OVERVIEW OF HYDROTHERMAL CARBONIZATION TECHNIQUE FOR SOLID BIOENERGY PRODUCTION IN AFRICA

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ABSTRACT

Access to affordable and sustainable energy sources is crucial for the growth and development of African countries. Bioenergy, particularly from biomass, plays a vital role in meeting the energy demands in many developing regions, such as sub-Saharan Africa. However, technological barriers hinder the widespread utilization of biofuels as energy sources. Thermochemical conversion processes, including hydrothermal carbonization (HTC), offer promising solutions for efficient biomass conversion. HTC has gained significant attention globally but its implementation in Africa remains limited. This paper provides an overview of the theoretical concepts of HTC process as it is cost-effective and environmentally friendly method for converting biomass into high-carbon energy dense products. The evolution, mechanism, and potential of HTC are discussed, highlighting its ability to process biomass with high moisture content without prior drying. Furthermore, it emphasizes the importance of renewable energy sources in global sustainable development initiatives and recognizes the need for African countries to explore and adopt hydrothermal carbonization technology.

Keywords: *Bioenergy, Hydrothermal Carbonization, Africa, Renewable Energy, Thermochemical conversion*

1.0 INTRODUCTION

Access to affordable, reliable, and modern energy services is increasingly being required for growth and development across Africa (Lynd et al., 2015), as over 80 % of its population relies upon solid biomass fuels, such as wood, charcoal, animal dung, and agricultural residues for their primary cooking and heating need (world bank, 2010). Bioenergy plays a vital role in meeting the local energy demand in many developing countries especially in sub-Saharan Africa that is heavily reliant on row biomass energy (Wicke et al., 2011; Japhet et al., 2020; Kammila et al., 2014; Pye et al., 2020). Zhang (2010) and Tushar et al. (2019), reported that, biomass is considered as the fourth largest energy resource. The increasing attention towards the utilization of biomass materials is supported by their affordability, eco-friendliness, and availability (Nwabunwanne et al., 2021).

One of the primary challenges in promoting biofuels lies in the technological barriers that hinder their widespread utilization as energy sources (Akogun and Waheed, 2019). Energy in biomass can be released through different biological and thermochemical processes (Zhang et al., 2010). One of such processes is the hydrothermal carbonization (HTC) process which offers distinct benefits. It enables the production of inexpensive and sustainable solid carbonaceous materials with desirable nanostructure and functionalization patterns. These materials hold great potential for solid bioenergy (Titirici and Antonietti, 2010).

2.0 BIOMASS WASTE

Biomass residues are derived from various sources involved in biomass production and processing, encompassing municipal waste, industrial waste, animal manures, agricultural and forestry residues, among others (Nizami et al., 2017). In the context of bioenergy applications, biomass waste can be categorized as either lignocellulosic or organic waste, depending on its moisture content. Lignocellulosic biomass waste, such as agricultural and forest residues, typically contains low moisture levels (often below 60%), making it suitable for treatment using thermochemical methods. On the other hand, organic or fermentable biomass waste includes residues with high moisture content and wastewater. This type of waste often exhibits high levels of moisture (usually exceeding 60%), making it appropriate for biochemical treatment. Examples of such residues include livestock manure, the organic fraction of municipal waste, industrial waste, and wastewater (Ochieng et al., 2022).

2.1 Availability of Biomass Waste

Increasing population triggered the cultivation of high yielding crop varieties and utilization of modern cultivation practices. This increased production of food grains also increased the production of crop residues in the form of stalks, stubbles, leaves, seed pods (Prasad et al., 2020). Considerable amount of these crop residues are left unutilized on the field/farms. Iye et al. (2013) reported that, the total amount of agricultural residue available in Nigeria was 55,900,000 MT/year which equals the potential energy value of 657.01 PJ. Wowrzeczka (2021) also reported that anticipated world annual municipal waste generation will increase by 70% in comparison with current levels, and will reach 3.40 billion tons in 2050.

3.0 THERMOCHEMICAL PROCESS

Thermochemical conversion involves utilizing heat to transform biomass into useful chemicals and fuels (Shen, 2020; Hu et al., 2010). Pyrolysis and HTC (Figure 1) represent two distinct methods within the realm of thermochemical conversion technology, aimed at generating bio/hydrochar as their primary outputs (Masoumi et al., 2021; Heilmann et al., 2010). The selection of the conversion process relies on several factors; the characteristics and quantity of the biomass feedstock, type of feedstock (wet or dry), the specific energy form required for the intended application, adherence to environmental regulations, economic considerations, and project-specific factors (Goyal et al., 2008).

3.1 Hydrothermal Biomass Conversion Process

Hydrothermal process is a thermochemical process that take place in hot liquid, either subcritical or supercritical water (Kumar, 2012). Hydrothermal process is one of the most promising technologies, as it can use the high inherent moisture of biomass to its advantage (Güleç et al., 2021). The objective is to transform biomass into valuable products or biofuels (Tekin et al., 2014; Heidari et al., 2019). According to the phase diagram of water (Figure 2), hydrothermal conversion can be categorized into three types; hydrothermal gasification (HTG), hydrothermal liquefaction (HTL), and HTC. This process is an environmentally friendly and inexpensive technique. Biomass is treated in water under mild temperatures (≤200 °C) (Kruse et al., 2013; Tekin et al, 2014).

4.0 HYDROTHERMAL CARBONIZATION IN PERSPECTIVE

HTC refers to a thermal and chemical process conducted at elevated temperatures (180-250 °C), and for 5–240 min under subcritical water pressure (2-10 MPa), that enables the conversion of biomass into a high-carbon product (Tushar, et al., 2019). HTC is a highly favoured thermal conversion method due to its ability to effectively process feedstocks with high moisture content of 70-90 % by weight without prior drying (Maqhuzu et al., 2019; Antero et al., 2020)

4.1 Evolution of Hydrothermal Carbonization

The concept of hydrothermal carbonization was initially suggested by Friedrich Bergius as early as 1913. He documented the hydrothermal conversion of cellulose into materials resembling coal (Bergius 1913; Kumar et al., 2018). A more comprehensive exploration was undertaken by Berl and Schmidt in 1932, where they investigated various biomass sources and subjected different samples to treatment in the presence of water at temperatures ranging from 150 to 350 degrees Celsius. These researchers, through a series of papers published in 1932, compiled the existing knowledge at that time regarding the formation of coal. This technology is already well-established worldwide, with more than 200 companies and organizations conducting research and professional activities on this topic (Romano et al., 2023).

4.2 Hydrothermal Carbonization Process Mechanism

This process involves Hydrolysis, dehydration decarboxylation, condensation, polymerization, and aromatization, reactions (Figure 3) to enhance the carbon content and ultimately achieve a higher calorific value in the resulting product (Reza et al., 2014; Wang et al., 2018; Hoekman et al., 2013)

During the hydrolysis, the ester and ether bonds of the hemicellulose, cellulose and lignin break down into many fragments. The next two important reactions are dehydration and decarboxylation which are responsible for reducing H/C and O/C ratios. Dehydration also releases more water in the reaction medium.

By decarboxylation, carboxyl and carbonyl groups degrade and release CO2 and CO. The next important reaction is condensation and polymerization, during which some of the highly reactive fragments of the previous reactions participate. Two molecules combine, resulting in the simultaneous formation of a larger molecule and release of a small molecule (usually water). Moreover, aromatization reactions will result in aromatic polymer structures which are stable under hydrothermal conditions and are considered as the building blocks of the hydrochar (Heidari et al., 2019).

4.3 Hydrothermal Carbonization Technology and Renewable Development

Global initiatives are actively striving to enhance the adoption of renewable energy sources on a global scale, aiming to mitigate greenhouse gas emissions (Nomanbhay et al., 2017). He et al. (2018); Sharma et al. (2019) reported that significant endeavours have been undertaken to investigate alternative, cost-effective, and renewable energy sources (RES) that have minimal or no adverse effects on the environment.

Thermochemical and biochemical conversions are recommended as the appropriate treatment methods due to the dual benefits, both in environmental safety and resource reuse. Among them, HTC has been developed with the purpose of upgrading biowastes in the presence of water, which can simultaneously avoid the over-consumption of energy in drying process (Zhuang et al., 2019). It has the potential to transform lingnocellulose into substances resembling coal, imitating the natural process known as hydrochar formation (Shen, 2020). In addition to the variety of different lignocellulosic biomass, HTC can also be used for wastes such as sewage sludge, animal manure, and municipal solid wastes which have significantly different structures (Heidari et al., 2019).

5.0 SNAPSHOT ON HYDROTHERMAL CARBONIZATION

5.1 Status

Despite being in an evolutionary phase, HTC has gain significant attention (Xiao et al., 2012; Singh et al., 2019). Over the past years, there has been a substantial surge in HTC-related patents globally since

1996, (Figure 4) indicating the extensive research being conducted worldwide in this field. Numerous pilot plants, as well as several full-scale plants (Table 1), have been constructed and operated in Europe, China, the United States, and the European Union emerge as the primary regions demonstrating keen interest in the industrial application of HTC (Romano et al., 2023).

As can be seen in the Table 1, many facilities have already been established, while others are in the process of being approved or realized; examples of this are the Piombino and Chiusi facilities in Italy. The Piombino project received a positive assessment from the Environmental Impact Assessment Commission by the Tuscany Region. The company Ingelia Italia is now dealing with the final authorization procedure. The plant will have 10 reactors with a capacity of 60,000 tons/year and will be able to produce 15,000 tons of bio-carbon and 2000 tons of fertilizer concentrate (http://www.ingelia.it/portfolio/piombino/).

The final project in Chiusi has been handed over to ACEA Ambiente, the plant's owner. The SIA and all the documentation necessary to start the single authorization process were presented to the evaluation commission of the Tuscany Region in November 2018. In this production hub, there will be 8 reactors, and it will be able to treat 80,000 tons/year of biological sludge. It will be able to produce 8000 tons of biocarbon and 6000 tons of biofertilizer with a high phosphorous and potassium content (http://www.ingelia.it/portfolio/chiusi/).

Africa is completely left out in this innovative technology that has gain significant attention worldwide. Few research output from the entire region is presented in Table 2, no known pilot or full scale plant in the region based on the available information to the researcher.

5.2 Available Technology

Meanwhile, bioenergy, which is an energy derived from biomass could be produced directly or indirectly in form of biofuel. Direct production of bioenergy occurs via combustion of the raw biomass and co-firing while indirect means occur via bioethanol, biodiesel, biogas etc. for further use. Among these, direct combustion and co-firing with coal are currently the dominant technologies, which contribute to more than 90% of the global bioenergy deployment (Akogun and Waheed, 2019).

Oyelaran et al. (2015) and Jekayinfa and Omisakin, (2005), reported that agricultural residues are still directly used inefficiently for cooking and other domestic heating purposes. More than 700 million Africans (82%) depend primarily on solid fuels for their cooking needs. Various findings have reported that this technology is unhealthy as the release of particulate matter, carbon monoxide, and other harmful products of incomplete combustion from solid-fuel use for cooking is strongly linked to acute lower respiratory infections, chronic obstructive pulmonary disease, lung cancer, ischemic heart disease, cerebrovascular diseases, cataracts, and low birth weights (Kammila et al., 2014).

Pyrolysis is an improved technology over the direct combustion and many research output have been produce from the region and full scale plants. However, this is face with the high temperature requirement of 500-1200 °C for the production of the biochar (Shen et al., 2017)

5.3 Economic feasibility

The economic feasibility to realise a sustainable construction need to have a clear support by adequate analysis connected to the energy consumption consequently to the new target reduction in greenhouse gas emission for HTC (Sesana et al., 2013). Maleka, (2016), investigated on the feasibility of five energy conversion processes (direct combustion, gasification, pyrolysis, anaerobic digestion and hydrothermal carbonization) with Cocoa pod husk as feedstock. Anaerobic digestion and hydrothermal carbonization were found to be the most suitable conversion processes and both were found to be economic feasible with Net Present Value (NPV>0). HTC was found to have higher NPV value, meaning it is more profitable.

5.4 Challenges

There are a few limitations to hydrothermal carbonization method such as the lack of reaction-kinetic data and reaction-passage and mass-transport, which are important guideline for procedure optimization and arrangement of kinetic-reaction during hydrothermal carbonization method (Hasan et al., 2023). Also key component of a potential industrial HTC plant is the reactor. Most of the reactors used in the literature are the batch type, however, for an industrial plant, a continuous reactor that can work at a high temperature and pressure is required (Heidari, et al., 2019).

6.0 CONCLUSION

Improving energy efficiency requires technological innovation whereby modern technologies need to be developed in order to make more efficient use of energy. Hydrothermal carbonization (HTC) presents a promising avenue for bioenergy production in African countries, addressing the pressing need for affordable, reliable, and sustainable energy sources. While HTC holds promise for sustainable waste management and resource recovery, in Africa its widespread adoption may face challenges related to technology transfer, infrastructure requirements, and financial investments. It would require tailored assessments.

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Table 1: HTC pilot/full scale plant around the world

Country/Region	Name	Capacity Tons/Year	Reference
China	HTC sludge treatment plant	14,000	(https://www.swisswater.ch/en/references/china/jining
Mexico	TerraNova Company	23000	https://www.youtube.com/watch?v=CSfytiNxpPg&t=135s
USA	PXVNEO	-	https://whyy.org/articles/phoenixvilles-wastewater-treatment-plant-to-get-a-first-of-its-kind-upgrade/
Karlsruhe Germany	AVA-CO2	84000	https://www.innoenergy.com/discover-innovative-solutions/online-marketplace-for-energy-innovations/oxypower-htc/
Relzow Germany	HTCycle AG	-	https://www.innoenergy.com/discover-innovative-solutions/online-marketplace-for-energy-innovations/oxypower-htc/
Naquera Spain	Ingelia	14,000	http://www.ingelia.it/portfolio/valencia/
UK	Immingham	-	https://cplindustries.co.uk/htc-hydrothermal-carbonisation/
Heinola Finland	C-Green’s	20,000	https://www.innoenergy.com/discover-innovative-solutions/online-marketplace-for-energy-innovations/oxypower-htc/

Table 2: HTC Research output from African

Country	Work	References
-	Potential for thermal conversion of brewer's spent grain into biocoal via hydrothermal carbonization in Africa.	Maqhuzu, et al., 2019
Zimbabwe	The effect of coal alternative fuel from municipal solid wastes employing hydrothermal carbonization on atmospheric pollutant emissions in Zimbabwe.	Maqhuzu, et al., (2019)
South African	Studied Hydrothermal Carbonization of Different Recycling Paper Mill Waste Streams in South African.	Assis, et al., (2021)
South African	Wastewater sludge and sugarcane bagasse using hydrothermal carbonization for the production of biocoal in South African.	Mkhwanazi, and Isa, (2023)
South African	Fuel properties and combustion performance of hydrochars prepared by hydrothermal carbonization of different recycling paper mill wastes.	Assis, and Chirwa, (2023)
South Africa	Hydrothermal Carbonization of Searsia lancea Trees Grown on Mine Drainage.	Setsepu, et al.,(2021)
Côte d'Ivoire	Assessment of the implementation of alternative process technologies for rural heat and power production from cocoa pod husks.	Maleka, D. (2016)

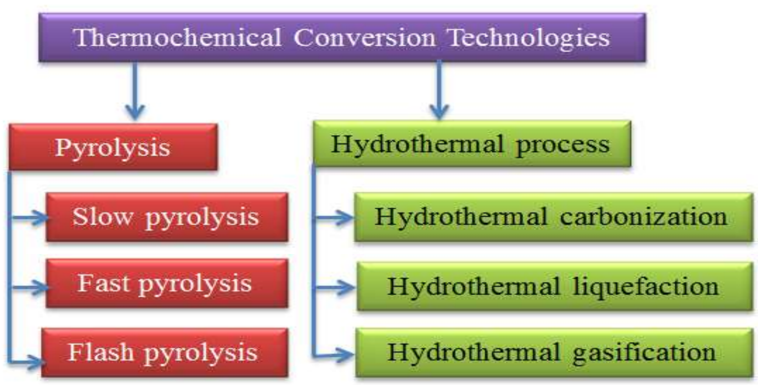

Figure 1: Thermochemical conversion of Biomass (masoumi *et al.*, 2021)

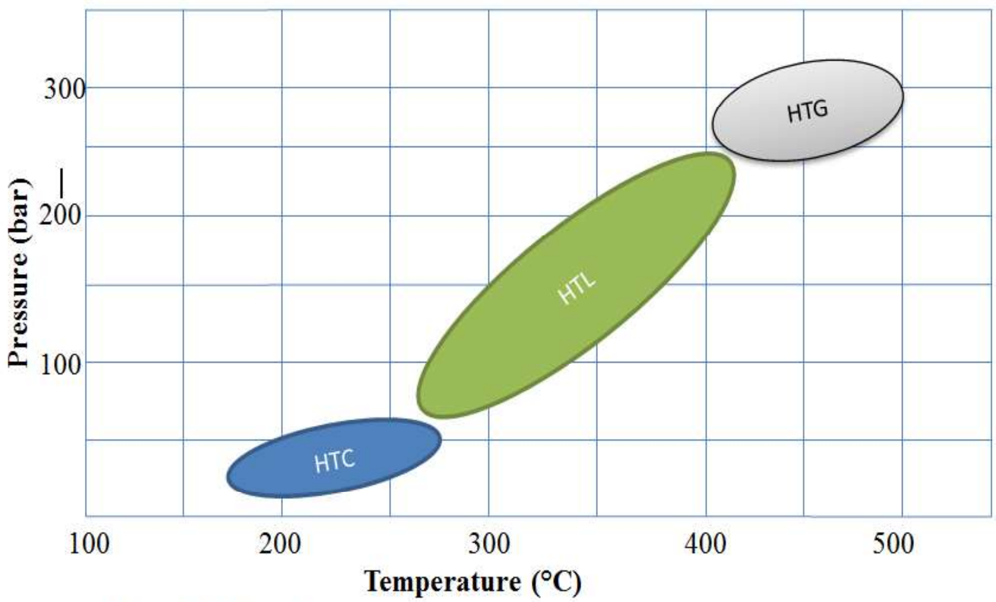

Figure 2: Hydrothermal process

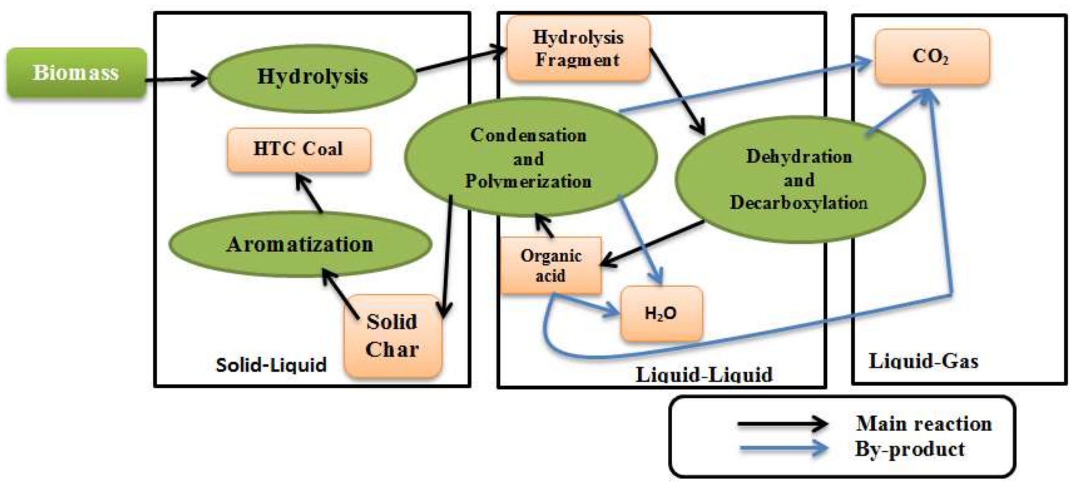

Figure 3: Overview of hydrothermal carbonization mechanism (Heidari *et al.*, 2019).

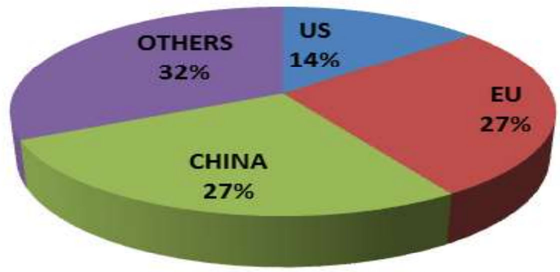

Figure 4: patent registration