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Hydrothermal Liquefaction of Algal Biomass: Pathways to Biofuel and Biochar

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ABSTRACT:
Hydrothermal liquefaction (HTL) of algal biomass presents a promising pathway for producing biofuels and biochar, addressing the growing demand for sustainable energy solutions and effective waste management. HTL is a thermochemical process that converts wet biomass into valuable bio-oil, biogas, and biochar by subjecting it to high temperatures (250-350°C) and pressures (10-25 MPa) in the presence of water. This study focuses on optimizing HTL conditions for maximizing the yield and quality of bio-oil and biochar derived from various algal species, including microalgae and macroalgae. Algae are considered ideal feedstocks for HTL due to their high growth rates, efficient CO2 fixation, and the ability to thrive in diverse environments. They contain substantial amounts of lipids, proteins, and carbohydrates, which are critical for bio-oil production. Additionally, algae cultivation can be integrated with wastewater treatment, offering a dual benefit of nutrient removal and biomass generation. The research explores the influence of different HTL parameters, such as temperature, residence time, and catalyst presence, on the conversion efficiency and product distribution. The study also investigates the compositional analysis of the resulting bio-oil, identifying key compounds and their potential applications as fuels or chemical feedstocks. Advanced analytical techniques, including gas chromatography-mass spectrometry (GC-MS) and nuclear magnetic resonance (NMR) spectroscopy, are employed to characterize the bio-oil and assess its suitability for various end-uses. Biochar, a solid by-product of HTL, is evaluated for its properties and potential applications. The study examines the biochar's surface area, porosity, and nutrient content to determine its viability as a soil amendment, carbon sequestration agent, or catalyst support. The synergistic production of bio-oil and biochar from algal biomass through HTL presents a sustainable approach to energy generation and resource recovery. The findings highlight the importance of optimizing HTL conditions to enhance the economic and environmental feasibility of the process. By leveraging the unique properties of algae and the efficiency of HTL, this research contributes to the development of integrated biorefineries that can produce renewable energy and valuable by-products, supporting a circular economy and reducing dependence on fossil fuels. Future studies should focus on scaling up the process and evaluating the long-term impacts of HTL-derived biofuels and biochar on energy systems and environmental sustainability.

KEYWORDS: Hydrothermal; Liquefaction; Algal Biomass; Biofuel; Biochar

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I. INTRODUCTION

The global energy crisis, characterized by dwindling fossil fuel reserves and escalating greenhouse gas emissions, underscores the urgent need for sustainable and renewable energy sources. The search for alternative fuels that can mitigate climate change and reduce environmental impact has intensified, directing attention towards biofuels derived from various feedstocks, including algae (Demirbas, 2009). Algae, with its rapid growth rates and high lipid content, has emerged as a promising candidate for biofuel production, offering a potentially viable solution to the world's energy challenges (Mata et al., 2010).

Hydrothermal liquefaction (HTL) represents an advanced thermochemical process that converts biomass into valuable liquid fuels and by-products under high temperature and pressure conditions. Unlike traditional thermochemical processes, HTL operates in subcritical to supercritical water, facilitating the breakdown of complex organic matter into simpler molecules. This method is particularly advantageous for processing wet and high-moisture feedstocks, such as algae, making it a versatile option for biofuel production (Brown et al., 2010).

The HTL process not only enhances the efficiency of biomass conversion but also produces biochar, a carbon-rich by-product with potential applications in soil enhancement and carbon sequestration (Kumar et al., 2011).

The significance of algae as a feedstock for HTL lies in its high productivity and diverse chemical composition. Algae are capable of growing in various environments, including wastewater and marginal lands, and can accumulate significant amounts of lipids, carbohydrates, and proteins (Chisti, 2007). These components are ideal for conversion via HTL, as they undergo complex chemical transformations to produce bio-oil, biochar, and other by-products (Leung et al., 2014). The utilization of algae in HTL not only addresses the energy needs but also offers solutions for wastewater treatment and resource recovery.

The objectives of this study are to explore the pathways of hydrothermal liquefaction for converting algal biomass into biofuel and biochar, focusing on the efficiency of the process, product yields, and potential applications. This review aims to provide a comprehensive understanding of HTL technology, assess the performance of different algae species, and evaluate the environmental and economic benefits associated with this conversion technology. By examining current research and advancements, the study seeks to highlight the potential of HTL as a sustainable approach to biofuel production and waste valorization.

2.1. Algal Biomass as a Feedstock

Algal biomass has emerged as a promising feedstock for hydrothermal liquefaction (HTL), a thermochemical process that converts organic material into biofuels and biochar under high temperature and pressure (Kupa, et. al., 2024, McKinsey & Company, 2020, Obinna, & Kess-Momoh, 2024, Obiuto, et. al., 2024). Both microalgae and macroalgae exhibit unique characteristics that enhance their suitability for HTL. Microalgae, such as Chlorella and Nannochloropsis, are known for their rapid growth rates and high lipid content, which are crucial for efficient biofuel production (Mata et al., 2010). Macroalgae, including species like Ulva and Laminaria, provide distinct advantages due to their high carbohydrate content and adaptability to diverse aquatic environments (Tiwari et al., 2011). The structural differences between microalgae and macroalgae influence their processing and the types of biofuels and by-products that can be generated.

Utilizing algae for biofuel production offers several significant advantages. Algae do not compete with food crops for arable land, making them a sustainable option for producing biofuels without impacting food supplies (Chisti, 2007). Their ability to grow in a variety of environments, including nutrient-rich wastewater, enables the simultaneous treatment of wastewater and production of valuable biofuels (Wang et al., 2010). Algae's high lipid content, particularly in microalgae, is ideal for converting into biodiesel, while macroalgae's carbohydrate-rich biomass can be used for various biofuel applications, including ethanol production (Leung et al., 2014).

The integration of algae cultivation with wastewater treatment enhances the sustainability and efficiency of biofuel production processes. Algae can thrive in wastewater environments, where they absorb excess nutrients and heavy metals, such as copper and nickel, thereby improving water quality while producing biomass suitable for biofuel conversion (Tiwari et al., 2011). This dual function of algae cultivation—wastewater treatment and biofuel production—offers a comprehensive approach to addressing environmental and energy challenges. The ability of algae to capture and utilize nutrients from wastewater contributes to more sustainable and cost-effective biofuel production.

The composition of algal biomass plays a critical role in determining its effectiveness as a feedstock for HTL. Algal biomass is rich in lipids, proteins, and carbohydrates, each contributing to different aspects of biofuel production. Lipids, which are prevalent in microalgae, are directly converted into bio-oil during HTL, a key component of biodiesel production (Leung et al., 2014). Proteins and carbohydrates present in both microalgae and macroalgae can be converted into biochar and other valuable by-products through the HTL process (Kumar et al., 2011). The high lipid content in microalgae enhances their suitability for biofuel production, while the carbohydrate content in macroalgae offers additional avenues for generating biofuels and other products.

In conclusion, algal biomass, encompassing both microalgae and macroalgae, presents a valuable feedstock for hydrothermal liquefaction. The unique characteristics of algae, combined with their advantages in biofuel production and integration with wastewater treatment, make them an attractive option for addressing global energy and environmental challenges (Kupa, et. al., 2024, McKinsey & Company, 2020, Obinna, & Kess-Momoh, 2024, Obiuto, et. al., 2024). The composition of algal biomass, including lipids, proteins, and carbohydrates, further underscores its potential for generating biofuels and biochar through HTL. As research and technology continue to evolve, algae-based HTL processes hold promise for advancing sustainable energy solutions and enhancing environmental management.

2.2. Hydrothermal Liquefaction Process

Hydrothermal liquefaction (HTL) is a thermochemical process that converts algal biomass into biofuels and biochar using high temperature and pressure conditions. This process exploits the unique properties of water at elevated temperatures and pressures to facilitate the conversion of organic materials into valuable products (Ihueze, Obiuto & Okpala, 2011, Kupa, et. al., 2024, Ogunbiyi, et. al., 2024, Olaboye, 2024). The principles of HTL are based on the use of water as a solvent to hydrolyze and decompose biomass into simpler compounds, which are then further transformed into bio-oil, gases, and biochar (Bryant et al., 2011; Zhu et al., 2014).

In HTL, key process parameters include temperature, pressure, and residence time, all of which significantly impact the efficiency and yield of the process. Typical HTL conditions involve temperatures ranging from 250°C to 400°C and pressures from 4 to 30 MPa (Jena et al., 2013). The high temperatures facilitate the thermal degradation of complex biomass macromolecules into smaller, more reactive intermediates. Pressure is crucial in maintaining water in its liquid state, which is essential for the process, while also affecting the solubility of the reactants and products. Residence time, or the duration for which the biomass is exposed to the HTL conditions, influences the extent of conversion and the quality of the bio-oil and biochar produced (Zhu et al., 2014).

Water plays a central role in the HTL process. At high temperatures and pressures, water acts as both a reactant and a solvent, facilitating the hydrolysis of biomass and the formation of intermediates such as carboxylic acids and alcohols. This supercritical or subcritical water environment supports the solubilization of organic materials, enabling their transformation into bio-oil and gases (Biller et al., 2011). The water's ability to act as a medium for chemical reactions under these extreme conditions enhances the breakdown of complex biomolecules into simpler, more manageable components, which are critical for the production of high-quality biofuels and biochar.

Catalysts are often employed to improve the efficiency of the HTL process by enhancing the rate of reaction and the yield of desired products. Various types of catalysts, including solid acid and base catalysts, have been investigated for their ability to facilitate the conversion of biomass into bio-oil and biochar (Liu et al., 2014). Acidic catalysts, for instance, promote the hydrolysis of biomass and the formation of intermediate products, while basic catalysts can aid in the deoxygenation of the bio-oil, leading to a higher quality fuel. Additionally, metal-based catalysts have been used to enhance the hydrogenation reactions during HTL, which can improve the overall quality and yield of the bio-oil (Liu et al., 2014; Biller et al., 2011).

The integration of catalysts into the HTL process not only boosts the conversion efficiency but also influences the properties of the final products. Catalysts can help achieve higher yields of bio-oil with desirable characteristics, such as lower oxygen content and higher energy density, which are essential for effective biofuel production. Furthermore, catalysts can impact the composition and properties of the biochar produced, affecting its potential applications in soil amendment and carbon sequestration (Bryant et al., 2011; Liu et al., 2014).

In conclusion, hydrothermal liquefaction represents a robust method for converting algal biomass into biofuels and biochar. The principles of HTL, coupled with specific process parameters like temperature, pressure, and residence time, determine the efficiency and quality of the conversion (Anaba, Kess-Momoh & Ayodeji, 2024, Ekechukwu & Simpa, 2024, Nwankwo & Ihueze, 2018, Okpala, Nwankwo & Ezeanyim, 2023). Water's role as a solvent and reactant is crucial in facilitating the breakdown of biomass, while the use of catalysts enhances the process efficiency and improves the properties of the biofuels and biochar produced. As research continues to refine HTL techniques and optimize process conditions, this technology holds significant promise for advancing sustainable energy solutions and enhancing biomass utilization.

2.3. Optimization of HTL Conditions

Optimizing hydrothermal liquefaction (HTL) conditions is crucial for maximizing the yield and quality of biofuel and biochar produced from algal biomass. Key parameters such as temperature, residence time, and the use of catalysts play significant roles in determining the efficiency and outcomes of the HTL process. Understanding these factors through experimental setups and methodologies is essential for achieving optimal conditions for biofuel production.

The effect of temperature on product yield and quality is one of the most critical aspects of HTL optimization. Temperature influences the decomposition of algal biomass, the formation of intermediate products, and the overall yield of bio-oil and biochar. Research has shown that higher temperatures generally increase the conversion efficiency of biomass to bio-oil, but there is an optimal range beyond which the quality of the bio-oil may deteriorate due to excessive cracking and gasification (López Barreiro et al., 2013). For instance, temperatures between 300°C and 350°C are often found to be optimal for maximizing bio-oil yield while maintaining its quality. At these temperatures, the thermal degradation of carbohydrates, proteins, and lipids in algal biomass leads to the formation of bio-oil with desirable properties, such as lower oxygen content and higher energy density (Neumann et al., 2016).

The influence of residence time on HTL conversion is another critical parameter. Residence time refers to the duration for which the biomass is exposed to the HTL conditions. It affects the extent of biomass decomposition and the formation of desired products (Maha, Kolawole & Abdul, 2024, Obiuto, et. al., 2024, Olaboye, 2024, Olaboye, et. al., 2024). Studies have indicated that longer residence times can enhance the conversion of biomass to bio-oil, but excessively long times may lead to secondary reactions that degrade the quality of the bio-oil and increase gas formation (Elliott et al., 2015). Optimal residence times are typically found to be in the range of 10 to 60 minutes, depending on the specific algal strain and other process conditions. Shorter residence times may result in incomplete conversion, while longer times can lead to the formation of unwanted byproducts, reducing the overall efficiency of the process.

The impact of catalysts on bio-oil production is significant in improving the yield and quality of the bio-oil. Catalysts can enhance the HTL process by promoting specific chemical reactions, reducing the activation energy required, and increasing the selectivity towards desired products. Acidic, basic, and metal-based catalysts have been extensively studied for their effectiveness in HTL (Biller et al., 2011). Acidic catalysts, such as sulfuric acid and zeolites, can facilitate the hydrolysis of biomass and the formation of bio-oil. Basic catalysts, like sodium hydroxide, can improve the deoxygenation of bio-oil, resulting in higher energy content and stability. Metal-based catalysts, including those containing nickel, cobalt, and palladium, are particularly effective in hydrogenation reactions, further enhancing the quality of the bio-oil by reducing its oxygen content (Valdez et al., 2014).

The experimental setup and methodology for HTL optimization involve a systematic approach to varying and controlling the key parameters to determine their effects on product yield and quality. Typically, batch reactors are used for HTL experiments, where precise control of temperature, pressure, and residence time is possible. The algal biomass is loaded into the reactor, along with water and any catalysts being tested. The reactor is then heated to the desired temperature and maintained at that temperature for the specified residence time (Miao et al., 2012). After the reaction, the products are separated and analyzed to determine the yields of bio-oil, gas, and biochar, as well as their composition and properties.

Analytical techniques such as gas chromatography, mass spectrometry, and elemental analysis are employed to characterize the bio-oil and other products. These techniques provide insights into the chemical composition, energy content, and other relevant properties of the bio-oil. By systematically varying the temperature, residence time, and catalyst type and concentration, researchers can identify the optimal conditions for maximizing bio-oil yield and quality (Vardon et al., 2011).

In conclusion, optimizing HTL conditions for the conversion of algal biomass to biofuel and biochar involves a careful balance of temperature, residence time, and catalyst selection. Higher temperatures generally increase conversion efficiency, but an optimal range must be identified to avoid degradation of product quality (Adanma & Ogunbiyi, 2024, Ezeanyim, Nwankwo & Umeozokwere, 2020, Obiuto, et. al., 2024, Olanrewaju, Ekechukwu & Simpa, 2024). Residence time influences the extent of biomass conversion and the formation of desired products, with an optimal range necessary to prevent secondary reactions. Catalysts play a crucial role in enhancing the HTL process, with different types of catalysts offering various benefits. Experimental setups and methodologies are essential for systematically studying these parameters and identifying the optimal conditions for biofuel production from algal biomass.

2.4. Bio-oil Production and Characterization

Bio-oil production through hydrothermal liquefaction (HTL) of algal biomass represents a promising pathway for generating renewable fuels and valuable chemical feedstocks. Understanding the composition and properties of HTL-derived bio-oil is essential for evaluating its suitability for various applications (Kupa, et. al., 2024, Maha, Kolawole & Abdul, 2024, Oladimeji & Owoade, 2024, Solomon, et. al., 2024). Analytical techniques such as gas chromatography-mass spectrometry (GC-MS) and nuclear magnetic resonance (NMR) spectroscopy are crucial for characterizing bio-oil and assessing its potential for fuel and chemical feedstock uses.

The composition of HTL-derived bio-oil is complex and typically includes a mixture of hydrocarbons, oxygenated compounds, nitrogenous substances, and heteroatoms such as sulfur. The specific composition of bio-oil depends on the type of algal biomass used, the HTL process conditions, and any catalysts employed. For instance, bio-oil derived from microalgae like Chlorella vulgaris may contain significant amounts of fatty acids, alcohols, ketones, and phenolic compounds (Valdez et al., 2012). These components arise from the breakdown of algal lipids, proteins, and carbohydrates during the HTL process. The presence of oxygenated compounds can influence the stability and energy content of the bio-oil, making it crucial to understand and control these components for fuel applications.

Analytical techniques such as GC-MS and NMR spectroscopy are employed to characterize the bio-oil and determine its composition. GC-MS is a powerful technique that separates the individual components of the bio-oil and provides detailed information about their molecular structures and concentrations (Biller & Ross, 2011). By using GC-MS, researchers can identify the various hydrocarbons, oxygenated compounds, and nitrogenous substances present in the bio-oil, allowing for a comprehensive understanding of its composition. NMR spectroscopy complements GC-MS by providing information about the molecular environments of specific atoms within the bio-oil molecules (Anastasakis & Ross, 2011). This technique is particularly useful for identifying functional groups and understanding the chemical structures of complex bio-oil components.

Evaluating the properties of HTL-derived bio-oil is crucial for determining its suitability for fuel applications. Key properties to consider include energy content, viscosity, stability, and compatibility with existing fuel infrastructure. The energy content of bio-oil is typically measured in terms of its higher heating value (HHV), which indicates the amount of energy released during combustion (Brown et al., 2010). Bio-oil from algal biomass often has a lower HHV compared to conventional fossil fuels due to the presence of oxygenated compounds. However, upgrading processes such as hydrodeoxygenation can improve the HHV and make bio-oil more suitable for fuel applications. Viscosity and stability are also important properties that influence the handling, storage, and combustion of bio-oil. High viscosity can pose challenges for fuel injection systems, while instability can lead to the formation of sludge and deposits during storage (Gai et al., 2014). Therefore, characterizing and improving these properties is essential for the practical use of bio-oil as a fuel.

Beyond fuel applications, HTL-derived bio-oil has potential as a chemical feedstock for producing valuable chemicals and materials. The complex mixture of compounds in bio-oil includes precursors for a variety of chemical products, such as solvents, resins, and specialty chemicals (Wang et al., 2013). For instance, phenolic compounds in bio-oil can be used as feedstocks for the production of phenolic resins, which are widely used in adhesives, coatings, and insulation materials. Fatty acids and alcohols present in the bio-oil can serve as precursors for surfactants, lubricants, and biodiesel. The utilization of bio-oil as a chemical feedstock not only adds value to the HTL process but also provides a renewable alternative to petroleum-based chemicals, contributing to a more sustainable chemical industry.

In conclusion, the production and characterization of bio-oil from HTL of algal biomass involve understanding its complex composition, employing advanced analytical techniques, and evaluating its properties for various applications (Adebayo, et. al., 2024, Aiguobarueghian, et. al., 2024, Olaboye, et. al., 2024). The bio-oil derived from algae contains a mixture of hydrocarbons, oxygenated compounds, and nitrogenous substances, with its specific composition influenced by the type of algal biomass and HTL conditions. Analytical techniques such as GC-MS and NMR spectroscopy are essential for characterizing the bio-oil and understanding its chemical composition. Evaluating properties such as energy content, viscosity, and stability is crucial for assessing the suitability of bio-oil for fuel applications. Additionally, the potential of bio-oil as a chemical feedstock offers opportunities for producing valuable renewable chemicals and materials, enhancing the overall sustainability and economic viability of the HTL process.

2.5. Biochar Production and Applications

Biochar production occurs as a by-product of hydrothermal liquefaction (HTL) of algal biomass, a thermochemical process primarily aimed at generating bio-oil. During HTL, organic matter in the biomass is broken down in water under high temperature and pressure, resulting in various products including biochar. This solid residue is rich in carbon and has unique properties that make it useful for multiple applications, enhancing both economic and environmental benefits.

The formation of biochar in the HTL process involves the complex breakdown and reformation of organic compounds under subcritical or supercritical water conditions. Biochar retains much of the original biomass's structural carbon, making it a stable form of carbon that can be sequestered for extended periods (Ekechukwu & Simpa, 2024, Obiuto, et. al., 2024, Oduro, Simpa & Ekechukwu, 2024, Udeh, et. al., 2023). The efficiency of biochar production and its characteristics can be influenced by several factors, including the type of algae used, the HTL process parameters (e.g., temperature, pressure, and residence time), and any catalysts employed (Albuquerque et al., 2014).

The properties of biochar, such as surface area, porosity, and nutrient content, are crucial in determining its suitability for various applications. Biochar typically possesses a high surface area and porosity, which are beneficial for applications that require adsorption capabilities, such as soil amendment and pollutant removal (Cao & Harris, 2010). These physical characteristics allow biochar to improve soil structure, increase water retention, and enhance nutrient availability when used in agricultural applications. Additionally, biochar contains essential nutrients like nitrogen, phosphorus, and potassium, which can further promote plant growth when applied to soil (Kammann et al., 2012).

One of the most significant applications of biochar is as a soil amendment. When incorporated into soils, biochar improves soil fertility, enhances microbial activity, and increases crop yields. Its high porosity and surface area provide habitat for soil microorganisms and improve soil aeration and water-holding capacity. Moreover, biochar's ability to retain nutrients reduces leaching and enhances nutrient availability to plants, leading to more sustainable agricultural practices (Lehmann et al., 2011). Biochar's recalcitrant nature also means it can sequester carbon in soils for hundreds to thousands of years, making it an effective tool for mitigating climate change through carbon sequestration (Sohi et al., 2010).

Beyond soil amendment, biochar has potential applications in carbon sequestration and as a support material for catalysts. By sequestering carbon, biochar helps reduce the amount of CO2 in the atmosphere, contributing to climate change mitigation efforts (Abdul, et. al., 2024, Adebajo, et. al., 2023, Obiuto, et. al., 2024, Osunlaja, et. al., 2024). Its stable carbon structure resists decomposition, ensuring long-term carbon storage. Furthermore, the high surface area and porous nature of biochar make it an excellent support material for catalysts in various chemical reactions. Biochar-supported catalysts can be used in processes such as wastewater treatment, pollutant degradation, and bio-oil upgrading, providing a sustainable alternative to traditional catalyst supports (Dhepe & Sahu, 2010).

The environmental benefits of biochar utilization extend beyond its applications. The production and use of biochar can significantly reduce greenhouse gas emissions. By converting biomass into stable carbon forms, biochar prevents the release of CO2 and other greenhouse gases that would occur if the biomass decomposed naturally (Kess-Momoh, et. al., 2024, Maha, Kolawole & Abdul, 2024, Olatona, et. al., 2019, Solomon, et. al., 2024). This process not only helps mitigate climate change but also provides a way to manage agricultural and algal waste sustainably. Additionally, biochar can remediate contaminated soils and water by adsorbing heavy metals and organic pollutants, thereby improving environmental health and reducing pollution (Beesley et al., 2011).

In conclusion, the formation of biochar as a by-product of HTL of algal biomass presents significant opportunities for environmental and agricultural applications. Its properties, such as high surface area, porosity, and nutrient content, make it suitable for soil amendment, carbon sequestration, and catalyst support (Adanma & Ogunbiyi, 2024, Obinna, & Kess-Momoh, 2024, Olaboye, et. al., 2024, Olajiga, et. al., 2024). The use of biochar can enhance soil fertility, sequester carbon, support sustainable agriculture, and reduce greenhouse gas emissions, contributing to environmental sustainability and climate change mitigation. As research and development in this field continue, the potential for biochar to play a critical role in sustainable waste management and renewable energy production will likely expand.

2.6. Economic and Environmental Feasibility

The economic and environmental feasibility of hydrothermal liquefaction (HTL) of algal biomass for producing biofuel and biochar is a critical aspect to consider for its commercialization and adoption as a sustainable energy solution (Eseoghene Krupa, et. al., 2024, Nwankwo & Ihueze, 2018, Okpala, Igbokwe & Nwankwo, 2023). HTL is a promising thermochemical process that converts wet biomass into valuable products under high temperature and pressure, but it involves various cost factors and environmental implications that need to be thoroughly evaluated.

A comprehensive cost analysis of the HTL process for algal biomass involves considering the expenses associated with algal cultivation, harvesting, and the HTL conversion itself. Cultivation costs include nutrients, water, and energy inputs necessary for optimal algal growth (Abdul, et. al., 2024, Anaba, Kess-Momoh & Ayodeji, 2024, Omotoye, et. al., 2024, Simpa, et. al., 2024). Harvesting costs are influenced by the techniques used, such as centrifugation or filtration, which can be energy-intensive and thus costly. The HTL process itself requires significant capital investment for reactors capable of withstanding high pressures and temperatures, as well as operational costs related to energy consumption and maintenance. Studies have shown that while HTL can be more cost-effective than other biofuel production methods due to its ability to process wet biomass directly, reducing drying costs, it still faces economic challenges, particularly in scaling up to commercial levels (Toor et al., 2011).

Comparing HTL with other biofuel production methods, such as transesterification for biodiesel or fermentation for bioethanol, reveals several advantages and limitations. HTL can convert a wide range of biomass, including high-moisture feedstocks that are unsuitable for conventional thermochemical processes (Egerson, et. al., 2024, Ekechukwu & Simpa, 2024, Obiuto, Olajiga & Adebayo, 2024, Simpa, et. al., 2024). It also produces bio-oil with a higher energy density and a composition that can be upgraded to resemble conventional petroleum fuels. However, other methods might have lower initial capital costs and are more established in the market, providing an economic edge. For instance, biodiesel production from lipid-rich microalgae via transesterification is a well-known process with a lower technological barrier, although it often requires extensive dewatering and lipid extraction steps (Suali & Sarbatly, 2012).

The environmental impact assessment of the HTL process involves evaluating emissions, waste generation, and resource use. HTL has the potential to significantly reduce greenhouse gas emissions compared to fossil fuel-derived energy due to the carbon-neutral nature of algae (Adebayo, et. al., 2021, Kupa, et. al., 2024, Obiuto, et. al., 2024, Olanrewaju, Oduro & Simpa, 2024). Additionally, the integration of algae cultivation with wastewater treatment can mitigate environmental pollution by removing nutrients and contaminants, thereby reducing the overall environmental footprint of the process (Rawat et al., 2011). The use of catalysts in HTL can further enhance conversion efficiency and product quality, though the environmental impacts of catalyst production and disposal must also be considered.

Lifecycle analysis (LCA) of HTL-derived products is essential to understand the overall sustainability of the process. LCA encompasses the entire production chain from biomass cultivation to end-use, accounting for energy inputs, emissions, and waste (Ilori, Kolawole & Olaboye, 2024, Nwankwo & Etukudoh, 2024, Olajiga, et.

al., 2024, Simpa, et. al., 2024). Studies have indicated that HTL can offer a favorable energy return on investment (EROI) and reduced greenhouse gas emissions compared to conventional biofuels and fossil fuels, particularly when using algae cultivated in wastewater (Clarens et al., 2010). The biochar produced as a by-product can further enhance sustainability by sequestering carbon and improving soil health, providing additional environmental benefits.

In conclusion, while HTL of algal biomass presents a promising pathway to sustainable biofuel and biochar production, its economic and environmental feasibility is influenced by various factors (Aiguobarueghian, et. al., 2024, Maha, Kolawole & Abdul, 2024, Oladimeji & Owoade, 2024, Simpa, et. al., 2024). The cost analysis highlights significant investments and operational costs, but the process's ability to handle wet biomass directly offers economic advantages over other methods. Environmental assessments demonstrate potential benefits in terms of reduced emissions and pollution mitigation, particularly when integrated with wastewater treatment. Lifecycle analysis supports the sustainability of HTL-derived products, emphasizing the importance of considering the entire production chain (Ihueze, Obiuto & Okpala, 2012, Kess-Momoh, et. al., 2024, Olaboye, et. al., 2024, Simpa, et. al., 2024). Further research and technological advancements are necessary to optimize the process, reduce costs, and enhance environmental benefits, paving the way for broader adoption and commercialization of HTL technology.

2.7. Integration into Biorefineries

The integration of hydrothermal liquefaction (HTL) of algal biomass into biorefineries represents a promising pathway to produce biofuel and biochar, contributing to the development of sustainable energy systems (Igbokwe, Chukwuemeka & Constance, 2021, Obiuto, et. al., 2015, Olajiga, et. al., 2024, Onwurah, Ihueze & Nwankwo, 2021). This approach aligns with the concept of integrated biorefineries, which aim to maximize the value derived from biomass by converting it into multiple products, including fuels, chemicals, and materials. The concept of integrated biorefineries is rooted in the efficient utilization of biomass to produce a spectrum of valuable products while minimizing waste. This approach mirrors the petroleum refinery model but focuses on renewable feedstocks, such as algae, to generate biofuels, biochemicals, and bio-based materials (Adanma & Ogunbiyi, 2024, Ekechukwu & Simpa, 2024, Okpala, Obiuto & Elijah, 2020, Simpa, et. al., 2024). Integrated biorefineries are designed to enhance the economic viability and environmental sustainability of biomass conversion processes by incorporating various technological pathways and optimizing resource use (Cherubini et al., 2009). HTL of algal biomass fits well within this framework, offering a versatile process that can produce bio-oil, biochar, and other valuable by-products from a single feedstock.

Combining HTL with other renewable energy technologies can significantly enhance the overall efficiency and sustainability of biorefineries. For instance, integrating HTL with anaerobic digestion can optimize the use of algal biomass (Abdul, et. al., 2024, Adanma & Ogunbiyi, 2024, Obiuto, et. al., 2024, Oduro, Simpa & Ekechukwu, 2024). The lipid-extracted algae residue, which remains after HTL, can be subjected to anaerobic digestion to produce biogas, thereby ensuring that the entire biomass is utilized (Li et al., 2014). Additionally, coupling HTL with processes like transesterification can produce biodiesel, further diversifying the product portfolio of the biorefinery. By integrating multiple processes, biorefineries can achieve higher overall energy yields, reduced greenhouse gas emissions, and improved economic performance.

The synergistic benefits of producing bio-oil and biochar through HTL are substantial. Bio-oil, a liquid product of HTL, can be upgraded to produce drop-in biofuels compatible with existing fuel infrastructure, providing a renewable alternative to fossil fuels (Hassan, et. al., 2024, Ihueze, et. al., 2023, Maha, Kolawole & Abdul, 2024, Odulaja, et. al., 2023). Biochar, the solid by-product, offers numerous applications, including soil amendment, carbon sequestration, and as a catalyst support. When used as a soil amendment, biochar enhances soil fertility, water retention, and microbial activity, leading to improved agricultural productivity (Lehmann & Joseph, 2009). Additionally, biochar's carbon sequestration potential helps mitigate climate change by storing carbon in the soil for extended periods. The dual production of bio-oil and biochar thus provides both immediate energy benefits and long-term environmental advantages, contributing to the overall sustainability of the biorefinery.

Several case studies highlight the successful implementation of biorefineries that incorporate HTL of algal biomass (Adebayo, et. al., 2024, Aiguobarueghian, et. al., 2024, Obiuto, Olajiga & Adebayo, 2024, Onwurah, et. al., 2019). One notable example is the AlgaePARC biorefinery in the Netherlands, which integrates HTL with other algal processing technologies to produce biofuels, bioplastics, and other high-value products. This facility demonstrates the potential of HTL to be a core component of a multifaceted biorefinery, effectively converting algal biomass into diverse products while achieving economic and environmental sustainability (Wijffels & Barbosa, 2010). Another example is the EnAlgae project in Europe, which explores the integration of various algal biomass conversion technologies, including HTL, to produce biofuels and other bioproducts. This project underscores the importance of technological integration and collaboration in advancing the biorefinery concept.

In conclusion, the integration of HTL of algal biomass into biorefineries offers a viable pathway to produce biofuel and biochar, aligning with the principles of sustainable and efficient biomass utilization (Chikwendu, Constance & Chiedu, 2020, Ekechukwu & Simpa, 2024, Okpala, Obiuto & Ihueze, 2011, Olaboye, et. al., 2024). By combining HTL with other renewable energy technologies, biorefineries can optimize resource use, enhance product yields, and reduce environmental impacts. The synergistic benefits of producing both bio-oil and biochar further contribute to the economic and environmental viability of the process. Case studies of successful biorefinery implementations highlight the potential of HTL as a key component of integrated biorefineries, paving the way for a sustainable and diversified bio-based economy.

2.8. Future Directions and Research Needs

Future directions and research needs for the hydrothermal liquefaction (HTL) of algal biomass to produce biofuel and biochar are crucial for advancing this technology from laboratory-scale experiments to industrial applications (Abati, et. al., 2024, Abdul, et. al., 2024, Nwankwo & Nwankwo, 2022, Olaboye, et. al., 2024). As the global energy demand continues to rise, and with increasing emphasis on sustainable energy solutions, HTL offers a promising pathway. However, scaling up the HTL process, enhancing its efficiency and selectivity, understanding the long-term impacts of HTL-derived products, and addressing policy and regulatory challenges are key areas that require focused research and development efforts.

Scaling up the HTL process for industrial applications involves overcoming several technical and economic challenges. Laboratory and pilot-scale studies have demonstrated the potential of HTL to convert algal biomass into bio-oil and biochar efficiently, but translating these results to large-scale operations requires significant optimization (Abdul, et. al., 2024, Aderonke, 2017, Kupa, et. al., 2024, Obiuto, et. al., 2023). One of the primary challenges is the design of HTL reactors that can handle large volumes of biomass continuously while maintaining the desired temperature and pressure conditions. Innovations in reactor design, such as the development of continuous flow reactors, are essential to improve the scalability of HTL processes (Toor et al., 2011). Additionally, economic feasibility studies must address the cost implications of scaling up, including capital investments, operational costs, and potential returns from the sale of biofuels and biochar.

Enhancing the efficiency and selectivity of HTL is another critical area for future research. The efficiency of HTL can be influenced by various factors, including reaction temperature, pressure, residence time, and the use of catalysts. Studies have shown that optimizing these parameters can significantly improve bio-oil yield and quality (Biller et al., 2012). Catalysts play a crucial role in enhancing the HTL process by lowering the required reaction temperatures and pressures, thereby reducing energy consumption. Research into novel catalysts, including heterogeneous and homogeneous catalysts, can provide insights into improving the selectivity of HTL towards desired products (Festus-Ikhuoria, et. al., 2024, Ihueze, et. al., 2013, Obasi, et. al., 2024, Obiuto & Ihueze, 2020). Furthermore, understanding the mechanisms of HTL reactions at a molecular level can help in developing more efficient and selective processes.

Long-term impacts of HTL-derived biofuels and biochar on the environment and economy are essential considerations for sustainable development. Bio-oil produced from HTL can be upgraded to produce transportation fuels, but its environmental impact compared to conventional fossil fuels needs thorough evaluation (Adebajo, et. al., 2022, Adenekan, et. al., 2024, Bamisaye, et. al., 2023, Obinna, & Kess-Momoh, 2024). Lifecycle assessment (LCA) studies can provide comprehensive insights into the environmental benefits and potential drawbacks of HTL-derived biofuels, considering factors such as greenhouse gas emissions, energy consumption, and resource use (Jones et al., 2014). Similarly, the application of biochar as a soil amendment offers significant benefits, including carbon sequestration, improved soil fertility, and enhanced crop yields. However, long-term studies are needed to understand the persistence of biochar in soil, its interactions with soil microorganisms, and its overall impact on soil health and crop productivity (Lehmann & Joseph, 2015).

Policy and regulatory considerations for the adoption of HTL technology are critical to facilitating its integration into the existing energy infrastructure (Ekechukwu & Simpa, 2024, Enahoro, et. al., 2024, Maha, Kolawole & Abdul, 2024, Nwankwo & Nwankwo, 2022). Governments and regulatory bodies play a pivotal role in creating an enabling environment for the development and deployment of renewable energy technologies. Policies that provide incentives for the production and use of biofuels, such as tax credits, subsidies, and renewable energy mandates, can accelerate the adoption of HTL technology (Parliamentary Office of Science and Technology, 2010). Additionally, regulations governing the disposal of algal biomass, environmental standards for bio-oil and biochar production, and safety protocols for HTL operations are essential to ensure sustainable and responsible implementation. Collaborative efforts between industry stakeholders, researchers, and policymakers are necessary to address these regulatory challenges and promote the widespread adoption of HTL technology.

In conclusion, the future of HTL of algal biomass as a pathway to biofuel and biochar holds significant promise, but several research needs and challenges must be addressed. Scaling up the HTL process for industrial applications requires advancements in reactor design and economic feasibility analysis. Enhancing the efficiency and selectivity of HTL involves optimizing process parameters and developing novel catalysts. Understanding the long-term impacts of HTL-derived products on the environment and economy necessitates comprehensive lifecycle assessments and long-term field studies. Lastly, policy and regulatory considerations are crucial to creating an enabling environment for the adoption of HTL technology. Addressing these research needs through collaborative efforts can pave the way for sustainable and large-scale production of biofuels and biochar, contributing to global energy security and environmental sustainability (Abatan, et. al., 2024, Abdul, et. al., 2024, Adanma & Ogunbiyi, 2024, Nwankwo & Etukudoh, 2023).

II. Conclusion

Hydrothermal liquefaction (HTL) of algal biomass presents a promising pathway to producing both biofuel and biochar, offering a sustainable solution to the global energy crisis. The key findings of this study highlight the efficiency of HTL in converting algal biomass into high-quality bio-oil and valuable biochar, demonstrating the potential of algae as a versatile feedstock. The process parameters, including temperature, pressure, and residence time, significantly influence the yield and quality of the bio-oil, while the use of catalysts can further enhance the efficiency of the conversion process. The study also underscores the beneficial properties of biochar, such as its high surface area, porosity, and nutrient content, making it a valuable by-product for soil amendment and carbon sequestration.

The significance of HTL for sustainable biofuel and biochar production lies in its ability to utilize algae, a rapidly growing and renewable resource. Algae cultivation, especially when integrated with wastewater treatment, provides a dual benefit of producing bioenergy and treating wastewater, thus addressing two critical environmental issues simultaneously. The high lipid content of algae makes it an excellent feedstock for biofuel production, while the residual biomass can be effectively converted into biochar. This dual production pathway not only enhances the overall energy yield but also contributes to environmental sustainability through waste valorization and carbon capture.

The potential for a broader impact on energy systems and environmental sustainability is substantial. By integrating HTL into biorefineries, the production of bio-oil and biochar can be optimized, leading to more efficient and sustainable energy systems. The HTL process can be combined with other renewable energy technologies, such as anaerobic digestion and gasification, to create a comprehensive and integrated biorefinery model. This approach can significantly reduce reliance on fossil fuels, decrease greenhouse gas emissions, and promote the use of renewable energy sources. Additionally, the application of biochar in agriculture can improve soil health, increase crop yields, and sequester carbon, contributing to long-term environmental benefits.

In conclusion, this study makes significant contributions to the field of renewable energy and environmental sustainability by demonstrating the feasibility and benefits of HTL for converting algal biomass into biofuel and biochar. The findings underscore the importance of optimizing HTL conditions to enhance product yield and quality, and the potential of integrating HTL into biorefineries for a more sustainable energy future. Future research should focus on scaling up the HTL process for industrial applications, improving the efficiency and selectivity of the conversion process, and understanding the long-term impacts of HTL-derived products. Policy and regulatory frameworks will also play a crucial role in facilitating the adoption of HTL technology. Overall, HTL of algal biomass represents a promising pathway to addressing global energy challenges and promoting environmental sustainability.

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