



# Biomass processing technologies for bioenergy production: factors for future global market

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## Abstract

Biomass processing technology plays a key role in the production of bioenergy, which has the potential to reduce carbon emissions and mitigate climate change. This review article presents the current state of biomass processing technology, its potential advantages for bioenergy production, and factors that may influence the future global market. This review begins with an overview of biomass industry and its role in bioenergy production. Various biomass processing techniques, including thermochemical and biochemical methods, are then reviewed, along with their advantages and limitations. Moreover, it discusses current bioenergy market trends in the past, present, and future growth potential. In addition, this article examines the factors that may influence the future global market for biomass processing technology and bioenergy. Factors including technological advancements, regulatory policies, market competition, and global energy demand are discussed. The results emphasize the importance of choosing the appropriate processing technology based on the specific biomass feedstock and desired end product. The need for R&D investments to improve biomass processing technology and increase the efficiency and scalability of bioenergy production is conclusive. The review points out the importance of political support to promote bioenergy adoption and boost market demand. Despite challenges to overcome, the potential advantages of using biomass processing technology to produce bioenergy make it a promising candidate for meeting global energy needs and reducing carbon emissions. This review article provides a comprehensive overview of biomass processing technologies and their potential role in the global bioenergy market. This highlights the importance of continued investment in research and development and supportive policy frameworks to enable bioenergy deployment and accelerate the transition to a more sustainable energy future.

**Keywords** Bioenergy · Biofuel · Thermochemical conversion · Biological conversion · Biofuel global market

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## Introduction

Bioenergy is a type of energy produced from organic material, or biomass, originating from plants (Srivastava et al. 2021). During photosynthesis, plants utilize atmospheric carbon in the formation of biomass. Bioenergy is useful as it is used in various settings and sectors, from solid bioenergy and biogases to liquid biofuels used in cars, boats, and aircraft (Martinez-Hernandez et al. 2021). Additionally, it usually utilizes existing infrastructure. For instance, end-user gear and natural gas pipelines already in place are used for biomethane. The majority of drop-in liquid biofuels, however, may be utilized in most vehicles and may be able to utilize current oil distribution networks with only minor modifications.

Another advantage of using bioenergy is that using effective systems and sustainable resource development may



eliminate significant amounts of greenhouse gases (GHG) (Li 2022). Specific systems and significant potential future developments, such as systems of perennial agriculture, bio-material leftovers and modern conversion techniques, can reduce emissions by up to 80–90 percent to the baseline using fossil fuels (Meadowcroft et al. 2018). However, the overall beneficial impacts of GHG mitigation can be lessened and, in some instances, even outweighed by land use changes and forest planning, which result in a loss of carbon stocks. These effects are known as direct and indirect land use change. Climate change effects, such as temperature rise, modifications in rainfall patterns, and an increase in severe incidents, will impact and be associated with the potential sources of biomass (Thanigaivel et al. 2022). Even though this interaction is still not fully understood, significant geographic differences are expected. Climate change has an impact on the production of biomass feedstock, but if global temperature rise is limited to 2 °C above pre-industrial levels, there may not be many limitations on the production of biomass feedstock. Bioenergy may have more sustainable potential when integrated with adaptive strategies and biomass resource development (Calvin et al. 2021).

The bioenergy industry is a rapidly growing sector focused on utilizing organic matter such as plants and waste to produce renewable energy. It consists of several subsectors including solid biomass, liquid biofuels, and gaseous biomass (Chia et al. 2022). Solid biomass includes wood, crop residues, and other organic materials that can be used to generate heat and electricity through combustion (Kumar and Samadder 2017). Liquid biofuels such as biodiesel and bioethanol are produced through chemical processes that convert biomass into liquid fuels that can be used as fuel for transportation (Yew et al. 2020). Gaseous biomass, such as biogas and syngas, is produced by thermochemical and biological processes that convert organic matter into gases that can be used to generate heat, electricity, and transportation fuels (Mallikarjuna et al. 2021). The bioenergy industry has the potential to play an important role in reducing greenhouse gas emissions and promoting energy security, but it also faces challenges regarding raw material availability, processing costs and political support (Ha et al. 2022).

Manufacturing technologies for bioenergy production can be broadly classified into two categories. Thermochemical and biological technology. Thermochemical techniques involve converting biomass into energy through processes such as liquefaction, combustion, gasification, and pyrolysis (Okolie et al. 2022). Liquefaction is the method of converting biomass into liquefied products by combining physical and chemical processes (Ibrahim et al. 2020; Hong et al. 2021). Combustion burns biomass to produce heat, which is converted into electricity or used for heating (Liu et al. 2021b). Gasification involves heating biomass to high temperatures in the presence of

limited oxygen to produce gas that can be used for heating or as fuel for engines (Sikarwar et al. 2016). Pyrolysis heats biomass in the absence of oxygen to produce bio-oil, biochar, and syngas (Roy and Dias 2017). These technologies are highly efficient and suitable for large-scale power generation. Biological technology, on the other hand, uses microorganisms and enzymes to convert biomass into energy. These techniques include anaerobic digestion, fermentation and enzymatic hydrolysis (Nanda and Beruti 2021a). In anaerobic digestion, microorganisms break down organic matter in the absence of oxygen to produce biogas (Duarte et al. 2021). Fermentation uses microorganisms to convert biomass into biofuels such as ethanol and butanol (Esercizio et al. 2021). Enzymatic hydrolysis uses enzymes to break down cellulose and hemicellulose in biomass to produce sugars that can be used as biofuels (Fu et al. 2021). Biological technologies are generally suitable for small-scale energy production, making them more sustainable and environmentally friendly. Overall, thermochemical and biological technologies each have their strengths and weaknesses, which are important for the development of a sustainable bioenergy industry.

As biomass burns and releases carbon during combustion and only comes back to the environment when it is used to produce power, modern bioenergy has the potential to be a nearly emission-free fuel (Gheidani et al. 2021). Modern bioenergy makes up the majority of renewable energy sources worldwide, contributing more than 6% of the world's energy supply and 55% of all renewable energy. The Net Zero Emissions by 2050 Scenario claims that the use of bioenergy in place of fossil fuels will significantly enhance by 2030. Between 2010 and 2021, the use of modern bioenergy rose by an average of 7% per year. More work is required to accelerate the deployment of current bioenergy. The Net Zero Scenario requires deployment to increase by 10% a year between 2021 and 2030; to be realized, deployment must expand while ensuring that bioenergy production does not have detrimental social and environmental effects.

The need for biofuel will rise by 41 billion liters, or 28%, between 2021 and 2026 under the current scenario. One-fifth of this demand growth is due to a return to consumption levels before COVID-19. Governmental policies primarily cause the remaining rise. However, other factors like costs, the design of specific programs, and the overall demand for transportation fuels play a significant role. There are numerous unknown factors influencing the demand for biofuels. For instance, in reaction to the current high price of feedstock, which has the effect of lowering demand, numerous countries have reduced or delayed their mandates for mixing biofuels. But soon, substantial policy debates in China, the USA, Europe, and India raise the prospect of a demand increase for biofuels that would more than double in the expedited scenario.

The present review highlights the various types of bioenergy industries including solid biomass, liquid biofuel, and gaseous and their significance. In addition, this review presents and discuss the processing and manufacturing technologies includes thermochemical and biological methods with a particular focus on their limitations and suggestions for the improvement in the adopted technology in a defined set of environments, global bioenergy scenario, market players, economic impacts, opportunities, and challenges, with particular COVID-19 and strategies to combat these impacts. Moreover, this review discusses the main factors manipulate the biofuel in future. Finally, the recommendation and future prospective of bioenergy market are presented.

## Bioenergy industry

### Solid biomass industry

Most biomass, used into generating heat and power, comes from reliable sources. Agricultural, municipal, and commercial wastes, energy crops, and forest litter are potential sources of solid biomass. Several techniques have been devised to densify biomass due to the variety of these sources, harvesting procedures, and transportation costs (Bajwa et al. 2018). Solid biomass plays a crucial role in the energy industry, with wood being an especially important renewable energy source on a global scale. The future of solid biomass is complex and multifaceted, with numerous potential applications. As a raw material, solid biomass is essential in the development of progressive bioenergy sources, and it is also utilized directly as a fuel for heating and electricity generation.

Solid biomass materials, including wood and crop leftovers, are gathered from widely separated locations and stored at the appropriate time and cost in power plants, combined heat and power plants, and district heating systems. The problem has been overcome in many locations across the world. For instance, wood pellets with a suitable amount of durability, a high energy density, and low moisture content are shipped by sea from Southwestern Europe to the Netherlands and Southeast Asia to Japan. Straw and crop residue in countries like India and Pakistan are collected and utilized to produce heat and electricity for rural areas. To ensure a successful supply chain, contracts are crucial in guaranteeing the availability of feedstock at the right price and quality. Nonetheless, larger amounts of residues remain uncollected, especially from farms globally and industrialized nations with managed logging forests. For solid biomass trading to prosper in an ever-growing global energy and commodity market, standardization of biomass feedstocks is likely to play a critical role. The European Commission projects that 42% of the world's renewable energy consumption will come from producing heat and power from solid biomass fuels in 2030 (Bórawski et al. 2022). Pre-processing of the feedstock, such as drying and densification, aids in achieving quality standards (Clauser et al. 2021). Figure 1 illustrates the various forms of solid biomass that can be used as feedstock for bioenergy.

Solid biomass can be obtained from various sources including agricultural waste, harvested natural resources like forest litter or entire trees, and readily available crops and their byproducts such as corn which can be used for ethanol production. All of these sources are considered significant sources of solid biomass. Large amounts of biomass with consistent qualities are mainly available from agricultural

**Fig. 1** Various forms of solid biomass as feedstock for bioenergy production



wastes. However, they do not have enough density to be delivered affordably to where they will be used for energy production. Agricultural biomass is, therefore, a prime candidate for densification before usage. Energy requirements for biomass densification to enhance bulk and energy densities are comparatively low. By being cautious in the process, it is possible to reduce the transportation expenses associated with bringing the biomass to the desired location and also improve the feedstock properties of the biomass. As a result, the ability of the biomass to generate energy can be increased. Pellets production and other densified procedures are utilized in small businesses and at home.

Even though brand-new, large-scale conversions are mainly a thing of the past, it is thought that biomass still ranks among the most effective options to transition heat generation away from fossil fuels. Several wood waste-based projects are in progress in many parts of the world, like Germany. Similar initiatives are anticipated to develop in Poland, which, after Germany, has the second-largest asset of coal-fired power plants in Europe. In addition, new replacement or conversion projects are emerging in France, Spain, and Portugal. For instance, in other parts of the world, like North America, biomass potential is excellent, but subsidies are insufficient. With new technologies like hydrogen production or carbon capture and storage in the future, bioenergy is believed to become more significant in the global decarbonization paths.

While the advantages of using solid biomass for energy production are apparent, there are still obstacles to its widespread adoption in industries. One such challenge is the need to enhance the mechanical and chemical processes used for different types of feedstocks. Additionally, there is a need to establish a framework for determining the appropriate scale of processing and power facilities, which represents another hurdle in effectively utilizing solid biomass for bioenergy generation (Bajwa et al. 2018).

### Liquid biofuel industry

A viable replacement for fossil fuels based on petroleum is liquid biofuel. Since it is not necessarily food-competitive, lignocellulosic biomass is viewed as a possible primary source of liquid biofuel. It comes from various sources, including agricultural waste, forestry waste, grass, and energy crops (Yousuf et al., 2020). The primary sources of bioethanol production, one of the most common forms of bioenergy, are derived from starch-rich crops like sugar, maize, and others. Long-chain alkyl esters are the primary component of biodiesels, which are diesel substitutes made from vegetable or animal fat and generated typically by reacting lipids with alcohols (Ackermann 2005).

The markets for liquid biofuels are pretty developed, active, intricate, and strongly linked to agricultural

commodities. Additionally, significant quantities of feedstocks (starch, sugar, and oil crops) are traded and converted into biofuels in the country of import, with the focus here being on bioethanol and biodiesel (USDA 2017). It is worth noting that liquid biofuel is one of the primary sources of employment in the energy industry (Fig. 2). Ethanol, FAME biodiesel, and HVO are all produced by the liquid biofuel sector. Together, these make up almost all of the current global production and usage of biofuels.

Additionally, the industry is generating and selling new kinds of biofuels for new markets, particularly the aviation and marine industries. These provide better outcomes in terms of carbon footprints and other sustainability metrics. As the bioeconomy expands, there is rising interest in manufacturing biomaterials and other biochemicals.

The liquid biofuel industry faced a significant decrease in demand for transportation fuels in 2020 due to the COVID-19 epidemic, which resulted in a considerable impact on production and profitability. During the height of the crisis, more than half of the US ethanol industry's production capacity was idle. For example, ADM announced that it would shut down four of its plants for at least four months in the middle of 2020. From January 2020 to April 2020, the global price of ethanol decreased by 28%. However, by the end of the year, it had recovered to nearly its January value, with prices falling by as much as 19% in Brazil due to less ethanol demand. As a result, more sugarcane was utilized to produce sugar than bioethanol.

Without a doubt, liquid biofuels would have a less environmental impact than diesel (fossil fuel). However, liquid biofuels offer advantages and disadvantages just like any other product. The biggest of these is the usage of many enzymes, which requires additional spending and financial strain on the environment, energy consumption, and other resources. As a result, the production of advanced biofuels is still in its early stages, with a focus on improving production efficiency and reducing the price of producing bioethanol (Jakub 2021).

### Gaseous biomass industry

The least expensive energy source of labor and capital expenditures is gaseous biofuels (Mallikarjuna et al. 2021). Gaseous biomass is common in rural areas in developing countries. The gaseous biofuels made from biomass most frequently produced include biogas, biomethane, hydrogen, and syngas. Several techniques can convert biomass into gaseous fuels like methane or hydrogen. Compared to their gasification, which is more cost-effective but produces hazardous gases, anaerobic digestion and dark fermentation are highly recommended processes for generating gaseous fuels from organic wastes (Rathour et al. 2018). Another intriguing option for producing



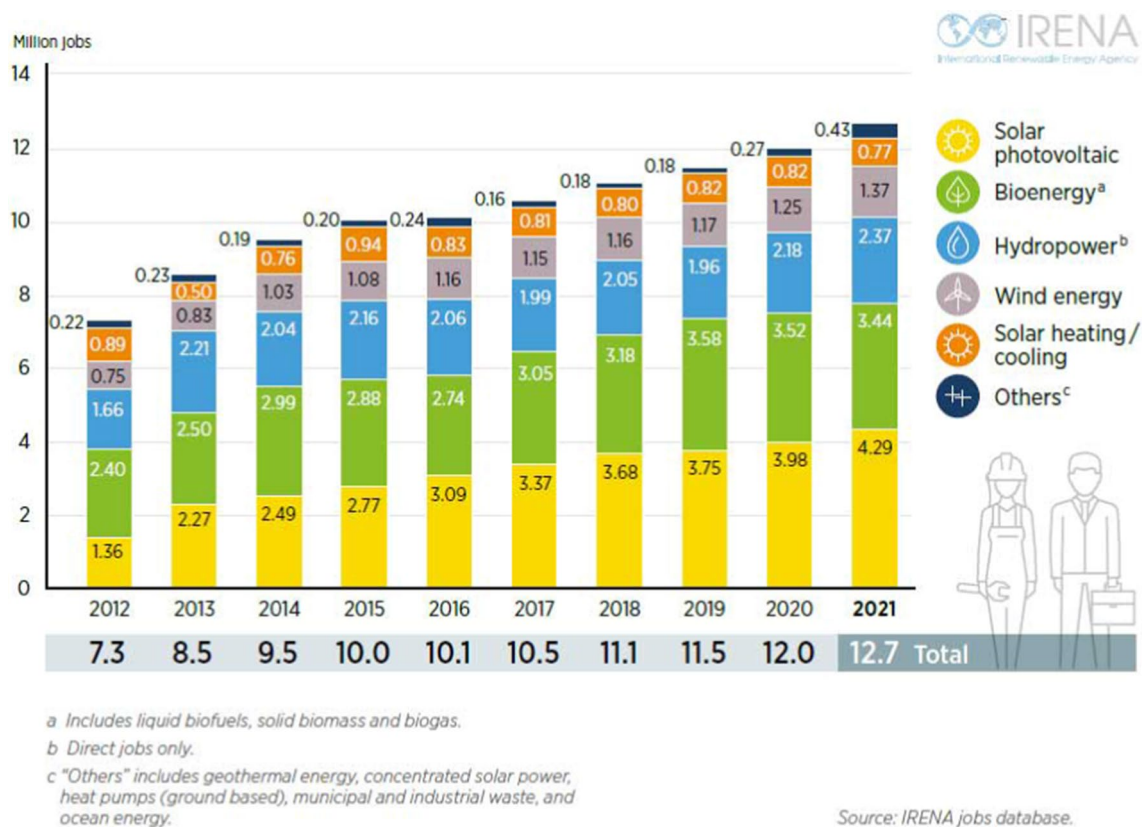


Fig. 2 Evolution of global renewable energy employment by technology, 2012–2021 (Source: IRENA)

gaseous fuel is pyrolysis. In small concentrations, the components of the pyrolysis gas are H<sub>2</sub>O, CO<sub>2</sub>, CO, CH<sub>4</sub>, H<sub>2</sub>, CH<sub>3</sub>–CH<sub>3</sub>, and CH<sub>2</sub>=CH<sub>2</sub>. Fast pyrolysis produces primary gases that make up less than 5% wt of the dry feed and have a composition of roughly 53% wt carbon dioxide, 39% carbon mono oxide, 6.7% hydrocarbons (including CH<sub>4</sub>), and 0.8% hydrogen gas. The organic vapors are partially decomposed into secondary gases containing 9% weight percent carbon dioxide, 63% carbon monoxide, 27% hydrocarbon, and 1.4% hydrogen gas. The pyrolysis gases that result from the severe secondary cracking of the organic vapors have a lower heating value (LHV) of 20 MJ m<sup>3</sup> (Diebold and Bridgwater 1997; Klass 1998). The commercial potential of the gaseous biomass industry is noteworthy as it can contribute to reducing greenhouse gas emissions, producing heat, electricity, transportation fuel, and managing waste, while addressing various social, economic, and environmental issues. Nevertheless, there are certain challenges that need to be addressed, including the complexity of organic waste and a lack of knowledge regarding conversion technologies (Chavan et al. 2022).

## Manufacturing technologies used for bioenergy

Utilizing biomass has been deemed a viable strategy for long-term energy supply and reduction in CO<sub>2</sub> emission, as well as one that offers extra advantages for the environment and rural economies, particularly in developing nations (Parvez et al. 2021). Sustainable fuels increasingly rely on biomass due to the steady depletion of petroleum supplies (Ferreira et al. 2013; Chandra et al. 2019). When biomass is utilized as biofuels directly, it faces many significant challenges, including high moisture and oxygen concentrations, poor calorific value, and highly varied composition (Bahng et al. 2009). Based on their nature and intended purpose, over the last few decades, numerous technologies have been created to process various feedstocks for bioenergy generation (Vassilev et al. 2012). Knowledge of the techno-economy of biomass processing is crucial since the price of crude oil heavily influences it. As a result, most bioenergy industries now focus on surviving in the low-oil price environment (Liu et al. 2021a).



Biomass conversion technologies for biofuel production are generally classified into two main groups: thermochemical (pyrolysis, liquefaction, gasification, and combustion) and biological technologies (hydrolysis, fermentation and anaerobic digestion). However, the properties of biofuels obtained from biomass are highly dependent on the source of biomass rather than the conversion technologies used (Sekar et al. 2021; Venkatachalam et al. 2022).

### Thermochemical technologies

The most practical method for turning biomass into biofuel is thermochemical conversion, which includes combustion, torrefaction, pyrolysis, hydrothermal liquefaction, and gasification (Asadullah et al. 2014). By adjusting process variables, the primary objective of thermochemical conversion is to remove undesired byproducts (Hoang et al. 2021). As a viable replacement for fossil fuel-based energy sources, the production and use of bio-based feedstocks have gained relevance in recent years. The biomass-powered energy systems lessened reliance on fossil fuels and may also help eliminate factors contributing to global warming (Ahmadi et al. 2020). Combustion is the most straightforward method for generating CO<sub>2</sub>, tar, water vapor, heat, alkaline ash particles, and smoke as a consequence of the reaction from biomass (Sadaka and Johnson 2000). Surprisingly, combustion is employed to process almost 90% of the biodegradable materials used as energy derivatives. In the prehistoric period, direct combustion may have been utilized to produce the energy needed for drying agricultural products or heat or steam (Sector 2012). Throughout the agriculture-related processing factories like those for rice, coffee, sugar cane, and other agricultural products, direct combustion is quite common (B.-C. F. R. De 2002). The first biomass-based power station with a 6 GW power supply was debuted in the USA in 1989 (van den Broek et al. 1996). Direct combustion with biomass as fuel was once thought to be a way to eliminate organic waste. The low-efficiency boiler from using these cheap fuels has given rise to new possibilities for energy production technology. In addition, the trade-off between efficiency and investment has been impacted by local issues, including duties, power costs, and pollution reduction rules

(Environmental laws). The three basic combustion applications are the interactions between fuel, energy, and ambient factors. In the boiler, biomass fuel combustion produces flammable vapors that volatilize and burn like flames. This unpredictably degrading combustion product is divided into three parts: a vaporous component of CO, CO<sub>2</sub>, and H<sub>2</sub>; a condensable fraction of H<sub>2</sub>O, aldehydes, and ketones; and a part composed of alcohols and tar. As a result, the carbon char's residual substance burns in more air. It is possible to use the heat generated by combustion as a resource for other conversion procedures that result in electrical energy, which again depends on a few more factors.

Additionally, due to the significant carbon dioxide formation in some circumstances, biomass combustion is not always preferable for bioenergy production. However, in reality, various other gases, including CO<sub>x</sub>, SO<sub>x</sub>, NO<sub>x</sub>, and CH<sub>4</sub>, are also released, depending on the biomass's origin and the nature of the combustion reaction. As the produced gases may affect the environment and human health, such emissions must be appropriately managed.

### Biomass pyrolysis

Pyrolysis occurs when lignocellulosic biomass is thermally decomposed in the absence or in a limited oxygen supply into solids and liquids rich in carbon. The three main lignocellulosic biomass constituents, cellulose, hemicellulose, and lignin, thermally degrade between 300 and 500 °C. A developing pyrolysis method can generate various products which produce renewable energy that may be utilized in various industries. Temperature, biomass, and the duration of the vapor and solids' residence times all affect the product yields. The two types of pyrolysis that are most frequently utilized are slow and fast pyrolysis. Other pyrolysis modes include intermediate, slow, torrefaction, and gasification.

Biochar is the main result of the pyrolysis process (called slow pyrolysis), which happens at moderate temperatures, moderate heating rates, and extended residence durations. However, bio-oil, produced using a rapid heating rate and brief residence time, is the main byproduct of fast pyrolysis (Table 1). Biofuel production rates and

**Table 1** Different modes of pyrolysis and product composition. Adopted from (Azargohar et al. 2013)

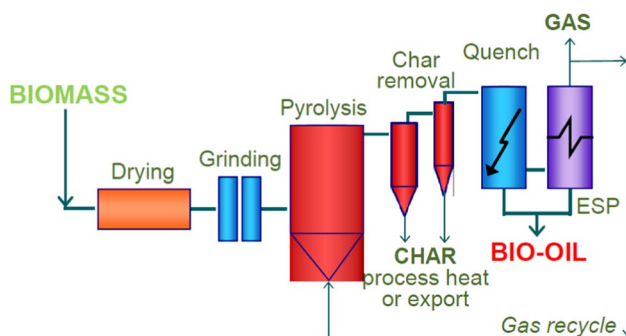
Mode	Conditions Wt % products	Liquid	Char	Gas
Fast	500 °C or less; a very brief hot vapor residence period (RT) of 1 s; brief solids RT	75%	12%	13%
Intermediate	500 °C; 10- to 30-s HVRT; moderate solids RT	50% in 2 phases	25%	25%
Slow	400 °C; lengthy HVRT; extremely long solids RT	35%	35%	30%
Torrefaction	300 °C, long HVRT, and long solids RT	Vapors	85% solid	15% vapors
Gasification	800–900 °C; brief HVRT; brief solids RT	1–5%	< 1% (all burned)	95–99%

product quality by fast pyrolysis are better than those by slow pyrolysis (Brown et al. 2011; Jahirul et al. 2012).

Usually, a reactor, cyclone, and condenser are found in a pyrolyzer. The reactor is supplied by biomass, which undergoes several thermochemical reactions to produce various chemicals. The cyclone separates liquid and gaseous components from solid ones (Stevenson 2009). After being promptly quenched in the condenser, the vapor products and solid products are separated, and bio-oil is separated from other gases. The pyrolyzer often recycles non-condensable gases for fluidization and heating (Stevenson 2009). Catalytic pyrolysis and catalytic upgrading are two additional ways that some pyrolyzers combine biomass and catalysts to increase the conversion efficiency and quality of the pyrolysis products (Dickerson and Soria 2013; Biddy et al. 2013). The different modes of pyrolysis and product composition are given in Table 1.

According to Azargohar et al. (2013), each method has a particular application because the pyrolysis setup and operation circumstances affect the yield and properties of pyrolysis products. Fast/flash pyrolysis is employed if maximizing bio-oil is the goal, while moderate to medium-speed pyrolysis is preferred if a higher production of bio-char is required. Figure 3 depicts an example of a pyrolysis reactor.

Several studies demonstrate pyrolysis technologies (Vamvuka 2011; Meier et al. 2013; Laird et al. 2017), usage of pyrolysis products (Laird et al. 2017; Ahmad et al. 2014), upgrading of pyrolysis products (Xiu et al. 2011; Bridgwater 2012), and co-pyrolysis (Roy and Dias 2017). To ensure the effective implementation of technology for rapid pyrolysis, there is a need to improve it to reduce costs, increase the quality and quantity of liquid production. Moreover, further research and testing are required to upgrade the quick pyrolysis liquid (Lee et al. 2020; Yong and Wu 2022).



**Fig. 3** A typical pyrolysis reactor. Reproduced according to (Bhatia et al. 2021)

## Biomass liquefaction

Direct liquefaction is the method of converting biomass into liquefied products by combining physical and chemical processes. In this instance, the heat breaks down the biomass macromolecules into smaller molecules (either with or without a catalyst) (Karimi-Maleh et al. 2022). A biomass liquefaction thermochemical process occurs when a catalyst presents high pressure and a moderate temperature. The method produces a liquid containing a small amount of solid and gas. In some circumstances, the process's incorporation of hydrogen improves the product's production under liquefaction circumstances. The focus on the liquefaction process is low because of the difficulties in the fuel-feeding systems and reactors. In addition, the liquefaction process is more expensive and complex than pyrolysis (Sri Shalini S et al. 2021). High moisture feeds are used in hydrothermal liquefaction (HTL), which produces biofuels and other chemicals. A catalytic or non-catalytic conversion process known as HTL operates at low temperatures and high pressures. The ideal HTL setting for different feedstocks typically ranges from 250 to 375 °C and 4 to 25 MPa in pressure (Akhtar and Amin 2011; Dimitriadis and Bezergianni 2017; Kumar et al. 2018). The hydrolysis of lignin, hemicellulose, and cellulose present in biomass is facilitated by water in HTL, degraded, and repolymerized, turning them into biofuels like bio-oil, char, and gases (Kruse et al. 2013). Biomass is hydrolyzed into monosaccharides, disaccharides and polysaccharides as the first stage of hydrothermal conversion. Following this, there are preparatory procedures such as isomerization to make phenol and cyclic ketones, which result in volatiles and char (Akhtar and Amin 2011).

The temperature of the reaction, rate of heating, pressure, period of retention, the ratio of feed, solvents, kind of catalyst, and atmosphere are some key variables that influence the reaction and its byproducts. There have been studies on a variety of feedstocks, including raw cellulose and lignin (Minowa et al. 1998; Sasaki et al. 2000; Kumar and Gupta 2008; Sinağ et al. 2009; Wang et al. 2012), agricultural and forest residues (Xu and Lancaster 2008; Hammerschmidt et al. 2011; Zhang et al. 2011; Theegala and Midgett 2012; Yang et al. 2016; Déniel et al. 2016). Better fuels with more energy can be produced via hydrothermal liquefaction in nations with abundant biomass resources. In this situation, bio-oils with traceable or zero SO<sub>x</sub> emissions and claims of carbon neutrality or greenhouse gas neutrality can be employed extensively. Even though HTL may create bio-oil with a more effective content of heteroatoms like N, O, and S than petro-crude, the current difficulty of reducing heteroatoms in bio-oil necessitates more research and development (Brindhadevi et al. 2021). The requirement for tiny particle sizes in the feedstock and the need for processing equipment that can tolerate high pressure and



corrosive conditions in the reaction environment are both disadvantages of HTL (Gollakota et al. 2018). Regardless of the liquefying method employed, the intermediate bio-crude will fall short of meeting all requirements for either diesel or gasoline. Thickening, phase separation, tar development, and char/coke production are a few examples of heat-induced bio-crude modifications (Lehto et al. 2014). Other significant difficulties with burning bio-crude include the number of particles and water in the fuel, how it ignites, how much it heats, and the pollution it produces. Each bio-crude must undergo extensive inspection and testing for the specified end-use application.

### Biomass gasification

Syngas or producer gas is a mixture of gases created by the gasification process, which employs gasification agents, including air, oxygen, steam, or their mixtures in a sub-stoichiometric environment while maintaining the equivalency ratio (ER) within 0.2–0.4 (air-to-fuel ratio: 1.5:1–1.8:1) (Keche et al. 2015; Sansaniwal et al. 2017). The gasification process depends on the quality of the biomass fuel, and it must be kept at an acceptable moisture level of 9–22% (Maglinao et al. 2015). Complex thermochemical processes that result in the simultaneous transformation of solid and gaseous species occur during the gasification process. The main processes are gasification, pyrolysis, partial oxidation, and drying (Situmorang et al. 2020). The partial oxidation of the biomass results

in heat, which fuels the following processes and lowers the biomass feedstock's original moisture content. Biomass catalytic gasification, followed, for example, by CO<sub>2</sub> metanation via Fischer–Tropsch technology, are potential energy-valued growth routes (Ren et al. 2020).

A gasification process often comprises numerous simultaneous processes. Exothermic processes can provide heat for endothermic ones when specific reactions are endothermic, and others are exothermic. The complexity of gasification itself means that several variables will affect how effective it is, including biomass content, gasifying agents, biomass particle size, gasification operating conditions (temperature and pressure), and gasifier type (Situmorang et al. 2020). The gasification process for various biomass forms generally falls within comparable parameter ranges, implying that the gasification system's operational or design limitations affect the ability to produce high-quality syngas rather than the type of biomass being utilized. The type of gasifier utilized for engine fuel is not a critical factor since it has been determined that downdraft gasifiers must be utilized. As the consequences of using syngas are the same across all engines, several types of motors, including compression engines, spark-ignition engines, and homogeneous charge compression ignition (HCCI) engines, can be utilized for power generation. Therefore, rather than the kind of biomass used, the crucial factors for gasification systems are the design and operation of the gasifier and the selection of the appropriate engine for the desired application (Mishra and Upadhyay 2021; Nanda

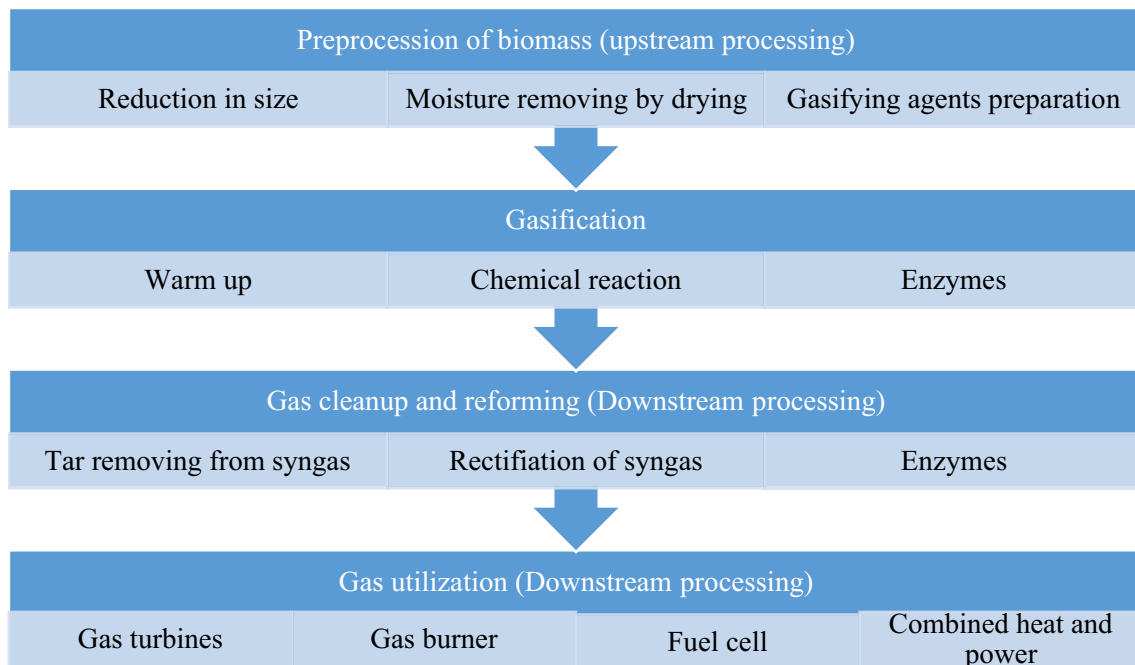


Fig. 4 Phase of gasification process (Farzad et al. 2016)



and Berruti 2021b). The various phases of gasification process are shown in Fig. 4.

Recent applications include the fixed bed, fluidized bed, SCW reactor, dual fluidized bed, and entrained flow. Combustion of biomass is a technique that holds great promise for replacing fossil fuels. Harming bioenergy for everyday uses is crucial due to the rise of health-related problems and global warming. Various factors, including the kind of feedstock, the working environment's pressure and temperature, the residence's length, the type of bed, etc., significantly influence biofuel production. As shown, these variables significantly impact the syngas quality of biomass. However, for some of the parameters mentioned and because of the high costs of energy, capital, and finished goods, biomass gasification cannot make up for them. Therefore, a difficult task for renewable energy is scaling biomass energy to broad areas (Mishra and Upadhyay 2021).

### Biomass combustion

Combustion is considered the most effective and promising technology among the several biomass usage techniques, including gasification, pyrolysis, and combustion (Lim et al. 2016). The simplest method for converting biomass into energy is combustion, since biomass combustion is acknowledged as a carbon-neutral process (Saxena et al. 2009). In addition to its substantial share (82%) in renewable heat generation, solid biomass also has the potential to be attractive due to its benefit of cheaper energy prices compared to fossil fuels. In contrast to gasification and pyrolysis, alternative thermochemical conversion techniques, combustion technology for biomass is well-established, frequently used, and commercially accessible.

Additionally, it has minimal capital expense. Hardwood, softwood, crop residues from grass (cereal) crops, non-grass crops, and biomass-containing trash are relevant categories for biomass feedstocks that are burned as fuel. The projected cost decrease for biomass combustion is lower than for other renewable energy technologies because it is already an established technology. The parameters of the biomass feedstock, such as its moisture content, size, and LHV, as well as the generation system, such as the type of combustor or turbine, all affect the conversion efficiency in biomass combustion technology (Morató et al. 2020).

Treatment of these emissions during the heating process is one of the main obstacles to using biomass as an energy source (combustion). During the thermal processes of biomass, nitrogen oxides (NO<sub>x</sub>) and particulate matter are among the primary gases emitted. Because they affect the environment and human health, these emissions must be managed. Improved knowledge of the fuel-N process aids in creating combustion techniques that produce fewer NO<sub>x</sub> emissions. Extensive combustion facilities use various

methods to minimize NO<sub>x</sub> emissions, including selective and non-selective catalytic reduction, fuel gas recirculation, and fuel and air staging (Mladenović et al. 2018). Due to technological/operational challenges, high abatement costs compared to the price of the heating device, and the inapplicability of the existing control approaches to small systems, NO<sub>x</sub> emissions from domestic biomass combustion are challenging to regulate.

The large ash concentrations during biomass burning are a significant problem as well. SiO<sub>2</sub>, CaO, and K<sub>2</sub>O make up most of the ash produced by combustion, which typically accounts for more than 60% of the fresh biomass ash. Compared to ash from virgin biomass, waste biomass frequently has greater Al<sub>2</sub>O<sub>3</sub> and Fe<sub>2</sub>O<sub>3</sub>. Agricultural leftover ashes could be utilized as a fertilizer additive due to their high potassium content, low phosphate content, and minimal metal contamination. CaO, utilized to enhance soil quality, is abundant in forestry ashes. However, their more significant metal pollution levels may preclude them from being employed directly on forestry soils. It is becoming increasingly important to understand how lignocellulosic biomass thermally burns while minimizing the air pollution that results from this process. Several biomass burner designs have been developed for co-fired systems, including the BWE Bio-dust Burner and the Low-Emission Scroll-type Biomass/Coal Burner. These burners reduce NO<sub>x</sub> and CO emissions while maintaining combustion efficiency (Smith et al. 2020). A biomass-based combustion plant is typically 50 MW in size. With no technological restrictions, a single combustion unit has been stated to have a maximum capacity of 300 MW for both combustion processes (Smith 2006; Spellman 2011; Bryant Vickery et al. 2022).

Bioenergy is essential to reducing greenhouse gas emissions to reach the EU-28's 2020 goal of using renewable energy accounts for 20% of total final energy usage. Utilizing wood combustion to create bioheat is the primary bioenergy usage. In addition, future development of bioheat in the housing market is possible, for instance, due to the phase-out of fossil fuels, the requirement to replace old oil boilers, and the anticipated rise in the use of district heating; in the industrial sector, for instance, due to the use of biomethane; or for cold production (Anca-Couce et al. 2021).

### Biological technologies

#### Hydrolysis of biomass

Before fermentation or anaerobic digestion, which creates liquid or gaseous biofuel, lignocellulosic biomass must be hydrolyzed to yield monosaccharides—maximizing the output of monosaccharides, notably glucose, at a reasonable cost that might be utilized after fermentation to generate liquid fuels and other valuable byproducts is the ultimate



goal of pretreatment and enzymatic hydrolysis (Mosier et al. 2005; Chandra et al. 2007). Similarly, the hydrolysates produced during the hydrothermal pretreatment of microalgae biomass contained insoluble hydrolysis residues in addition to soluble proteins and carbohydrates. Additionally, the hydrolysis wastes contained organic debris that can be further degraded to produce biogas by anaerobic digestion. The soluble carbohydrates and proteins are appropriate for the anaerobic digestion (Fu et al. 2021).

The extensive research on lignocellulosic hydrolysis using diluted acid solutions is reviewed by Steinbach et al. (2017) and Kang et al. (2018). Additionally, Nitsos et al. (2013), Kačková et al. (2013), and Zhou et al. (2017) published research on the hydrothermal treatment of *Miscanthus x giganteus* and beech wood, respectively. However, lignocellulose resistance necessitates an expensive pretreatment. It leads to low-efficiency enzymatic hydrolysis and the formation of numerous toxic compounds that prevent yeast fermentation, making bioethanol economically unviable for commercial marketing (Palmqvist and Hahn-Hägerdal 2000). A study was carried out by Wang et al. (2014) utilizing an integrated technique that included lipid extraction. Utilizing 3% H<sub>2</sub>SO<sub>4</sub>, they hydrolyzed the cell membrane to release lipids and produce fermentable sugar. The lipid was separated using a solvent combination of 1:1 v/v ethanol and hexane. The hydrolysate was converted into bioethanol (by fermentation using *Saccharomyces cerevisiae*). They discovered that the maximum bioethanol yield was 56.1%, and 98.47% of the fuel was converted into biodiesel. Numerous studies have revealed that 30 to 50 °C and 5–7 pH are the ideal ranges for hydrolysis (Azman et al. 2016). However, humic acid inhibits hydrolysis by attaching to the active site of hydrolytic enzymes, altering the chemistry of the environment (Fernandes et al. 2015).

### Biomass fermentation

The three primary steps in ethanol generation using lignocellulosic biomass are pretreatment, hydrolysis, and fermentation. During the hydrolysis step, enzymes break down the cellulose and hemicellulose complexes to produce soluble sugars, which yeasts or bacteria will then consume during the fermentation stage to produce ethanol (Yong and Wu 2022). To produce energy carriers like bioethanol, biohydrogen, and biomethane, as well as oil extraction from lignocellulosic biomass that is high in protein under more hospitable circumstances and with a greater conversion efficiency, bacteria use the biological conversion method known as fermentation (Skjånes et al. 2007). Animal feces is fermented anaerobically, producing biogas as a byproduct (Babajide et al. 2010). Additionally, biogas and biomethane are created during fermentation bacteria' controlled anaerobic decomposition of microalgal biomass (Feng et al. 2019).

Additionally, a significant amount of bioethanol is produced from apple pomace by submerging it in fermentation (Magyar et al. 2016). Carrot pomace is fermented by the bacterium *Kluyveromyces marxianus* to yield bioethanol (Yu et al. 2013). According to Gómez-Marín and Bridgwater (2021), fermentation is one of the primary activities in bioenergy research (32% share) and is defined by biochemical processes. Under anaerobic and mild (30 °C) conditions, yeast and bacteria ferment monosaccharides into alcohol (Gamage et al. 2010). It has been effective in utilizing the bacteria *Clostridium acetobutylicum* in several cycles to create acetone, butanol, and ethanol from fermentation of biomass derived from microalgae and also include *Nannochloropsis* species, and *D. tertiolecta* are *Dunaliellasalina*, *Galdieria partita*, *C. vulgaris*, and *Nostoc* sp (Simas-Rodrigues et al. 2015).

Since a few years ago, it has been common practice to use specific biomass through fermentation, such as macroalgae (Milledge et al. 2014), sucrose and sugar beet (Hussy et al. 2005), food waste mixtures (Aggelopoulos et al. 2014), wastewater utilizing mixed microflora inoculum (Massanet-Nicolau et al. 2008), and waste streams rich in (Tsakona et al. 2014) gaining knowledge of fermentation techniques and viewpoints, such as those in future biorefinery reviews and bioelectrochemical systems for systems that produce fermentable hydrogen integrated systems. Delignification for fermentation is one specific pre-processing for biomass fermentation that has been thoroughly evaluated in the past (Gómez-Marín and Bridgwater 2021). Reviewing the data, the number of publications on fermentation peaked in 2016, nearly twice that of the prior years, and in 2019, and numbers are still increasing in 2022. The bioenergy production from algae and other biomass is confirmed by the studies done to date. This demonstrates that, under some circumstances, fermentation is a commercially and technologically feasible alternative for producing bioenergy.

### Anaerobic digestion

Organic matter is degraded and stabilized through anaerobic digestion (AD), a biological process without oxygen. According to Zhang et al. (2014), hydrolysis, acidogenesis, acetogenesis, and methanogenesis are the four phases of the entire anaerobic conversion process. These processes can all co-occur in a single-stage process or individually in a multi-stage process. Due to recent advancements in algal biotechnology and related technologies, as well as the growing need for renewable energy, the anaerobic digestion of wastewater-treated microalgal biomass has become a promising research option. Effective pretreatment techniques, microorganisms, or a combination of microbes with noticeably enhanced digesting capacities are required to effectively digest the microalgae anaerobically (Veerabadhran et al. 2021). For a



good digestive process, a high biological substance converting to methane rate must create a precise balance between the nutrient-supplying microbial populations and these activities (Lu 2006). However, there is a significant discussion surrounding the challenges of performing food waste anaerobic digestion with high efficiency and stability. The biological process may be negatively impacted by several things, including a high level of labile organic matter, a lot of salt, fat, and protein, a low level of carbon/nitrogen, and a lack of vitamins.

Recently, many researchers have been utilizing various forms of anaerobic digestions technology to recover bioenergy from organic materials. According to studies comparing wet and dry anaerobic digestion procedures, the dry procedure offers a more outstanding  $\text{CH}_4$  production (0.48 L/gVS) and a lower volatile solid rate for the treatment of mixed wastes (85.6%) than the wet process (Yi et al. 2014). Compared to the wet process, the dry anaerobic digestion system makes it possible to improve volatile fatty acid (VFA) and organic loading rate (OLR), reducing the ability to impede AD. Studies on how temperature affects the breakdown of organic waste show that the mesophilic AD system generates 150 mL/g VS  $\text{CH}_4$  less  $\text{CH}_4$  than the thermophilic system (Li et al. 2017). According to reports, two-stage anaerobic digestion effectiveness for biomethane production was 30% higher than that of a single-stage anaerobic digestion system (Voelklein et al. 2017). According to Zhang et al. (2017), in comparison to a single-stage AD system, the multi-stage AD system for digesting organic waste produces up to 54% more  $\text{CH}_4$  and has an efficiency of 83.5% VSR.

The breakdown of food waste anaerobically has previously been thoroughly examined, with numerous articles appearing in this publication. When evaluating the anaerobic digestion of food waste, earlier studies gave biological processes and process parameters for anaerobic digestion priority over all other topics, such as biomass and food waste co-digestion (Zhang et al. 2014; Jain et al. 2015). Various reviews attempted to look into the perspectives on the anaerobic decomposition of food waste, performing outstanding effort in terms of the conceptual methodologies employed; nevertheless, data collection has failed concerning unused food, i.e., the information was mainly concerned with substrate co-digestion (Tyagi et al. 2018). Once more, the assessments of several authors emphasized the separation stages of anaerobic digestion to improve functioning (Chatterjee and Mazumder 2019). Other authors paid more attention to social, political, and environmental issues (Khalid et al. 2020). Numerous additional reviews indicated efforts to think more deeply about digesting food waste anaerobically, but they only provided scant information (Paritosh et al. 2017; Xu et al. 2018).

As previously mentioned, specialized bacteria in an anaerobic environment employ a series of four complex

processes called hydrolysis, fermentation, acetogenesis, and methanogenesis to create biogas. The culmination of all four processes is made more accessible by anaerobic digesters, which yield biogas. Typical biogas compositions include moisture, trace gases, 45% to 65%  $\text{CH}_4$  and 30–40%  $\text{CO}_2$ . The greatest potential feedstocks for biogas should be given to a digester to produce the most biogas. By feeding the digester at the optimum loading rate, properly mixing the digestate across the digester profile, and maintaining the optimal environmental conditions inside the digester, it is possible to ensure consistent biogas output over time (Kirk and Gould 2020).

## Bioenergy markets

### Global key players in the biofuel market

Research estimates that in 2021, the market for biofuels was valued US\$ 109.96 billion and will grow at an estimated compound annual growth rate (CAGR) of 8.3% from 2021 to 2030 to reach US\$ 201.21 billion. The market for biofuels is being driven primarily by rising demand for environmentally friendly transportation fuel, increased awareness of the usage of renewable energy sources, and increased attention to reducing greenhouse gas emissions.

The global biofuel industry's main players are expected to experience substantial growth opportunities due to new biofuel applications. Biofuels are predicted to be used as an economical and reliable source of aviation fuel, and scientists have discovered a production process that simplifies the manufacture of jet fuel from biomass. The sector has also witnessed a decline in biofuel production costs, which is one of the primary drivers for replacing fossil fuels (Khoshevisan et al. 2018). Another factor that is expected to stimulate the industry's growth potential in the near future is the introduction of novel feedstocks for biofuel production. Moreover, the growing focus on biofuel production by developing countries globally to reduce greenhouse gas emissions is creating opportunities in the industry (Kleiman et al. 2021).

Due to rising research & development (R&D) spending by significant market participants and raising awareness of using renewable energy sources, significant growth is anticipated in Asia–Pacific. Another element projected to stimulate the increasing emphasis is on the target industry's growth in the Asia Pacific region on applying governmental rules to decrease greenhouse gases. With a fantastic CAGR of about 5.5% from 2021 to 2030, in 2020, the Asia Pacific region had a gross domestic product (GDP) of USD 21,858.0 million. The companies concentrating on R&D are anticipated to dominate the global biofuel industry. The following are the top rivals in the global biofuels market: BT Global



Limited, Renewable Energy Group, Inc., Abengoa Bioenergy S.A., Cargill, DowDuPont, Inc., Wilmar International Ltd, POET, LLC, Archer Daniels Midland Company, VERBIO Vereinigte BioEnergie AG, My Eco Energy, China Clean Energy Inc.

### Global market past, present, and future status of the biofuel market

The capacity for producing bioenergy has recently increasing worldwide (Adsul et al. 2020; Sun et al. 2022). Nevertheless, compared to an average growth rate of 6% during the preceding ten years, the global production of biofuel decreased by 6% in 2020. Many different government agencies from various countries have put policies into place to promote bioenergy development with the hope that it will be commercially viable (Singh et al. 2019). For instance, China produces 1.14 billion liters of biodiesel and more than 3 billion liters of ethanol annually. However, the Chinese government has set ambitious targets to increase ethanol and biodiesel production to 12.7 billion and 2.3 billion liters annually by 2020. However, the COVID-19 pandemic has had a significant impact on the objective. The first EU biofuel regulation was introduced in 2003 with the goal of promoting the use of renewable energy and biofuels for transportation. With 31% of the world's biodiesel production, which totaled 14.6 billion liters in 2019, the EU is currently among the top producers in the world (EU 2009). In order to address a variety of bioenergy issues, such as solid biofuels, poultry recovery, and other issues, Russia started its Comprehensive Biotechnology Development Program in 2012 (Vassilieva et al. 2012).

From COVID lows, the biofuel market increased to levels comparable to 2019 in 2021. However, in 2022, researchers anticipated slower demand growth than we had anticipated due to higher oil and biofuel prices and weaker GDP estimates. Even with more moderate growth in transportation fuels, the demand for biofuels will increase yearly by 5% in 2022 and 3% in 2023 due to stronger biofuel policy and rising transportation fuel prices.

The demand for biofuel rose to nearly 2019 levels in 2021, reaching 155,400 million liters. Demand increased by 8,700 million liters yearly, which is in line with the expectation for renewable energy in 2021 from December 2021. However, the recovery across fuel types varied. The demand for ethanol increased by 6% annually in 2021 but remained 7% lower than in 2019. In contrast, the usage of renewable diesel increased by around 70% from 2019, while the demand for biodiesel increased by 0.2% from 2019. The invasion of Ukraine by Russia has shocked the oil and agricultural industries, making already high prices worse. As a result, in 2022, the global demand for biofuels is predicted to slow by 20%, or 2,200 million liters, as opposed to the

earlier prediction of a larger increase of 11,000 million liters. It was projected that, as of 4 April 2022, the world's oil demand growth rate would be 1.2% lower than predicted in January. The lower estimate results from poorer GDP growth and mobility limitations in China connected to COVID-19. Because biofuels are blended with gasoline and diesel, slower growth in the transportation sector directly affects the demand for biofuels, with losses being most pronounced in major biofuel markets like Europe, the USA, and Brazil.

The agriculture sector is experiencing price shocks, which have increased biofuel prices across the board. By geography and fuel, increases can differ. For instance, starting in January 2022, the price of ethanol in Brazil has increased by 20%, while it has increased by 30% in the USA. Biodiesel prices have increased by 20–30% worldwide just this year. In addition to high levels, prices have increased since December 2021. As a result, numerous governments are loosening or delaying regulations, slowing demand increase.

### Recommendations and prospects

Algal biomass production for third-generation biofuels has faced several difficulties that hinder its commercialization and replacement of the first two generations of biofuels. Primarily due to cost concerns, third-generation biofuels still have not completely replaced older biofuels. However, COVID-19 has encouraged international organizations to seize the chance and invest in a world without carbon emissions. The key focus is that the third-generation or advanced biofuels are to replace traditional transportation and aviation fuels. In the transportation sector, biofuel consumption is anticipated to triple by 2030, exceeding biofuel production by a factor of three. Due to the COVID lockdown and restricted migration, biofuel manufacturing is hindered in some countries. Therefore, this could be a chance to advance to third-generation biofuels and encourage their use.

Moreover, increasing the production of non-food crop feedstocks could help to reduce land use and provide higher lifecycle of GHG emissions when used to make advanced biofuels. Similarly, it strongly advises increasing the use of third-generation biofuels in shipping, aviation, and domestic and international transportation. This will significantly lower emissions related to transportation and aviation as well as boost the post-pandemic economy. Bio-jet fuels have the potential to gradually replace conventional jet fuel at lower long-term costs, which would benefit the present pandemic scenario. In addition, the following issues and suggestions for synthesizing and marketing sustainable biofuels should be taken into account:

1. The type, complexity, and preparation of lignocellulosic biomass affect its ability to be scaled up. Therefore, a

greater comprehension of the different pretreatment effects on the complexity of the biomass and the use of cost-effective strategies are needed. Further research should be done into developing high-value coproducts as their production may flood the market.

2. Biomass-based power plants will play a big role in the energy sector in the next years to meet electricity demand. Biomass is a feedstock for electricity production and includes materials like rice husk, wheat straw, bagasse, wood scraps, and municipal solid waste. The complete combustion of solid biomass generates a substantial amount of biomass ash, which needs to be properly disposed of and managed to support sustainable development.
3. One important consideration is the use of biomass in cutting-edge technologies as a catalyst and energy storage application. The most recent advances in membrane technology for using fly ash from biomass is the use of applications for membrane technology range from fuel catalysis to environmental applications.

## Conclusion

In the next few years, the demand for biomass as an energy source is expected to increase, leading to a potential mismatch between biomass supply and consumption as early as 2023. Agricultural biomass, forest residues, and specially bred biomass crops will be important sources of biomass feedstock for energy production. To enhance our understanding of current green technology for biomass conversion and its potential benefits for bioenergy production, a review of the current state of the industry is necessary. While biomass production and bioenergy are promising sectors, the rapidly evolving industry of biomass processing green technologies requires further focus and effort. Despite some early-stage efforts and ongoing research into how biomass production and processing technologies can optimize production by reducing inputs and increasing outputs, challenges and barriers still exist. Therefore, it is crucial to raise awareness in both developed and underdeveloped nations. Additional research projects, collaborations, and international initiatives may provide innovative technologies with potential financial value. However, these efforts must address the various challenges and obstacles associated with the implementation of these technologies.

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**Data availability** The authors confirm that the data supporting the findings of this study are available within the article.

## Declarations

**Conflict of interest** The authors declare that they have no conflict of interest.

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