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Physicochemical Conversion Technologies of Biomass for Bioenergy Production

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Abstract

Global energy consumption has continued to escalate due to rising population, urbanization, and industrialization. The world energy landscape has been dominated by fossil-based (FB) energy sources with attendant rising dangerous emissions, worsening air quality, and deteriorating ecosystems. Meeting the energy demand will require the conversion of biomass and other waste materials into renewable energy, including bioenergy as a sustainable and eco-friendly alternative to the debilitating FB energy sources. This study explores the various physicochemical conversion technologies for biomass conversion to bioenergy. The conversion of biomass to bioenergy through various technologies such as hydrothermal conversion processes, supercritical fluid extraction, microwave-assisted conversion, solvent liquefaction, hydrogenation, and carbonization processes yield biooil, biocrude, hydrochar, biochar, hydrogen, syngas, chemicals, and other bioproducts. The review concludes that physicochemical conversion technologies are easy to achieve, cost-effective, require little or no pretreatment, and ensure the production of high energy density products. The deployment of physicochemical techniques for biomass conversion will reduce overreliance on FB energy sources, contribute to energy security, and environmental sustainability. Development of innovative reactor designs, use of nanocatalysts, optimization, and modelling of process parameters, incentivizing waste conversion, and dilution of sociocultural biases against waste utilization will assist in overcoming the challenges associated with physicochemical biomass conversion and escalate bioenergy production from biomass.

1. Introduction

Due to increased population growth, industrialization, and urbanization, global energy consumption has continued to rise. From a mere 12 131 terawatt-hours (TWh) in 1900, the global primary energy rose to 122 868 TWh in 2000 and 183 230 TWh in 2023 [1]. However, the global energy landscape is still heavily dominated by energy from fossil-based (FB) sources. Currently, over 85 % of the global primary energy consumption is derived from FB sources (oil, coal, and gas) [2]. This has increased global greenhouse gas (GHG) emissions from 8.54 billion tonnes (t) in 1900 to 40.77 billion t in 2000 and further to 53.85 billion t in 2023 [3] (Figure 1). Biomass, an organic material derived from plants and animals, is one of the neglected renewable energy (RE) sources that can be used as a substitute for FB energy sources. Biomass contains stored chemical energy that could be converted for cooking and heating across many jurisdictions. As of 1900, about 50 % of the global primary energy was sourced from biomass, but the share of biomass in the global energy has since plummeted. Though the global supply of primary energy from biomass rose from 41.7 exajoules (EJ) in 2000 to 57.5 EJ in 2020 (Figure 2), the share of biomass energy in the global energy consumption is less than 7 % as of the end of 2023 [2, 4]. This shows that the capacity of biomass to contribute significantly to the global energy mix is grossly underexploited. The continuous dependence on FB sources for global energy has impacted environmental sustainability and made universal access to affordable and clean energy sources (SDG 7) unachievable. Currently, about 675 million people lack access to clean electric energy, while about 2.3 billion people still depend on unsafe and polluting fuels for heating and cooking [5]. The deployment of RE for the global energy supply ensures lower GHG emissions, energy reliability, job creation, and environmental sustainability [4, 6].

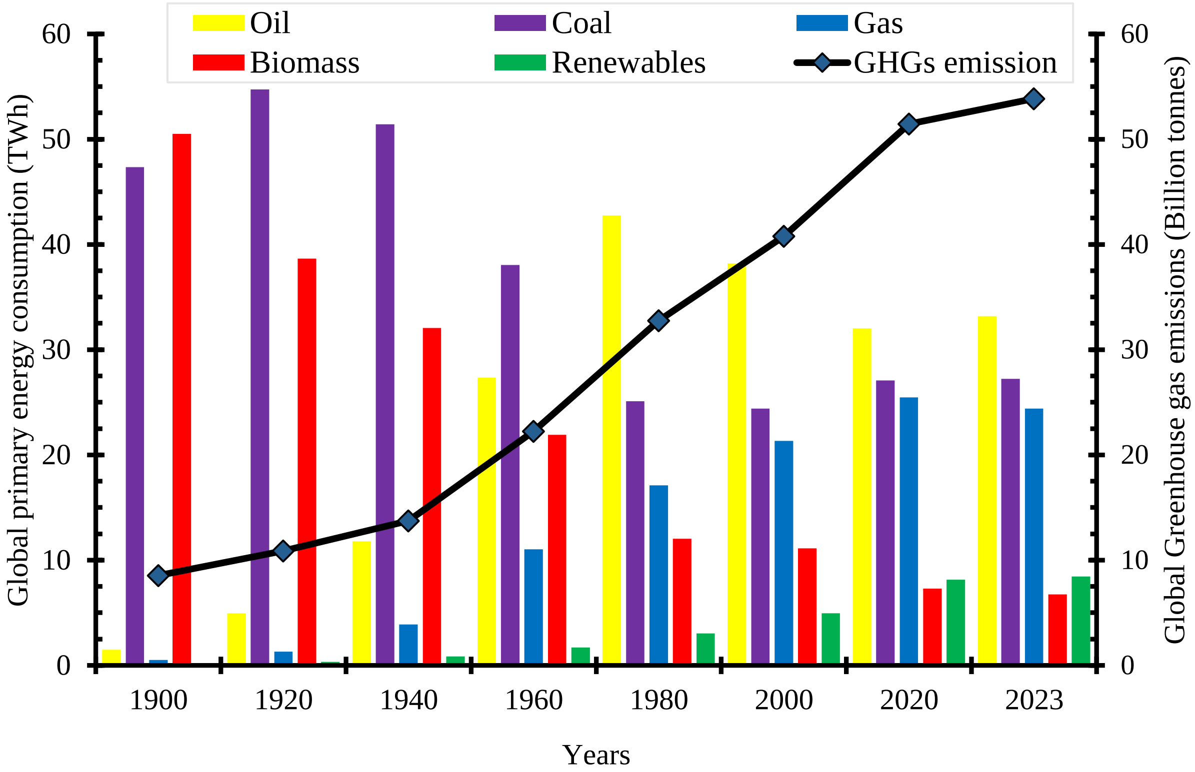

Figure 1. Global primary energy consumption (TWh) and GHG emissions (billion tonnes). Adapted from [3]

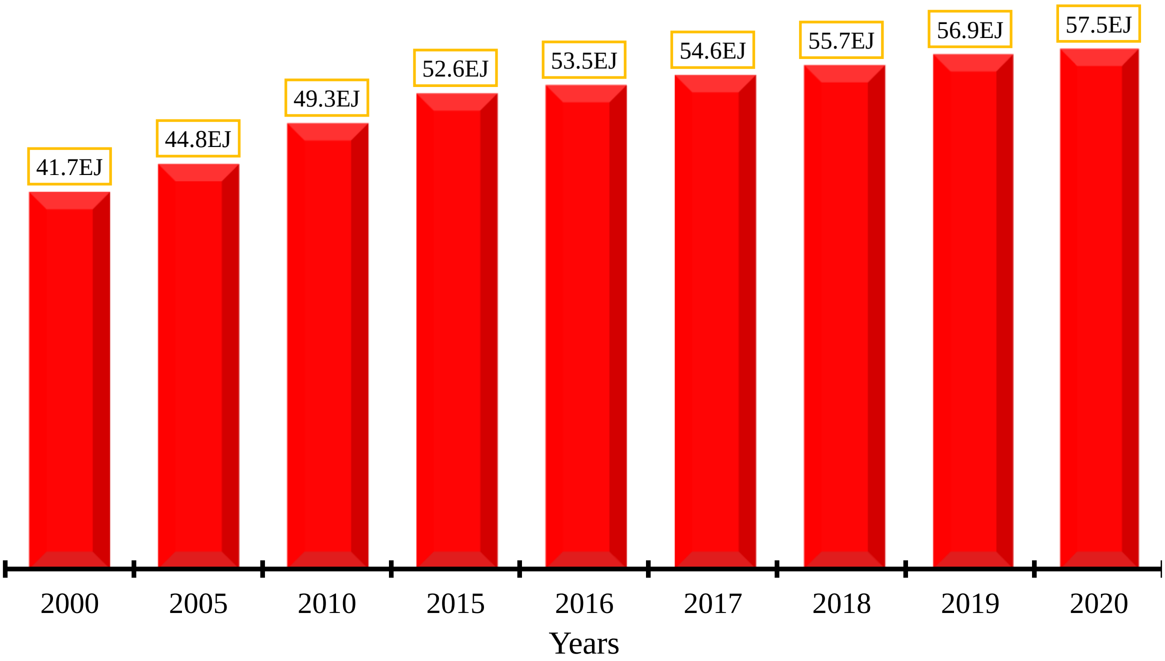

Figure 2. Global primary energy supply from biomass (EJ). Adapted from [2, 4]

One of the challenges militating aging the exploitation and usage of energy from biomass is the difficult and ineffective conversion process. Over the years, researchers have exploited diverse techniques in converting various biomasses into useful forms [7]. From ancient times, physical, chemical, biological, catalytic, and thermal techniques have been deployed to convert biomass into useful products. Over time, these age-long techniques were amalgamated to optimize the benefits and downplay the drawbacks associated with the individual process. Hence, thermophysical, physicochemical, thermochemical, biochemical, thermobiological, and other integrated technologies were adopted to transform biomass into biofuels and other value-added bioproducts [6, 7]. These integrated conversion technologies ensure easily achievable, largely affordable, low-energy consumption, eco-friendly, moderate conversion process parameters, high conversion efficiency, and high purity products. Physicochemical biomass conversion techniques, which combine physical and chemical methods, could effectively transform various biomass into useful products.

Physical biomass conversion involves the modification of biomass through various pre-processing activities to achieve size reduction, dehydration, and densification, while chemical conversion entails the use of chemical reagents for biomass transformation [8]. By employing physicochemical conversion technologies, we tend to combine the low energy consumption, low infrastructure requirement, and higher energy density of physical biomass conversion methods with the speed, high product quality, and possibility to transform large quantities of biomass achievable in chemical biomass conversion [9, 10]. In a recent study, Zhi et al. [10] deployed hydrothermal carbonization to convert biomass into biofuel and other biochemicals, while Chai et al. [11] utilized supercritical fluid extraction technology to valorize tropical biomass waste. The use of microwave-assisted [12], solvent liquefaction [13], hydrogenation [14], and carbonization technologies [15] for biomass conversion has been presented in the literature. The outcomes of these studies revealed that adopting physicochemical conversion technologies could ensure low-cost, easily achievable, and effective conversion of biomass from various sources, compositions, and moisture contents into bioenergy and other useful products. Products derived from physicochemical conversion for biomass conversion are of proven quality and the process needs minimal pretreatment and can be upgraded into an industrial proportion.

However, in the opinion of the authors, there is still no single publication that aggregates the processes, strategies, outcomes, benefits, challenges, and future research directions of physicochemical conversion technologies for easy accessibility and understanding. This forms the motivation and novelty of the current intervention. Thus, this chapter aims to discuss the various physicochemical techniques for converting biomass into bioenergy and other useful products. The objective is to increase awareness among researchers and other stakeholders on the modalities and benefits of adopting physicochemical strategies to convert various biomass into bioenergy and other valuable products. This is to evolve more robust, cost-effective, easily achievable, and effective strategies for renewable energy production from waste and other low-cost feedstocks. The scope of the current study is limited to discussing the strategies for various physicochemical technologies for biomass conversion to bioenergy. The actual experimental physicochemical conversion technologies of biomass, and the use of mathematical, optimization, modelling, and statistical tools to analyze the various conversion processes are beyond the scope of the current work. The outcome of this study will arouse more interest in the capacity of biomass to ameliorate the global affordable and clean energy deficit, reduce environmental pollution caused by inappropriate disposal and management of wastes, and meet the Sustainable Development Goals (SDGs).

The first section of the review contains the introduction, trends in global energy consumption and GHG emissions, motivation, objective, and scope of the study. Other subsequent sections discuss the various physicochemical technologies for biomass conversion, such as hydrothermal conversion, hydrothermal liquefaction, supercritical fluid extraction, microwave-assisted conversion, solvent liquefaction, and hydrogenation and carbonization processes. The challenges and future research perspectives of physicochemical conversion technologies are highlighted in a separate section. The conclusion section summarizes the key findings of the study and recommends appropriate strategies for effective physicochemical conversion of biomass toward a sustainable circular bioeconomy, RE integration, and global energy security in line with SDGs.

2. Hydrothermal conversion processes

The hydrothermal conversion technologies use water and heat to convert biomass to bioenergy and other valuable products. The conversion takes place in a pressurized vessel or reactor maintained at a specified temperature and pressure. During the process, water or steam is subjected to elevated temperatures, usually between 200 °C and 350 °C, and elevated pressures between 4 MPa and 22 MPa which degrades the water and turns it into supercritical fluid [16]. When compared with other biomass conversion technologies, hydrothermal conversion technologies have been widely used due to their versatility, flexibility of process parameters, and ability to handle diverse feedstocks, including those with high moisture content. The technology also operates with low energy consumption, guarantees high conversion efficiency, supports a low carbon footprint, requires little or no pretreatment, and generates valuable co-products. Depending on the temperature, pressure, and desired product, hydrothermal conversion can be classified as hydrothermal carbonization (HTC) and hydrothermal liquefaction (HTL). Table 1 compares the description, processing temperature, pressure, advantages, and disadvantages of HTC and HTL technologies.

Table 1. Comparison of hydrothermal conversion technologies

Technology	HTC	HTL
Description	Degradation of wet biomass using pressurized water at high temperature	Use of heated and compressed water to breakdown biomass
Process temperature (°C)	180 - 250	250 - 374

Pressure (MPa)	2 - 4	Up to 18
Types of feedstock	Wet biomass, waste, sewage sludge, municipal solid waste, cattle manure	Wet biomass, forest residue, agricultural waste, food leftovers, dairy waste, microalgae, human sewage
Products	Hydrochar, biooil, and other carbonaceous products	Biocrude, dense liquid product
Product yield (%)	52 to 69	30 to 60
Product application	Solid fuel, energy storage, wastewater treatment, soil remediation, bio-based product manufacturing	Bioenergy production, feedstock petrochemical industries, carbon sequestration, soil improvement, fertilizer production
Advantages	• Cost-effective and eco-friendly • Requires no preliminary dehydration • Low operating temperature • Reduced air pollution	• Requires no preliminary drying • Can handle varieties of feedstocks • High energy density of products
Drawbacks	• High reaction temperature • High energy requirement • Generation of oxides nitrogen and sulphur	• Requires special equipment • High capital costs • High temperature and pressure • Limited feedstock options
Reference	[17]	[18]

2.1. Hydrothermal carbonization

Hydrothermal carbonization of biomass usually occurs in water at 180 - 250 °C and 2 – 4 MPa during which biomass of diverse sources, composition, and moisture content are converted to hydrochar and other carbonaceous products. When compared with other hydrothermal biomass conversion technologies, HTC operates at low temperatures and pressure, is cost-effective, and energy efficient. Though CO and CO_2 are emitted during the reaction, the process parameters can be optimized to achieve reduced toxic emissions and improved desired product yield [20].

2.1.1. Products characteristics

The HTC process involves a series of complex reactions that are accomplished in three major steps: dehydration, decarboxylation, and condensation [10]. During the process, the selected biomass is heated in compressed water, followed by the hydrolysis of polysaccharides, which leads to the formation of soluble oligosaccharides and an organic phase. The formed organic phase subsequently undergoes several reactions and processes, including condensation, resulting in the formation of hydrochar and other byproducts. Several factors such as biomass type, feedstock moisture content, reaction temperature and pressure, residence time, catalyst, feedwater pH, substrate concentration, heating rate, etc., influence the reaction mechanism and product formation of the hydrothermal carbonization process. With the advancement in technology, the processing is optimized to increase product yield, product quality, and energy consumption [10, 17, 20].

2.1.2. Catalysts and solvents

The addition of appropriate catalysts and solvents speeds up the reaction and enhances product quality and yield. Zhi et al. [10] report that the use of acids (HCl, H_2SO_4, CH_3COOH, etc.) alkaline (NaOH, $Ca(OH)_2$, NaCl, etc.), salts ($Fe\ (NO_3)_3$, $FeCl_3$, etc.), surfactants, and hydrotalcite have significant effects on the reaction rate, product properties and usage, energy consumption, and production costs. For example, the deployment of citric acid in the HTC reaction accelerates the carbonization process while the addition of surfactants speeds up moisture and heavy metal absorption [20].

2.1.3. Catalysts and solvents

The main product of HTC is hydrochar, a form of biochar, which is approximately expressed as $(C_3H_2O)n$. When compared with conventional biochar produced from other biomass conversion techniques, hydrochar is slightly more acidic and contains more oxygenated functional groups. The hydrochar produced through HTC contains about 62.5–70.2% carbon, 2.7–4.0 % hydrogen, 26.0–33.9 % oxygen, 2.19-8.4 % nitrogen, and 0.01-1.8 % sulphur while its volatile matter, ash content, and Fixed carbon could range between 37.2-66.87 wt.%, 24.80-53.08 wt.%, and 1.07-14.11 wt.%, respectively [10]. The properties and composition of hydrochar generated through HTC are influenced by biomass type, reaction temperature, pressure, residence time, and catalyst type. Hydrochars usually demonstrate high calorific value, porosity, low degradability, and a high degree of homogeneity. The high calorific value, energy content, and heating capacity of hydrochar make it useful for bioenergy production and storage. Based on the good adsorption capacity and better porous structure of hydrochar, it is commonly used as a low-cost material for soil amelioration, pollutant adsorption, water and wastewater treatment, catalyst support, and carbon sequestration [21].

2.2. Hydrothermal liquefaction

2.2.1. Basics of HTL

HTL is a form of hydrothermal conversion technology where heated and compressed water is applied to break down the solid biopolymeric structure in biomass into biocrude and other dense liquid products. During the process, wet biomass is subjected to heating at 250 – 374 °C and a pressure of up to 18 MPa in the presence of a catalyst and hydrogen to achieve the depolymerization of the feedstock [18]. HTL can handle various biomass of varying moisture content without any need for preliminary drying of the biomass. Products of HTL contain high energy density, improved cetane number, and are less hygroscopic. Despite these advantages, the high cost of catalyst, frequent replacement and regeneration of catalyst, management of spent catalyst, a large volume of water requirement, and the need for further upgrading of biooil produced during HTL are some of the major challenges of the technology [22].

2.2.2. HTL Reactor Configurations

The transformation of wet biomass into biocrude and other dense liquid products using the HTL technology are carried out in reactors of different configurations. Several HTL reactor types and configurations such as batch reactors (BRs), continuous stirred tank reactor (CSTRs), and plug flow reactors (PFRs), have been used for the effective conversion of biomass [22]. Figure 3 shows the schematic representation of a typical HTL process. Different types of reactors have been used with different parameters such as temperature, pressure, water quantity, heating rate, feedstock quantity, reaction rate, product yield, etc., to ensure efficiency and scalability of the process [23]. BRs operate in closed, discontinuous cycles and are best suited for small-scale biomass conversion and kinetic studies, particularly in hydrothermal liquefaction and pyrolysis. They offer precise control over reaction parameters but are limited by low scalability and energy inefficiency. The CSTRs maintain uniform reaction conditions through complete mixing, making them ideal for fermentation and anaerobic digestion. Although their conversion efficiency is reduced by back-mixing, they support steady-state operation and industrial scalability. The use of PFRs enable high conversion rates via axial flow with minimal back-mixing, facilitating spatially resolved reaction kinetics and efficient heat and mass transfer. They are optimal for large-scale thermochemical processes such as gasification and biogas production. Reactor selection should align with product goals, feedstock type, and process scale [18, 22]. Table 2 shows the description, operating conditions, advantages, and disadvantages of BRs, PFRs, and CSTRs. Demand for more reactor effectiveness, improved conversion efficiency, and product quality has led to optimization of reactor parameters and configurations, upgrading and scalability, and hybrid configurations. These have led to improved ease of operation, conversion efficiency, product quality improvement, upgrading, and sustainability of the process [24].

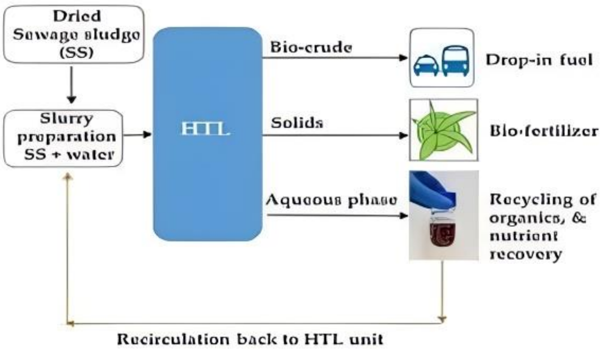

Figure 3. Schematic representation of a typical HTL process. Adapted from [25]

Table 2. Comparison of HTL reactors

Parameter	BRs	CSTRs	PFRs
Description	- Biomass and water are fed into the reactor at a desired temperature and pressure, and for a particular time until liquefaction, followed by product separation	- Stirring and homogenous mixture of biomass and water in a tank reactor at a specified temperature, pressure, and duration until liquefaction followed by product separation.	- Feeding of wet biomass and water into a heated and compressed reactor until liquefaction, followed by product separation
Operating conditions	- Temperature: 220-400 °C - Pressure: 10-25 MPa - Residence time: longer than 30 min. - Catalysts: Alkali metals, noble metals, carbon-based - Solvent: Water, methanol, ethanol	- Temperature: 250-400 °C - Pressure: 10-25 MPa - Residence time: 5-60 min. - Catalysts: Alkali metals, noble metals, carbon-based - Solvent: Water, methanol, ethanol	- Temperature: 250-400 °C - Pressure: 10-25 MPa - Residence time: 1-10 min. - Catalysts: Alkali metals, noble metals, carbon-based - Solvent: Water, methanol, ethanol
Product yield	- 44 – 50 % (biocrude) - 15 – 32 % others	- 1.2 g/L·h	- 0.20 L/g (biogas) - 0.73 m^3 CH_4
Advantages	- Simple operation - Compact in size - Cost-effectiveness - Flexibility in feedstock choice - Scalability - Low investment cost - Greater control - Enhanced safety	- Continuous operation - High reaction rate - High product yield - Improved mixing - Better heat and mass transfer	- Generate high-quality product - Low residence time - Easy to control - Moderate reaction parameters - High conversion efficiency - High product yield - Less thermal

			degradation
Disadvantages	• Slow reaction • Low product yield • Limited heat and mass transfer • Lower efficiency • Higher risk of product contamination • Limited scalability • Higher labour requirement	• High residence time • Presence of dead volume • High thermal degradation • Increased maintenance • Higher capital investment • Lower product quality • Inefficient energy use	• Complexity in design • Expensive construction and operation • Capital intensive • Fouling issues • Difficult to scale-up • High operation maintenance • High safety risk
Reference	[24]	[23]	[22]

2.2.3. Process parameters and their effects

Process parameters of HTL reactors perform a critical role in controlling the conversion efficiency, product yield, and product quality of the transformation of wet biomass into biocrude and other useful bioproducts. Process parameters like reaction temperature, pressure, residence time, heating rate, and biomass-solvent feed ratio affect the operation of the HTL reactor. The main purpose of the process temperature is to develop enough energy to break the barrier and bond between biomass and intermediates. Temperature also increases the fragmentation and degradation of recalcitrant cellulose, hemicellulose, and lignin in lignocellulosic biomass. Pressure helps to minimize the phase change of the solvent into vapor throughout subcritical and supercritical operations, thereby reducing the excess energy needed to maintain a two-phase system [26]. The residence time or retention time is the total period the biomass is in the reactor and maintained at the desired temperature. The residence time depends on the heating rate and it affects the biomass conversion, product composition, and yield.

The heating rate, which is the rate of temperature rise per unit time, affects the aggregate of product formation and reaction rate, and ensures the timely attainment of the desired temperature. The biomass-solvent feed ratio is an important HTL parameter that affects biomass conversion and product yield. The volume of water used by the solvent must be enough for an adequate solvolysis process, while the quantity of biomass must be commensurate with the solvent volume to guarantee effective biomass hydrolysis and liquefaction [23]. Other factors, such as the addition of a catalyst, the use of co-solvents, the extraction of solvent, etc., play significant roles during the liquefaction process. For example, the addition of catalysts, such as copper, iron, nickel, zinc, zeolites, borax, NaOH, KOH, HCl, acetic acid, etc., affects biomass decomposition, reaction rate, production costs, product yield, and properties during HTL [13]. Typical biocrude yields range from 20-60 wt%, depending on feedstock composition and operating parameters. Additional products include an aqueous phase (20-30 wt%), gas (5-15 wt%), and solid residue (10-20 wt%). HTL is particularly effective for high-moisture feedstocks such as algae, food waste, and sewage sludge. Table 3 compiles the effects of major process parameters affecting the HTL reaction.

Table 3. The effects of HTL reactor process parameters and their products [18, 26]

Process parameter	Parameter range	Effects
Temperature (°C)	180-400	• Low temperature slows down reaction rate and product yield • High temperature leads to increased reaction rate and higher product yield • Excessive high temperature impacts product yield and quality
Pressure (MPa)	4-25	• Low pressure is unsuitable • High pressure enhances thermal stability, conversion efficiency, and product yield • Higher pressure leads to higher energy consumption, production costs, and safety risks
Residence time (min)	10-60	• Short residence time leads to low conversion rate and incomplete biomass degradation and conversion of feedstock • Long residence time favours product formation and • Residence time above 60 mins promotes repolymerization/carbonization, decreases biooil yield, stimulates breaking down of oil and organics into char and gas, and exacerbates production costs
Heating rate (°C/min)	5-140	• Low heating rate promotes repolymerization of intermediates and biooil fractions to char, prolongs the residence time and reaction rate • High heating rate fast-tracks hydrolysis and product formation • Excessive fast heating rate provokes secondary cracking of long-chain hydrocarbons and aromatics, hence the formation of more gaseous products
Biomass-solvent feed ratio	1/10-8/10 g/L	• Very low biomass-solvent feed ratio results in low product yield and high production cost per unit • A high feed ratio increases the biooil yield and minimizes carbon losses

		- Higher biomass concentration prevents effective biomass hydrolysis while excessive water quantity exacerbates the cost of pumping and mixing and causes turbulence
Catalyst	NA	- Addition of catalysts allows faster biomass decomposition, hampers secondary reactions, and reduces the temperature and pressure requirements. - Preparation of catalyst and disposal of spent impacts the environment and imposes exacerbates
Product yield (wt%)	- Biocrude: 20-60 % - Aqueous phase: 20-30 % - Gas: 5 – 15 % - Solid: 10 – 20 %	- Product yield generally varies significantly depending on feedstock type, reaction conditions, and reactor design. - Biocrude yield depends on lipid content; algae and food waste give higher yields

NA = not applicable

2.2.4. Products and Applications of HTL

Products derived from the HTL processing of biomass can be categorized as solid, liquid, and gaseous phases. The major products include biocrude, biochar, aqueous phase products (APPs), and other gaseous products are used for bioenergy production, environmental remediation, pollutants adsorbents, and industrial feedstocks. The deployment of HTL for the conversion of biomass and other wastes to these products contributes to waste management and conversion, promotes energy and environmental sustainability, and supports circular bioeconomy.

Biocrude, also known as biooil, or heavy oil, is one of the major products of HTL and consists of a complex blend of hydrocarbons, alcohols, alkanes, alkenes, nitrogenated organic compounds, and oxygenated aromatics [27]. Biocrude is a viscous but thermally stable liquid fuel usually immiscible with hydrocarbon fuel and contains about 39 MJ/kg. In its impure state, it contains sulfur and nitrogen, owing to its biomass origin. Biocrude has higher oxygen content than fossil oils and is rich in phenolics, furans, aldehydes, and other compounds. Due to its impressive energy content, biocrude can be upgraded by hydrotreatment and catalytic cracking processes and used as a renewable alternative for FB fuels in power generation and as transportation engine fuel. Biocrude has been successfully used as an industrial feedstock for producing polymers, solvents, resins, and other chemicals [28].

The black or dark brown carbonaceous solid residue generated from the HTL of biomass is called biochar. Biochar generated from HTL of biomass is rich in carbon, low in ash, heavy metals, and soluble organics. The high energy content, excellent porosity, and expansive surface area of biochar explain its usage as a solid biofuel, low-cost adsorbent, fertilizer, for water treatment, waste management, soil amendment, and environmental remediation material. The APPs generated from HTL of wet biomass are soluble in water and contain organic acids, monosaccharides, furans, phenolics, and nitrogen-containing compounds. The APPs can be further processed and serve as low-cost feedstock for the production of animal feeds, biofertilizers, bioplastics, and other high-value products. The gaseous products generated from HTL include methane, ethane, propane, short-chain alkenes, hydrogen, CO_2, CO, and other volatile organic compounds (VOCs) [23, 26]. Methane, ethane, and hydrogen can be used as engine fuel, heating, and raw materials for other products. However, VOCs are unwanted byproducts and must be extracted from other useful products, while the effect of emissions such as methane, CO, and CO_2, which impact human health and the ecosystem, and exacerbate global warming, must be addressed [29].

3. Supercritical fluid extraction

3.1. Basics of supercritical fluid extraction

The supercritical fluid extraction (SFE) is the use of an extracting fluid to aid recalcitrant biomass valorization to yield a form of bioenergy and other value-added co-products. Supercritical fluids are highly pressurized gases with demonstrable combined properties of gases and liquids created by deliberate increments of temperature and pressure of the substance above a given threshold. Common supercritical fluids used in biomass valorization include supercritical CO_2, ammonia, methanol, ethanol, xenon, ethane, mixtures of CO_2 and water, etc. Most supercritical fluids display some unique properties such as polarity, polarizability, high coefficient of diffusion, low density, low viscosity, non-flammability, nontoxicity, and ready solubility [30]. However, CO_2 is the most widely applied supercritical fluid due to its selectivity, ready availability, nontoxicity, non-flammability, recyclability, and cost-effectiveness. Also, CO_2, in its supercritical phase, possesses high solubility and impressive mass transfer properties [31]. Over the past decades, SFE has become progressively popular due to its many advantages, such as versatility, selectivity, effectiveness, impressive extraction efficiency, low residence time, eco-friendliness, generation of high-purity products, and minimum post-extraction processing.

3.2. Extraction mechanism

The SFE process consists of about seven steps, namely: sample preparation, sample matrix loading, extraction with the solvent, product separation, extract recovery and collection, post-extraction processing, and CO_2 recycling. The sample preparation step involves pulverization and removal of unwanted materials and contaminants before loading them into the SFE chamber [32]. During the sample preparation, biomass is pulverized, and all unwanted materials and contaminants are removed before being charged into the extraction chamber. The biomass is thereafter charged into the extraction chamber, the supercritical fluid is pumped into the chamber and the temperature and pressure are raised to the desired level for the extraction to occur. The dissolved matrix is transferred into the separator, where the solvent is detached from the solute. The recovered, collected extract is subjected to filtration, dehydration, distillation, and other post-processing operations. The last step is the recovery and recycling of the supercritical CO_2 for future reuse [11, 30]. Strict adherence to these steps guarantees the purity and concentration of the products and contributes to making the SFE process economical, eco-friendly, and sustainable.

3.3. Equipment and operating conditions for SFE

The SFE process occurs in a reactor consisting of an extraction cell or vessel, CO_2 tank, CO_2 pump, heat heater, pressure controller, separation vessel, and product collection vessel (Figure 4). The extraction vessel is usually made of materials capable of withstanding high temperature and pressure, and corrosion-resistant. The heater supplies the heat to maintain the desired temperature, while the pressure gauge regulates the pressure. The solvent pump ensures the CO_2 is at the desired pressure. The separation of the CO_2 from the analyte matrix occurs in the separation vessel, while the collection vessel receives the final products [33]. In some recent designs, there are facilities in the SFE equipment for the storage of the extracted product, recovery and collection of CO_2, and control of temperature, pressure, flow rate, and other process parameters [34].

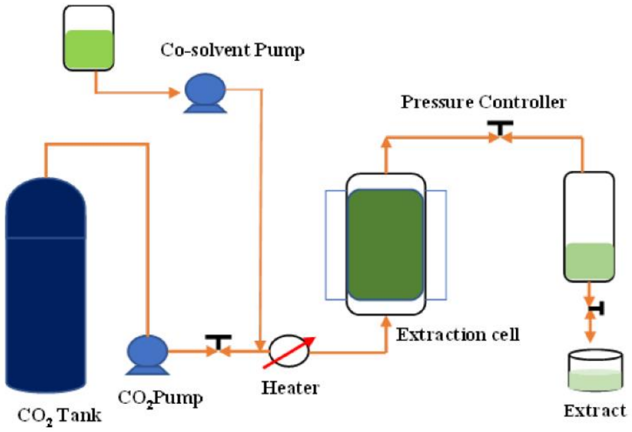

Figure 4. Schematic representation of SFE equipment [33]

Though the type and composition of biomass, flow rate, and reaction time play an important role in the SFE process, pressure and temperature are critical operating conditions that must be controlled to achieve optimal results. The pressure should be high enough to convert and maintain the CO_2 in the supercritical state. Achieving and maintaining the desired pressure ensures the solubility of the biomass in the supercritical CO_2, reduces reaction time, and contributes to high product yield and quality. Excessively high pressure could lead to biomass denaturing while too low pressure reduces biomass solubility and hence product yield. In a recent study of the extraction of bioenergy from marine crustacean waste streams, Nunes et al. [35] recommend 100-500 bar as the optimum pressure for the SFE process. Maintaining a desired temperature is necessary for obtaining and maintaining the supercritical CO_2 conditions needed for an effective SFE process. Maintaining a temperature high enough ensures the solubility of the biomass, reduces reaction time, and promotes product quality. An optimum temperature ranges of 31-100 °C is recommended for a cost-effective and sustainable SFE process [36].

The flow rate of supercritical CO_2 is another important processing condition that ensures the required volume of solvent is available to ensure effective selectivity and promote extraction efficiency. Too fast a flow rate reduces the contact time between the supercritical CO_2 and the biomass and causes nonhomogeneity of the matrix. A slow flow rate of supercritical CO2 impacts extraction efficiency, increases reaction time, and leads to higher production costs. Generally, the critical flow rate of 1-10 mL/min has been recommended for SFE CO_2 [37]. The use of two solvents as supercritical fluids contributes to improved biomass degradation, higher extraction efficiency, and product yield. The combination of CO_2 and water, CO_2 and ethanol, and other mixtures increases production costs but ensures better product yield [26, 38].

3.4. Application of SFE products

The SFE process is a thermophysical technology for converting biomass and other forms of waste into bioenergy and other useful products. Researchers in waste conversion have deployed the SFE technology to extract valuable products from diverse biomass to meet the demand for affordable clean energy and industrial raw materials to find alternatives to FB fuels, ensure effective waste management, and environmental sustainability while leveraging the circular bioeconomy approach. Earlier, Scopel et al. [38] deployed SFE technology to extract fatty acids, sterols, alcohols, and phenolics from elephant grass leaves and stems for bioenergy production and low-cost raw materials in the food, cosmetic, and pharmaceutical industries. Bioethanol and yeast were also extracted from Napier grass and the products were applied as biofuel for transport engines and feedstock for chemical and pharmaceutical industries [39]. Using supercritical CO2 as a solvent, Attard et al. [40] deployed SFE technology to obtain waxes and lipids from waste agricultural and forestry residues. The research demonstrated SFE as an effective technology for the cleaner and sustainable generation of biofuels and consumer products from residual cellulosic biomass. Other studies by Chai et al. [11], Chen et al. [32], Ahangari et al. [34], Akalın et al. [41], and Scaglia et al. [42] have demonstrated the application of SFE technology for bioenergy production and synthesis of food additives, essential oils, flavour and fragrances, natural insecticides, pigments, pharmaceuticals, nutraceuticals, and other valuable raw materials for various industries. The adoption of SFE technology for the conversion of biomass and other waste streams to bioenergy, fuels, chemicals, and other products is cost-effective, reduces GHG emissions, creates job opportunities, supports environmental remediation, and promotes the development of local economies and social systems.

4. Microwave-assisted conversion technology

The microwave-assisted conversion uses microwave energy to generate heat to break down and partition the biomass matrix into bioenergy and other valuable products. The technology is an innovative approach that adopts the power of microwave irradiation to heat, disintegrate, and convert lignocellulosic biomass and other waste materials into useful products, thus contributing to sanitation, waste management, ecological protection, and circular bioeconomy initiatives. The process is efficient, fast, consumes less energy, and can simultaneously handle diverse biomass samples. The high cost of equipment, complex operating procedures, scalability, safety and health concerns, and limited application of the technology are some of the major challenges limiting its wide application [12, 43].

4.1. Mechanisms of microwave heating

Microwave-assisted conversion technology uniquely uses electromagnetic waves to transfer and dissipate heat energy to partition heterogeneous and recalcitrant biomass to convert it to useful products. The technology adopts three main heating mechanisms namely; dipolar polarization, ionic conduction, and interfacial polarization [43, 44]. Having a basic understanding of these heating mechanisms is vital in designing and achieving efficient, effective, and sustainable microwave-assisted extraction processes for various biomass and waste materials.

Heating by dipolar polarization, also known as orientational or displacement polarization, happens when permanent dipoles in asymmetric molecules in the biomass respond to the applied electric field. The resultant friction leads to the desired heat generation. The dipolar polarization microwave heating mechanism permits selective heating, allows localization of biomass heating, and rapid heat gain, and subsequently reduces biomass processing time [45]. Compared with conventional heating mechanisms, the dipolar microwave form of heating requires less energy for heating thereby lowering energy costs. However, dipolar polarization microwave-assisted heating exhibits localized and uneven heating, biomass degradation, and extraction. The heating mechanism can be expensive and complex, requires more maintenance, and may pose serious safety concerns. Adhering to established safety protocols lessens the risk of using dipolar polarization [46].

In ionic conduction microwave heating, ions, cations, or anions, oscillate within the electric field of the microwave, which results in collisions. The effective collision within the charged particles generates heat which is harnessed for biomass conversion. Heating by ionic conduction is achieved when microwave radiation at specified frequencies excites ions and instigates movement which produces heat during the process. The presence of appropriate electrolytes in wet biomass energizes and facilitates the movement of the ions which serves as a motivation for heat generation through the ionic conduction process [47]. Heat generation by ionic conduction is more rapid, efficient, precise, and safer. Though the heating by ionic conduction is often localized, it is, however more evenly distributed when compared with other microwave-assisted heating processes [47, 48].

The interfacial polarization heating mechanism concerns the movement of charges across interfaces between two or more materials [48]. During the biomass extraction process, heat could be generated when the fluctuating electric field in the water molecules triggers the dipoles to rearrange themselves as a result of the alignment between the biomass and solvent matrix. The interfacial polarization heating technique offers rapid, efficient, and energy-efficient heating. The high selectivity of the interfacial polarization heating mechanism ensures the extraction of only the desired compounds from the biomass, increases product purity, and leads to a drastic reduction in separation costs [49].

4.2. Microwave-assisted pyrolysis of biomass

Microwave-assisted pyrolysis (MAP) of biomass is a material extraction technique that utilizes microwave heating technology to fractionalize biomass materials into valuable products. This is achieved when electromagnetic radiation in the microwave range is deployed to achieve fast heating, vaporization, and degradation of intricate and recalcitrant organic structures in biomass. The technology for the MAP of biomass is a proven and mature technique for effective and sustainable bioenergy production, biomass valorization and upgrading, and waste conversion and management. Recent advancements have introduced the use of catalysts and co-pyrolysis to achieve more rapid heating, biomass depolymerization, and product yield. Ren et al. [50], Yue et al. [51], and Mohabeer et al. [52] reported that the deployment of different catalysts such as zeolites, metal oxides, metal-based, and hybrid catalysts, ensures fast attainment of higher pyrolytic temperatures, increases biomass degradation and formation of monocyclic aromatic hydrocarbons, product yield, and quality. Outcomes of recent studies have shown that co-pyrolysis of biomass, waste plastic, agricultural residues, and other waste streams in a single reactor enhances yield, quality, purity, and overall properties including heating value, pore structure, etc. of the products [51, 53, 54]. Figure 5 shows the schematic representation of the MAP reactor developed and used by Mohabeer et al. [52].

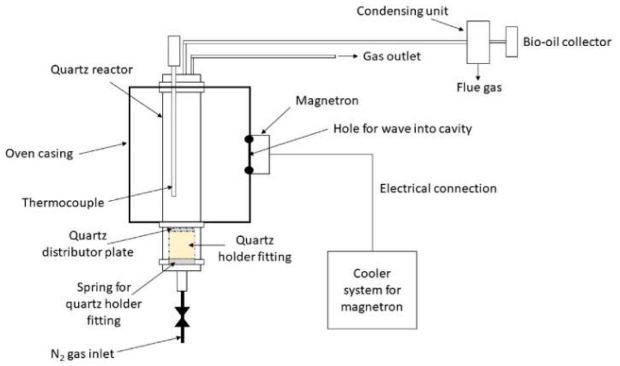

Figure 5. Schematic representation of MAP. Adapted from [52]

Major products of MAP of biomass include biochar, biooil, and syngas. Products of MAP of biomass are used for bioenergy generation, wastewater treatment, carbon capture and storage, soil fertility improvement, and feedstocks for ethanol, butanol, phenols, ketones, aldehydes, adhesives, resins, and other important chemicals. The deployment of MAP for biomass valorization offers rapid heating, reduced processing time, improved product yield, better product quality, and energy energy-efficient process. However, the widespread application of MAP of biomass and other waste streams has been hampered by high equipment costs, difficult scalability, high energy requirements, limited applications, and safety concerns [50, 54].

4.3. Microwave-assisted hydrothermal process

Microwave-Assisted Hydrothermal Process (MAHP) combines microwave and hydrothermal technologies to achieve fast and energy-efficient degradation of biomass to produce biofuels, bioproducts, and chemicals. During the process, biomass immersed in pressurized water is first heated to an elevated temperature in a microwave reaction to create a supercritical water ecosystem inside the reactor, with water as a solvent. The supercritical water helps break down the complex and recalcitrant molecular structure of the biomass sample and convert it to bioenergy and other valuable products. In effect, the MAHP fully exerts the advantages of the rapid and efficient heating associated with microwave technology, with the effect of compressed supercritical water of the hydrothermal technology to achieve a more effective and efficient process [55, 56].

The deployment of MAPH for biomass depolymerization yields several products, including biofuels, biochar, biooil, hydrogen, and chemicals. Biofuels such as biodiesel, bioethanol, and biomethane are used for heating and power generation while hydrogen serves as a clean fuel and feedstock for chemical industries. MAPH presents a low-cost and sustainable platform for the production of lactic acid, formic acid, bioplastics, resins, and other bioproducts. MAPH has been widely used for biomass valorization owing to its low energy requirements, fast reaction, high product yield, ability to work with a variety of biomass, and ability to convert biomass into a wide range of biofuels and other chemicals. However wide application and commercialization of the MAPH technology have been hindered by high operational costs, the complexity of the process, limited scalability options, feedstock variability, and underdeveloped technology [56]. Further studies and optimization of the process parameters are desirable to develop optimal conditions among complex and competing situations for improved product quality and to ensure value for money.

5. Solvent liquefaction

5.1. Microwave-assisted hydrothermal process

Solvent liquefaction is a biomass conversion technology for the production of liquid fuels. The technology uses pressurized and heated solvents to treat biomass such as lignocellulosic biomass, wood pellets, grasses, agricultural residues, etc., under anaerobic conditions. During the process, the supercritical solvent dissolves the biomass and transforms it into a liquid fuel. The desired fuel in the liquid phase is removed from the solid residue by distillation before further purification [57]. The quality, composition, and properties of the resulting products of solvent liquefaction significantly depend on the choice of solvent, type of biomass, biomass/solvent ratio, and reaction temperature [13]. Some of the commonly used solvents include ethanol, methanol, water, 1-butanol, 1,4-dioxane, acetone, propanol, heptane, etc. [57, 58]. In a recent study, Ming et al. [13] and Yan et al. [59] reported that the combination of two or more solvents increased biomass conversion, enhanced biooil yield, and improved the properties and ester concentration of the liquid products. Solvents participate and alter the course of the liquefaction reaction by enhancing the dissolution and dispersion of the reactants, allowing the reaction to continue even at lower temperatures, and inhibiting the side reaction capable of impacting the liquefaction process [13].

5.2. Steps in solvent liquefaction

The deployment of the solvent liquefaction process for the conversion of biomass feedstock into useful products is achieved in three broad stages namely; pretreatment, liquefaction, and product recovery and upgrading.

Biomass pretreatment entails subjecting the biomass feedstock to processes that degrade the structural molecules of the biomass and make the biomass easy to convert. Several pretreatment techniques including mechanical, chemical, thermal, or biological are deployed to soften the recalcitrant lignin and hemicellulose preparatory to the actual liquefaction conversion process. Widely used pretreatment techniques include grinding, drying, etc. to reduce the particle size, increase the surface area, and reduce the moisture content of biomass. The pretreatment of biomass can also involve the use of chemicals to break down, soften, and ensure better penetration of solvents into the fabric of the biomass and ultimately a better and more efficient liquefaction process. Biomass pretreatment reduces reaction time and energy consumption, increases product yield, and improves biooil quality [60, 61]. However, additional equipment and time are needed for pretreatment which exacerbates production costs.

Before the actual liquefaction reaction, there is a need for the selection of an appropriate solvent for the process. Water, methanol, and ethanol are the most widely used solvents due to their ready availability and effectiveness [61]. The selected solvent is mixed with the biomass in an appropriate ratio in an agitator to ensure a thorough and homogeneous mixture. The biomass-solvent mixing ratio could be optimized. The liquefaction process starts with heating the mixture of the biomass and solvent to a temperature between 250 °C and 400 °C at a pressure range of 10 MPa and 50 MPa. The high temperature and pressure ensure the breakdown of the complex macromolecules of the biomass-solvent mixture into simple fractions and the formation of crude bio-based oil and solid residue [57, 58].

The product recovery and upgrading start with the cooling and separation of the products from the slurry. The crude liquid product is extracted by the distillation process while the solid residue is collected from the reactor. The product upgrading process involves the deployment of appropriate purification techniques to renovate the crude liquid into final products. The resulting liquid final product is rich in aromatic chemicals and is further upgraded to gasoline, diesel, jet fuel, biooil, biochemical, and other bioproducts through hydroprocessing and other refining techniques [13]. The need to improve the solvent liquefaction process offers avenues for further research in process optimization, solvent selection, economic viability, and energy-efficient biomass conversion processes.

5.3. Solvent selection and properties

The choice and selection of solvents play a significant role in the solvent liquefaction process. The choice of solvent influences the residence time, conversion efficiency, product yield, quality, and composition. Studies have shown that solvent properties such as dielectric constant, density, and boiling point of solvents play significant roles in their selection, performance, and product yield [13]. Most organic solvents have a low dielectric constant and have been widely and effectively used for solvent liquefaction of biomass into biooil. Solvents with a low dielectric constant are volatile, have low surface tension, and a low boiling point, and facilitate the decomposition of high-molecular-weight compounds compared to water solvent during liquefaction reaction. Low dielectric constant solvents such as methanol, ethanol, ketone, acetone, ethers, benzene, etc., promote the formation of biooil while inhibiting the formation of solid char [62, 63].

Solvents with low density and viscosity ensure more interaction with the biomass, percolate more into the fabric of the biomass, facilitate effective solubilization and dispersion of organic substances in the biomass, and increase the surface area available for reaction. The action and interaction of such biomass promote biomass depolymerization and biooil formation. Notable examples of solvents with low density and viscosity include water, ethanol, methanol, etc. [64]. The boiling point of the solvent is directly linked to its saturated vapour pressure and is an important factor in solvent selection. Solvents with high vapour pressure facilitate thermal cracking, re-polymerization, re-condensation, and biooil yield. However, solvents with excessively high vapour pressure impede biopolymers and hemicellulose decomposition, hence biooil formation. Solvents with high boiling points minimize the conversion efficiency of biomass into biooil [65]. The use of co-solvents is to harness the advantages of some solvents to counter the drawbacks of other solvents.

Water is one of the most commonly used solvents due to its ready availability, low cost, and easy handling. Water is a polar solvent and easily dissolves the hydrogen bond in the biomass structure, thereby favouring product formation. However, the use of water as a solvent impacts global water availability and exacerbates water scarcity. Alcohols (methanol, ethanol, propanol) are polar, have high boiling points, and ensure effective dissolution of most biomass. Methanol is relatively cheap, demonstrates hydrogenation properties, and accelerates production of biooil more than other alcohols. Other supercritical fluids such as CO_2 are widely used as solvents has low toxicity, are recyclable, and cost-effective. However, CO_2 contaminates the products and requires extensive separation and purification of biooil.

5.4. Reactor types and product analysis

Solvent liquefaction reaction occurs in reactors of different configurations. The reactor is a vessel that accommodates the biomass and solvent for a specified time until the products are formed. The solvent liquefaction reactor can be a batch reactor (BR), continuous stirred tank reactor (CSTR), fixed bed reactor, fluidized bed reactor, or microwave-assisted reactor. The selection of the reactor depends on the type of biomass, solvent, process parameters, and product specifications [66].

In a BR production, the biomass and solvent are loaded into a closed vessel in the reactor and left for a specified time until the reaction is completed and the product is evacuated. No new feedstock or solvent is injected during the liquefaction process. The CSTR, on the other hand, allows continuous feeding of the biomass and solvent and simultaneous removal of the products. In a fixed-bed reactor, the biomass is placed in a fixed bed while the solvent is allowed to continuously flow through the bed to decompose the biomass, and the liquid product is collected at the base of the reactor. When the biomass is fluidized by an appropriate gas flowing upward through the bed and the solvent is brought in contact with the fluidized biomass to generate the product, the process is called a fluidized bed reactor process. The microwave-assisted reactor utilizes microwave energy to heat the biomass and solvent. The heat generated by the microwave energy rapidly raises the heating temperature, resulting in fast, unadulterated, and efficient heating and high product yield. Liquid fuel from microwave-assisted reactors is free from impurities and of good quality [57, 66].

After the extraction of the liquid product from the solid residue, the crude biooil is purified and subjected to physicochemical properties and characterization analysis. Properties such as density, heating value, kinematic viscosity, pour point, flash point, cetane number, and other fuel properties help in the determination of the fingerprint of the fuel and suggest possible areas of application [13]. The use of testing techniques such as gas chromatography-mass spectrometry (GCMS), nuclear magnetic resonance spectroscopy (NMR), Fourier transform infrared spectroscopy (FTIR), thermogravimetric analysis (TGA), and differential thermogravimetry (DTG) for the characterization of liquid oil has become popular in recent years [67].

6. Hydrogenation and carbonization processes

6.1. Hydrogenation of biooil

Biooil is usually considered a crude liquid fuel and a feedstock for other high-grade fuels. To upgrade it to a more stable and higher quality fuel, a hydrogenation process is performed. Hydrogenation of biooil is a chemical reaction between the unsaturated bonds in the biooil and the hydrogen gas to produce a higher grade of saturated bonds, more energy-dense, and cleaner liquid fuel. During the process, the crude biooil is subjected to high temperature and pressure in a reactor to convert the unsaturated fatty acids in the crude biooil to a less unsaturated or fully saturated fatty acid. Catalysts with diverse configurations are constructed and introduced to promote the hydrogenation reaction. Figure 6 shows the schematic representation of the hydrogenation of biooil.

In a study, Yang et al. [68] performed catalytic hydrogenation on crude biooil over a biochar-based CuO catalyst. The process yielded 81 % alcohols and other products including, 1, 4-butanediol, 1, 3-cyclopentadiol, 1, 3-cyclohexanediol, and 2-cyclohexenol. The hydrogenation of crude biooil in a steel autoclave maintained at 150 °C - 350 °C and 3 MPA over ruthenium and platinum catalysts yielded 2-methoxycyclohexanol, cyclohexanol, phenol, and other useful products. A needle-plate dielectric barrier discharge reactor was deployed for the hydrogenation of crude biooil into higher-grade liquid fuel at moderate temperature and pressure. During the process, the calorific value of bio-oil increased from 25.78 MJ/kg to 32.69 MJ/kg while the pH rose from 3.67 to 4.83 [69]. The authors were unanimous on the efficacy of hydrogenation reaction to upgrade biooil by increasing the energy density, eliminating contaminants, and generation of renewable fuel transportation engines application. However, the high cost of the process, expensive catalysts, and management of the wastewater and spent catalysts are some of the drawbacks of the process. Products of hydrogenation of biooil are used as renewable transportation fuels, alcohols, phenols, methyl ethyl ketone, feedstock for lubricant production, soil amendments, and other agricultural, horticultural, environmental, and industrial applications.

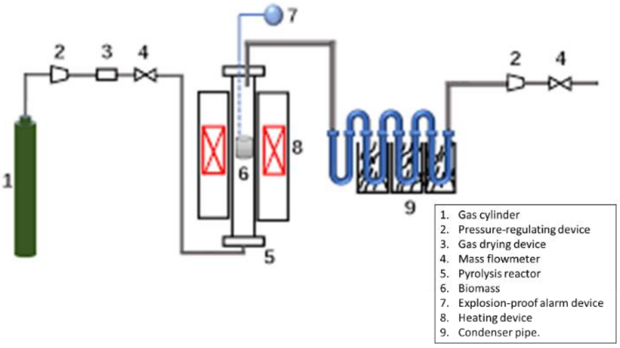

Figure 6. Schematic representation of hydrogenation of biooil. Adapted from [70]

6.2. Carbonization and char production

Carbonization is a pyrolytic conversion of organic compounds including biomass into solid carbon-rich residue and other secondary products. It is a complex anaerobic reaction process involving dehydrogenation, condensation, hydrogen transfer, and isomerization reactions occurring almost simultaneously. During these processes, complex organic compounds in the feedstock are broken down into simple hydrocarbon products such as charcoal, activated carbon, hydrochar, or biochar. The carbonization of organic materials into char includes dehydration of the feedstock, thermal decomposition of the dry feedstock in an anaerobic environment, maintaining a moderate heating rate, and withdrawal and cooling of the produced char from the furnace. The quality, characteristics, and composition of the produced char largely depend on process parameters such as feedstock type, temperature, heating rate, and residence time. Usually, carbonization occurs at 300 – 900 °C, 15-20 bar, slow heating rate (not more than 10 °C/min), and long residence time [71, 72]. The carbonization of cattle manure [72], brewer's spent grain and wood waste [73], and fruit waste [74] into various configurations of char shows the effectiveness of the process for RE generation, mitigates GHG emission, waste conversion, and environmental and industrial applications. However, high-temperature requirements, long residence time, need for close monitoring and control are some of the drawbacks of the process. Overall, the char formed during the carbonization of biomass is suitable for power generation and heating, as a sustainable substitute to FB fuels and a major contributor to a low-carbon future [75-76].

7. Benefits and challenges of physicochemical conversion

7.1. Benefits of physicochemical conversion technologies

7.1.1. Renewable energy production and energy security benefits

Physicochemical conversion technologies offer a low-cost, effective, and easily achievable route for the conversion of diverse grades of waste materials, including crop residues, food waste, municipal solid waste, agricultural waste, wood waste, etc., into RE resources. Major products of physicochemical conversion technologies are used as alternatives to the debilitating FB energy sources, promote sustainable ecosystems, and serve as sustainable alternatives to the unwanted FB energy sources [77, 78]. Physicochemical conversion technologies promote energy diversification and make local economies less vulnerable to supply disruptions and price volatility associated with FB fuels.

7.1.2. Waste reduction, resource recovery, and circular economy benefits

The use of biomass and other waste materials as feedstock for physicochemical conversion technologies is a sustainable waste management strategy. It promotes waste reduction and conversion of waste to biofuel and other useful products. Precious elements and compounds recovered from physicochemical conversion processes are used as feedstock for the production of chemicals, lubricants, and other bioproducts. Conversion of biomass and waste promotes sanitary health, reduces the volume of waste in landfills, and contributes to the circular bioeconomy [79].

7.1.3. Economic and job creation benefits

Farmers and households earn extra income by selling their waste to waste converters, thereby boosting economic viability and economic growth. Youths and women groups are employed by waste converters in the waste conversion value chain, thereby providing jobs, reducing idleness and crimes, and promoting social inclusion.

7.1.4. Operational benefit

Physicochemical conversion technologies are flexible and scalable. Virtually all types of biomass can be converted irrespective of source, moisture content, and composition. Unlike other conversion technologies, there is no need to design special systems for each type of waste, and it requires little or no pretreatment of feedstock. The technologies for physicochemical conversion can be operated with little or no technical expertise, and the infrastructure and systems are easily upgraded and scaled up without compromising quality [80, 81].

7.2. Challenges of physicochemical conversion technologies

7.2.1. Technological challenges

Some of the technologies for physicochemical conversion of biomass could be complex and cannot be fabricated and maintained locally. In many cases, specialized equipment is required to achieve the high temperature and pressure, and other process parameters required for the depolymerization of feedstock. The preparation of catalysts, supercritical water, and other process requirements poses potent challenges to local people. Also, the design, fabrication, installation, operation, and maintenance of some physicochemical conversion technologies require specific technical expertise that is not easily available and retained in local communities [82].

7.2.2. Feedstock availability and variability challenges

The quantity and quality of feedstock significantly affect the operation, performance, and products of physicochemical conversion. The supply of some biomass is seasonal and is impacted by geographical location and weather conditions. Variations in the type, quality, and composition of feedstock impact the performance of physicochemical conversion technologies. The lack of consistency in the quantity and quality of feedstock constitutes a major challenge to the success and wide acceptability of the various physicochemical conversion technologies.

7.2.3. Economic and environmental viability challenges

Physicochemical conversion technologies should convert biomass into energy and other useful products at a competitive cost while preserving environmental integrity. Most of the physicochemical conversion technologies require high energy costs, operational costs, lead to the emission of GHGs, and impact sustainability. The emission of toxic gases from the conversion of biomass impacts air quality and exacerbates environmental pollution. The development of novel and effective conversion technologies to guarantee maximum conversion efficiency at the minimum cost possible will guarantee a return on investment. Adhering to regulatory and ethical standards will ensure environmental sustainability and promote social impact.

8. Conclusion

The high cost, environmental degradation, and pollution impact of continuous exploitation and utilization of FB energy sources have continued to be a source of worry to researchers, energy enthusiasts, environmentalists, and other stakeholders alike. The search for alternatives to FB fuel to meet the energy demand of the growing population and expanding industrial sector has heightened in recent decades. Bioenergy, a form of RE generated from biomass and other waste materials, is among the options for meeting energy demand, ensuring energy security, and promoting environmental sustainability. The conversion of biomass into various forms of bioenergy has been challenging, prompting the commissioning of multidisciplinary investigations into myriad existing conversion techniques. The deployment of physicochemical conversion technologies such as hydrothermal conversion, supercritical fluid extraction, microwave-assisted conversion, solvent liquefaction, hydrogenation, and carbonization technologies for the transformation of diverse biomass into bioenergy and other bioproducts are highlighted in this chapter. Physicochemical conversion technologies are easily achievable, cost-effective, and can handle biomass of different moisture content.

Unlike other conversion techniques, physicochemical conversion technologies require little or no pretreatment of biomass, thereby saving the time and cost of pretreatment. Apart from the low-cost production of biooil, bioethanol, butanol, biocrude, biochar, hydrochar, syngas, and other fuel types, physicochemical techniques also generate feedstocks for aldehydes, adhesives, resins, and other important chemicals. Products from physicochemical conversion are used for carbon storage and sequestration, soil remediation and amendment, water and wastewater treatment, soil fertility improvement, and other important applications. Among physicochemical biomass conversion methods, HTL offers the highest product yield, particularly for wet feedstocks such as algae, food waste, and sewage sludge. Operating under subcritical water conditions, HTL facilitates the direct conversion of biomass into biocrude oil without the need for energy-intensive drying. Biocrude yields commonly range from 40 - 60 wt%, with additional fractions including aqueous phase (20 - 30 wt%), gas (5 - 15 wt%), and solid residue (10 - 20 wt%).

The high carbon recovery and energy efficiency of HTL, combined with its compatibility with diverse feedstocks, make it a superior choice for maximizing liquid fuel production in integrated biorefinery systems.

Going forward, more multidisciplinary studies are required to update existing techniques for the physicochemical conversion of biomass. There is a need to design, develop, and produce innovative reactors for faster biomass conversion rates, better conversion efficiency, lower energy consumption, and improved product quality. Researchers must continuously carry out process optimization and modelling to optimize operation parameters such as temperature, pressure, catalyst dosage, residence time, and feedstock characteristics. Innovative strategies to minimize material wastage, lower energy consumption, improve conversion efficiency, and enhance product quality should be developed. Considering the significance of effective catalysts in some of the biomass conversion technologies, the deployment of nanotechnology in the development and fabrication of nanocatalysts and other nanomaterials is required for improved biomass conversion, product separation, and product quality. Development of innovative pathways for in situ product upgrading and integration of two or more conversion technologies to achieve improved conversion efficiency and high-quality products should be prioritized.

Adopting physicochemical technologies for biomass conversion into bioenergy and other bioproducts will support waste conversion, reduce GHG emissions, and contribute to socioeconomic growth towards meeting some of the SDGs. The overreliance on imported FB petroleum products will be reduced to the barest minimum if adequate attention and resources are devoted to physicochemical biomass conversion technologies. The government should continue to encourage small and medium-scale waste converters by providing incentives such as tax holidays, tax credits, and other financial incentives. Aggressive sensitization and campaigns are needed to dilute some of the old myths and sociocultural biases associated with waste conversion and utilization.

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Author contributions

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Conflicts of interest

The authors declare no conflicts of interest.

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