction methods, including solvent extraction, supercritical fluid extraction, ultrasound-assisted extraction, microwave-assisted extraction, and enzyme-assisted extraction, are employed to isolate bioactives from seaweed biomass. Subsequently, characterization techniques such as HPLC, GC-MS, FTIR, NMR, and mass spectrometry provide insights into the chemical composition, structure, and functional properties of seaweed-derived compounds. By combining extraction and characterization approaches, researchers can identify novel bioactive compounds with diverse pharmacological activities, paving the way for the development of new drugs and therapeutic agents derived from seaweeds (Cikoš et al. 2018; Mathew et al. 2024b).

## 14.7 Applications of Bioactive Compounds from Sea Weeds in the Pharmaceutical Industry

Table 14.1 provides an overview of various bioactive compounds derived from different classes of seaweeds and their potential pharmaceutical applications. You can find specific examples of seaweed species for each category based on research findings and known bioactive properties.

**Table 14.1** Applications of bioactive compounds from seaweeds in the pharmaceutical industry

Bioactive compounds	Pharmaceutical application	Seaweed source	Examples of species	References
Polysaccharides	Antiviral agents Anti-inflammatory drugs Anticoagulants Wound healing agents Tissue engineering scaffolds	Red algae (Rhodophyta) Brown algae (Phaeophyceae) Green algae (Chlorophyta)	<i>Chondrus crispus</i> <i>Fucus vesiculosus</i> <i>Ulva lactuca</i>	de Jesus Raposo et al. (2015), Mathew et al. (2024c)
Polyphenols	Antioxidant Anti-inflammatory drugs Anticancer agents Neuroprotective agents Cardioprotective agents	Red algae (Rhodophyta) Brown algae (Phaeophyceae) Green algae (Chlorophyta)	<i>Ecklonia cava</i> <i>Sargassum</i> spp. <i>Chlorella vulgaris</i>	Besednova et al. (2021) Inobeme et al. (2024b)
Peptides	Antimicrobial agents Antihypertensive drugs Immunomodulators Anticancer agents Neuroactive peptides	Red algae (Rhodophyta) Brown algae (Phaeophyceae) Green algae (Chlorophyta)	<i>Porphyra</i> spp. <i>Ascophyllum nodosum</i> <i>Spirulina platensis</i>	Afzal et al. (2023)
Pigments	Photoprotective agents Antioxidants Anti-inflammatory agents Probiotic supplements	Red algae (Rhodophyta) Brown algae (Phaeophyceae) Green algae (Chlorophyta)	<i>Palmaria palmata</i> <i>Laminaria digitata</i> <i>Dunaliella salina</i>	Gomez-Zavaglia et al. (2019), Adetunji et al. (2024a)
Lipids	Anti-inflammatory drugs Neuroprotective agents Cardioprotective agents Anticancer agent Emulsifiers	Red algae (Rhodophyta) Brown algae (Phaeophyceae) Green algae (Chlorophyta)	<i>Gracilaria</i> spp. <i>Macrocystis pyrifera</i> <i>Codium fragile</i>	Jaworowska and Murtaza (2022)

Seaweeds, also known as marine macroalgae, are rich sources of bioactive compounds with diverse pharmacological properties. These compounds have attracted significant interest from the pharmaceutical industry due to their potential therapeutic benefits. Following are some key applications of bioactive compounds derived from seaweeds in pharmaceutical research and development. Bioactive compounds extracted from seaweeds, particularly polysaccharides such as carrageenans and fucoidans, have demonstrated potent antiviral activity against a range of viruses, including herpes simplex virus (HSV), human immunodeficiency virus (HIV), and influenza virus. These compounds inhibit viral replication and attachment to host cells, making them promising candidates for the development of antiviral drugs (Øverland et al. 2019).

Polyphenols and polysaccharides from seaweeds exhibit significant anti-inflammatory properties by modulating immune responses and reducing the production of pro-inflammatory mediators. These bioactive compounds have potential applications in the treatment of inflammatory disorders such as arthritis, asthma, and inflammatory bowel disease. Sulfated polysaccharides extracted from seaweeds, such as heparin-like compounds found in red and green algae, possess anti-coagulant and antithrombotic activities. These compounds inhibit blood clotting by interfering with the coagulation cascade and platelet aggregation, offering therapeutic potential for the prevention and treatment of thrombotic disorders (Khursheed et al. 2023).

Phenolic compounds, pigments, and peptides derived from seaweeds exhibit potent antioxidant properties by scavenging free radicals and reducing oxidative stress. These bioactive compounds protect cells and tissues from oxidative damage and may help prevent age-related diseases such as cardiovascular disease, neurodegenerative disorders, and cancer. Peptides, polysaccharides, and lipids from seaweeds possess antimicrobial activity against a wide range of bacteria, fungi, and viruses. These bioactive compounds disrupt microbial cell membranes, inhibit enzyme activity, and interfere with microbial growth and replication, making them valuable for the development of antimicrobial drugs and topical treatments for infectious diseases (Michalak et al. 2022).

Polysaccharides, peptides, and growth factors derived from seaweeds promote wound healing and tissue regeneration by stimulating cell proliferation, angiogenesis, and collagen synthesis. These bioactive compounds accelerate the repair of damaged tissues and enhance the closure of wounds, making them useful for the development of wound dressings and therapeutic agents for chronic wounds and burns. Polyphenols, peptides, and lipids from seaweeds exhibit neuroprotective properties by reducing oxidative stress, inflammation, and neuronal damage in the brain and nervous system. These bioactive compounds may have potential applications in the prevention and treatment of neurodegenerative disorders such as Alzheimer's disease, Parkinson's disease, and stroke. Polysaccharides, polyphenols, and lipids from seaweeds have cardio-protective effects by reducing blood pressure, cholesterol levels, and inflammation, and improving vascular function and endothelial health. These bioactive compounds may help prevent cardiovascular

diseases such as hypertension, atherosclerosis, and coronary artery disease (Keykhaee et al. 2023).

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## 14.8 Recent Report on Application of Bioactive Compounds from Seaweeds in Pharmaceutical Industries

Seaweeds, or marine macroalgae, have gained increasing attention in the pharmaceutical industry due to their rich bioactive compound content and diverse pharmacological properties. Recent research has focused on exploring the potential of seaweed-derived compounds as novel therapeutics for various human health conditions. This report provides an overview of recent developments and advancements in the application of bioactive compounds from seaweeds in pharmaceutical industries (Lomartire and Gonçalves 2022).

**Bioactive compounds from seaweeds:** Seaweeds are abundant sources of bioactive compounds, including polysaccharides, polyphenols, peptides, pigments, and lipids, which exhibit a wide range of biological activities. Recent studies have elucidated the mechanisms of action and therapeutic potential of these compounds in the treatment and prevention of various diseases (Hentati et al. 2020; Mathew et al. 2024d).

**Antiviral agents:** One of the most promising applications of seaweed-derived bioactive compounds is in the development of antiviral agents. Research has shown that sulfated polysaccharides from red algae, such as carrageenans and fucoidans, possess potent antiviral activity against enveloped viruses, including herpes simplex virus (HSV), human immunodeficiency virus (HIV), and influenza virus. These compounds inhibit viral entry and replication, making them promising candidates for the development of novel antiviral drugs (Liyanage et al. 2023).

**Anti-inflammatory drugs:** Polyphenols and polysaccharides from seaweeds have demonstrated significant anti-inflammatory properties by modulating immune responses and reducing the production of pro-inflammatory mediators. Recent studies have highlighted the potential of these compounds in the treatment of inflammatory disorders such as arthritis, asthma, and inflammatory bowel disease. Furthermore, seaweed-derived peptides have shown promise as anti-inflammatory agents by inhibiting the activity of inflammatory enzymes and cytokines (Liyanage et al. 2023).

**Anticoagulants and cardiovascular drugs:** Sulfated polysaccharides from seaweeds, including heparin-like compounds found in red and green algae, exhibit anti-coagulant and antithrombotic activities. These compounds have potential applications in the prevention and treatment of thrombotic disorders such as deep vein thrombosis (DVT) and pulmonary embolism (PE). Additionally, polyphenols and lipids from seaweeds have cardio-protective effects by reducing blood pressure, cholesterol levels, and inflammation, thereby lowering the risk of cardiovascular diseases such as hypertension and atherosclerosis (Kuznetsova et al. 2021; Olorunsola et al. 2024).

Antioxidants and neuroprotective agents: Seaweed-derived polyphenols, pigments, and peptides possess potent antioxidant properties, scavenging free radicals and reducing oxidative stress in cells and tissues. Recent research has focused on the neuroprotective effects of these compounds in the prevention and treatment of neurodegenerative disorders such as Alzheimer's disease and Parkinson's disease. Furthermore, lipids from seaweeds have shown neuroprotective effects by enhancing neuronal survival and function (Lomartire and Gonçalves 2023).

Antimicrobial agents: Bioactive compounds from seaweeds, including polysaccharides, peptides, and lipids, exhibit antimicrobial activity against a wide range of bacteria, fungi, and viruses. Recent studies have investigated the potential of these compounds as alternatives to conventional antibiotics for the treatment of antibiotic-resistant infections. Furthermore, seaweed-derived peptides have shown promise as novel antimicrobial agents with broad-spectrum activity against pathogenic microorganisms (Lomartire and Gonçalves 2023).

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## 14.9 Conclusion

The recent report underscores the significant potential of bioactive compounds derived from seaweeds in revolutionizing the pharmaceutical industry. Seaweeds, with their rich diversity of polysaccharides, polyphenols, peptides, pigments, and lipids, offer a vast reservoir of compounds with diverse pharmacological activities. The applications of these bioactives span various therapeutic areas, including antiviral, anti-inflammatory, anticoagulant, cardiovascular, antioxidant, neuroprotective, and antimicrobial agents. Recent advancements in research have elucidated the mechanisms of action of seaweed-derived compounds and their therapeutic potential in addressing a wide range of human health conditions. From combating viral infections and inflammatory disorders to preventing cardiovascular diseases and neurodegenerative disorders, seaweed-derived bioactives offer promising solutions to some of the most pressing healthcare challenges of our time. Moreover, the sustainable and eco-friendly nature of seaweed cultivation makes it an attractive source of bioactive compounds for pharmaceutical applications. Seaweeds grow rapidly and require minimal resources, making them a renewable and environmentally responsible source of raw materials for drug discovery and development.

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# Regulations, Policy Framework and Acts Related with the Application of Marine Biomass/Recycling in Different Countries

# 15

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**Abstract**

Civilisation and urbanisation have generated a great amount of pollutants through their accompanied processes such as agriculture and industrialisation. Most of these wastes from various components of the environment end up in water bodies, thereby contaminating the marine ecosystem. The ocean ecosystem has varying levels of biomass at different trophic levels. There are numerous sectors where biomass is generated and processed, which include forestry, agriculture, marine, and other bio-based industrial processes. This marine biomass has the potential of usage as raw materials in various processes such as energy generation. The management and recycling of marine biomass is paramount but must however be regulated due to the environmental impacts of their associated wastes. As a result of this, governments in various nations of the world have put forward pragmatic policies and regulatory standards for checkmating the use of marine biomass as well as the recycling processes. This chapter discusses the various regulations, acts and policy frameworks that are connected with the usage of marine biomass and recycling in various countries. It presents the sources and types of marine biomass. It highlights the strengths and weaknesses of some of the policies. The numerous challenges associated with compliance with the existing policies in some countries are also examined.

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**Keywords**

Biomass · Marine · Policies · Recycling

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**15.1 Introduction**

The utilisation of marine biomass and the implementation of recycling practices are critical components of sustainable marine resource management. This abstract provides an overview of the regulatory frameworks, policies, and legislative acts pertaining to marine biomass/recycling applications across various countries. The document begins by examining global frameworks and agreements such as the United Nations Convention on the Law of the Sea (UNCLOS) and the Convention on Biological Diversity (CBD), highlighting their significance in shaping international standards. It further explores regional regulations, focusing on the European Union, the United States, Australia, Canada, Japan, and China, each with its distinct set of laws governing marine resource management and environmental conservation. Key legislative acts and policies within each jurisdiction are analyzed, including the Common Fisheries Policy (CFP) in the EU, the Magnuson-Stevens Fishery Conservation and Management Act in the US, and the Fisheries Management Act in Australia. Additionally, emphasis is placed on circular economy initiatives and waste management strategies integral to promoting sustainable practices. Furthermore, the abstract discusses case studies and best practices, illustrating successful implementations of marine biomass/recycling policies while addressing challenges and lessons learned. Through this comprehensive examination, the abstract aims to provide insights into the regulatory landscape surrounding marine

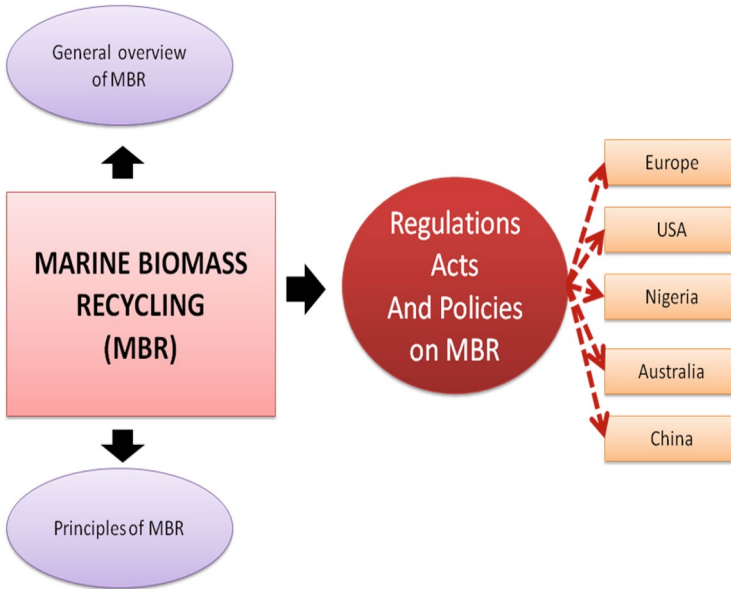
biomass and recycling, offering a foundation for informed decision-making and future policy development in the realm of marine resource sustainability.

## 15.2 General Overview of Marine Biomass Recycling

Marine biomass refers to organic matter derived from marine organisms, including algae, seaweed, and aquatic plants, as well as fishery by-products such as shells, bones, and offal. Recycling marine biomass involves the recovery and reuse of these materials to create value-added products, reduce waste, and minimise environmental impact. Marine ecosystems are vital for sustaining life on Earth, providing food and oxygen, and regulating climate. However, human activities such as overfishing, pollution, and habitat destruction have led to the depletion and degradation of marine resources. Marine biomass recycling offers a sustainable alternative by harnessing renewable resources and minimising dependency on finite materials. Marine biomass recycling encompasses various processes, including collection, processing, and utilisation of marine-derived materials. Collection methods range from manual harvesting of seaweed to advanced technologies such as aquaculture and offshore cultivation. Processing techniques involve drying, milling, and extraction to obtain valuable compounds such as proteins, lipids, and bioactive molecules. Utilisation pathways include food and feed additives, biofuels, bioplastics, and pharmaceuticals, catering to diverse industries and consumer needs (Nag et al. 2022; Inobeme et al. 2023a).

The marine biomass recycling sector is witnessing rapid growth and innovation driven by increasing demand for sustainable products and technologies. Seaweed cultivation, in particular, has emerged as a promising industry with applications in food, cosmetics, and biomedicine. Other trends include the development of bio-based materials, marine biorefineries, and integrated waste management systems that utilise multiple biomass streams for maximum efficiency and resource recovery. Marine biomass recycling offers several environmental benefits, including carbon sequestration, nutrient cycling, and habitat restoration. Seaweeds, for example, absorb CO<sub>2</sub> during photosynthesis, mitigating ocean acidification and climate change. By converting organic waste into valuable resources, marine biomass recycling helps reduce pollution, eutrophication, and marine litter, contributing to cleaner oceans and healthier ecosystems (Khan et al. 2024).

Marine biomass recycling presents significant economic opportunities for coastal communities, entrepreneurs, and industries. The growing market for sustainable products and the development of bioeconomies worldwide create favourable conditions for investment and innovation. However, challenges such as limited infrastructure, regulatory barriers, and market uncertainty hinder the scalability and profitability of marine biomass recycling ventures, necessitating collaborative efforts and supportive policies to overcome barriers and unlock the sector's full potential. The future of marine biomass recycling is promising, with ongoing research and development efforts aimed at improving efficiency, sustainability, and scalability. Advances in biotechnology, materials science, and ocean engineering hold promise for unlocking new applications and value chains. Key research areas include genetic engineering of seaweeds for enhanced traits, optimisation of cultivation techniques, and development of novel processing technologies to maximise



**Fig. 15.1** Schematic representation of chapter

resource utilization and minimise environmental footprint (Holland and Shapira 2024). This chapter presents various international laws, acts, regulations, and policies on marine biomass recycling (Fig. 15.1).

### 15.3 Principles of Marine Biomass Recycling

The principles of marine biomass recycling are rooted in sustainability, circular economy, and environmental stewardship. This comprehensive overview delves into the fundamental principles that guide the practice of marine biomass recycling, highlighting its significance, objectives, and key considerations. At the core of marine biomass recycling lies the principle of sustainability, which entails meeting the needs of the present without compromising the ability of future generations to meet their own needs. Sustainable marine biomass recycling aims to utilise marine resources in a manner that maintains ecosystem integrity, biodiversity, and resilience. This involves adopting responsible harvesting practices, minimising waste generation, and promoting ecosystem-based management approaches that ensure the long-term health and productivity of marine ecosystems (Okumus et al. 2024).

Marine biomass recycling embodies the principles of the circular economy, which seeks to minimize resource extraction, waste generation, and environmental impact by maximising resource efficiency, reuse, and recycling. In a circular economy model, marine-derived materials are viewed as valuable resources that can be continuously reused, repurposed, and recycled within

closed-loop systems. By transforming waste streams into new products and by-products, marine biomass recycling helps close the resource loop, reduce reliance on virgin materials, and minimize the environmental footprint of marine industries. A fundamental principle of marine biomass recycling is the valorisation of marine-derived materials, whereby organic waste streams are transformed into high-value products and commodities. Marine biomass, including seaweeds, algae, and fishery by-products, contains a wealth of valuable compounds such as proteins, lipids, carbohydrates, and bioactive molecules that can be utilised in various applications, including food, feed, pharmaceuticals, cosmetics, and bioplastics. By extracting and processing these compounds, marine biomass recycling creates economic value from otherwise underutilised or discarded resources, thereby incentivising sustainable resource management practices (Sharma et al. 2021).

Environmental stewardship is a guiding principle of marine biomass recycling, emphasising the responsibility of individuals, organisations, and governments to protect and conserve marine ecosystems and biodiversity. Marine biomass recycling seeks to minimize environmental impact and promote ecosystem health by adopting sustainable harvesting practices, reducing pollution and waste generation, and mitigating adverse effects on marine habitats and species. This involves adherence to strict environmental regulations, monitoring and assessment of ecological impacts, and implementation of conservation measures to safeguard marine resources for future generations (Bennett et al. 2018; Adetunji et al. 2024).

Innovation and collaboration are essential principles driving the advancement of marine biomass recycling. The development of sustainable technologies, processes, and value chains requires collaboration between stakeholders from diverse sectors, including government, industry, academia, and civil society. Open innovation platforms, research networks, and public-private partnerships facilitate knowledge sharing, technology transfer, and the co-creation of solutions to complex challenges facing marine resource management. By fostering a culture of innovation and collaboration, marine biomass recycling enables the development of new products, markets, and business models that contribute to economic growth, environmental sustainability, and social well-being (Sharma et al. 2021).

Socioeconomic considerations play a crucial role in the implementation of marine biomass recycling initiatives, as they impact the livelihoods, well-being, and cultural values of coastal communities and stakeholders. Sustainable marine biomass recycling seeks to promote equitable distribution of benefits, create employment opportunities, and enhance social cohesion and resilience in coastal regions. This involves fostering inclusive and participatory decision-making processes, supporting community-based enterprises and initiatives, and respecting traditional knowledge and indigenous rights. By addressing socioeconomic inequalities and promoting social justice, marine biomass recycling contributes to the achievement of sustainable development goals and the well-being of coastal communities (Abubakar et al. 2022).

## 15.4 Regulations, Acts and Policy Framework on the Application of Marine Biomass Recycling in Europe

The European Union (EU) has implemented a comprehensive regulatory framework to promote sustainable resource management, including the application of marine biomass recycling. This overview explores the key regulations, acts, and policy frameworks governing marine biomass recycling in Europe, highlighting their objectives, provisions, and implications. The Common Fisheries Policy (CFP) is a central component of EU fisheries management, aimed at ensuring the sustainable exploitation of marine resources and the protection of marine ecosystems. The CFP sets out rules and regulations for fishing activities, including quotas, catch limits, and technical measures to prevent overfishing and minimize bycatch. In the context of marine biomass recycling, the CFP encourages the utilization of fishery by-products such as offal, shells, and discards for value-added purposes, thereby promoting resource efficiency and waste reduction (Ferronato and Torretta 2019; Inobeme et al. 2024a).

The Waste Framework Directive is a key piece of EU legislation that sets out the legal framework for waste management and recycling activities in the European Union. The Directive aims to prevent waste generation, promote recycling and recovery, and minimize the environmental impact of waste disposal. In the context of marine biomass recycling, the Waste Framework Directive provides a regulatory framework for the management of waste streams generated from marine activities, including fishing, aquaculture, and marine biotechnology. It encourages the development of innovative recycling technologies and value-added products from marine-derived materials while ensuring compliance with environmental standards and regulations (Abubakar et al. 2022; Mathew et al. 2024a).

The Blue Economy Strategy is an overarching policy framework of the European Union aimed at promoting sustainable growth, jobs, and innovation in the maritime sector. The Strategy encompasses a wide range of initiatives and actions to support the development of marine industries, including fisheries, aquaculture, maritime transport, tourism, and renewable energy. In the context of marine biomass recycling, the Blue Economy Strategy recognises the potential of marine-derived materials as valuable resources for supporting economic diversification, innovation, and competitiveness in coastal regions and beyond. It encourages investment in research, infrastructure, and skills development to unlock the full potential of the blue economy while safeguarding marine ecosystems and biodiversity (Pace et al. 2023).

Furthermore, the European Union has established a robust regulatory framework to support the application of marine biomass recycling as part of its broader objectives for sustainable resource management, circular economy, and blue growth. By implementing regulations, acts, and policy frameworks such as the Common Fisheries Policy, Marine Strategy Framework Directive, Circular Economy Action Plan, Waste Framework Directive, and Blue Economy Strategy, the EU aims to promote the sustainable utilization of marine resources, reduce environmental impact, and foster economic development in coastal regions (Kumar et al. 2021).

## 15.5 Regulations, Acts and Policy Framework on Application Marine Biomass Recycling in the United States of America

In the United States, the application of marine biomass recycling is governed by a combination of federal laws, regulations, and policies aimed at promoting sustainable resource management, environmental conservation, and economic development. This overview examines the key regulations, acts, and policy frameworks that shape marine biomass recycling initiatives in the United States, outlining their objectives, provisions, and implications (Kumar et al. 2023).

**Magnuson-Stevens Fishery Conservation and Management Act (MSA):** The Magnuson-Stevens Fishery Conservation and Management Act (MSA) is the primary federal law governing fisheries management in the United States. Enacted in 1976 and subsequently reauthorized, the MSA aims to prevent overfishing, rebuild overfished stocks, and promote sustainable fisheries practices. Under the MSA, fisheries management plans are developed and implemented by regional fishery management councils, which set regulations on fishing quotas, gear types, and bycatch mitigation measures. In the context of marine biomass recycling, the MSA encourages the utilization of fishery by-products such as offal, shells, and discards for value-added purposes, thereby reducing waste and promoting resource efficiency (Macpherson 2018; Inobeme et al. 2024b).

**Marine Debris Act:** The Marine Debris Act, enacted in 1987 and amended in 2006, addresses the issue of marine debris pollution in U.S. waters. The Act authorises the National Oceanic and Atmospheric Administration (NOAA) to develop and implement programmes to research, prevent, and mitigate marine debris, including abandoned fishing gear, plastics, and other waste materials. In the context of marine biomass recycling, the Marine Debris Act emphasises the importance of waste reduction, recycling, and clean-up efforts to protect marine ecosystems and wildlife from the harmful effects of marine debris (Prata et al. 2019; Inobeme et al. 2023b).

**National Ocean Policy:** The National Ocean Policy, established by Executive Order in 2010, provides a framework for coordinated and integrated ocean management across federal agencies. The policy aims to protect, maintain, and restore the health and resilience of ocean ecosystems while supporting sustainable economic activities such as fishing, shipping, and recreation. Under the National Ocean Policy, federal agencies are directed to develop regional ocean plans that address key issues such as marine spatial planning, ecosystem-based management, and stakeholder engagement. In the context of marine biomass recycling, the National Ocean Policy promotes the sustainable use of marine resources and the development of innovative recycling technologies to minimize waste and environmental impact (Blackwelder 2020; Adetuyi et al. 2024).

**Endangered Species Act (ESA):** The Endangered Species Act (ESA) is a federal law enacted in 1973 to protect and conserve endangered and threatened species and their habitats. Under the ESA, species listed as endangered or threatened are afforded legal protections, and federal agencies are required to develop recovery

plans and implement conservation measures to restore their populations. In the context of marine biomass recycling, the ESA helps safeguard vulnerable marine species and habitats from the adverse effects of overfishing, habitat degradation, and pollution, thereby supporting ecosystem health and resilience (Greenwald et al. 2019).

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## 15.6 Regulations, Acts and Policy Framework on Application of Marine Biomass Recycling in China

In China, the application of marine biomass recycling is governed by a combination of national laws, regulations, and policies aimed at promoting sustainable resource management, environmental protection, and economic development. This overview explores the key regulations, acts, and policy frameworks that shape marine biomass recycling initiatives in China, outlining their objectives, provisions, and implications (Cao et al. 2017; Mathew et al. 2024b).

**Fisheries Law of the People's Republic of China:** The Fisheries Law of the People's Republic of China, enacted in 1986 and subsequently amended, serves as the primary legislation governing fisheries management and aquaculture activities in Chinese waters. The law aims to promote sustainable fisheries practices, conserve marine resources, and protect aquatic ecosystems. Under the Fisheries Law, regulations are established to control fishing activities, including licensing, quotas, gear types, and fishing seasons. In the context of marine biomass recycling, the Fisheries Law encourages the utilization of fishery by-products such as offal, shells, and discards for value-added purposes, thereby reducing waste and promoting resource efficiency (Fu and Liu 2023).

**Marine Environmental Protection Law:** The Marine Environmental Protection Law, enacted in 1982 and amended in 2017, addresses the prevention and control of marine pollution in Chinese waters. The law sets out regulations to monitor, assess, and mitigate pollution from various sources, including industrial discharges, shipping activities, and coastal development. In the context of marine biomass recycling, the Marine Environmental Protection Law emphasises the importance of waste reduction, recycling, and clean-up efforts to protect marine ecosystems and wildlife from the harmful effects of pollution (Manisalidis et al. 2020).

**Circular Economy Promotion Law:** The Circular Economy Promotion Law, enacted in 2008 and revised in 2020, aims to promote resource conservation, waste reduction, and sustainable development in China. The law encourages the adoption of circular economy principles across various sectors, including industry, agriculture, and services, to maximise resource efficiency and minimize environmental impact. In the context of marine biomass recycling, the Circular Economy Promotion Law provides a policy framework for the utilization of marine-derived materials and the development of recycling technologies to support circular economy objectives (Negrete-Cardoso et al. 2022).

**National Sword Policy:** The National Sword Policy, implemented in 2017, is a national initiative aimed at cracking down on illegal imports of foreign waste, including plastics, paper, and other recyclable materials. Under the policy, stricter inspection and enforcement measures are imposed on imported waste materials to ensure compliance with environmental standards and regulations. In the context of marine biomass recycling, the National Sword Policy underscores the importance of domestic waste management and recycling efforts to reduce reliance on imported materials and minimize environmental pollution (Li and Mu 2024).

**Basic Act on Ocean Policy:** The Basic Act on Ocean Policy, enacted in 2008, provides a comprehensive framework for the development and management of China's marine resources and maritime activities. The Act sets out principles and guidelines for ocean governance, marine spatial planning, and sustainable utilization of marine resources. In the context of marine biomass recycling, the Basic Act on Ocean Policy emphasizes the importance of promoting sustainable fisheries practices, conserving marine biodiversity, and supporting innovative approaches to marine resource management, including the recycling of marine-derived materials (Sereda et al. 2021).

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## **15.7 Regulations Acts and Policy Framework on the Application of Marine Biomass Recycling in Australia**

In Australia, the application of marine biomass recycling is governed by a combination of federal and state laws, regulations, and policies aimed at promoting sustainable resource management, environmental conservation, and economic development. This overview explores the key regulations, acts, and policy frameworks that shape marine biomass recycling initiatives in Australia, outlining their objectives, provisions, and implications (Anuardo et al. 2022).

**Fisheries Management Act:** The Fisheries Management Act, enacted at both federal and state levels, serves as the primary legislation governing fisheries management and aquaculture activities in Australia. The act aims to ensure the sustainable utilization of fisheries resources, conservation of marine ecosystems, and protection of aquatic biodiversity. Under the Fisheries Management Act, regulations are established to control fishing activities, including licensing, quotas, gear types, and fishing seasons. In the context of marine biomass recycling, the act encourages the utilization of fishery by-products such as offal, shells, and discards for value-added purposes, thereby reducing waste and promoting resource efficiency (Ward et al. 2022).

**Australian National Waste Policy:** The Australian National Waste Policy, developed by the federal government in collaboration with state and territory governments, provides a strategic framework for waste management and recycling efforts across Australia. The policy aims to reduce waste generation, promote recycling and resource recovery, and minimize the environmental impact of waste disposal. Under the Australian National Waste Policy, measures are implemented to support the

development of recycling infrastructure, increase public awareness and participation in recycling programmes, and facilitate the transition to a circular economy model. In the context of marine biomass recycling, the policy encourages the utilization of marine-derived materials and the development of innovative recycling technologies to reduce waste and promote resource efficiency (Jones 2020; Adetunji et al. 2024).

**National Plan for Maritime Environmental Emergencies:** The National Plan for Maritime Environmental Emergencies is a federal initiative aimed at preventing, preparing for, and responding to maritime pollution incidents in Australian waters. The plan provides a coordinated approach to emergency response and clean-up efforts in the event of oil spills, chemical releases, or other hazardous incidents that may impact marine environments. Under the National Plan, strategies are developed to mitigate environmental damage, protect sensitive habitats and species, and restore affected areas following an emergency. In the context of marine biomass recycling, the plan emphasizes the importance of pollution prevention and waste management measures to minimize the risk of environmental emergencies and protect marine ecosystems from harm (Abubakar et al. 2022).

**State and Territory Regulations:** In addition to federal regulations, each Australian state and territory has its own set of laws and regulations governing marine resource management, waste management, and environmental protection. These regulations may include specific provisions related to marine biomass recycling, such as licensing requirements, pollution control measures, and waste disposal regulations. State and territory governments also play a role in implementing national policies and programmes related to marine biomass recycling and may provide support and incentives for recycling initiatives at the local level (Wang et al. 2023).

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## 15.8 Future Perspective on Regulations and Policies on the Application of Marine Biomass Recycling

Looking ahead, the future perspective on regulations and policies concerning the application of marine biomass recycling in Australia holds immense potential for fostering sustainability, innovation, and economic growth. As the importance of marine biomass recycling continues to be recognised globally, Australia is poised to play a pivotal role in advancing this field through proactive regulatory frameworks and strategic policy initiatives. Here's an overview of potential future directions and considerations for regulations and policies on marine biomass recycling in Australia (Halog et al. 2021; Mathew et al. 2024c).

**Strengthening Circular Economy Initiatives:** Australia is increasingly focusing on transitioning towards a circular economy model, where resources are used more efficiently, waste is minimised, and value is maximised through recycling and reuse. Future regulations and policies on marine biomass recycling are likely to align closely with circular economy principles, aiming to promote resource efficiency, waste reduction, and sustainable consumption and production patterns. This may involve the development of targeted strategies to support the collection, processing,

and utilization of marine-derived materials in various sectors, including fisheries, aquaculture, and biotechnology (Abubakar et al. 2022).

**Promoting Research and Innovation:** To unlock the full potential of marine biomass recycling, there is a need for continued investment in research, development, and innovation. Future regulations and policies may prioritise funding and support for research initiatives aimed at advancing recycling technologies, improving resource recovery methods, and identifying new applications for marine-derived materials. Collaboration between government, industry, academia, and research institutions will be essential to drive innovation and address technical, economic, and environmental challenges associated with marine biomass recycling (Sharma et al. 2021).

**Enhancing Environmental Protection Measures:** Environmental protection and conservation will remain key priorities in future regulations and policies on marine biomass recycling. Efforts to minimize environmental impacts, protect marine ecosystems, and preserve biodiversity will be paramount. This may involve strengthening regulations related to waste management, pollution prevention, and habitat conservation, as well as implementing monitoring and enforcement mechanisms to ensure compliance with environmental standards. Additionally, strategic planning and spatial management approaches may be employed to mitigate potential conflicts between marine biomass recycling activities and conservation objectives (Ward et al. 2022).

**Supporting Industry Growth and Market Development:** Future regulations and policies are expected to focus on supporting the growth of the marine biomass recycling industry and fostering market development opportunities. This may include providing incentives, grants, and tax credits to encourage investment in recycling infrastructure, technology adoption, and business development initiatives. Government procurement programs, public-private partnerships, and industry collaboration platforms may also be established to stimulate demand for recycled marine-derived materials and promote the creation of new markets and value chains (Sharma et al. 2021; Mathew et al. 2024d).

**Strengthening International Cooperation:** Given the transboundary nature of marine ecosystems and resources, future regulations and policies on marine biomass recycling in Australia may emphasize international cooperation and collaboration. This could involve participation in multilateral agreements, partnerships, and initiatives aimed at addressing global challenges such as marine pollution, overfishing, and climate change. By engaging with international stakeholders, sharing best practices, and harmonising regulatory frameworks, Australia can contribute to the development of global standards and guidelines for sustainable marine biomass recycling (Barrowclough and Birkbeck 2022).

**Empowering Indigenous and Coastal Communities:** Indigenous and coastal communities play a vital role in marine resource management and stewardship. Future regulations and policies on marine biomass recycling should prioritise the empowerment and involvement of these communities in decision-making processes, resource allocation, and economic opportunities. This may involve recognising traditional knowledge, customary rights, and cultural values related to marine

resources, as well as providing support for community-based enterprises, capacity building, and sustainable livelihood initiatives (Fischer et al. 2022; Olorunsola et al. 2024).

## 15.9 Conclusion

In conclusion, the application of marine biomass recycling holds immense promise for addressing pressing environmental challenges, promoting sustainable resource management, and driving economic development in Australia and beyond. As the global community increasingly recognises the importance of harnessing marine resources in a responsible and efficient manner, Australia is well-positioned to lead the way in advancing marine biomass recycling initiatives through proactive regulations and strategic policies. Through a comprehensive regulatory framework grounded in circular economy principles, Australia can promote resource efficiency, waste reduction, and sustainable consumption and production patterns. By supporting research and innovation, enhancing environmental protection measures, and fostering industry growth and market development, Australia can unlock the full potential of marine biomass recycling to create new economic opportunities, protect marine ecosystems, and mitigate environmental impacts. Moreover, by strengthening international cooperation, engaging with indigenous and coastal communities, and fostering collaboration between government, industry, academia, and civil society, Australia can contribute to global efforts to address marine pollution, conserve biodiversity, and promote sustainable development. By embracing a holistic and inclusive approach to marine biomass recycling, Australia can pave the way for a more resilient, prosperous, and sustainable future for coastal communities, marine ecosystems, and future generations. Through concerted efforts and collective action, Australia can harness the power of marine biomass recycling to build a more sustainable and prosperous world.

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