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Review

Fueling the future: biomass applications for green and sustainable energy

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Abstract
Biomass has become a key contender in the race to find sustainable energy options, as we move toward a more environmentally friendly future. This extensive assessment explores the potential of biomass to transform the global energy landscape. We have examined different conversion technologies, including thermal technologies such as combustion and gasification, as well as biochemical technologies such as anaerobic digestion and biofuel production, and we delved into the renewable nature of biomass, which is derived from organic sources such as agricultural residues, forestry waste, and special energy crops. We highlight the adaptability of biomass for the production of energy, heat, and biofuels. Furthermore, we evaluated the socioeconomic and environmental impacts of biomass use, including greenhouse gas emissions, land use, and community effects. To increase the potential of biomass as a renewable energy source, it is essential to understand how these three factors interact. To maximize energy production while curtailing environmental problems, this review examines obstacles, ongoing research, and recent developments in effective biomass-based energy systems.

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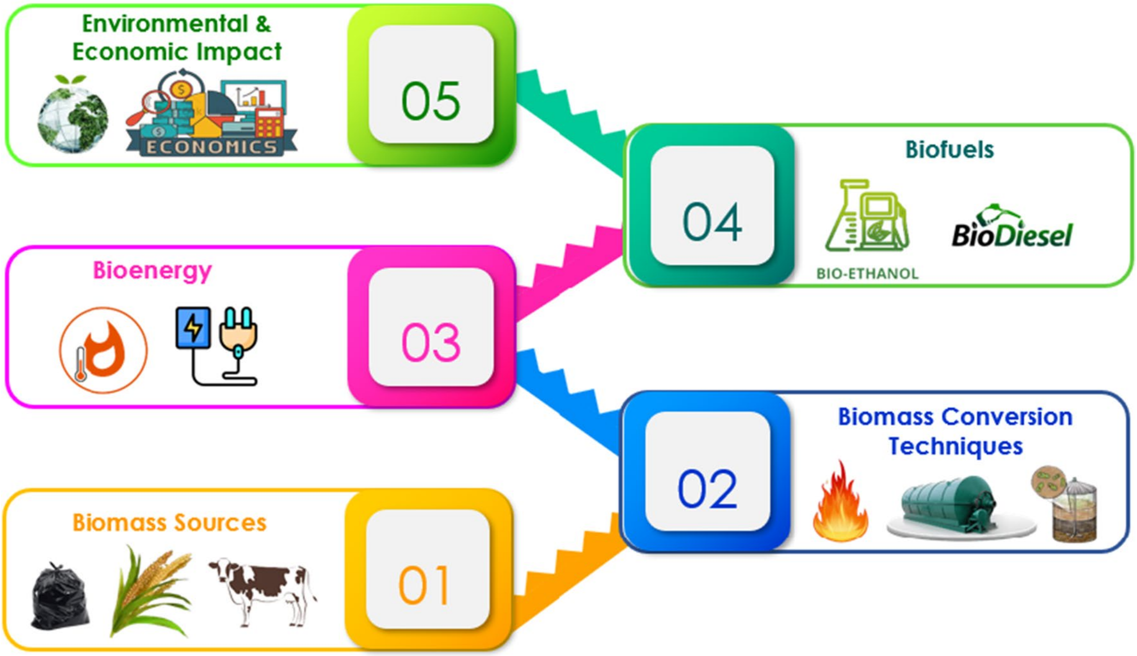
Graphical Abstract



Keywords Biomass · Biomass sources · Green energy · Sustainable energy · Energy crises

1 Introduction

Owing to rising energy demand, depleting fossil fuel supplies, and environmental concerns, energy crises have emerged as a serious worldwide issue. In this study, the severity of the global energy issue was examined and the need for sustainable energy solutions was emphasized [1, 2]. The existing energy landscape and the necessity for prompt action were illuminated by statistical data. The primary energy demand increased by 4.6% in 2021, driving an increase in global energy consumption fueled by emerging economies such as China and India [3]. Coal, oil, and natural gas continue to dominate the world's energy mix, accounting for approximately 80% of all energy used in 2020 [4]. Oil reserves could last 50 years and coal stockpiles several centuries, however, there are concerns about the finite nature of fossil fuel deposits [5]. Additionally, the burning of fossil fuels results in record-high greenhouse gas emissions, with the world's CO_2 output hitting 36.8 billion metric tons in 2019 [6, 7]. Now more than ever, there is a dire need to cut emissions and switch to low-carbon opportunities.

Renewable energy sources, such as biomass, solar, wind, hydropower, and geothermal energy, have emerged as competitive substitutes for fossil fuels [8, 9]. Governments, legislators, and international organizations are putting more effort into encouraging the development of renewable energy sources to combat climate change, lessen reliance on fossil fuels, and attain energy security [10]. The largest renewable source, hydropower, was used to generate 29% of the world's electricity in 2021, followed by wind and solar [11]. Investments in renewable energy technology have been rising as their potential has become more widely understood. Therefore, evaluating the contribution of biomass and other renewable energy sources in the search for a greener and more sustainable future relies critically on knowing the global energy environment [12].

Any organic material derived from plants, animals, or microorganisms is referred to as biomass [13]. It comes in a variety of forms, including organic waste, wood pellets, energy crops, and agricultural residues [14]. On the other hand, biomass energy is the energy produced when biomass is transformed into heat, electricity, or liquid fuels. The advantages of biomass over other renewable energy sources include its consistent energy supply, ability to use organic waste, and ease of integration into current infrastructure for a smooth transition to renewable energy [15, 16].

Various techniques and technologies for conversions are used in the generation of biomass energy. Biomass combustion, which involves burning organic resources to produce heat and power, is one popular technique [17]. Biogas is created during the breakdown of organic waste by anaerobic digestion. Pyrolysis or the Fischer–Tropsch method, can also be used to convert biomass into liquid fuel. The Fischer–Tropsch technique is a catalytic chemical process that produces liquid hydrocarbons like gasoline and diesel from syngas, which is a mixture of hydrogen and carbon monoxide. Although it does not directly involve pyrolysis, this is an alternative process for turning biomass into liquid fuels. 400–600 °C are typical high temperatures for this process, depending on the particular feedstock and desired output [18]. Biomass is heated through thermal gasification to produce syngas, which can be used for power generation, heating, or as feedstock for chemicals and biofuels. These innovations help to ensure a sustainable future by utilizing biomass energy. The processes of gasification, combustion, pyrolysis, enzymatic hydrolysis, and fermentation have been reviewed by Osman et al. [19] Low temperature (below 300 °C) and high-temperature (above 300 °C) thermochemical processes include gasification, combustion, and pyrolysis. Pyrolysis is one of the most promising and oldest used techniques because it can function at temperatures as low as 500 °C, which is considerably lower than the gasification temperature range of 800–1300 °C. Azeta et al. [20] also reported the pyrolysis of coconut biomass into sustainable energy.

The importance of biomass energy has increased owing to several reasons. First, biomass can be replaced by organic processes such as plant and tree growth, which is why it is regarded as a renewable energy source [21]. It differs from fossil fuels, which have a limited supply and cause environmental issues, such as climate change. Second, using biomass energy results in a net-zero carbon footprint because the CO_2 released during biomass combustion is balanced by the CO_2 absorbed during biomass growth [22, 23]. According to the International Renewable Energy Agency (IREA), doubling the proportion of renewable energy by 2030 would result in a 12% decrease in worldwide CO_2 emissions connected to energy. Biomass effectively minimizes greenhouse gas emissions [24]. Additionally, biomass energy uses organic waste to produce useful energy while reducing pollution and greenhouse gas emissions from landfills. A study by Liang-Nian [25] revealed that Soybean dregs were used to create Nitrogen-rich porous carbon materials with up to 4% nitrogen content and a variety of nitrogen forms. The materials' impressive CO_2 adsorption capabilities at 0 °C and 25 °C at air pressure were 6.3 and 3.6 mmol/g, respectively [26]. They also contain ultra micro pores and nitrogen-containing groups. According to Dinesha et al. [27], biomass that has been pyrolyzed or hydrothermally carbonized (HTC) into char has been shown to have excellent CO_2 adsorption capacity.

Additionally, biomass cultivation, harvest, processing, and distribution jobs are created by the production and use of biofuels, boosting rural economies [28]. Additionally, the rise of the biofuel industry attracts funding for research and development (R&D), technological developments, and infrastructure, which further stimulates economic growth [29]. Utilizing biofuels will help create a more diverse and sustainable energy sector, which will benefit local economies, jobs, and overall economic resilience [30, 31].

This review paper explores the various ways that biomass can be used to produce green energy, showing its promise as a clean, sustainable energy source. We seek to provide a thorough understanding of the role biomass plays in the shift to a greener energy environment by investigating diverse biomass conversion methods, such as combustion, anaerobic digestion, pyrolysis, and thermal gasification. The economic, environmental, and social advantages of using biomass are also covered in this review study, with a focus on how it helps with the creation of new job opportunities, waste management, energy security, and lower greenhouse gas emissions. By highlighting the various ways in which biomass is used in green energy, we seek to stimulate additional study, the creation of new regulations, and the use of biomass-based solutions to the top-priority problems faced by our energy system.

2 Biomass resources for green energy

There is enormous potential to produce clean, renewable energy from various biomass sources. We may lessen our reliance on fossil fuels and alleviate the environmental effects of conventional energy sources by utilizing the power of agricultural residues, energy crops, forestry waste, and organic municipal trash. In addition to being a feasible option, the use of biomass for green energy also opens up opportunities for effective waste management, rural development, and the transition to a greener and more sustainable future [32]. Here's a summary of the many biomass feedstocks, which include forestry waste, energy crops, agricultural residues, and organic municipal garbage.

2.1 Agricultural wastes

The byproducts and waste products produced during agricultural operations are commonly referred to as agricultural residues. Crop wastes such as corn stalks, wheat straws, rice husks, and sugarcane bagasse are among these products as shown in the Table 1. These leftovers from agricultural operations are plentiful and widely accessible. Agricultural waste products can be utilized as biomass feedstock for a variety of purposes, such as the manufacture of biofuels, bioenergy, and bioproducts [33]. Hafif et al. [34] reviewed the usage of rice husk and straw for sustainable and greener energy production. In another study by Alisaraei et al. [35], wheat straw is discussed as a source of biofuels.

2.2 Forestry trash

Forestry waste is made up of byproducts and remnants from logging and the maintenance of forests. This contains sawdust, bark, tree-tops, and branches. Environmental pollution is a result of frequent burning or abandonment of forestry debris which is shown in Fig. 1. However, it can be used as biomass feedstock for a variety of purposes, such as the production of heat and power, biofuels, and wood-based products. Borowski [36] and Navarre [37] reported the conversion of bamboo bark and birch bark for green energy and biofuel production. Ali et al. [38] agriculturalists all over the world produce a wide range of crop residues that can be treated and produced in different ways to turn them into biofuels. These methods include thermochemical conversion (combustion, pyrolysis, gasification, and hydrothermal liquefaction), biochemical conversion (microbial fermentation, enzymatic hydrolysis, and anaerobic digestion), and chemical treatment (transesterification, for example).

2.3 Organic municipal garbage

Organic municipal waste, also referred to as organic or green waste, is biodegradable waste produced by homes, eateries, and other organic waste-producing establishments. This comprises trash made of paper, yard waste, and food scraps. Organic municipal garbage can be handled by anaerobic digestion or composting to create biogas or nutrient-rich compost, rather than ending up in landfills where it will eventually add to greenhouse gas emissions [39, 40]. Anaerobic digestion, composting, and biomass combustion are a few examples of creative methods that can transform these materials into useful energy sources. Green trash and yard waste can be composted to create nutrient-rich soil amendments, while food waste and biosolids can be anaerobically digested to produce biogas, a sustainable energy source high in methane. Paper, wood refuse, and agricultural wastes can all be used as fuel

Table 1 Utilizing agricultural waste as biomass resources to produce renewable energy

Agriculture waste	Description	Potential uses in green energy production
Crop residues	Staying husks, leaves, and stalks following harvest	Biogas generation with biomass boilers
Bagasse	Fibrous residue that remains after processing sugarcane	Cogeneration and biomass boilers in sugar mills
Rice husk	During milling, the outer layer of the rice grains detached	Gasification and biomass boilers for electricity
Corn stover	Leftover cobs, stalks, and leaves following corn harvest	Fuel cells and ethanol manufacturing

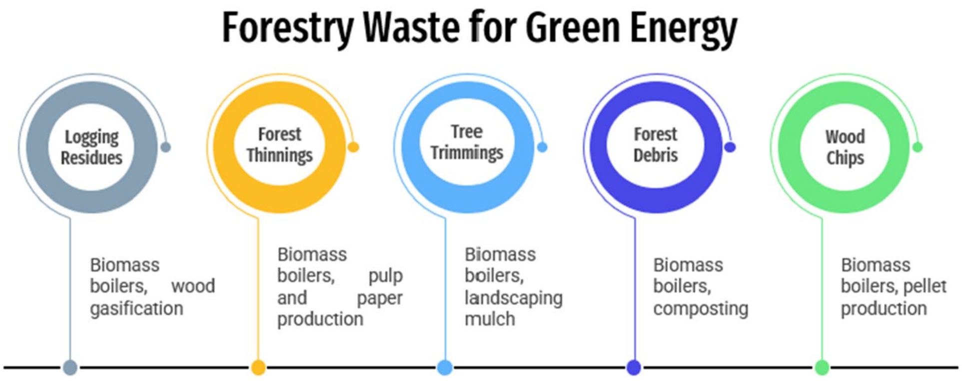


Fig. 1 Forestry waste for sustainable energy

in biomass boilers to produce heat and power. Communities may contribute to a cleaner, more sustainable energy future while simultaneously reducing landfill waste by utilizing the energy potential of organic municipal trash.

2.4 Energy crops

These plants are grown expressly for their ability to produce biomass. These plants have a high energy content and can be utilized to produce power or as a renewable source of fuel. Trees like poplar, willow, and miscanthus are examples of energy crops. These plants can be gathered and processed for biomass energy applications, and are grown in marginal soils that are unsuitable for food crops [41]. Stanton [42] reported on the usage and economic impact of hybrid poplar biomass production for biofuels and bioproducts in the Pacific Northwest. Similarly, Paul et al. [43] showed that rubber trees can also be used as a source of green energy. A graphical representation of all the possible sources of biomass is given below in Fig. 2,

It's essential to remember that the selection of biomass feedstock is influenced by a variety of variables, including regional availability, logistical concerns, and the particular requirements of the intended use. These biomass feedstocks can be transformed into useful forms like biofuels, heat, electricity, and bioproducts using a variety of technologies and methods, which further contribute to a more ecologically friendly and sustainable energy industry [46–48].

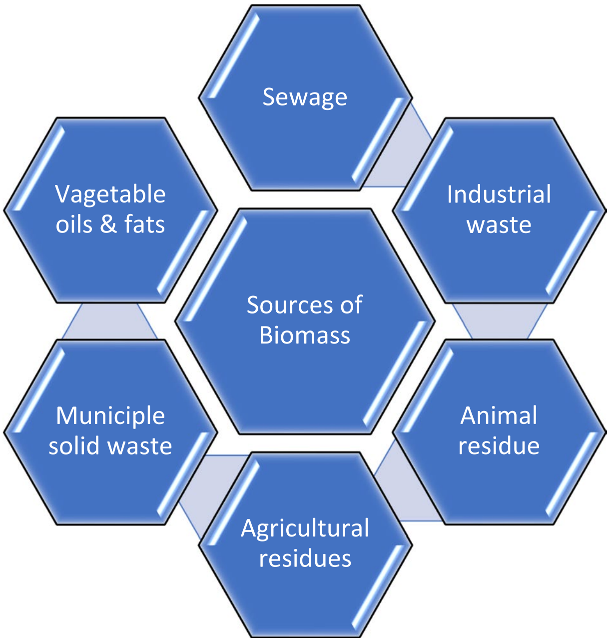
2.5 Solid waste

Solid waste is an important biomass resource for the production of energy. It includes municipal solid waste (MSW), agricultural residues, and forestry residues. Solid waste can be transformed into sustainable energy sources by procedures like gasification, combustion, and anaerobic digestion. Organic waste is broken down via anaerobic digestion, producing biogas—mainly carbon dioxide and methane—that can be used to heat buildings or generate energy. Combustion plants produce heat by burning solid waste, which is then utilized to produce steam or direct electricity. Solid waste can be directly used for heat and power or converted into liquid fuels through the process of gasification, which turns it into syngas [49, 50].

3 Biomass conversion technologies

Technologies for converting biomass resources into useful forms of energy, fuels, and chemicals include a variety of procedures. These technologies are essential for using biomass as a long-term replacement for fossil fuels, lowering greenhouse gas emissions, and facilitating the path to a more ecologically friendly energy source and are shown in the Fig. 3.

Fig. 2 Sources of biomass [44, 45]



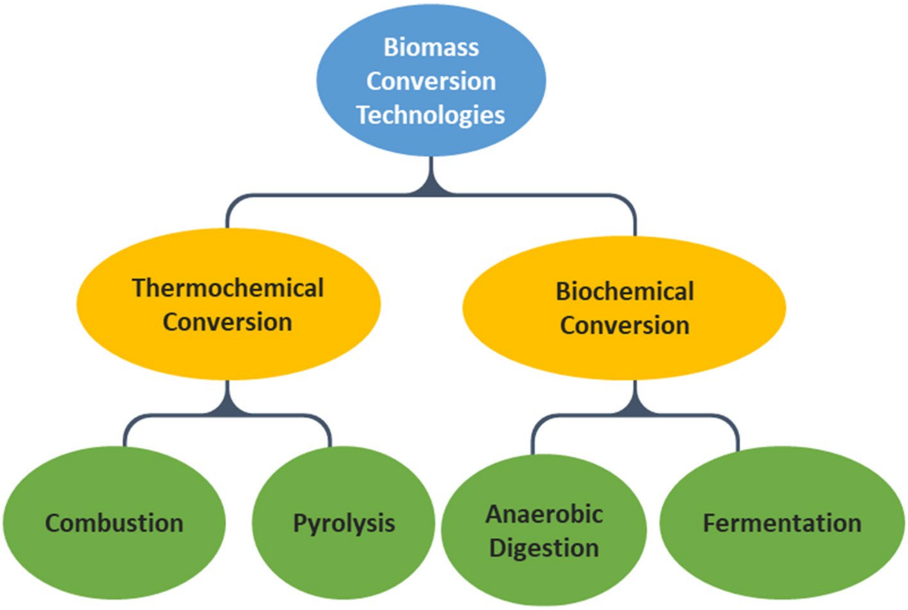


Fig. 3 Conversion technologies for biomass

3.1 Combustion

There are benefits and drawbacks to using combustion as a strategy to turn biomass into biofuels. Direct combustion is one of the main methods for burning biomass; in this method, the biomass is burned to produce heat, which is then utilized to create power or heat industrial operations [51, 52]. This approach has the benefit of being reasonably mature and straightforward because it can make use of infrastructure already in place for fossil fuel combustion [53]. In addition, using biomass to produce energy can be economical. But when biomass is burned directly, greenhouse gases like carbon dioxide and nitrogen oxides are released into the atmosphere, causing air pollution and climate change [54]. Furthermore, the efficiency of biomass combustion is typically lower than that of other bioenergy conversion processes [55, 56]. A study by Marangwanda et al. [57] presented that particle drying, devolatilization, heterogeneous combustion, and homogeneous combustion are all combustion models. Particle tracking, heat transfer, and turbulence simulations are examined as supporting models. The goals of recent developments in biomass combustion technology have been to increase fuel flexibility, lower emissions, and improve efficiency. Accurate regulation of combustion parameters is made possible by enhanced automation and control technologies, which raise energy conversion efficiency and reduce pollution emissions. More biomass feedstocks, including as agricultural wastes and municipal solid waste, may be used thanks to innovative combustion procedures like gasification and fluidized bed combustion. Integrating with combined heat and power (CHP) facilities optimizes energy use and fosters sustainability in the generation of green energy.

3.2 Pyrolysis

By thermally degrading biomass in the absence of oxygen, pyrolysis is a promising method for converting biomass to bioenergy. Fast pyrolysis, which quickly raises biomass temperatures, has benefits including a larger output of bio-oil and a priceless feedstock for fuels and chemicals [58]. The volatility of bio-oil and the high-energy requirements of the process are obstacles as well [59, 60]. The process of converting biomass into bioenergy and biofuels is depicted in the Fig. 4, which also includes a detailed description of the pyrolysis procedure.

Slow pyrolysis, which results in a higher proportion of biochar and has benefits including increased stability and lower energy needs, creates heat at a slower rate [61]. However, slow pyrolysis produces a reduced output of bio-oil, which restricts its ability to produce liquid fuels [62]. Amrullah et al. [63] proposed in his work that In a batch-style reactor, U. lactuca underwent gradual pyrolysis at 400–600 °C for 10–50 min. The analysis revealed large amounts of amines/amides (15.33–23.31%), phenolics (9.73–31.89%), carboxylic acids (22.63–35.28%), and N-aromatic compounds (14.04–15.68%) in the bio-oil. The final study showed that the atomic ratios of carbon and oxygen in the biochar were lower than those in the feedstock, indicating that dehydration and decarboxylation events occurred during pyrolysis. Although both strategies offer potential, more work must be done to increase their effectiveness and overcome their drawbacks [64–66].

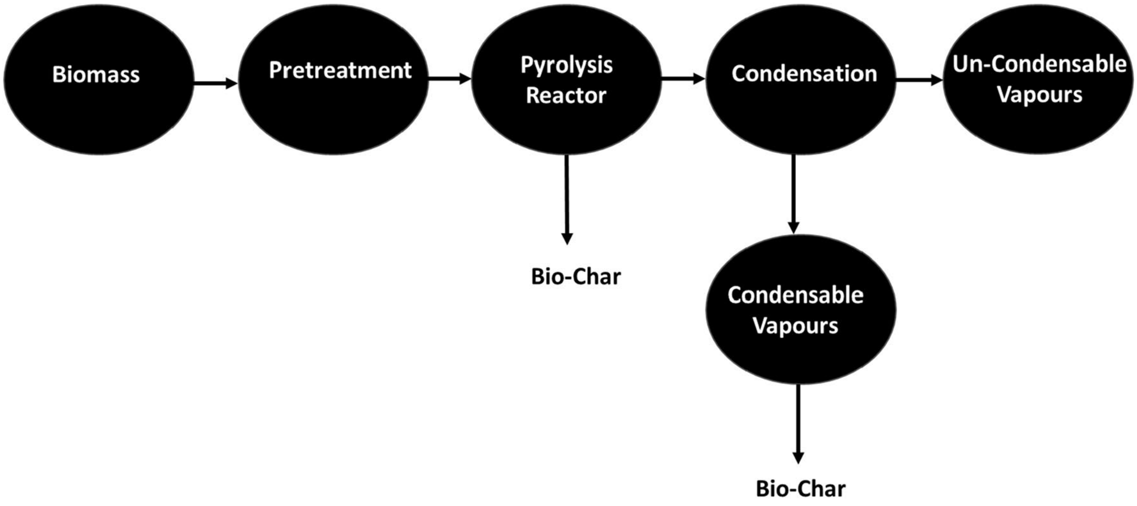


Fig. 4 Schematic diagram of pyrolysis process

Catalytic pyrolysis improves biomass conversion by using catalysts to transform biomass into useful products. It has benefits like enhanced selectivity, enabling management of product attributes and composition. Higher-value chemicals and fuels may be produced as a result [67]. Additionally, catalytic pyrolysis can reduce energy requirements and operating temperatures, thereby increasing the total energy efficiency [68, 69]. However, the complexity of catalyst design and selection, expense, deterioration of the catalyst, and potential deactivation by contaminants in the biomass feedstock are obstacles. Current research focuses on creating reliable and affordable catalysts and improving the circumstances of the reaction in catalytic pyrolysis [70–72]. Wang et al. [73] reported the catalytic pyrolysis of biomass with Ni/Fe-CaO-based catalysts for hydrogen gas production and found that the most favorable reaction conditions for the generation of H_2 are 650°C in the presence of Ni–Fe/CaO, according to thermodynamic simulation and pyrolysis tests.

Recent advancements in biomass pyrolysis have completely changed the industry and provided effective means of using biomass for resource recovery and energy production. Key developments in biomass pyrolysis technology are shown below in Fig. 5.

3.3 Gasification

To create versatile synthesis gas, which is made up of carbon monoxide, hydrogen, and trace gases, gasification uses partial oxidation of biomass [74]. Gasifiers with fluidized beds, updrafts, and downdrafts are among the methods. It has the advantages of efficient energy utilization and the capacity to produce power, industrial feedstock, and biofuels. Whereas other factors are also involved in viable energy systems as shown in Fig. 6. However, difficulties include the need for high-quality feedstock, high installation, and operating capital costs, and the difficulty of cleaning and conditioning syngas for effective use [75–77].

The ultimate success of gasification as a bioenergy conversion method depends on overcoming these technological and financial obstacles [78]. Using Aspen Plus software, Martins et al. [79] investigated three different biomass gasification methods (conventional, plasma, and supercritical water). By modifying the steam-to-biomass ratio, gasifier temperature, pressure, and biomass moisture, they were able to maximize hydrogen generation. The hydrogen output increased with higher SBR and lower feed concentration, while supercritical water gasification demonstrated a considerable increase in the hydrogen molar percentage at 400–600 °C. The pressure adjustments had no effect, and more hydrogen was produced when the moisture content of the biomass was higher.

3.4 Anaerobic digestion

In the process of converting biomass, anaerobic digestion uses microorganisms that break down organic material in the absence of oxygen to create biogas that is largely made up of methane and carbon dioxide [80, 81]. Anaerobic digesters have a variety of shapes and sizes, such as continuously stirred tank reactors, plug flow digesters, and anaerobic lagoons [82]. The ability to handle organic waste and wastewater while simultaneously producing renewable biogas for energy is

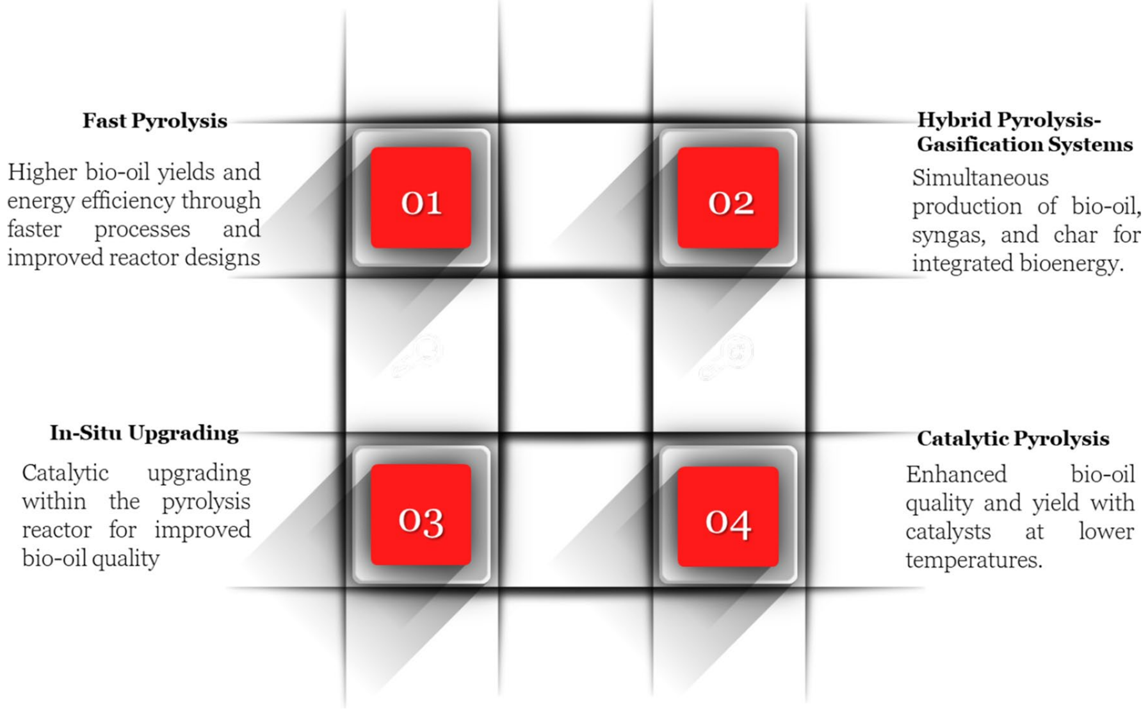


Fig. 5 Key developments in biomass pyrolysis technology

Fig. 6 Numerous factors that influence economically viable biomass-based energy systems

one of the many benefits of anaerobic digestion. Digestate, a byproduct of this process that is rich in nutrients and can be utilized as a natural fertilizer, is also produced. However, anaerobic digestion systems can be sensitive to changes in feedstock composition, necessitating careful management and monitoring [83]. The method's slowness in comparison to other bioenergy conversion techniques restricts the types of biomasses that may be used and makes greater reactor volumes necessary for commercial-scale operations. The need for investment in digesters and biogas upgrading might be a barrier to wider adoption, and the economics of anaerobic digestion significantly depends on the availability of

Table 2 Calorific values of multiple fuels [86, 88]

Source of fuels	Calorific value (approx.)	Equivalent to 1m^3 biogas (approx. 6kWh/m^3)
Diesel	12KWh/Kg	0.50kg
Cow dung	5KWh/Kg	1.20kg
Plant residues	4.5KWh/Kg	1.30kg
Wood	4.5KWh/Kg	1.30kg
Food crops	3.5 KWh/Kg	1.70 kg
Grassy biomass	3.0 KWh/Kg	2.00 kg
Oil-rich algae	22 KWh/Kg	0.27 kg
Organic waste	4 KWh/Kg	1.50 kg

adequate feedstock [84, 85]. Yogeli et al. [86] reported the anaerobic digestion of some of the biomass sources and found that a handsome amount of calorific values can be obtained via these fuels given in Table 2 [86, 87].

Technological developments in anaerobic digestion increase process stability and biogas output through enhanced reactor designs and co-digestion procedures. While composting and nitrogen recovery from digestate maximize value and improve sustainability, advanced monitoring systems optimize conditions. Its potential for sustainable energy generation and waste management is highlighted by examples such as its application in wastewater treatment plants and on-farm digesters [87].

4 Bioenergy from biomass

A viable route toward developing a more sustainable energy system is the conversion of biomass to heat and power. This renewable energy strategy offers various important benefits by utilizing the organic resources obtained from plants, animals, and waste goods [89]. Through sustainable techniques, biomass may be constantly renewed, lowering greenhouse gas emissions and mitigating climate change [90]. Direct combustion or gasification methods are used to convert biomass into heat, producing thermal energy for district heating and industrial use [91]. Burning biomass produces steam, which powers turbines attached to electricity generators to produce electricity. Some systems' inclusion of waste heat recovery improves total energy efficiency even more [92]. According to Islam Fattah [93], under 40% operational efficiency, palm oil biomass can provide about 5000 MW of power. Malaysia's yearly dependency on coal may have been replaced by this substantial electricity potential.

One of the best-case studies for the production of biomass-based heat and electricity is the Danish Skaerbkvrket Power Plant. It functions as a biomass-based CHP plant and burns primarily wood pellets, wood chips, and agricultural waste [94]. The facility, which has a capacity of approximately 390 MW for electricity generation and approximately 810 MJ/s for heat generation, is vital for sustainably supplying Denmark's energy demands [95, 96]. Fluidized-bed boiler technology, which generates steam to power turbines for electricity generation and district heating, is essential for its operational efficiency. This facility serves as an example of the environmental advantages and carbon savings possible through biomass utilization by utilizing 1.2 million tons of biomass annually and reducing over 1.1 million tons of CO_2 emissions [97, 98].

Additionally, by utilizing organic materials and waste products to produce electricity and heat, biomass power plants play a vital part in the shift to renewable energy sources. The ability of biomass power plants to reduce greenhouse gas emissions is one of their main benefits. The carbon dioxide generated when organic materials are burned or converted into biogas is balanced by the carbon taken in during the growth of the biomass feedstock, making it a carbon–neutral energy source. Therefore, biomass power plants are a desirable choice to minimize carbon emissions and combat climate change [99–103].

Humbert [104] and Lee [105] reported the statistical data on the Drax power station in the UK which is the finest example of a biomass power plant. One of the largest biomass power stations in the world, Drax, was formerly a coal-fired plant. Its main fuel source is wood pellets obtained from sustainably managed forests in the US and Canada. A big step forward for green energy, the renovation of Drax, has resulted in a significant drop in greenhouse gas emissions. The data show that as of 2020, Drax's biomass operations have reduced carbon emissions by 86% when compared to

Table 3 Biomass Potential for energy production in Malaysia [106]

Biomass type	Amount (k ton/year)	Annual production potential (GWh)	Maximum energy potential (MW)
Fruit fibers	12,200	28,000	3,150
Palm shell	4,900	28,000	3,150
Wood chips	2,200	600	70
Rice husks	400	300	30

their prior coal-fired state, significantly advancing the UK's renewable energy targets. Shamsuddin [106] in his study, revealed the Malaysian strategies to capture carbon dioxide in the power plants which is shown below in the Table 3.

Energy-efficient technologies called Combined Heat and Power (CHP) systems concurrently produce heat and electricity from a single fuel source, providing the opportunity for optimal energy use by capturing waste heat for heating applications [107]. CHP systems have become a desirable choice for sustainable energy generation, waste reduction, and greenhouse gas emission reduction when biomass is integrated as the primary fuel source [108, 109]. The Växjö Biomass Gasification CHP plant in Sweden, which uses wood chips and forest leftovers to generate electricity and district heating through gasification, is an example of successful integration [110, 111]. Biomass CHP-powered district heating systems provide lower emissions and higher energy efficiencies. Denmark's decentralized biomass CHP systems serve as an example of how to effectively employ local biomass as feedstock while fostering local participation in sustainable energy practices and energy independence. Critical analyses are required to ensure effective biomass utilization and to optimize contributions to a greener and more sustainable energy sector [112–114].

The desire for sustainable and renewable energy sources has fueled major developments in biomass-to-bioenergy conversion technologies in recent years. The main developments in biomass-to-bioenergy technology are compiled in Table 4 [115].

5 Biofuels from biomass

Biofuels are renewable substitutes for fossil fuels made from biomass feedstocks, such as bioethanol and biodiesel. Biodiesel is created through the transesterification of vegetable or animal fats, and bioethanol is created through the fermentation of sugar, starch, or cellulose-rich feedstocks [116, 117].

Karimi et al. [118] gave a statistical overview of the production of bioethanol in the US, where corn is a common feedstock, and bioethanol production is demonstrated largely. The United States, one of the world's major producers of bioethanol, receives most of its renewable fuel from corn ethanol. Shaik et al. [119] reported that over 13.9 billion gallons of bioethanol were produced in the U.S. as of 2020, largely from corn. Replacing over 46% of the carbon dioxide emissions from gasoline in each gallon of corn-based ethanol considerably reduces greenhouse gas emissions [120]. A possible threat to food supplies and their effects on food prices has been raised by the use of food crops for biofuel production, such as maize [121].

Similarly, the manufacturing of biodiesel has become increasingly popular worldwide, especially when using feedstocks, such as soybean oil, rapeseed oil, and palm oil [122]. Kareem et al. [123] investigated canola oil for the production of biodiesel at a large scale. Safaripour [124] in one study, reported the potential of jojoba oil for biodiesel production. The European Union is one instance in which biodiesel production has increased significantly. The EU generated 12.2 million metric tons of biodiesel in 2020, mostly from vegetable oils. With a much smaller carbon footprint than regular diesel, biodiesel is a greener substitute. However, due to concerns about deforestation and biodiversity loss in areas where palm oil plantations are expanding, the use of palm oil as feedstock has been controversial.

Other biofuels, such as jet fuels and biogas, are being developed and commercialized, in addition to bioethanol and biodiesel. Bio-jet fuels made from biomass feedstock are being investigated to reduce the carbon footprint of the aviation industry. Anaerobic digestion of organic waste results in the creation of biogas, which predominantly consists of methane and can be utilized for transportation, heating, and energy generation. With a market share of over 20% for biogas by 2020, nations such as Sweden have made major progress in utilizing it in their transportation sector. Table 5 shows the applications of various types of biomass for biofuel generation.

Table 4 Developments in biomass-to-bioenergy technology

Technology	Description	Advantages
Advanced gasification	Uses high-temperature biomass conversion to produce synthesis gas, or syngas	Increased adaptability and efficiency; capacity to use a variety of feedstock kinds
Hydrothermal liquefaction	Produces bio-oil from biomass under circumstances of high pressure and temperature	Higher bio-oil yield compared to traditional pyrolysis; Potential for wet biomass utilization
Anaerobic digestion	Biochemical process that produces biogas (a mixture of carbon dioxide and methane) from organic materials	Economical and effective; appropriate for managing organic waste

Significant progress has been made in feedstock utilization and conversion processes in the field of biomass-to-biofuel technology as a result of continuous research and development activities. Recent developments in biomass-to-biofuel technologies are summarized in Table 6 [133].

6 Environmental and economic considerations

Compared with conventional fossil fuels, biomass energy can minimize greenhouse gas emissions, which is an important feature. Carbon dioxide (CO_2) is released into the atmosphere when biomass is burned; however, the carbon released is a component of the natural carbon cycle. This implies that the carbon absorbed by plants during growth balances the carbon released during combustion. This procedure can be regarded as carbon neutral because it does not result in a net rise in atmospheric CO_2 levels, provided that the biomass is obtained from sustainable sources. However, owing to concerns about deforestation, changes in land use, and unsustainable harvesting methods, the carbon neutrality of biomass energy is in question. Maintaining carbon neutrality requires sustainable sourcing and a balance between consumption and regeneration [134–138].

Although biomass energy lowers greenhouse gas emissions, it has environmental drawbacks. Particulate matter, nitrogen oxides, volatile organic compounds, and carbon monoxide are only a few pollutants released during combustion that affect air quality and human health [139]. Strict emission regulations, modern air pollution management technology such as electrostatic precipitators and scrubbers, and enhanced conversion technologies are some mitigation techniques [140]. Regular compliance checks and monitoring are essential to ensure that biomass power facilities follow all applicable environmental laws [141, 142].

Cost, cost structure, technological development, and government incentives all affect the economic viability of biomass energy [140]. In areas with abundant resources, it can be competitive, eliminating dependency on imported fossil fuels and giving money to biomass producers. However, the initial setup costs and infrastructure required for biomass collection and transportation can be significant, and the cost-effectiveness of biomass is affected by changes in the prices of other energy sources [143]. The cost of producing biomass energy is anticipated to decrease as technology advances, thereby increasing its long-term economic appeal [144]. In order to comprehend the economic dynamics of producing energy from biomass, a number of elements must be examined. The following figure highlights the essential components that determine the systems' economic viability and feasibility.

Furthermore, supportive laws and policies are essential to encourage the adoption of biomass energy and sustainable development. Governments can encourage biomass production and investment by providing financial aid, tax breaks, subsidies, feed-in tariffs, and renewable energy targets. Strong environmental laws are necessary to examine and reduce the effects of biomass energy generation. These rules should concentrate on sustainable sourcing, emission reduction, and land-use strategies that prevent deforestation and safeguard biodiversity. International collaboration and agreements make it easier for best practices to be shared, thus ensuring the ethical use of biomass energy worldwide. Policymakers should encourage the growth of biomass energy while positively impacting the energy mix and efforts to mitigate climate change by integrating environmental considerations and economic incentives.

Table 5 Biofuel production from various feedstock

Generation of biofuels	Feedstocks	Examples	References
1st generation	Starch, sugar, vegetable oils	Biodiesel, biogas, bio-alcohols	[125]
1st Generation	Waste cooking oil	Biodiesel	[126]
2nd Generation	Wheat straw, energy crops, wood, lignocellulose	Biodiesel, biohydrogen	[127]
1st Generation	Molasses, palm oil, cotton oil	Ethanol, biodiesel	[128]
1st generation	Sunflower, manure, food waste	Biodiesel, biogas	[129, 130]
1st generation	Sweet potato, rice	Biodiesel, ethanol	[131]
3rd Generation	Sea weeds, algae	Bioethanol, biodiesel	[132]

Table 6 Recent developments in biomass-to-biofuel technologies

Technology	Description	Advantages
Hydrothermal processing	Produces liquid hydrocarbon fuels from biomass in subcritical water conditions	High conversion efficiency; Minimal energy and processing time usage
Enzymatic hydrolysis	Uses enzymes to convert biomass into sugars that may be fermented to produce biofuel	Specificity and effectiveness of the release of sugar; suitability for a variety of feedstocks
Catalytic upgrading	Uses catalysts to transform biogas or biooil into higher-quality biofuels	Improved fuel qualities; decreased instability and contaminants

7 Future prospects and research direction

Biomass has great potential to help generate renewable energy and reduce greenhouse gas emissions. However, to fully realize their potential, several issues must be resolved. The struggle for biomass resources between energy generation and other applications, such as agriculture and forestry, is a major hurdle. To prevent possible disputes, ensure food security, and maintain ecosystem health, it is essential to sustain the source and distribute biomass feedstocks. To address this difficulty, future initiatives should promote integrated biomass usage strategies that use agriculture and forestry leftovers for both energy production and soil enrichment. Additionally, it is crucial to invest in research to find and create abundant non-food lignocellulosic biomass sources that do not directly compete with food production.

Another crucial challenge is to boost the efficiency of biomass conversion procedures. There is still an opportunity for improvement in terms of energy generation, waste reduction, and process stability, even though technologies such as anaerobic digestion and pyrolysis have shown promise. To increase the overall effectiveness of biomass-to-energy conversion, more research is required to optimize the operating conditions, catalysts, and reactor design. Additionally, there are technological and logistical problems associated with integrating these processes into the current energy infrastructure, which necessitate careful planning and investment. Realizing the full potential of biomass applications for green energy requires the development of scalable and financially effective waste-to-energy systems.

8 Conclusion

This comprehensive review analyzes the use of biomass energy as a sustainable energy source and its possible utilities for the future. When harvested sustainably, biomass has enormous potential as a renewable energy source to lower greenhouse gas emissions. It is a workable option for lowering carbon footprints because of its adaptability to a range of industries, from power generation to transportation. Biomass is crucial for addressing climate change because it can be made carbon–neutral through sustainable land management. Enhancing the economic viability and competitiveness of biomass worldwide requires ongoing research, legislative support, and international cooperation. While there are still obstacles to overcome, biomass can be a key in creating a cleaner and more sustainable energy environment, along with other renewables. To realize its full potential and to open the door to a brighter, more eco-friendly future, coordinated efforts are required. To maximize the potential of biomass as a renewable energy source, it is essential to understand how these three factors interact. To maximize energy production while minimizing environmental problems, this review examines obstacles, ongoing research, and recent developments in effective biomass-based energy systems.

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Data availability Data will be made available on request.

Declarations

Competing interests The authors declare no competing interests.

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