REVIEW ARTICLE

A concise review of technologies for converting forest biomass to bioenergy

Asif Raihan

Institute of Climate Change, Universiti Kebangsaan Malaysia, Bangi 43600, Selangor, Malaysia

Corresponding Author: Asif Raihan: asifraihan666@gmail.com, ORCID ID: 0000-0001-9757-9730
Received: 05 August, 2023, Accepted: 16 August, 2023, Published: 18 August, 2023

Abstract
The use of biomass is vital in reducing the negative effects of rising fossil fuel consumption. Given its quantity and diversity, forest biomass has garnered a lot of interest among the many kinds of biomass. This study evaluates the various strategies for transforming woody waste into usable biofuels. Carbon dioxide emissions from traditional energy generation systems could be mitigated through the direct utilization of forest biomass. Low energy conversion rates, as well as soot emissions and residues, are some of the problems that come up when directly using forest biomass. The sustainability of direct energy generation from forest biomass is also seriously threatened by the lack of constant access to biomass. Co-combustion with coal and pelletizing biomass is two solutions proposed for this issue. Co-combustion of forest biomass with coal has the potential to lower the process's emissions of carbon monoxide, nitrogen oxides, and sulfides. This article reviews and discusses the biochemical and thermochemical mechanisms that can transform forest biomass into a variety of liquid and gaseous biofuels. Future research using cutting-edge sustainability assessment tools like life cycle assessment, exergy, etc. should investigate the sustainability of forest biomass conversion processes to bioenergy further.

Keywords: Forest; Biomass; Bioenergy; Biodiesel; Biogas

Introduction

The escalating utilization of fossil energy sources is mostly responsible for the generation of greenhouse gases (GHGs) and other detrimental gases, which have emerged as a significant worldwide issue (Ali et al., 2022; Borowski, 2022; Raihan, 2023a; Sultana et al., 2023). GHGs have been widely recognized as a pivotal determinant in the phenomenon of global warming, exerting a significant influence on the intricate dynamics of climate change (Agan & Balcilar, 2023; Raihan, 2023b; Voumik et al., 2023). Numerous studies have demonstrated that the utilization of alternative carbon sources such as biomass has the potential to mitigate these difficulties (Sarwer et al., 2022; Raihan, 2023c). The existing body of literature on the utilization of biomass for energy production encompasses discussions regarding the contentious issue of the relative significance of forest biomass (Plank et al., 2023; Raihan, 2023d). In general, forest biomass can be categorized into two main types: firewood and commercial roundwood (Raihan, 2023e; Siarudin et al., 2023). Fuelwood is obtained from forested areas and is either burned directly to produce usable heat or transformed into bioenergy and biofuels to generate heat and power (Manikandan et al., 2023; Raihan, 2023f). Fuelwood exhibits great potential as a feedstock for several conversion processes, including thermochemical transformation, biological conversion, liquefaction, and gasification, owing to its substantial concentration of macromolecular carbohydrates such as cellulose and organic matter (Manikandan et al., 2023; Raihan, 2023g). Forest biomass has the potential to be utilized either in co-combustion with fossil fuels or as a standalone fuel source in power generation equipment such as boilers (Raihan et al., 2018; Kalak, 2023). In the context of formulating national energy development strategies, there is a considerable emphasis on the efficient usage of forest biomass resources as a means to address environmental crises (Jaafar et al., 2020; Yana et al., 2022; Raihan, 2023h). As an illustration, within the spectrum of energy sources accessible in China, around 54.2% of forest biomass is employed for power generation and fuel production (Cavali et al., 2023).

The energy derived from forest biomass has the potential to meet around 15.4% of the overall global energy demand (Kalak, 2023). From 2004 to 2015, the total power generation derived from forest biomass was around one million kilowatts per year (Fujino & Hashimoto, 2023). This contribution played a significant role in the removal of forest wastes and the attainment of ecological-zero carbon dioxide (CO_2) emissions, as highlighted by Nunes et al. (2018). As an example, the utilization of forest biomass as an alternative to fossil fuels in Australia results in a yearly reduction of around 25 million tons of atmospheric CO_2 emissions (Raihan et al., 2021a). Additionally, according to the contribution played a significant role in the removal of forest wastes and the attainment of ecological-zero CO_2 emissions statistical data from the European Union (EU), there is a discernible upward trajectory in the potential of forest waste to meet human energy demands between 2010 and 2030 (Singh et al., 2022). Table 1 displays the statistical data provided by the EU about energy production derived from various forms of forest biomass in the year 2010, together with projected estimations for the year 2030. Given the considerable importance of forest biomass within the future global energy market, this study seeks to provide a concise overview of diverse approaches for converting forest biomass into bioenergy and biofuel.

Table 1. Energy production is derived from various forms of forest biomass in the EU.

Type of forest biomass	The potential of biomass (TJ × 10^4)		Sources
	2010	2030	
Wood processing	419	427	Searle & Malins (2016)
Forest crops	180-193	427-615	Böttcher & Graichen (2015)
Forest residue	180	163-301	Moiseyev et al. (2014)
Total	**779-792**	**1017-1343**	

The imperative to decrease the burning of fossil fuels has become increasingly apparent to achieve the global objectives for reducing carbon emissions (Begum et al., 2020; Oyebanji & Kirikkaleli, 2022; Raihan, 2023i). Furthermore, it is worth mentioning that fossil fuel reserves are finite resources, and the reserves of coal, oil, and gas are gradually diminishing as a result of excessive use driven by the rapid global population expansion (Raihan, 2023j; Wang et al., 2023). The utilization of forest biomass for bioenergy production has the potential to make significant contributions to the attainment of long-term environmental and economic sustainability objectives (Raihan et al., 2019; Voumik et al., 2022), while also aiding in the mitigation of adverse environmental consequences associated with the utilization of fossil fuels (Isfat & Raihan, 2022; Pramanik et al., 2023; Raihan, 2023k). Bioenergy production plays a crucial role in enhancing both energy efficiency and energy security, while concurrently stimulating economic growth through the creation of new employment opportunities (Tănasie et al., 2022; Raihan & Tuspekova, 2023a). Bioenergy has emerged as a prominent subject within the global discourse on climate change (Raihan & Tuspekova, 2023b). However, there exists a dearth of comprehensive research that offers a comprehensive examination of bioenergy production, specifically focusing on the conversion technologies employed to generate bioenergy from forest biomass (Rocha-Meneses et al., 2023). A notable research deficiency exists within the current body of literature on the process of converting forest biomass into bioenergy (Rani et al., 2023). Hence, the primary objective of this study is to present a comprehensive review of the many methods utilized in the conversion of forest biomass into bioenergy. The current research addresses the existing knowledge gap about the intersection of bioenergy for environmental sustainability and forest-based bioenergy production technologies. This review article provides valuable insights for future endeavors aimed at advancing sustainable bioenergy production from forest biomass and its potential to replace fossil fuels. This research specifically addresses the pressing issues of global warming and climate change by emphasizing the importance of bioenergy production from forest biomass and lowering emissions resulting from the combustion of fossil fuels.

Methodology

This study conducted a systematic literature review to address the potential technologies for converting forest biomass to bioenergy. The systematic literature review is a reliable framework (Benita, 2021). After settling on a research topic, relevant publications were found and downloaded using several research databases including Scopus, Web of Science, and Google Scholar. Multiple search terms were used to find relevant documents, including "forest biomass," "bioenergy," "biodiesel," "biogas," "bioenergy production," "forest biomass to bioenergy," "bioenergy conversion," "bioenergy technology," and so on. At first, there was a great deal of published material returned by the keyword search. Since it's been impossible to read all the found articles since 2020, the literature exhibition has had to be limited in various ways. According to the study's purpose, 429 articles were retrieved from the databases. All of the retrieved publications and papers were evaluated based on a set of encoded measures for insertion and elimination of primary research papers. After reading the titles, abstracts, and entire pieces, it filtered out 282 unrelated publications that had been copied from an earlier search. A number of 147 articles were selected to use in this review based on their relevance to the study's stated objective of "technologies for converting forest biomass to bioenergy." Figure 1 depicts the evolution of review criteria used to choose appropriate documents for analysis.

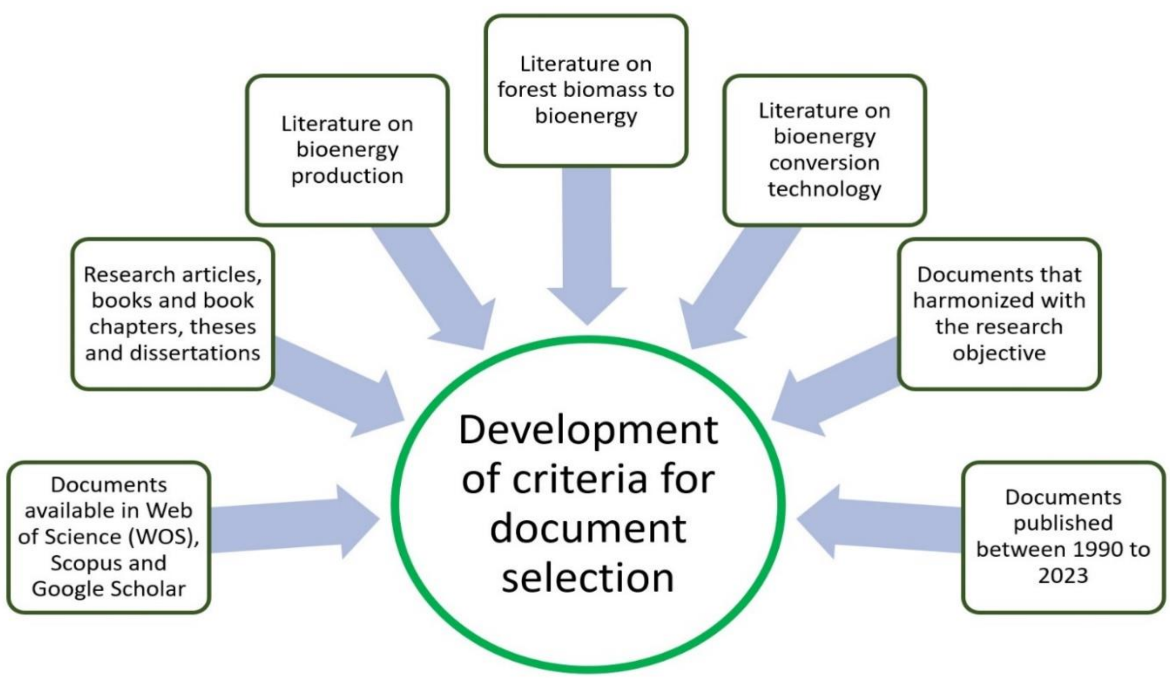

Figure 1. The development of criteria for document selection.

This study solely used research articles published in peer-reviewed journals to assure the quality of the results, which provide a foundation for future research and management considering the conversion of forest biomass to bioenergy. These papers were then reviewed to determine if their primary topic was similar to that of the current investigation. The next step is a systematic review of all 147 papers, wherein the study topics and other features, such as the methodologies, settings, and theoretical frameworks underlying the investigations, are dissected and analyzed. The qualitative and quantitative secondary literature on the production of bioenergy from forest biomass is also discussed. In addition, this study examined interrelated topics, opening up fresh avenues for future study. Comprehending the research outcomes on the conversion of forest biomass to bioenergy, the study also examined future direction prospects and research concerns. Figure 2 depicts the systematic review processes that were employed in the present investigation. Following the selection of the research topic, this study proceeded to identify and locate pertinent articles, conduct an analysis and synthesis of various literature sources, and compile written materials for article review. The synthesis phase involved the gathering of diverse articles that were afterward compiled into conceptual or empirical analyses that were pertinent to the completed research.

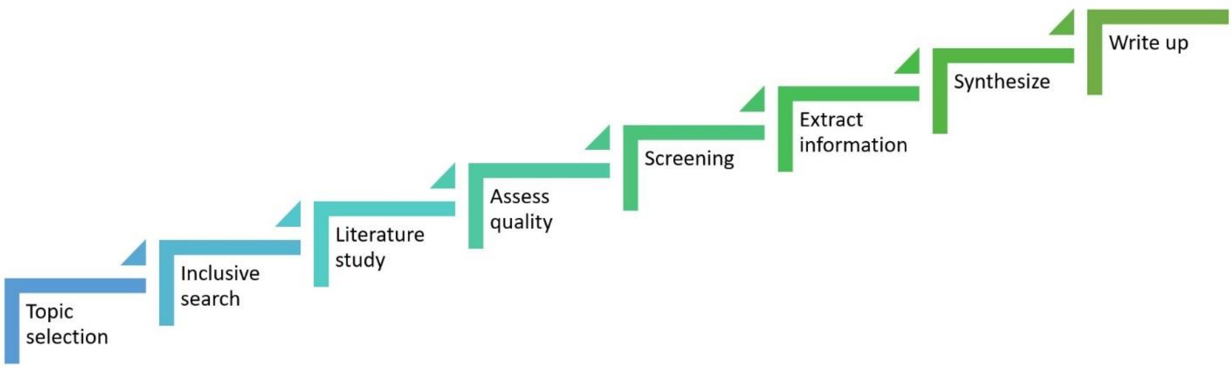

Figure 2. The procedure of systematic review conducted by the study.

Results and Discussion

Direct use of forest biomass

One notable benefit associated with forest biomass is its potential for direct combustion (Borowski, 2022). The direct combustion method is a type of thermochemical procedure in which biomass undergoes combustion in an unconfined environment, resulting in the conversion of the chemical energy contained in the biomass through photosynthesis into thermal energy (Li et al., 2023). While the combustion of forest biomass does result in the release of CO_2, particulate matter (PM2.5), sulfur dioxide (SO_2), and other detrimental compounds, the quantities emitted are comparatively lower than those generated by the combustion of fossil fuels (Arya, 2022; Raihan et al., 2022a). For instance, prior studies have demonstrated that the combustibility of forest biomass yields a 20% reduction in CO_2 emissions compared to the utilization of fossil fuels (Sasaki, 2021). Nevertheless, the utilization of forest biomass is accompanied by specific limitations (Míguez et al., 2021). One of the identified drawbacks is the relatively poor energy conversion rate (Ramos et al., 2022). Additionally, the process of direct combustion results in the formation of soot and debris (He et al., 2021).

The practice of utilizing the direct burning of biomass for electricity generation has persisted since the 1990s (Amalina et al., 2022). According to Chen et al. (2021), biomass-fired combined heat and power (CHP) systems consist of a vibratory grating furnace, condensation steam turbine, and electric generator. The vibratory grating boiler is a type of automated combustion equipment characterized by its simplistic structure and relatively low capacity (Silva et al., 2023). The surface of the grate undergoes vibrations due to alternating inertial forces, which in turn propel biomass forward, facilitating automated combustion (Ciliberti et al., 2022). The combustion of forest biomass generates thermal energy within the boiler, which in turn facilitates the conversion of water into steam through a process known as the steam Rankine cycle (Chen et al., 2022). Following the process of water evaporation within the boiler, steam is subsequently introduced into the turbine to undergo expansion and engage in mechanical activity (Cortazar et al., 2023). Subsequently, the pressure is diminished, leading to the condensation of the steam and its conversion back into water (Hejazi, 2022). It is important to acknowledge that the steam-driven Rankine cycle holds significant importance as a thermodynamic cycle in the realm of energy production (Dincer and Bicer, 2020). The observed rate of conversion of forest biomass to electricity using the Rankine cycle falls within the range of 39-44% (Oyekale et al., 2020). Consequently, the combustion of a single ton of forest biomass yields approximately 4.4 kilowatt-hours (kWh) of electrical energy (Esfilar et al., 2021). An evident benefit associated with the utilization of electric energy is the mitigation of CO_2 emissions derived from the power generation sector, which predominantly relies on fossil fuels (Raihan et al., 2022b). Table 2 presents a comprehensive tabulation of the reductions in CO_2 emissions achieved by power plants that utilize forest biomass as compared to those reliant on fossil fuels.

Table 2. Reductions in CO_2 emissions are achieved by power plants that utilize forest biomass as compared to those reliant on fossil fuels.

Biomass type	Country	Power plant type	Power plant capacity (MW)	Reduction of CO_2 emission (t/yr)	Source
Forest waste (wood chips)	United States	Thermal power plant	70	552,032	Campbell & Mika (2009)
Palm tree waste	Iran	Rankine cycle steam power plant	8	40,500	Mallaki & Fatehi (2014)
Forest waste	Portugal	Thermal power plant	314	1,000,000	Nunes et al. (2014)
Forest waste (woody biomass)	Japan	Thermal power plant	5.7	30,934	Nakano et al. (2015)
Forest waste (wood chips, wood pellets, and black pellets)	Japan	Thermal power plant	500	198,000-252,000	Furubayashi & Nakata (2018)

One notable challenge associated with the utilization of forest biomass to obtain energy generation through direct burning is the geographical distance between these waste materials and industrial as well as residential regions (Yana et al., 2022; Al-Bawwat et al., 2023). In addition, it should be noted that forests encompass extensive areas, and the process of collecting biomass presents intricate challenges (May et al., 2023). Consequently, the absence of consistent availability of biomass is a significant issue in ensuring the long-term viability of utilizing forest biomass for direct energy generation (Al-Bawwat et al., 2023; Raihan & Tuspekova, 2022a). However, it is advisable to

establish forest biomass-based companies across a radius of 120 km from forested areas to address this issue (Daneshmandi et al., 2022). However, substantial financial expenditure and considerable storage capacity are required (Saravanakumar et al., 2022).
Furthermore, the utilization of co-combustion presents a viable and uncomplicated approach to address the issues linked to the direct burning of forest biomass (Míguez et al., 2021). These concerns encompass the availability of biomass continuously, the space needed for storage, and the economic challenges involved with transportation and distribution (Zahraee et al., 2022). One notable benefit associated with the co-burning of biomass and coal in comparison to the exclusive combustion of coal is the potential reduction in emissions of carbon monoxide (CO), nitrogen oxides (NOx), and sulfides, while simultaneously maintaining production efficiency (Syrodoy et al., 2022). The burning of forest biomass and coal employs pulverized coal boilers and fluidized bed boilers as the reactor, from a technical standpoint (Ling et al., 2023). The addition of forest biomass in fluidized-bed boiler results in a decrease in the production of nitric oxide (NO) and enhances the efficiency of the combustion process (Żukowski et al., 2023). In contrast to coal, biomass has a higher volatile content, which is a positive characteristic for facilitating quick ignition (Raihan et al., 2022c). Recent research has revealed that the substitution of a single ton of coal by forest biomass in co-combustion processes has the potential to result in a reduction of around 87 tons of CO_2 emissions (Ye et al., 2023). According to Twumasi et al. (2022), there is an anticipated rise in biomass consumption of 450,000 metric tons per year in the year 2030 and beyond. This increase is expected to result in a corresponding decrease of around 395,000 metric tons per year in CO_2 emissions (Chen et al., 2023). In addition, the combustion of biomass can result in the formation of alkaline ash, which has the potential to impede the release of SO2 emissions through coal and mitigate global acidification (Putra et al., 2023).
Co-combustion is regarded as a cost-effective approach for using available biomass resources for power generation, owing to its capacity to mitigate the emission of hazardous gases and enhance the reliability of power generation (Borowski, 2022; Raihan & Tuspekova, 2022b). In light of this information, thermal power plants have the potential to utilize biomass as an environmentally friendly and economically viable combustion co-fuel in conjunction with coal (Srivastava et al., 2023; Raihan & Tuspekova, 2022c). Nevertheless, forest biomass has other notable limitations, including but not limited to inadequate energy density, elevated particle emissions, inconsistent combustion performance, and challenges associated with storage and transportation (Ramos et al., 2022; Sarker et al., 2023). Therefore, future research endeavors must focus on developing effective strategies to address and alleviate these challenges.

Pellets from forest biomass

Numerous methodologies have been devised to enhance the transportation and optimize the conversion efficiency of forest biomass, such as the mechanical treatment of biomass into a granular form known as pellets (Mujtaba et al., 2023). The process of pelleting forest biomass enhances its density and decreases its water content (Ahmed et al., 2022). The combustion efficiency of biomass is significantly influenced by two crucial parameters, namely density and moisture content (Ramos et al., 2022). Therefore, the utilization of pelleted forest residue in combustion by itself or co-combustion with coal has the potential to enhance combustion efficiency (Borowski, 2022; Daba et al., 2023). For example, Ghorashi and Khandelwal (2023) indicated that the effectiveness of boilers utilizing pellets ranged from 5% to 90%, whereas wood-fired boilers exhibited a range of 75% to 85% efficiency. Figure 3 shows the steps of pellets production from forest biomass.

Figure 3. The steps of pellets production from forest biomass (Sarker et al., 2023).

The incorporation of forest biomass with other biomass materials can be employed to augment the collective characteristics of the combination, hence improving its suitability for pellet manufacture (Gupta et al., 2022). The endurance of biomass pellets can be influenced by their water content, which can be modified by incorporating different kinds of forest biomass (Song et al., 2023). In particular, the average durability of forest biomass significantly increases to 95% when the moisture level is lowered to a range of 1-5% (Míguez et al., 2021). This reduction in moisture content is advantageous for both the transportation and storage of biomass products (Ramos et al., 2022). In the context of forest biomass pellet production, it is necessary to pre-dry the biomass material before the manufacturing process (Yun et al., 2022; Raihan & Tuspekova, 2022d). A potential method for reducing the moisture content in aspen wood chips is the utilization of a rotary drier, which has demonstrated a moisture removal efficiency of approximately 17% (Bianchini, & Simioni, 2021). When comparing the data, it is observed that the moisture elimination rate for sawdust derived from *Robinia pseudoacacia* is significantly greater, reaching 31% (Dudziec et al., 2023). The observed variations can be attributed to disparities in the proportions of different categories of forest biomass (Puglielli et al., 2021). It is worth mentioning that in cases where the rotary drier fails to efficiently eliminate moisture, the pneumatic dryer presents itself as a viable alternative, with an enhanced drying rate of 22% (Palacios-Bereche et al., 2022). According to environmental analysis, the substitution of coal with biomass pellets for power generation is projected to result in an annual reduction of 205 million metric tons of CO_2 emissions (Ter-Mikaelian et al., 2023). In 2008, the European Union countries collectively prevented the release of approximately 12.6 million tons of CO_2 emissions by utilizing 8.2 million tons of pelleted wood.

When forest biomass pellets are combined with coal, they result in a comparatively lower environmental impact compared to traditional fuels such as sawdust and coal (Sarker et al., 2023). According to Masum et al. (2022), the combined combustion of woody biomass pellets and coal resulted in a notable 50% decrease in CO_2 emissions. Additionally, the ash generated during the combustion process constituted about 1% of the total, which is significantly lower compared to coal combustion, estimated to be 15-20 times less (Borowski, 2022). The utilization of wood pellets in conjunction with coal for co-firing purposes yielded a reduction in CO_2 emissions when compared to alternative renewable energy sources (Picciano et al., 2022; Raihan & Tuspekova, 2022e). There is an additional assertion that the inclusion of eggshells in the process of combustion of woody biomass pellets may result in the absorption of CO_2 due to the presence of calcium carbonate in eggshells, hence leading to a further reduction in greenhouse gas (GHG) emissions (Ivanović et al., 2023). The emissions levels of CO and NOx resulting from the combustion of pellets were found to be highly satisfactory (Saravanan et al., 2023). The implementation of co-firing biomass pellets with coal, namely by burning wood pellets in lower-row burners, has the potential to mitigate CO emissions (Daba et al., 2023). Notwithstanding the encouraging outcomes, power plants that depend on woody biomass pellets encounter a range of challenges. These include elevated energy consumption, a labor-intensive production process, comparatively higher prices compared to other solid biofuels, the requirement for larger storage capacity in comparison to oil, the necessity for ash removal, and the vulnerability of pellets to water exposure (Ibitoye et al., 2021).

Liquid biofuels from forest biomass

Diesel the combustion process in engines powered by diesel is well recognized as a significant factor in the exacerbation of worldwide air pollution (Peng et al., 2020; Raihan et al., 2023a). The emissions of utmost significance resulting from the process of diesel combustion encompass carbon dioxide (CO_2), nitrogen oxides (NOx), sulfur oxides (SOX), carbon monoxide (CO), and particulate matter (PM) emissions (Ni et al., 2020; Guven & Kayalica, 2023). There exists empirical evidence indicating that such emissions play a pivotal role in causing harm to the natural world and human well-being (Raihan & Voumik, 2022a; Raihan et al., 2023b). In response to the issue of emissions from diesel engines and the need to address environmental concerns, there is a significant demand for environmentally friendly alternatives to diesel fuel (Ni et al., 2020; Raihan & Voumik, 2022b; Das et al., 2022; Raihan et al., 2023c). Biodiesel, which refers to the methyl or ethyl esters of long-chain fatty acids, is mostly synthesized through the transesterification reaction utilizing short-chain alcohols such as methanol or ethanol (Santaraite et al., 2020). This reaction takes place in the presence of a catalyst, either a base or an acid. The combustion of biodiesel results in reduced emissions of smoke, particulate matter (PM), carbon monoxide (CO), and unburned hydrocarbons (HC) in comparison to diesel (Attia et al., 2022; Raihan & Tuspekova, 2022f). Additionally, biodiesel has a far lower impact on global warming compared to diesel since the carbon included in biodiesel primarily originates from biogenic CO_2 sources (Cabrera-Jiménez et al., 2022; Raihan & Tuspekova, 2022g). The research about the manufacturing of biodiesel has attained a level of maturity, leading to the substitution of conventional diesel fuel with diverse blends of biodiesel in numerous regions across the globe (Benti et al., 2023). It is noteworthy to mention that neat biodiesel, along with its blends of up to 20% with diesel, can be utilized in diesel-powered vehicles without necessitating any alterations to the engine (Gowrishankar & Krishnasamy, 2023). Despite the numerous advantages it offers, biodiesel faces certain limitations in terms of its physicochemical features that hinder its broad deployment (Akinwumi et al., 2022). These limitations include a higher viscosity compared to fossil diesel and inadequate cold flow properties (Devaraj et al., 2022). In addition, the manufacturing of biodiesel using first-generation feedstock, specifically edible vegetable oils, has resulted in elevated production expenses and instigated a rivalry between fuel and food for arable land and water resources (Mahmud et al., 2022). Second-generation biofuels, which are fuels obtained from waste biomass, have been categorized as a potential option to address the issue of competition between food and fuel (Singh et al., 2022). Tree species with a high oil content are considered to be appropriate raw materials for the synthesis of biodiesel (Osman et al., 2022). Pyrolysis is a thermochemical valorization approach that shows promise in the production of biofuels from forest waste (Osman et al., 2023). This process occurs at moderate temperatures, typically ranging from 300 to 1,300° C (Mlonka-Mędrala et al., 2021). Throughout this procedure, the chemical composition of the feedstock undergoes significant alterations (Murtaza et al., 2022). Pyrolysis is well recognized as a versatile process capable of generating a diverse range of solid, liquid, and gaseous outputs, contingent upon the specific circumstances employed throughout the pyrolysis procedure (Sivaranjani et al., 2023). The process of slow pyrolysis yields solid byproducts, namely biochar or charcoal, whereas quick pyrolysis leads to the generation of liquid products, specifically bio-oil (Costa et al., 2022; Raihan & Tuspekova, 2022h). According to Ramos et al. (2022), forest biomass has been identified as a very suitable feedstock for the process of pyrolysis. Various researchers have effectively carried out pyrolysis on forest biomass to generate bio-oil (Chireshe et al., 2020). It is important to acknowledge that the bio-oil generated using the pyrolysis method generally exhibits elevated levels of oxygen and water content. Consequently, it necessitates undergoing an upgrading procedure (Kumar & Strezov, 2021).

Gasification is an additional method that can be employed to enhance the value of forest biomass (Gomes et al., 2023). In a study conducted by González and García (2015), wood biomass was subjected to a gasification process followed by liquefaction (Fischer-Tropsch) to produce bio-oil. According to the findings of Natarajan et al. (2014), the implementation of five Fischer-Tropsch plants has the potential to make significant contributions toward Finland's 2020 objectives. These objectives include utilizing up to 58% of the accessible forest biomass for energy generation, achieving an overall reduction of 4% in emissions, and ensuring that the transportation sector is entirely powered by biofuel. Additionally, an estimation was made on the potential reduction of environmental impacts in the transportation sector of Norway by substituting fossil diesel with liquid biofuel derived from biomass from forests and woody wastes through the Fischer-Tropsch process (Jahangiri et al., 2023). The predicted greenhouse gas (GHG) reductions and decreases in greenhouse impacts (Raihan et al., 2022d) resulting from the production and utilization of Fischer-Tropsch biofuel derived from forest wastes are projected to range from around 20% to 90% over a 100-year timeframe (Cheng et al., 2023). It is important to acknowledge that biofuel production derived from forest biomass has the potential to not only mitigate CO_2 emissions but also present economic prospects, such as the generation of employment opportunities (Benti et al., 2022; Raihan & Said, 2022).

The investigation of bioethanol synthesis from biomass from forests has been underway since the beginning of the 1990s (Benti et al., 2022). Forest biomass, including species that consist of *Populus* L., *Salix babylonica*, and *Saccharum officinarum*, possesses a lignocellulosic composition and is characterized by its plentiful availability. These attributes render it a viable candidate for utilization as a feedstock in the production of second-generation bioethanol (Ko et al., 2020; Raihan et al., 2022e). The International Energy Agency (IEA) has projected that by the year 2030, harnessing around 10% of the world's forest and agricultural biomass has the potential to yield approximately 233 billion liters of bioethanol, which is equivalent to 155 billion liters of gasoline (Morales et al., 2021). Table 3 displays the bioethanol generation potentials of various forest biomass sources.

Table 3. Bioethanol generation potentials of various forest biomass sources.

Biomass species	Potential yield of bioethanol (L/ha)	Sources
Panicum virgatum	555–3,871	Zabed et al. (2016)
Manihot esculenta	4,500–4,901	Zabed et al. (2016)
Salix spp.	769–4,026	Zamora et al. (2014)
Miscanthus spp.	4,600–12,400	Ho et al. (2014)
Populus spp.	1,500–3,400	Ho et al. (2014)
Triticum aestivum	1,001–1700	Lebaka (2013)
Saccharum spp.	5,345–9,950	Lebaka (2013)

Bioethanol is widely recognized as a highly promising alternative to petroleum-derived gasoline, primarily due to its significantly reduced emissions across its entire life cycle (Ingrao et al., 2021; Raihan et al., 2022f). In a study conducted by Becerra-Ruiz et al. (2019), it was shown that substituting gasoline with bioethanol in 5500 W transportable engine generators of an alternating current resulted in significant reductions of 99%, 93%, and 67% in CO, HC, and NOx emissions, respectively. In contrast to first-generation bioethanol derived from crops like corn and sugarcane, second-generation bioethanol, which is produced from lignocellulosic feedstocks, exhibits a notable reduction in greenhouse gas (GHG) emissions over its entire life cycle (Hirani et al., 2018; Raihan et al., 2023d). In addition, it is worth mentioning that the bioethanol yields derived from forest biomass exhibit comparatively greater levels when compared to other forms of biomass (Fan et al., 2020). According to a study conducted by Mabee and Saddler (2010), the bioethanol yields obtained from forest biomass were found to vary from 0.12 and 0.3 m^3/t (dry basis), while the bioethanol yields from agricultural residues ranged from 0.11 to 0.27 m^3/t (dry basis). The processing of lignocellulosic materials into bioethanol primarily involves two methods: biochemical conversion and thermochemical conversion (Siwal et al., 2022; Raihan & Tuspekova, 2022i). The biochemical conversion process commences with a pretreatment step aimed at the separation of lignin and hemicellulose from cellulose (Sharma et al., 2020). Subsequently, cellulose undergoes hydrolysis to produce fermentable sugars (Sun et al., 2022). Ultimately, the process of fermentation results in the conversion of carbohydrates into ethanol (Tse et al., 2021; Raihan et al., 2022g). Pretreatment is a crucial stage in the process, and as such, the specific type and conditions of pretreatment significantly impact the overall technical feasibility of the whole procedure (Morales et al., 2021). According to Sharma et al. (2020), there are several pretreatment methods available, including chemical, physical, physicochemical, and biological approaches.

It is important to acknowledge that forest biomass generally exhibits increased lignin concentrations as a result of its inclusion of bark and immature wood (Siwal et al., 2022; Raihan & Himu, 2023). Consequently, the bioconversion of forest biomass into sugars is hindered to a greater extent compared to other biomass categories, such as agricultural leftovers (Manikandan et al., 2023). Despite the existence of pretreatment methods to address the significant challenge of recalcitrance in achieving effective sugar/biofuel production, these approaches are characterized by increased time requirements and higher costs. One of the techniques employed is the steam explosion treatment, which has been documented to enhance bioethanol production from Hemp fiber by as much as 70% (Zhao et al., 2020). Furthermore, it has been postulated that the utilization of surfactants, due to their distinctive composition and functional characteristics, may enhance the solubility, flowability, accessibility, and degradation of forest biomass, thus augmenting the bioethanol output (Azelee et al., 2023; Raihan, 2023l). According to Zheng et al. (2020), it has been suggested that the utilization of tween, polyethylene glycol (PEG), and sulfonate-based surfactants may potentially enhance the conversion rate of lignocellulose by approximately 10-20%. In contrast to biochemical converting, thermochemical processing, specifically gasification, exhibits wider applicability to many types of forest biomass (Ramos et al., 2022). The process of gasification involves the conversion of lignocellulosic biomass into syngas under high-pressure conditions and without the presence of inert gases (Mohanty et al., 2021). Subsequently, the syngas is subjected to the Fischer-Tropsch process to produce bioethanol (Laesecke et al., 2017). Moreover, the microbe *Clostridium ljungdahlii* can produce bioethanol through the utilization of syngas, facilitated by its inclusion of catalysts (Sajeev et al., 2023). Figure 4 depicts the thermochemical conversion procedure of biomass.

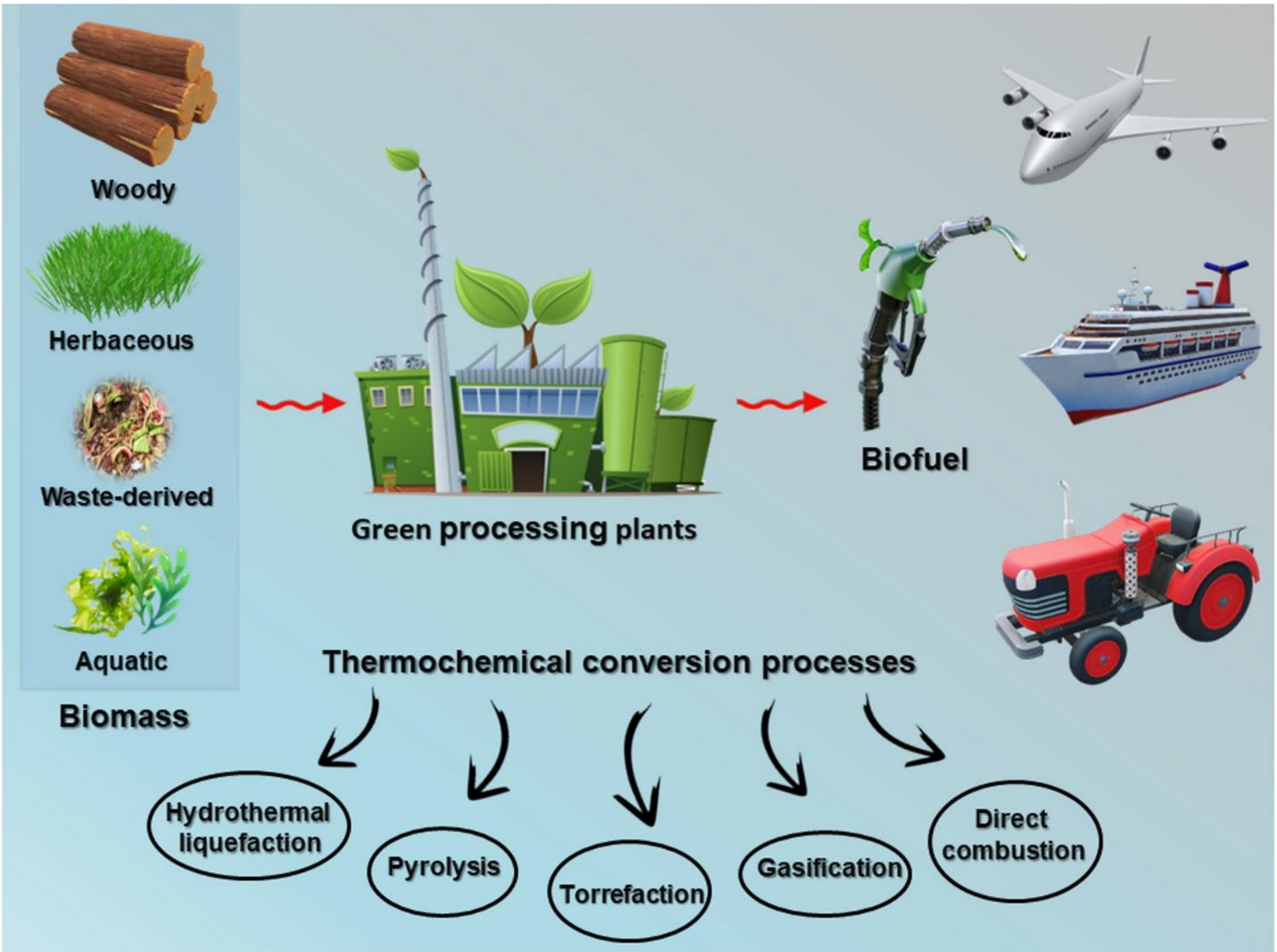

Figure 4. Thermochemical conversion procedure of biomass (Osman et al., 2021).

Forest biomass to gaseous biofuels

The gasification method of forest biomass results in the creation of syngas through a sequence of heat-induced cracking reactions (Zhang et al., 2020; Raihan & Tuspekova, 2022j). The pyrolysis of forest biomass, including various components such as seeds, leaves, trunks of trees, and fruit shells, can be conducted in a fixed-bed gasifier operating at elevated temperatures over 1,200°C (Samiran et al., 2016). This process yields syngas rich in hydrogen, which has garnered significant attention as a highly potential alternative energy source (Raihan et al., 2022h; Vuppaladadiyam et al., 2022). According to Duan et al. (2020), there is a claim that a biomass quantity of 1.3 Gt per year has the potential to generate an annual output of 100 Mt of hydrogen. Figure 5 presents the process of forest biomass to gaseous biofuel conversion.

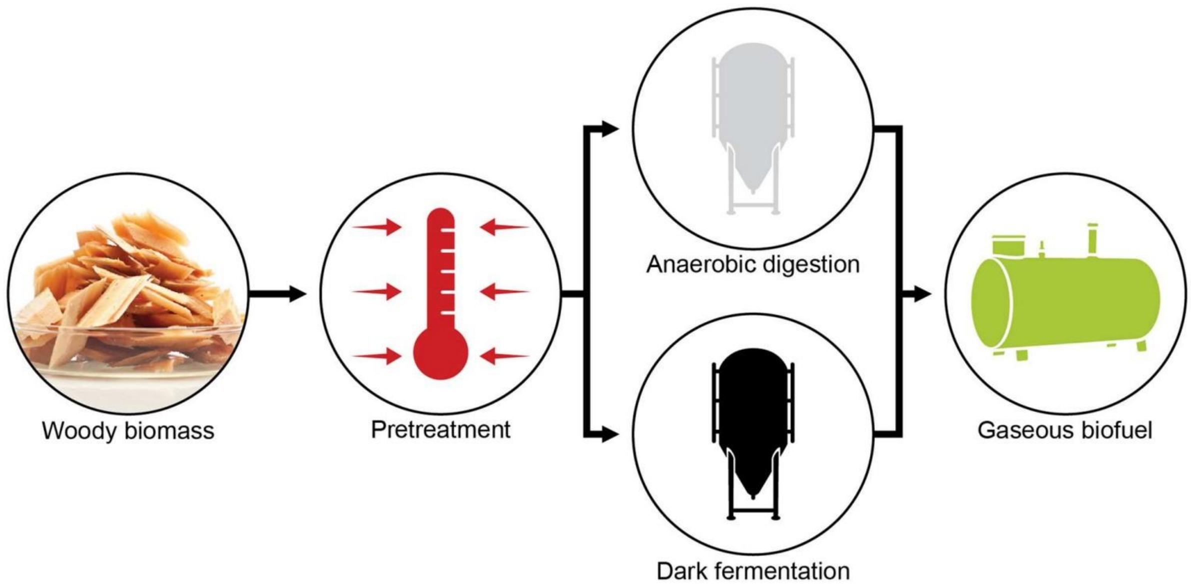

Figure 5. The procedure of forest biomass to gaseous biofuel conversion (Wijeyekoon & Vaidya, 2021).

The rate of the gasification process can be regulated by manipulating the flow rate of the gas (Luo et al., 2022). By employing this particular approach, it is possible to achieve a breakdown rate of up to 60% for forest biomass into hydrogen (Vuppaladadiyam et al., 2022; Gnanasekaran et al., 2023; Verma et al., 2023). The cost associated with the production of hydrogen from forest biomass via gasification is approximately 1.2-2.4 USD per kilogram of H2, which is over 50% lower compared to alternative methods (Lepage et al., 2021). It is important to acknowledge that commercial gasification equipment is commonly associated with power generation equipment, enabling the simultaneous production of energy and gas (Aguado et al., 2023). The latter can be distributed to neighboring houses.

The incorporation of suitable catalysts into the gasification process has the potential to enhance the composition of the produced gas (Galadima et al., 2022; Raihan et al., 2022i). In the experimental study on catalytic gasification, Eucalyptus residue was subjected to gasification using NiO as the catalyst (Ruivo et al., 2021). The results indicated a significant increase of 30% in the overall gas output. The application of catalytic gasification resulted in a reduction in both the biochar and ash contents, leading to an enhanced usage rate of biomass (Shrestha et al., 2022; Raihan et al., 2023e). There exists a contention that catalytic cracking exhibits more economic viability when compared to conventional techniques of biofuel production, namely pyrolysis and fermentation (Chia et al., 2022). Figure 6 presents the Biochemical conversion of biomass to biofuel that includes fermentation and anaerobic digestion.

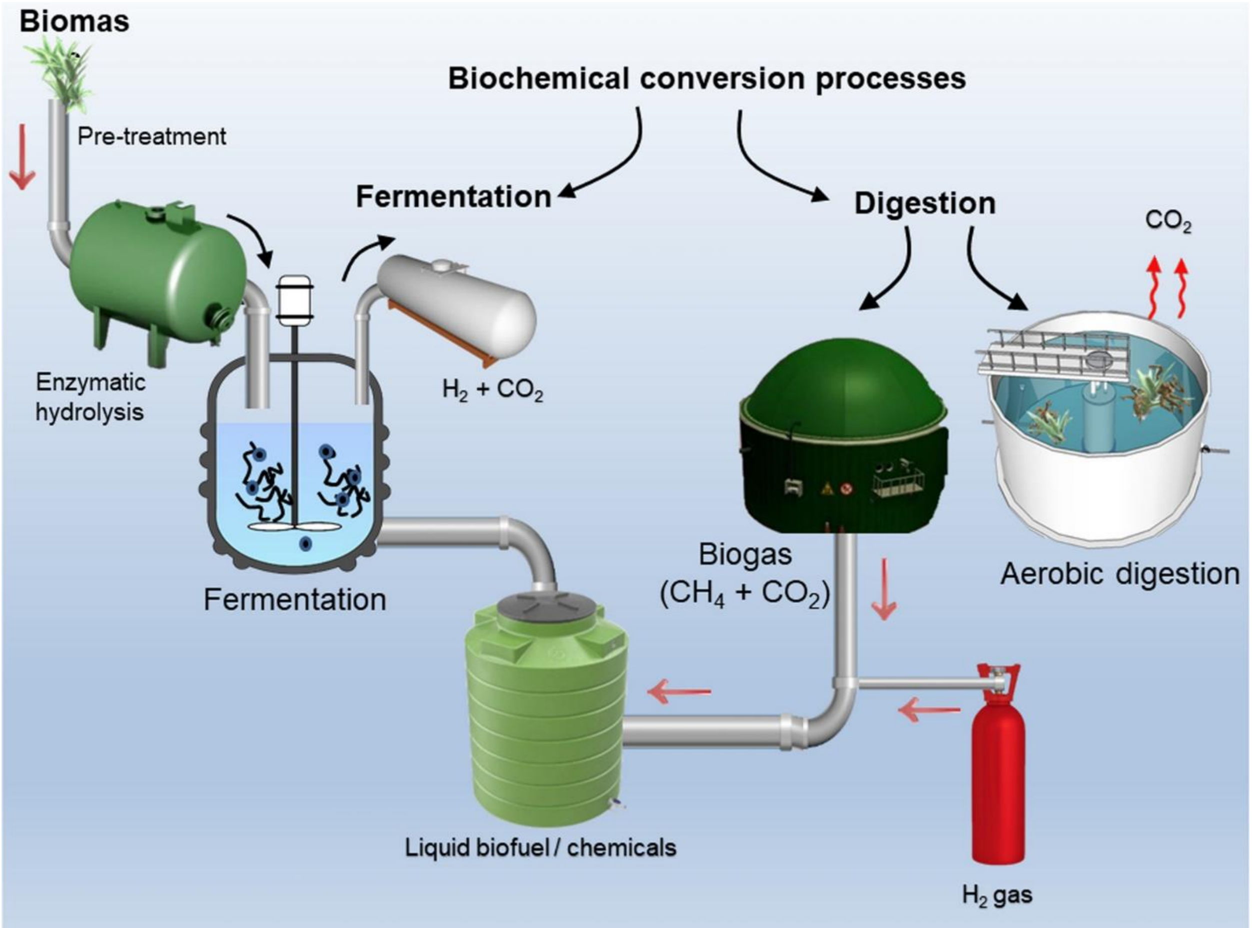

Figure 6. Biochemical conversion of biomass to biofuel includes fermentation and anaerobic digestion (Osman et al., 2021).

Furthermore, forest biomass has the potential to generate biogas via the process of anaerobic digestion, in addition to its capacity to produce syngas rich in hydrogen (Vuppaladadiyam et al., 2022; Raihan & Tuspekova, 2022k; Osman et al., 2023). The process of turning forest biomass into methane (CH_4) has reached a significant level of development and has been successfully employed for practical purposes for an extended period. The generation of biogas is significantly influenced by the structure of the raw materials, primarily consisting of CH_4 and CO_2 (Aghel et al., 2022; Raihan et al., 2022j). It is important to acknowledge that, apart from species, the physical characteristics of forest biomass may also be influenced by geographical location and growing environment disparities (Raihan et al., 2021b). One of the primary obstacles encountered in anaerobic digestion is the limited degradability of lignin in the absence of oxygen (Gao et al., 2022). Lignocellulosic organic resources, such as forest biomass, are characterized by a drawback in terms of the limited accessibility of hemicellulose and cellulose as biodegradable constituents for microbes and their associated enzymes (Periyasamy et al., 2023). However, like other forms of lignocellulosic biomass, forest biomass can also undergo various pretreatment methods, such as chemical (acid, alkali, or oxidant hydrolysis), physical (irradiation, cutting, thermal, and hydraulic shocks), and biological (fungi, actinobacteria, or their enzymes) in order treatments, to enhance its anaerobic biodegradation capabilities (Kumar et al., 2022).

Conclusion

The utilization of forest biomass as a source of energy has been demonstrated, both through direct and indirect means. In a more specific context, the utilization of forest biomass involves its direct combustion as a means to mitigate the CO_2 emissions linked to conventional methods of energy production. Nevertheless, the energy conversion efficiency of forest biomass is very low, resulting in the generation of soot and residues as byproducts. Furthermore, the limited availability of consistent biomass resources and the substantial financial requirements and storage capabilities pose significant challenges to the long-term viability of utilizing forest biomass for direct energy generation. When considering the reduction of emissions and the maintenance of production efficiency, the utilization of co-burning of biomass and coal can be seen as a potentially favorable approach in contrast to the exclusive combustion of coal. Furthermore, it partially addresses concerns about the accessibility of biomass, the spatial requirements for storage, as well as cost challenges associated with transportation and distribution.

Notwithstanding the aforementioned advantageous characteristics, forest biomass is subject to suboptimal energy density and excessive moisture content, both of which may be effectively mitigated through the process of pelleting forest biomass. The combustion rate is accelerated when pelleted forest biomass is directly combusted or co-combusted with coal, owing to its enhanced density and moisture content. However, power plants that depend on pellets from woody biomass encounter various challenges, including elevated energy consumption, a labor-intensive production method, and comparatively higher costs compared to alternative solid biofuels. The present study provides a comprehensive analysis of the biochemical and thermochemical processes used to convert forest biomass into bio-oil, bioethanol, and biogas.

With the increasing recognition of the ecological ramifications associated with the combustion of fossil fuels, the trajectory of the future will inevitably incline toward the utilization of biomass and biofuels. While there is existing knowledge on the conversion of forest biomass to bioenergy, it is important to note that further investigation is required to thoroughly evaluate its long-term sustainability. Future research should employ advanced sustainability assessment methodologies, such as life cycle assessment and exergy analysis, to provide a more comprehensive analysis of these processes.

Acknowledgment: Not applicable

Funding: This research received no funding

Conflict of Interest: The author declares no conflict of interest

Data availability: No new data were created or analyzed in this study. Data sharing is not applicable to this article.

Authors Contribution: Asif Raihan contributed to conceptualization, visualization, methodology, reviewing literature, extracting information, synthesize, and manuscript writing.

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