

A Review of Biomass Energy: Comparison of Utilization Methods and Future Prospects

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Abstract. Biomass refers to the biodegradable portion of products and residues from agriculture, forestry, and related industries, including municipal and industrial waste. It encompasses molecular and macromolecular compounds derived from plants and other organic sources. Biomass energy, considered sustainable and eco-friendly, can reduce greenhouse gas emissions and enhance energy security, contributing significantly to net-zero emission goals. Various methods for biomass utilization include thermochemical and biochemical conversions, as well as co-production. Thermochemical conversion methods like pyrolysis, gasification, and torrefaction transform biomass into fuels and chemicals, offering solutions for waste management and renewable energy. Biochemical methods, such as anaerobic digestion and fermentation, use biological processes to produce biogas and biofuels. Co-production, combining biomass with other energy sources (e.g., geothermal or coal), optimizes resource use and increases energy efficiency. While challenges remain, such as cost and technical barriers, biomass energy provides an effective, carbon-neutral path for reducing fossil fuel dependence. The paper highlights biomass energy's diverse technologies and its importance in the sustainable development and future energy landscape.

1 Introduction

Biomass is defined as the biodegradable portion of products and agricultural residues (including plant and livestock waste), forestry and related industries (including fisheries and aquaculture) residues, as well as other wastes such as industrial and municipal waste. Biomass includes all molecular and macromolecular compounds derived from vegetables, agricultural products, forestry products, and any remaining materials. Biomass energy is a sustainable and eco-friendly energy source that has garnered widespread attention [1]. It offers a promising solution to address environmental issues and the urgent need for a transition to green energy, as it can reduce greenhouse gas emissions while supporting national energy security. Integrating biomass energy with the pursuit of net-zero emission goals appears to be a symbiotic strategy with substantial potential to mitigate global climate issues [2]. Utilizing biomass energy is an effective means of reducing greenhouse gas emissions due to its renewable and carbon-neutral characteristics [3]. This is because biomass sources are carbon-neutral; the carbon dioxide emitted during energy production is offset by

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the carbon absorbed during the biomass growth cycle. As nations embark on the challenging journey toward net-zero emissions, leveraging the substantial potential of biomass energy seems to be a well-considered approach [3].

The types of biomass energy supply globally can be categorized into five major groups: solid biomass, liquid biofuels, municipal waste, industrial waste, and biogas, as shown in fig.1. In 2020, the global supply of biomass energy reached 57.5 exajoules (EJ). Of this, 86% came from solid biomass sources, including wood chips, wood pellets, and traditional biomass sources. Liquid biofuels accounted for 7%, municipal and industrial waste represented 2% to 3%, and biogas contributed 2%.

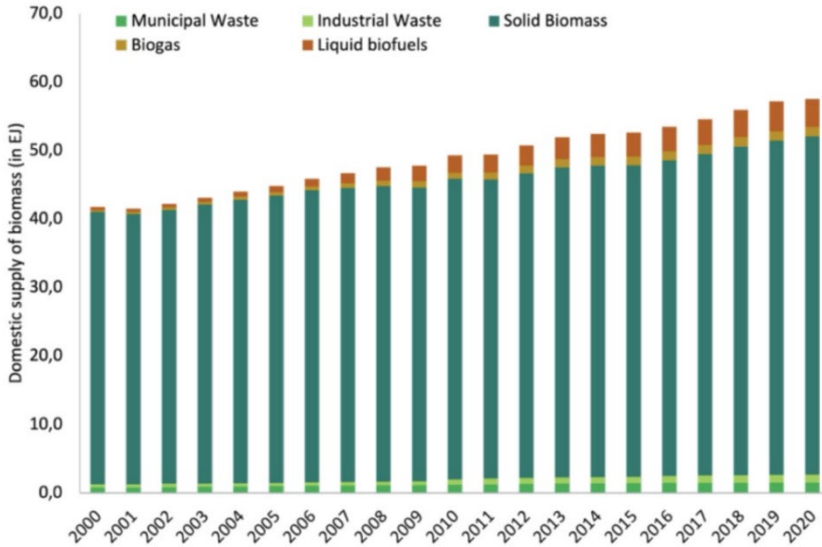


Fig. 1. Biomass Supply in 2020 [4].

There are currently several methods for utilizing biomass energy, including thermochemical conversion, biochemical conversion, biomass liquefaction, and co-production. Thermochemical conversion refers to the use of biomass through thermochemical processes, including pyrolysis, gasification, and torrefaction. Biochemical conversion involves the transformation of biomass through biological processes, including anaerobic digestion, fermentation, and enzymatic hydrolysis. Biomass liquefaction technology converts biomass into liquid fuels, including methods such as hydro-liquefaction and biodiesel production. Co-production combines biomass energy with other forms of energy, such as solar or geothermal, to enhance energy production. This article aims to introduce various biomass energy utilization methods and their environmental benefits.

2 Thermochemical Conversion Technology

Thermochemical conversion technology involves transforming biomass or other solid fuels into usable energy or chemicals through high-temperature heating. This technology efficiently utilizes waste or biomass resources, reduces environmental pollution, and provides sustainable energy.

2.1 Pyrolysis

Pyrolysis is the decomposition of biomass through heating in the absence of oxygen, producing charcoal, liquid, and gaseous fuels. The pyrolysis process can be classified into three types: conventional pyrolysis, fast pyrolysis, and flash pyrolysis. These categories are determined by variables such as temperature, heating rate, and vapor residence time [5]. Hemicellulose decomposes first at temperatures between 470 and 530 K, followed by cellulose in the range of 510 to 620 K, with lignin as the final component to undergo pyrolysis between 550 and 770 K. A process with low temperatures, high heating rates, and short gas residence times favors liquid fuel production. To increase charcoal yield, a process with low temperature and low heating rate is preferred. For maximizing gaseous fuel production, high temperature, low heating rate, and extended gas residence time should be considered.

Pyrolysis is commonly used for converting agricultural and forestry biomass, serving as a practical method to address both renewable energy security and waste management. Several agricultural and forestry residues, such as camelina meal, mustard meal, flax straw, hemp straw, and spruce wood, can be processed through pyrolysis [6].

2.2 Gasification

Gasification converts biomass into syngas (primarily composed of CO and H₂) under high temperatures and partial oxidation conditions. Syngas can be further used for power generation, hydrogen production, or the synthesis of liquid fuels. Gasification has the highest energy conversion efficiency, as it transforms biomass into fuel gas (known as syngas) through a series of chemical reactions. Syngas is a gas mixture composed of CO, CH₄, and H₂. The syngas generated from the gasification process can serve as a future alternative to fossil fuels. Using syngas produced by biomass gasification as a dual fuel in diesel power plants can reduce biodiesel consumption by 60% [7]. When using syngas with a calorific value of 4 MJ/kg produced from municipal solid waste (MSW) gasification as a dual-fuel material, diesel consumption can be reduced by 44% [8]. However, syngas is currently not widely used as a fuel for generators due to power loss issues. According to Molino et al. [9], the production of syngas depends on biomass type, gasification reactor, and operating parameters used during gasification, such as gasifying agent and temperature (T). To produce high-quality syngas, the gasification process requires $T > 750\text{ }^{\circ}\text{C}$ [9]. Air and O₂ are commonly used as gasifying agents, with air being the most widely used due to its accessibility and ease of use.

2.3 Torrefaction

Torrefaction, also known as biomass roasting, is referred to industrially as roasting, slow and mild pyrolysis, wood cooking, or high-temperature drying. This process involves low-temperature heating to remove moisture and volatile components from biomass, increasing its energy density and improving combustion performance. Torrefied biomass resembles low-rank coal and is suitable for power generation and heating. Torrefaction is often applied to the treatment of lignocellulosic biomass. The basic principle of this treatment method is the preferential and selective degradation of extractable compounds and polysaccharides (constituting the low-calorific-value portion) within the biomass [10]. The less thermally stable components of lignocellulosic biomass degrade first as the material is gradually heated. Compared with cellulose and lignin, hemicellulose in biomass is an organic compound with low calorific value and a high O/C atomic ratio [10]. Selectively removing hemicellulose increases the proportion of carbon-rich compounds and compounds with higher energy density in torrefied biomass, thereby reducing their reactivity and water absorption capacity

while enhancing thermal stability. Common biomass sources for torrefaction include maritime pine, chestnut, oak, eucalyptus, Caribbean pine, birch, pine, bagasse, bamboo, wood blocks, willow, beech, sessile oak, meranti, and oil palm waste.

3 Biochemical Conversion Technology

Biochemical conversion technology refers to the process of converting biomass or organic waste into useful products through biochemical reactions. This process relies on microorganisms, enzymes, or other biocatalysts to decompose organic matter, producing energy or other chemicals.

3.1 Anaerobic Digestion

Anaerobic digestion uses microorganisms to decompose organic matter under anaerobic conditions, producing biogas (primarily composed of CH₄, CO₂, hydrogen sulfide (H₂S), water vapor, etc.) and bio-fertilizer, which is rich in nitrogen, phosphorus, potassium, and trace nutrients that plants derive from fundamental resources such as soil and water. Biogas can be used for power generation, heating, or as a substitute for natural gas [11]. One of the advantages of biogas is its flexibility in applications, which range from heat and electricity production to vehicle fuel, provided it undergoes upgrading (removal of CO₂) or purification (removal of H₂S) [12]. Anaerobic digestion is considered one of the most sustainable and eco-friendly processes and plays a vital role in renewable energy production. The anaerobic nitrification process involves a series of four biochemical reaction stages: hydrolysis, acidogenesis, acetogenesis, and methanogenesis [13]. Process performance is highly dependent on operational strategies and process parameters, such as reactor type, inoculum and substrate used, hydraulic retention time, feed rate, and operating temperature. Additionally, parameters such as pH, alkalinity, and volatile fatty acid concentration determine microbial metabolism. Recent advancements in anaerobic digestion have opened up new possibilities for energy independence in urban, rural, and remote areas. Recent studies have highlighted the potential of anaerobic nitrification to reduce greenhouse gas emissions at national or regional levels [14].

3.2 Fermentation

Fermentation is a process that uses microbial fermentation of biomass to produce clean fuels, such as biohydrogen. This section focuses on bio-based hydrogen production, one of the currently practical clean fuels. Bio-based hydrogen can be produced through two main methods: dark fermentation and photofermentation. Dark fermentation has garnered considerable attention due to its high yield, short reaction time, and ability to use various organic waste materials as feedstock. In dark fermentation, anaerobic bacteria (e.g., Enterobacteriaceae, Clostridium, and Bacillus species) utilize organic waste and water to produce hydrogen. The amount of biohydrogen produced depends on the type of microorganism and is influenced by low substrate decomposition rates and the consumption of substrates by methanogens and acetogens [15]. Pure cultures in dark fermentation yield higher hydrogen output, but mixed cultures offer broader substrate options and easier process control [16]. Most hydrogen production processes are based on pure sugars (e.g., glucose, xylose, sucrose), making the process costly [17].

Another major challenge in the fermentation process is the recalcitrance of biomass due to its complex structure and lignin content, which hinders enzyme access to hydrolysable sugars. Biomass requires pretreatment prior to fermentation. Pretreatment methods are classified into

two categories: conventional methods (e.g., acid, alkali) and advanced methods (e.g., ionic liquids, supercritical fluids). The yield of biohydrogen and other by-products (such as acetate, butyrate, lactate, ethanol, and CH₄) from lignocellulosic biomass in dark fermentation depends on the type of microorganisms used and the operational conditions [18].

4 Co-Production (Polygeneration)

Biomass co-production is a method that uses biomass resources to simultaneously produce multiple products and forms of energy. By generating fuels, electricity, chemicals, and other products in a single process, it enhances resource utilization and economic efficiency. Key characteristics of biomass co-production include efficient resource use to maximize biomass utilization and minimize waste, improved economic benefits through diversified revenue streams, and environmental friendliness by reducing dependence on fossil fuels and lowering pollutant emissions. Common co-production models include biorefining (converting biomass into fuels and chemicals), combined heat and power (CHP) (simultaneously generating electricity and heat), and waste-to-energy (converting organic waste into energy and fertilizers). Despite challenges such as technical complexity, high costs, and supply chain management difficulties, biomass co-production contributes to sustainable development and is expected to play a larger role in energy and environmental sectors as technology advances and policy support increases.

4.1 Biomass and Geothermal Co-Production

Moret et al. explored the potential of combining woody biomass power plants with deep geothermal energy to meet urban energy demands [19]. Geothermal energy, a well-known green renewable energy source, is stored within the Earth. One of its main advantages is independence from weather conditions. This energy can reach the Earth's surface through volcanic eruptions, hot springs, or heat-bearing underground water and appears widely in various forms on the surface. Many countries use geothermal energy for various purposes, such as direct heating, power generation, cooling, and drying. In Italy, geothermal energy is the third-largest renewable thermal energy resource. By 2050, geothermal energy is projected to contribute up to 8.3% of global electricity generation, serving 17% of the world's population. However, factors such as technology limitations hinder geothermal energy development. For example, the emission of non-condensable gases in geothermal production poses a significant environmental issue, and the low power generation efficiency from low-temperature resources is another challenge. These obstacles have led to much lower geothermal system installations compared to wind or solar, despite geothermal energy's advantages over these renewables. One solution to this issue is to supplement geothermal energy with biomass. The combination of these two renewable energy sources allows for more efficient utilization of renewable energy potential.

4.2 Biomass and Coal Co-Production

Biomass is considered an alternative clean energy source. Partially replacing coal with biomass in power generation can reduce CO₂ emissions, and in combination with carbon capture technology, it can even achieve negative CO₂ emissions. Studies have also shown that co-firing coal and biomass can reduce emissions of CO₂, NO_x, SO_x, and PM_{2.5} [20]. Beyond theoretical validation through numerical simulations and experimental research, the fact that co-firing coal with biomass can reduce certain pollutant emissions has been proven in practice. Currently, most power plants are designed for coal combustion, with very few

boilers designed specifically for biomass. To fully utilize existing coal-fired power plants with minimal modification, co-firing coal with biomass waste is the most feasible option. Compared with burning biomass alone for power generation, coal and biomass co-firing technology offers higher power generation efficiency, lower equipment and operational costs, and greater flexibility with different types of biomass. Although co-firing coal and biomass has many advantages, the addition of biomass in coal-fired boilers, which are specifically designed for coal, inevitably leads to certain issues different from those encountered when burning coal alone. This is one of the current challenges facing this technology.

5 Conclusion

This paper provides a comprehensive review of biomass energy, focusing on various utilization methods and their future prospects. The article is divided into four sections. The first section introduces the importance of biomass as a renewable energy source and its potential in sustainable development. The second section analyzes thermochemical conversion technologies, such as pyrolysis, gasification, and combustion, comparing the efficiency and applications of these technologies. The third section discusses biochemical conversion technologies, including anaerobic digestion and fermentation, highlighting their role in biofuel production. The final section introduces the concept of co-production (polygeneration), emphasizing its potential in optimizing resource use and enhancing energy efficiency. The article concludes with a discussion on the future outlook of biomass energy, analyzing its role in the global energy transition.

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