Research progress in biomass conversion technology and its product application

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Abstract: Rapid economic growth since the turn of the century has often been accompanied by significant challenges, including fossil fuel depletion, environmental degradation, and energy security concerns. Urgent measures are essential to promote environmentally friendly advancements and adopt sustainable energy solutions. Biomass energy, an important component of renewable energy, stands out as the sole renewable energy source containing carbon and has attracted significant attention from governments and the scientific community worldwide. Attention to biomass conversion technologies and their practical applications has gradually increased. This paper provides an in-depth analysis of the utilization of biomass and its wastes, and systematically introduces the progress of the application of biomass conversion technologies, including biochemical and thermochemical conversion, to provide readers with a clear picture of the technological development. By meticulously summarizing the current status of the application of different products produced by these technologies, it provides a valuable reference for researchers and practitioners in the field of biomass energy, aiming to meet the challenges of clean energy production and biomass waste management, and to mitigate the adverse impacts of human activities on the environment. In addition, this paper explores the application of machine learning in the field of biomass conversion, especially its potential in optimizing the biomass conversion process, improving the accuracy of energy yield prediction, and enhancing process control. Despite challenges such as data quality and model interpretability, developments in machine learning, particularly advances in feature engineering and interpretable AI, promise to address these issues. This study contributes positively to advancing biomass energy technologies.

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1 Introduction

With the accelerating pace of economic development worldwide, sustainability challenges such as fossil resource scarcity, ecosystem deterioration, and energy security risks have become critical drivers of energy infrastructure transformation. Currently, fossil fuels represent 80% of global energy consumption, with demand expected to surge by 48% in the next two decades due to factors like population growth. The petroleum and natural gas industries encounter significant challenges in meeting this growing demand[1]. Despite their low cost and easy availability, fossil fuels have a significant impact on the environment and contribute to global climate change. Consequently, urgent measures are essential to promote environmentally friendly advancements and adopt sustainable energy solutions. Biomass energy, an important component of renewable energy, stands out as the sole renewable energy source containing carbon and has attracted significant attention from governments and the scientific community worldwide[2].

Biomass typically encompasses all renewable organic materials derived from biological growth processes, including plant and animal residues, metabolic byproducts, and other organic matter such as crop residues, forestry waste, grasses, straw, waste paper, secretions, and feces. The main characteristics of biomass energy include its abundant energy potential, wide distribution, extensive applications, renewability, and cleanliness[3]. It is estimated that by 2050, 15%-50% of global energy consumption will be sourced from biomass[4]. China, being a large agricultural country, boasts abundant biomass resources. According to statistics, China produces over 600 Mt of crop straw annually, of which around 400 Mt can be used as energy fuel. The forestry biomass resources amount to approximately 19 billion t, with an energy supply potential of about 300 Mt[5]. These figures indicate that China possesses rich biomass resources, laying a solid foundation for its sustainable development and showcasing its tremendous potential in the field of biomass energy.

Biomass can be cultivated under various conditions, making

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biomass feedstocks less dependent on location and climatic conditions compared to fossil resources[6]. Therefore, utilizing the potential of biomass to replace fossil resources can enhance the profitability and carbon efficiency of biorefinery processes[7]. Furthermore, despite biomass having a lower energy density than fossil fuels, it is comparatively easy to store and transport. Waste biomass is readily available as a low-cost fuel, making it a promising global energy source. As an alternative energy source[8], biomass holds a promising future and can significantly contribute to China's efforts to achieve its "carbon neutral" goal more effectively.

According to the United Nations, the global population currently stands at about 8 billion and is expected to continue growing in the coming years[9]. As the global population grows exponentially, so does the relative demand for food and energy. According to projections, a 51% increase in food production is required to meet the demand for food by the growing population[10]. However, food production has a significant impact on environmental pollution at all stages of its production to distribution, and about one third of global food production is lost or wasted during production, processing, storage, transportation, and consumption[11]. This wasted and lost food is usually disposed of by landfill decomposition and open burning[12,13]. However, these treatments can lead to significant greenhouse gas emissions that adversely affect the environment[14]. Landfills present serious problems in that they can pollute surface and groundwater through leachate while generating greenhouse gas emissions during the decomposition of organic waste, posing a threat to air quality, human well-being, and contributing to climate change. Sustainable management of biomass waste is particularly important given its significant environmental and economic impacts. The use of biomass conversion technologies can transform biomass waste into an efficient source of energy, addressing both energy needs and biomass waste management.

It's noteworthy that interest in biomass conversion technology and its practical applications is on the rise. According to Kataya et al.[15], the total number of publications with the keyword "biomass conversion technology and its applications" between 2003 and 2022 is close to 494 922. In 2003, the number of relevant publications was only about 4035, while in 2022, the number had increased significantly to 71 222, representing an increase of about 1664.8%. This data clearly highlights the growing interest in biomass conversion technologies.

This paper provides an in-depth analysis of the utilization of biomass and its wastes, and systematically describes the progress in the application of biomass conversion technologies, including biochemical and thermochemical conversion. By meticulously summarizing the current status of the application of different products produced by these technologies, it provides a valuable reference for researchers and practitioners in the field of biomass energy. In addition, this paper explores the application of machine learning (ML) in the field of biomass conversion, especially its potential for optimizing the biomass conversion process, improving the accuracy of energy yield prediction, and enhancing process control. Through ML models, key parameters and optimized production schedules are able to be predicted, providing new research directions in the field of biomass energy and practical technological pathways towards sustainable energy solutions.

2 Biomass feedstock

Biomass refers to organic material of plant origin that possesses the characteristic of being naturally replenished or renewed. It is a renewable resource obtained through the process of plant growth and regeneration encompassing various sources such as wood, crop residues, waste, food waste, algae, and more[16]. Since plants can grow and regenerate continuously, biomass stands as a sustainable source of energy. While all plants can be considered biomass, different types of biomass are often used as feedstock for producing or converting into various useful products. For example, sugarcane, extensively grown in southeastern Brazil, has been utilized by researchers for conversion into liquid fuels[17], gaseous fuels[18], and biochar materials[19]. Furthermore, some researchers have converted straw, rice husk, bagasse, fruit shells, and crops into biofuels through processes such as catalytic cracking, pyrolysis, and anaerobic digestion[20-23]. The utilization of wastewater solids, biomass obtained from water resource recovery facilities or wastewater treatment plants, has become widely discussed in recent research. Researchers are actively exploring the potential applications of these wastewater solids to develop new products[24]. The utilization of solid residues from wastewater treatment holds significant importance for a wide array of industrial activities, primarily due to the prevalent challenge of water issues confronting many industrial operations. Wastewater treatment inherently entails managing a portion of waste generated during the production process. Therefore, the efficient utilization of solid residues from wastewater represents a pivotal milestone in industrial practices[25].

In recent years, the diversity of biomass sources has emerged as a primary concern among researchers. This emphasis has directed their focus toward various types of biomass. The utilization of different types of biomass holds the potential to assist in the treatment and management of industrial wastes within the country, thereby facilitating resource utilization and environmental protection efforts. China, characterized by its large population, faces substantial demands for food. Agriculture has traditionally served as an important foundation for meeting these food demands and ensuring national food security. Furthermore, China's agricultural exports hold a significant position in the global market, covering a wide range of products such as grains, vegetables, fruits, and meat[26]. Agriculture in China has long served as a dependable source of biomass. Researchers have initiated exploration into the potential conversion of agricultural biomass and its by-products into various valuable products. These products span a range of applications, including bioethanol[27], bioenergy[28], fuel pellets[29], biofuels[30], biochar[31], and others. These products play an important role in advancing resource recycling, mitigating environmental pollution, and promoting sustainable development in both agriculture and energy sectors. As outlined by Fu et al.[32], considering the current state of bioethanol development and the roadmap for liquid biofuels in China, two distinct stages of bioethanol development have been defined. The initial stage, set for 2020, incorporates methodologies like the fusion statistical algorithm. Through this approach, they estimated the total potential bioethanol volume in China to be 21.55 Mt. According to the "2024-2029 bioethanol industry status quo and future development trend analysis report", China's bioethanol production in 2020 has exceeded 8 Mt[33], and the calculation of the data has a certain discrepancy. This is due to the first stage of the calculation being used in the production of corn for the relevant calculations. The corn can not be all used for the production of ethanol, so it is normal that there is a difference. Moreover, China's National Energy Administration in 2016 issued the "13th Five-Year Plan for Biomass Energy Development", which clearly put forward the 2020 biofuel ethanol development target of 4 Mt/a. The actual output is two times the target output, which is sufficient to illustrate the potential for the development of bioethanol in China[34]. The second stage spans from 2020 to 2030, during which, using the same method, they projected the potential bioethanol production to reach 145.42 Mt. These figures highlight the substantial potential of China's bioethanol production and exhibit the significant role of its renewable energy sector within the broader landscape of renewable energy. Concurrently, research and application of biochar have attracted increasing attention, resulting in numerous reviews pertaining to bio-preparation and application[35-38]. These reviews primarily focus on biochar synthesized from individual biomass sources, predominantly utilized for wastewater treatment or soil amelioration purposes (as listed in Table 1).

Table 1 Different types of biomass conversion and their products and uses

Types of biomass	Feedstock	Product	Use	Ref.
Stalks	Tobacco stalks	Bioethanol	Bioethanol can be used as a fuel or chemical raw material, and biochar can be used for soil improvement, carbon sequestration, etc.	[39]
	Sunflower stalks	Bioethanol		[40]
	Tobacco stalks	Biochar		[41]
	Corn stalks	Biochar		[42]
Oilseed crops	Soybean	Biodiesel	Biodiesel can be used as a transportation fuel and biojet coal can be used for aviation fuel substitution.	[43]
	Rapeseed	Biodiesel		[44]
	Brassica carinata	Aviation fuels		[45]
Aquatic plants	Hyacinth	Biogas	Biogas can be used for electricity or heating, and biofibers can be used in the textile and pulp industries.	[46]
	Eichhornia crassipes	Biofiber		[47]
Forest residues	Pine residues	Biofuel	Biogas can be used for power and heat generation, etc.	[48]
	Forest residues	Biofuel		[49]
Crop residues	Cassava stalks	Biothermal energy	Bio-thermal energy can be used for heating or electricity generation.	[50]
	Rice, coffee, and cocoa crops residues	Biothermal energy		[51]

3 Biomass conversion technology

Research has demonstrated that the efficient and cost-effective conversion of biomass waste into valuable resources can yield cost savings and safeguard natural resources[52]. Biomass conversion refers to the process of converting the organic matter in biomass into usable energy and high-value products. This process involves a range of technologies and methods, including biomass gasification, biomass liquefaction, and biomass fermentation[53]. Through biomass conversion, people can maximize the utilization of waste and residual materials, mitigate environmental pollution, and acquire renewable energy and other beneficial products to support sustainable development.

Broadly speaking, biomass conversion technologies can be categorized into two main groups: biochemical conversion and thermochemical conversion[54] (as shown in Figure 1). The selection of a specific conversion technology is influenced by various factors, including the type of feedstock and its moisture content, biomass quality and quantity, availability of resources, and desired end product. Additionally, economic considerations such as profitability and market accessibility, along with environmental concerns, play critical roles[55]. When deciding on a conversion technology, it is essential to take into account the type and moisture content of the feedstock, as different technologies have varying adaptations to biomass types and moisture levels.

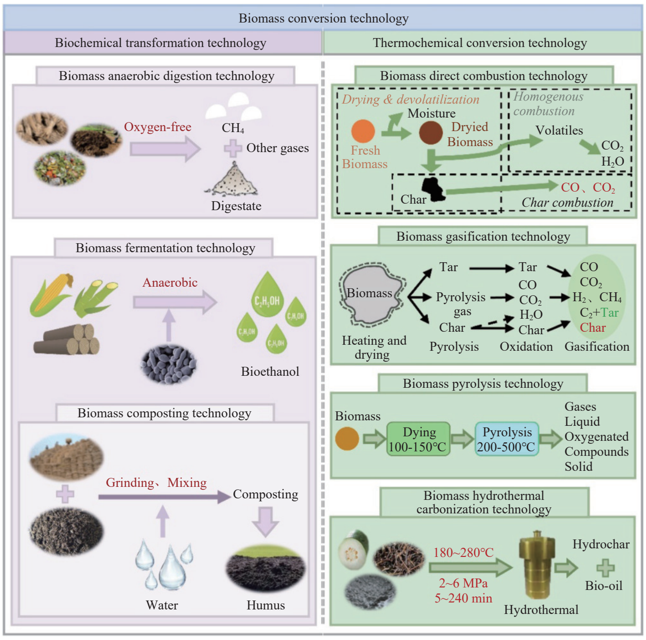


Figure 1 Comprehensive flow chart of biomass conversion technology pathways

3.1 Biochemical transformation technology

Biomass biochemical conversion is a technology that utilizes biomass (including organic matter produced by plants, animals, and microorganisms) as a feedstock, transforming it into useful chemicals and energy through a series of biochemical reactions. Typically, these reactions are catalyzed by biocatalysts, such as enzymes sourced from bacteria or other microorganisms[56]. This versatile technology enables the conversion of biomass into a range of valuable products, including biofuels like biodiesel and biogas, various chemicals such as bioplastics and biochemicals, fertilizers, and other valuable products[53].

Biomass biochemical conversion technologies include a variety of methods, including anaerobic digestion, fermentation, and composting processes. These conversion processes are selected based on the characteristics of the desired products and feedstocks, and they are optimized and controlled as necessary. Microbial catalysts, which typically include bacteria, fungi, and communities of microorganisms, play a critical role in the processes by breaking down, converting, and synthesizing organic matter[57]. Through the selection of various microorganisms, biomass can undergo biochemical conversion processes to yield different products such as hydrogen, biogas, ethanol, acetone, butanol, and organic acids[58]. Using the anaerobic digestion process alongside appropriate hydrogen-producing bacteria, biomass can be transformed into hydrogen, thus offering a renewable energy source[59]. Alternatively, by employing methanogenic microorganisms during anaerobic digestion, biomass can be converted into methane (biogas), which serves as an energy supply or can be utilized to generate electricity[59]. Through the fermentation process, along with suitable yeasts, sugars present in biomass can be converted into ethanol, an important biofuel and chemical feedstock[60]. Through biosynthetic processes and suitable microorganisms, biomass can be transformed into acetone, serving as an organic solvent and synthetic intermediate[60]. Using either anaerobic digestion or fermentation processes alongside compatible microorganisms, sugars within biomass can be converted into butanol, serving as a solvent or biofuel[61]. Furthermore, employing fermentation processes alongside appropriate microorganisms enables the conversion of sugars from biomass into organic acids like acetic acid[62], propionic acid[63], or succinic acid[64]. These organic acids find applications in chemical production or acid-base neutralization. The selection of microorganisms and conversion processes offers a diverse range of sustainable options, facilitating the utilization of biomass resources in an economically and environmentally viable manner.

3.1.1 Biomass anaerobic digestion technology

Anaerobic digestion (AD) is a microbial decomposition process of organic waste materials, including agricultural residues, food waste, and animal manure, conducted under anaerobic conditions. During anaerobic digestion, microorganisms break down organic waste into methane (biogas) and digestate, which can serve as organic fertilizer. Kumar and Ankaram provide a comprehensive explanation of the working principle behind anaerobic digestion, which involves the utilization of organic matter to produce energy within an oxygen-deficient environment[65]. As described by Sangeetha et al.[66], the AD process involves several interconnected stages, including hydrolysis, fermentation, acetogenesis, and methanogenesis. Throughout these stages, biogas, predominantly composed of methane, is generated as a byproduct. During anaerobic digestion, microorganisms decompose the organic components of waste, yielding biogas as a byproduct. Biogas typically comprises 40% to 65% methane and 35% to 55% carbon dioxide, alongside trace amounts of other gases like hydrogen (H_2) and hydrogen sulfide (H_2S). The precise proportions of these gases can vary depending on the composition of the waste and microbial activity during the digestion process[67]. Biogas possesses combustible and sustainable characteristics, making it suitable for use as an energy source or in various industrial applications.

AD represents a complex continuous biochemical process typically divided into four phases: hydrolysis, acidification, acid production, and methanogenesis[68,69]. These four stages occur simultaneously within the anaerobic digestion system, exhibiting interdependence and mutual constraint among microbial populations[70]. Figure 2 illustrates the flora involved in each stage.

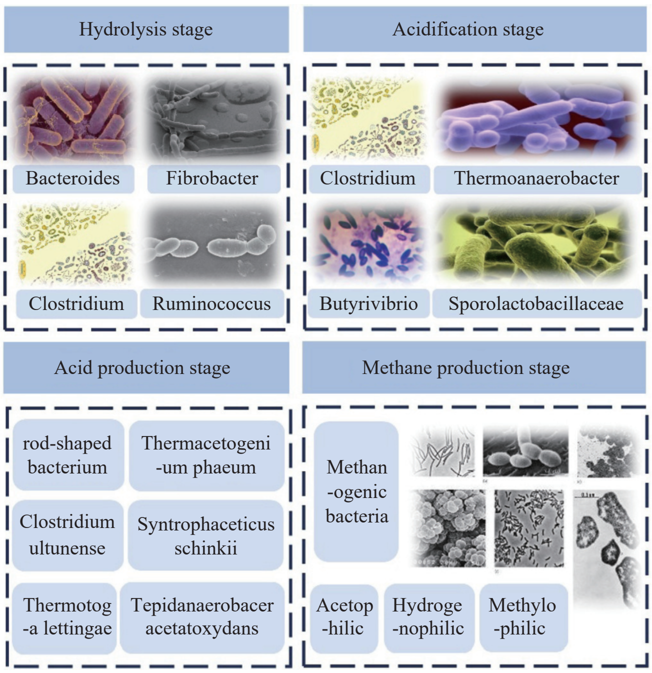


Figure 2 Participating flora in various stages of anaerobic digestion

The AD process, while beneficial, does come with limitations, particularly in agricultural applications. Challenges include the relatively slow conversion process, the emission of malodorous gases, the production of low-quality digestate, and constraints on energy recovery[71]. Consequently, some farms may opt for alternative waste treatment technologies like composting and gasification. These alternatives may better suit the treatment of large-scale agricultural wastes and offer improved control over odors and decomposition rates. Moreover, complementary technologies and methods can be employed alongside anaerobic digestion to address its limitations. These include solid-liquid separation, just-in-time digestate treatment, and control systems[72]. In summary, while the anaerobic digestion process offers numerous advantages in waste treatment, its limitations necessitate careful consideration of factors such as farm size, waste type, and viable treatment options to ensure system viability and effectiveness in agricultural settings.

3.1.2 Biomass fermentation technology

Fermentation is a process that utilizes microbial metabolic activities to convert organic matter into other useful chemicals. As described by Patra et al.[73], fermentation involves microorganisms (such as yeast or bacteria) converting biomolecules, such as glucose, into alcohols or acids under anaerobic conditions. By fermenting sugars, starchy substances, or cellulosic materials, biofuels or chemicals like bioethanol (the most common) and acetone can be produced. Food and agricultural wastes contain various sugars, some of which readily ferment to produce ethanol and other products. However, for substances like cellulose, hemicellulose, starch, and proteins, additional pretreatment processes are necessary to facilitate the fermentation process more effectively[74].

The range of fermentation feedstocks for ethanol production is broad and includes various options. These feedstocks can be categorized into three generations, which have evolved and refined over time, as depicted in Figure 3.

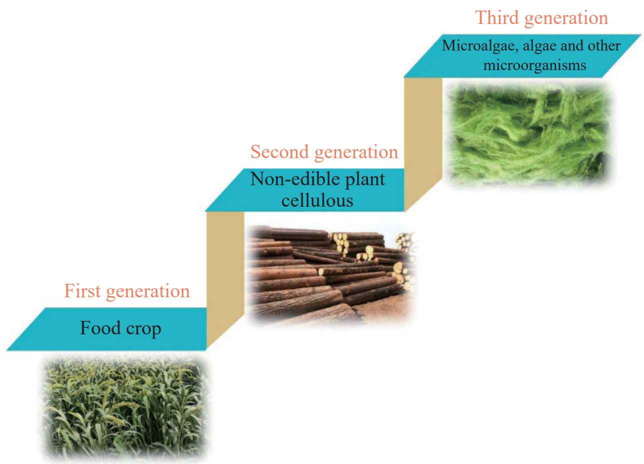


Figure 3 Development process of three generations of feedstocks for bioethanol

The first generation of bioethanol feedstocks primarily consisted of edible crops, such as corn, wheat, and sugarcane[75,76]. These crops, abundant in starch and sugar, could be converted to ethanol through fermentation. However, using edible crops as bioethanol feedstocks raised several concerns, including competition for food resources, impacts on food supply stability, and land use issues. Consequently, lignocellulosic feedstocks emerged as second-generation alternatives to address the limitations of first-generation bioethanol[66]. Second-generation bioethanol feedstocks predominantly comprise non-edible plant cellulose, including wood, straw, and reeds[77]. Cellulosic wastes pose challenges in fermentation due to the complex structure of cellulose, which is difficult to degrade. Therefore, pre-treatment methods such as milling, acid and alkaline treatment, or enzymatic treatment are necessary to make cellulose more accessible to microorganisms, facilitating its breakdown and fermentation into ethanol[78]. Second-generation bioethanol feedstocks offer greater sustainability compared to first-generation options as they do not compete with food resources and can utilize agricultural and forestry waste. Third-generation bioethanol feedstocks involve the use of microalgae, algae, and other microorganisms to produce ethanol[79,80]. These feedstocks boast potential for high energy efficiency, high bioethanol yields, and can be produced on a large scale on non-agricultural land.

Overall, bioethanol production is undergoing a gradual transition from traditional food crops to the utilization of waste and non-food plant cellulose as feedstocks, driven by technological advancements. These materials are abundant in agricultural countries, economically viable, and easy to use in industrial-scale plants. Moreover, cellulosic feedstocks, being non-food sources, mitigate competition with the food supply. Simultaneously, ongoing research and development into third-generation bioethanol feedstocks offer more sustainable and efficient options for bioethanol production.

3.1.3 Biomass composting technology

Composting is the microbial degradation process of organic wastes (e.g., agricultural and food wastes) facilitated by the right combination of moisture, oxygen, and temperature control. Throughout the composting process, microorganisms break down organic materials, yielding organic fertilizers that enhance soil quality and promote plant growth. This intricate process involves a series of biological and chemical reactions, necessitating optimal conditions of moisture, aeration, and temperature. Currently, composting technology finds widespread application in diverse fields, including agriculture[81], horticulture, and floriculture[82], as well as in landscape maintenance[83] and municipal waste treatment[84].

Composting is widely used in agricultural production, particularly in organic or green farming practices. Its application to farmland enriches the soil with essential nutrients, enhances soil structure, and maintains moisture content. For organic farming, composting stands as a vital organic fertilizer alternative, offering a sustainable replacement for chemically synthesized fertilizers[85]. Moreover, composting proves highly advantageous in horticulture and flower cultivation. It improves soil texture and water retention, furnishing plants with the necessary nutrients to promote robust growth and flower and prolific flower fruit yields[86]. Composting plays a critical role in landscape maintenance across parks, golf courses, sports fields, and various other green spaces. Its benefits extend beyond improving soil quality and supporting plants' resistance to pests, diseases, and environmental challenges. Composting also reduces reliance on chemical fertilizers and pesticides, promoting environmentally sustainable practices[87]. Additionally, composting technology is pivotal in municipal waste treatment endeavors. By composting organic waste such as food waste and flower cuttings, it mitigates the volume of waste destined for landfills, thereby reducing environmental pollution. Moreover, this process transforms organic waste into valuable fertilizers[88].

3.2 Thermochemical conversion technology

Biomass thermochemical conversion technology involves utilizing high temperatures and pressures to convert biomass into renewable energy. According to Mahinpe and Gomez, this method offers several advantages over conventional approaches, including reduced greenhouse gas emissions and the potential for independent power generation[89]. A variety of biomass wastes, including food waste, agricultural residue, algae, and forestry waste, serve as suitable feedstock for thermochemical conversion. The moisture content of biomass waste plays a critical role in selecting the appropriate thermochemical process. When the moisture content is low, drying technology is preferred, whereas high moisture content necessitates hydrothermal technology for conversion. The primary routes for thermochemical conversion include combustion, gasification, and pyrolysis, alongside hydrothermal treatment (HTT) options like hydrothermal carbonization[90,91].

3.2.1 Biomass direct combustion technology

Direct combustion involves burning biomass waste directly in the presence of oxygen to produce heat, H_2O, and CO_2. It stands as a simple and common thermochemical conversion method, representing one of the earliest applications of biomass conversion technology. Direct combustion is particularly suitable for dry biomass wastes like wood and straw. The heat generated through this process finds application in heating, power generation, and various industrial processes. However, it is important to note that inadequate oxygen supply during direct combustion can lead to incomplete combustion, releasing pollutants such as CO, NO_x, SO_2, and particulate matter into the atmosphere[92].

Direct combustion typically takes place in furnaces, turbines, or boilers within the temperature range of 800°C to 1000°C, as described by Lam et al[93]. This method is well-suitable for biomass materials with low moisture content (below 50%). The biomass combustion process can be summarized as follows: 1) drying: the removal of moisture from biomass materials is usually achieved through heating; 2) degreasing: biomass may contain organic substances such as fatty acids, which can produce toxic gases and pollutants during combustion. Therefore, it is essential to remove them as much as possible before combustion; 3) gasification: under suitable temperature and atmospheric conditions, biomass decomposes into gaseous products, including synthesis gases (CO and H_2), along with other organic gases; 4) charcoal combustion: charcoal, a solid residue formed from biomass after pyrolysis, undergoes combustion; and 5) gas-phase reactions: volatile substances and gaseous products from biomass combustion may participate in gas-phase reactions, which can generate secondary pollutants and impact the atmosphere. Figure 4 shows a simplified depiction of the phenomena occurring during biomass combustion in a fluidized bed[94].

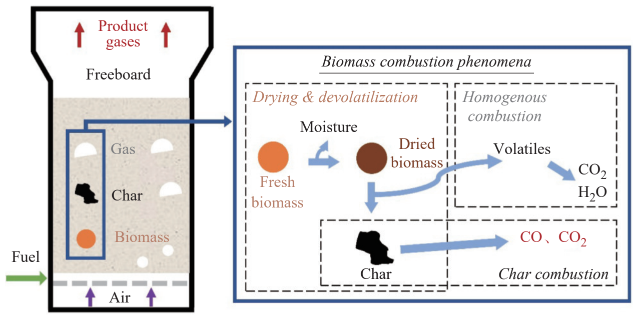


Figure 4 Simplified process of phenomena occurring during biomass combustion in a fluidized bed

Alexis et al. conducted a study on the biomass energy potential of direct combustion systems in Colombia, revealing that utilizing approximately half of the solid biomass in such systems could effectively replace the use of solid fuels like wood and coal[95]. Zhao et al. further elucidated that, beyond the feedstock, the principle of biomass direct combustion for power generation mirrors that of conventional thermal power generation. Biomass fuels include agricultural and forestry waste such as corn stalks, wheat straw, rice straw, bark, sawdust, and branches[96]. Despite its widespread adoption, direct combustion exhibits lower thermal efficiency and presents challenges related to air pollutant emissions and public health risks. Consequently, there is a growing interest in exploring more efficient and environmentally friendly biomass conversion technologies. Gasification, pyrolysis, and other thermochemical conversion methods are extensively researched and implemented to improve energy utilization efficiency while mitigating environmental impact.

3.2.2 Biomass gasification technology

Gasification is a process wherein biomass undergoes partial oxidation and reacts with water vapor to produce gases like CO, H_2, CO_2, CH_4, etc., through interaction with air, oxygen, and water vapor at higher temperatures[97,98]. The gasification process usually consists of four steps: heating and drying, pyrolysis, oxidation or partial combustion, and reduction or gasification, as shown in Figure 5.

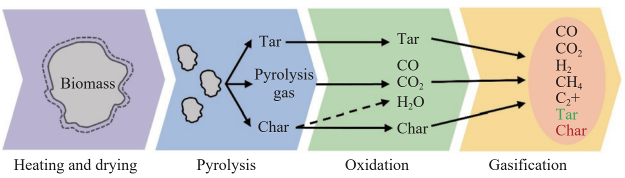


Figure 5 Main processes of biomass gasification[99]

In the initial stage, the feedstock undergoes heating and drying to remove moisture and volatile matter. The temperature typically reaches around 200°C, with a moisture content of 10%-15%[100], to achieve optimal conditions for gasification and enhance efficiency. Subsequently, the biomass undergoes thermal decomposition at high temperatures, yielding volatile compounds and char. These volatile compounds comprise small molecular gases and liquid products (tar). The third stage involves oxidation or partial combustion, typically occurring at temperatures exceeding 700°C. This phase releases heat, providing energy necessary for sustaining the pyrolysis and gasification processes. Reduction or gasification represents the final stage in the gasification process, typically occurring at temperatures surpassing 800°C. During this phase, residual carbon or char within the feedstock reacts with gasifying agents like O_2 and steam to yield synthesis gas or other valuable gases. Yao et al. conducted a comprehensive study on the biomass gasification process using a fixed-bed tubular reactor and drew the following conclusions[101]: As the gasification temperature rises, there is an increase in the generation of gaseous products, accompanied by a decrease in solid products. Moreover, the generation of liquid products experiences a rapid increase followed by a gradual decrease. In addition, increasing the concentration of oxygen in the gasifier leads to a decrease in the generation of solid products. The gasification process enables the regulation of gas composition by controlling reaction conditions and the choice of gasifying agent[102,103].

Gasification stands out as a preferred method for extracting value from biomass, whereby the resulting gas mixture fuels power plants, facilitating the generation of clean energy. Moreover, it can be used in the chemical industry to produce ammonia and methanol instead of natural gas[104]. Despite its considerable potential, biomass gasification encounters challenges related to the presence of tar, a complex mixture of aromatics, within the volatile components of biomass[105]. Figure 6 outlines the advantages and disadvantages associated with biomass gasification.

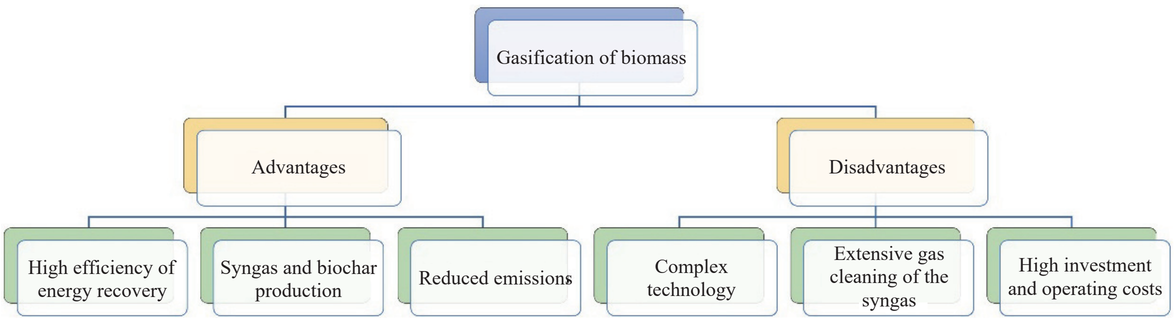


Figure 6 Advantages and disadvantages of biomass gasification

3.2.3 Biomass pyrolysis technology

Pyrolysis involves subjecting biomass pellets to high temperatures in the absence of oxygen, causing molecular breakdown and the formation of smaller molecules[106]. Depending on the heating rate, pyrolysis processes can be categorized into three types: slow, medium, and fast pyrolysis (or flash pyrolysis)[107]. Fast pyrolysis is particularly effective in bio-oil production and inhibits char formation compared to slow pyrolysis, which is tailored for biochar production[108-110]. Fast pyrolysis technology can convert biomass into bio-oil, biochar, and syngas, each holding significant economic potential[111]. After refinement, pyrolyzed bio-oil serves as a valuable fuel or chemical feedstock[112], while biochar finds application in soil amendment, catalysis, or as an adsorbent[113]. Furthermore, syngas can function as a renewable energy source for heat or power generation[114]. The operating conditions and main products of different pyrolysis types are outlined in Table 2.

Table 2 Operating conditions and main products of different pyrolysis types[115]

Pyrolysis type	Residence time	Heating rate	Temperature	Main products
Slow	Days	Very slow	400°C	Char
Conventional	5-30 min	(20°C-100°C)·min^{-1}	450-650°C	Liquid, gas, char
Fast	0.5-5 s	1000°C·s^{-1}	450-650°C	Liquid

Temperature plays a significant role in shaping the physicochemical properties of char. In a study conducted by Rajapaksha et al., tea waste was pyrolyzed at 300°C and 700°C to generate derived biochar. The study revealed that the carbon content increased from 70.05% to 85.11% as the temperature increased from 300°C to 700°C[116]. Additionally, the surface area of the biochar showed a substantial increase from 2.28 m^2/g to 342.22 m^2/g with the temperature increment. The solid carbon material typically exhibits a large specific surface area, which correlates closely with its superior adsorption capacity, water-holding capacity, remediation efficacy, and supercapacitor performance.

3.2.4 Biomass hydrothermal carbonization technology

Hydrothermal carbonization (HTC) is a thermochemical process that involves reacting biomass waste with water as the reaction medium under high temperature and pressure conditions. In this process, the temperature typically ranges from 180°C to 280°C, and the reaction occurs under water gasification pressure ranging from 2 to 6 MPa, lasting from 5 to 240 minutes[117,118]. The feedstock undergoes a cracking reaction, resulting in the formation of a new solid product called hydrothermal carbon. Compared with conventional high-temperature dry cracking, HTC technology can process biomass with high water content (75%-90%)[65] under mild reaction conditions. Moreover, it minimizes air pollution by dissolving nitrogen oxides (NOx) and sulfur oxides (SOx) in the water[119]. Additionally, it features lower energy consumption and cost, simple equipment and operation, and high adaptability. Numerous researchers both domestically and internationally have adopted the HTC process for treating various types of biomass, including lignocellulose[118], agricultural waste[120,121], and sludge[122], for resource utilization purposes. Hydrothermal carbonization technology has found widespread application across multiple fields. These applications include converting biomass into solid fuels, liquid fuels, soil conditioners, carbon material adsorbents, functional nanomaterials, and new carbon catalytic materials[121].

The HTC process is influenced by factors such as hydrothermal reaction temperature and reaction time. Among these, the reaction temperature stands out as the most significant factor affecting the product. Generally, higher reaction temperatures intensify hydrothermal reactions, consequently reducing the yield of hydrothermal carbon. However, higher pyrolysis temperatures are not conducive to the formation of a large number of functional groups. In their study, Guo et al. observed SEM (scanning electron microscope) images of tea tree branch-derived biochar produced by the HTC process at different temperatures. They found that the derived biochar exhibited internal porosity and cracks, potentially originating from cellulose decomposition during the heat treatment process. Moreover, SEM images clearly showed the effect of HTC temperature on the porosity of the biochar[123]. Biochar prepared at 120°C exhibited a typical plant fiber structure with barely discernible porous features. However, biochar prepared at 200°C and 240°C displayed more microporous and mesoporous particles on the surface. Consequently, it can be assumed that temperature affects the degradation process of various biomass components, thereby significantly influencing biochar yield as well as changes in its chemical and physical properties. Similarly, reaction time plays a significant role in the HTC process, where longer reaction times result in more vigorous hydrothermal reactions, consequently reducing the yield of the solid product[124]. The increase in reaction time leads to the hydrolysis of organic components in the feedstock, resulting in the formation of various small molecules dissolved in the liquid phase. Consequently, this process lowers the yields of hydrothermal carbon. However, due to energy consumption constraints, extending the reaction time or raising the reaction temperature indefinitely is often impractical. Therefore, conventional HTC processes typically opt for lower temperatures and shorter reaction times to mitigate energy consumption. However, this approach also yields lower quality hydrothermal carbon with relatively lower carbon content.

Thermochemical conversion is a versatile treatment method suitable for a wide range of biomass feedstocks, characterized by its lack of pre-treatment and short reaction times. The biomass feedstock undergoes a chemical reaction to transform into the desired product. Due to the chemical reaction involved, thermochemical conversion boasts high productivity, yielding a wide range of high-value products that can be further fractionated. In contrast, biochemical conversion necessitates the pretreatment of biomass feedstock and involves longer reaction times. Biochemical conversion typically employs microorganisms, enzymes, and/or chemicals, with its productivity usually limited to one or a few products. To broaden the product range, additional use of microorganisms and enzymes is often required. Furthermore, thermochemical conversion is not significantly influenced by climatic conditions and can be conducted in various environments. Conversely, biochemical conversion is more susceptible to ambient factors such as temperature and the conditions within anaerobic digesters. Additionally, biochemical conversion may produce secondary wastes, such as biomass sludge[125].

Considering the aforementioned factors, when choosing between biomass conversion technologies, whether biochemical or thermochemical, several aspects such as intended applications, logistical concerns, and the availability of specific biomass resources must be carefully evaluated. Each situation has its own unique advantages and disadvantages, requiring a comprehensive evaluation.

4 Biomass conversion products and their applications

4.1 Synthesis gas and its applications

Biomass conversion processes can produce a variety of gases, with synthesis gas (Syngas) being among the most prevalent. Syngas primarily comprises carbon monoxide (CO), carbon dioxide (CO_2), hydrogen (H_2), and lower hydrocarbons. Syngas is commonly used as a feedstock for various applications including chemical production, biofuels, thermoelectric power production, and hydrogen energy production.

As depicted in Figure 7, the CO and H_2 present in syngas serve as valuable feedstocks for chemical production. Through catalytic reactions, syngas can be converted into a range of chemicals including methanol, ethanol, propylene, acetic acid, ammonia, and more[126,127]. These chemicals find extensive applications across various industries, including the production of synthetic plastics, resins, solvents, and synthetic fibers. Moreover, syngas can be converted into liquid fuels such as biodiesel[128], bioethanol[129], and biomethane[130]. These biofuels offer a sustainable alternative to traditional fossil fuels, thereby reducing dependence on finite resources and cutting carbon emissions, thereby achieving a more sustainable energy supply. Furthermore, syngas can be directly utilized to generate electricity or heat[131]. By combusting syngas through internal combustion engines, gas turbines, gas boilers, and other equipment, electricity and heat can be efficiently produced. This form of energy utilization finds widespread application across industrial, commercial, and residential sectors. Syngas is rich in H_2 and can be used for hydrogen energy production[132]. Hydrogen can be used in fuel cell power generation, hydrogen combustion, and hydrogen storage, offering a clean and efficient energy solution essential for reducing carbon emissions and fostering sustainable development. Syngas's wide range of applications continues to be driven by ongoing research and technological advancements aimed at enhancing efficiency, reducing costs, and better aligning with energy needs and environmental sustainability goals.

Figure 7 Areas of application: Overview of the three forms of biomass conversion products and their uses

4.2 Biochar and its applications

Biochar is an incredibly versatile and multifunctional material that can undergo various conversion processes to yield different types of biochar, each serving distinct purposes. As illustrated in Figure 7, biochar can be used for wastewater treatment[133]. Due to its good adsorption properties, biochar can effectively adsorb and remove pollutants from water. Biochar can also serve as a precursor for catalysts in the preparation of catalysts for various chemical reactions[134]. Additionally, it can be utilized in the production of bio-oil or biodiesel[135,136]. Moreover, biochar functions effectively as a soil conditioner, acting as a fertilizer[137]. It enhances soil structure and texture, improves soil fertility, and promotes plant growth. Furthermore, biochar serves as an adsorbent, capable of adsorbing toxic elements, thus purifying soil, water, and gases[138]. Furthermore, it can be used for energy storage, serving as a renewable energy storage material to reduce carbon emissions from other energy sources[139].

The morphology of biochar significantly influences its functionality, with various forms exhibiting distinct structures and properties, including tubular biochar, spherical biochar, and nano-biochar[140], each suitable for different applications[141]. Spherical biochar, characterized by its low ash content and good adsorption properties, holds particular advantages in environmental remediation. It proves effective in purifying and ameliorating soil, water, and gases, aiding in the removal of pollutants[142,143]. Tubular biochar, conversely, holds promise as a potential mycorrhizal inoculation material, given its positive effect on microbial growth and reproduction. By facilitating the adsorption of water and nutrients by plant roots, tubular biochar contributes to improved plant health and growth outcomes[144]. Furthermore, tubular biochar can serve as a sustainable alternative to the expensive and non-renewable peat material traditionally used for inoculation purposes. Nano-biochar, on the other hand, finds application as a pollutant detector in sensors[145,146]. It boasts highly reliable accuracy and sensitivity, making it adept at detecting and monitoring environmental pollutants. Moreover, due to its high surface-to-volume ratio and porous structure, nano-biochar can also function as an effective enzyme carrier[147].

4.3 Bio-oil and its applications

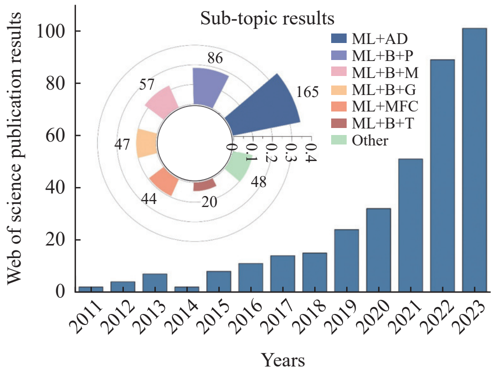
Biomass conversion processes also yield liquid products, with one of the most common being bio-oil, generated during biomass preparation for biofuels. Bio-oil, a condensable liquid derived from biomass through pyrolysis[148], primarily consists of organic compounds present in the biomass[149]. As depicted in Figure 7, following appropriate treatment and refinement, bio-oil finds application in power and heat generation, as well as transportation[150,151]. It serves as a versatile liquid fuel, including applications such as biodiesel, aviation fuel, and a substitute for liquefied natural gas (LNG). Moreover, the organic compounds within bio-oils can substitute chemical raw materials. Through further processing and chemical conversion, bio-oil can yield various chemicals and materials like plastics, solvents, paints, resins, and pigments[152,153]. Specific compounds within bio-oils are also valuable in synthesizing high-value chemicals such as pharmaceuticals, fragrances, and antioxidants[154]. Additionally, bio-oils contribute to the production of eco-friendly products like bio-based lubricants and paints, which have minimal carbon emissions and environmental impact.

Despite its potential, bio-oil applications encounter several challenges. Currently, bio-oil production costs remain relatively high, primarily attributed to the energy-intensive nature of processes such as biomass treatment, pyrolysis, and refining. Additionally, the development of efficient and stable catalysts, along with the implementation of more sustainable bio-oil production technologies, poses significant challenges. Moreover, the high oxygen content, elevated water content, and poor thermal stability of crude biomass oil limit its widespread utilization[155]. To address these limitations, various upgrading technologies, such as hydrotreating or hydrodeoxygenation, have been developed to enhance the efficiency of bio-oil production through the pyrolysis process.

Despite the challenges, the future of bio-oil appears promising. In recent years, microalgae bio-oil has emerged as a leading renewable fuel option, characterized by its low environmental impact and high yield, among other advantages[155]. With ongoing technological advancements and government support, bio-oil stands poised to evolve into a viable alternative to traditional fossil fuels.

5 Applications of machine learning in biomass conversion

In recent years, the application of ML to biomass conversion has received increasing attention. As shown in Figure 8, through a keyword search of the “Web of Science” database (covering various subfields of ML and biomass conversion), it is found that the number of related studies is showing a rapidly increasing trend (467 articles between 2011 and 2024, extracted from Web of Science). The application of ML can significantly improve the efficiency and sustainability of biomass conversion processes by reducing the number of experiments, increasing energy output, and reducing environmental impact through predictive models and optimization algorithms[156]. In order to highlight the potential of ML and to promote its use as a pass-through toolkit for researchers in the field of biomass conversion, the next section analyzes the potential of the application of ML in the field of biomass conversion from two perspectives: 1) the current status of the application of ML in the field of biomass conversion; 2) the limitations and prospects for the development of the application of ML in the field of biomass conversion.



Note: ML, Machine Learning; ML+AD, ML+Anaerobic digestion; ML+B+P, ML+Biofuel+Pyrolysis; ML+B+M, ML+Biofuel+Microalgae; ML+B+G, ML+Biofuel+Gasification; ML+MFC, ML+Microbial Fuel Cell; ML+B+T, ML+Biofuel+Torrefaction.

Figure 8 Areas of application: Overview of the three forms of biomass conversion products and their uses

5.1 Current status of machine learning applications in biomass conversion

The application of ML technology in the field of biomass conversion is mainly reflected in its ability to optimize the biomass conversion process by analyzing a large amount of data. This technology can predict and optimize key parameters in the biochemical conversion and thermochemical conversion processes, thus improving the efficiency and product selectivity of biomass energy conversion. In the biochemical conversion process, ML can be used to predict the optimal conditions for steps such as enzymolysis and fermentation[157]; while in the thermochemical conversion process, it can predict the product yields and properties for steps such as pyrolysis and gasification. In this way, ML technology helps to realize the automation and intelligence of the biomass conversion process, which in turn promotes the development of the biomass energy industry[158].

5.1.1 Biochemical conversion processes

In the field of biomass conversion, the biochemical conversion process is a key step in converting biomass feedstock into bioenergy and bio-based chemicals. The application of ML technology in this process aims to improve the conversion efficiency and product selectivity by optimizing each step, so as to realize the high-value utilization of biomass resources. This paper mainly categorizes the application of ML in the biochemical conversion process into the following three stages:

1) Initial stage: Feedstock pre-processing

ML techniques are playing an increasingly important role in the pre-processing of biomass. High-value utilization of biomass, especially lignocellulose, which consists of cellulose, hemicellulose, and lignin, involves a variety of pretreatment methods such as physical, biological, and chemical pretreatment[159,160]. These pretreatment processes are complex and multidimensional, and the interaction of different factors leads to different results. ML is able to learn and make predictions or conclusions by analyzing data, thus avoiding long experimental processes and high costs[161]. In the field of biomass fermentation, biomass feedstocks need to be pretreated to improve the efficiency of enzymatic digestion. During the enzymatic digestion process, ML models are able to predict the optimal enzymatic conditions, such as pH, temperature, and enzyme concentration, based on biomass properties and enzyme properties, so as to improve the saccharification efficiency of biomass. Wang et al.[162] used sodium hydroxide to pretreat wheat straw, and investigated and optimized various parameters affecting the enzymatic degradation of wheat straw through Box-Behnken design and response surface methodology, including solids content, enzyme loading, pH, and hydrolysis time, and improved the final enzymatic sugar yield. This step is crucial for the conversion of biomass into fermentable sugars, which directly affects the availability of feedstock for subsequent fermentation processes.

2) Core stage: Optimization of experimental conditions

Biochemical conversion processes, such as enzymatic digestion, anaerobic digestion, fermentation, and advanced fermentation, are key technologies for biomass conversion. These processes usually involve complex biochemical reactions, the optimization and control of which are crucial for improving the efficiency of biomass conversion[163]. ML techniques, especially artificial neural networks (ANN), support vector machines (SVM), random forests (RF), and Gaussian process regression (GPR), have been widely applied to model and optimize these processes[164]. These models are capable of recognizing and learning non-linear relationships between input parameters and output results, thus improving prediction accuracy and process control. Again, as an example from the field of fermentation, as the sugars produced by enzymatic digestion enter the fermentation process, ML techniques again come into play by analyzing data on microbial growth and metabolite accumulation during the fermentation process to predict and optimize the fermentation conditions in order to improve the yield and quality of biofuels and biochemicals. Optimization at this stage involves not only the adjustment of fermentation conditions, but also the selection and improvement of strains[165]. ML techniques can assist in screening strains with high yield and tolerance or predicting the performance of genetically engineered modified strains to improve the overall efficiency of the fermentation process. Khaleghi et al[166] discussed the application of metabolic flux analysis (MFA) and dynamic flux balance analysis (DFBA) to the fermentation process. MFA analyzes the metabolite production and consumption rates to determine the metabolic flux distribution, while DFBA considers the relationship between macro-state parameters and cellular physiological metabolic parameters during fermentation. And the combination of macrokinetic equations and DFBA produces more accurate predictive models, which can improve the efficiency and effectiveness of the fermentation process.

3) Final stage: Process analysis and control

In the final stage of the biochemical conversion process, the combination of process analytical techniques (PAT) and ML techniques allows for more accurate and automated process monitoring and control[167]. This not only helps to ensure product quality, but also to meet stringent regulatory requirements, especially in the pharmaceutical and food industries. By monitoring and adjusting process parameters in real time, ML techniques are able to predict and prevent potential production problems, reduce waste, and increase productivity[168]. Williams et al[168] used a novel refractive index-based PAT system to monitor the metabolic activity of HEK293T cell cultures in real time during lentiviral vector (LVV) production. The system was able to rapidly identify the relationship between bioreactor pH and culture metabolic activity and use this to develop a pH manipulation strategy that achieved a 1.8-fold increase in metabolic activity in a minimum number of bioreactor experiments compared to unoptimized bioprocesses, with the potential to facilitate the fine-tuning and rapid optimization of the production environment and to enable adaptive process control for enhanced process performance and robustness.

5.1.2 Thermochemical conversion process

The thermochemical conversion process is a key step in the conversion of biomass energy. Figure 9 presents an overview of ML applications in the thermochemical conversion process. Through literature search and reading, the most commonly used ML methods in the thermal conversion process are SVM[169], decision trees (DT)[170], ANN[171-177], and RF[178], while simulated degradation (SA)[179] and particle swarm optimization (PSO)[180] are the most commonly used optimization methods. Most studies use biomass characterization[174,177] (proximate and ultimate analysis) and pyrolysis conditions[173,175] (temperature, heating rate, residence time) as inputs to the ML model, while the yield and composition of the thermal conversion products[172,174] (bio-oil, bio-char, syngas) are frequently studied as target variables.

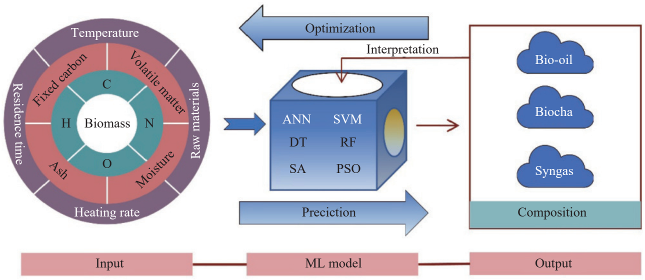


Figure 9 Overview of ML applications in the thermochemical conversion process

Hybrid models have been widely used in ML due to their advantages in improving prediction accuracy[181], adapting to different data distributions[181], providing probabilistic explanations[182], dealing with non-independent data[183], and applicability to large-scale problems[184]. García Nieto et al[185], based on an SVM and a Grid-Search (GS) optimizer, studied a novel artificial intelligence model for characterizing the high heating value HHV of biomass feedstocks based on experimentally determined parameters. The study surfaces that the coefficient of determination and the correlation coefficient of HHV estimation based on the model reached 0.8517 and 0.9229, respectively. Shi et al[186] proposed a hybrid optimization algorithm that combines PSO and Genetic Algorithms (GA) for beechwood at three heating rates. The pyrolysis of beechwood was experimentally investigated and a numerical solver was built to simulate the pyrolysis details. The results show that PSO-GA has the highest probability of obtaining the desired results, and with a fixed population size, PSO-GA converges to a lower value of the fitness function, resulting in a higher accuracy.

In addition, ML models are widely used to predict product yields and properties during biomass pyrolysis and gasification, as well as to identify potential reaction pathways and kinetic parameters[187]. For example, models based on RF and ANN have been used to predict the properties of biomass pyrolysis products and the composition of syngas from biomass gasification[188]. In addition, the use of feature selection in combination with ML techniques is a new trend in research, which allows for more accurate prediction of high calorific values of biomass and improved modeling accuracy by selecting the most important explanatory variables[189].

5.2 Limitations and development prospects of machine learning applications in biomass conversion field

Although ML has made some breakthroughs in the field of biomass conversion, there are still many issues that need to be further addressed. The first challenge is data collection, analysis, and adaptation, a step also known as feature engineering. On the one hand, data from biomass conversion processes are often nonlinear and high-dimensional, which requires ML models to be able to handle complex datasets. However, these datasets may require the processing of both continuous and discrete features, all of which increase the complexity of model training and prediction[188]. On the other hand, data quality is also a key factor affecting ML prediction in biomass conversion. Current literature often lacks explicit details or sharing of unsuccessful and negative samples, resulting in these samples being discarded in the data cleaning process. As a result, positive data dominate the collected datasets, leading to biased and unbalanced biomass conversion datasets. These biased datasets do not accurately reflect the real-time situation of biomass conversion, making further ML predictions meaningless[190].

Furthermore, with the development of ML technology, complex nonlinear relationships in big data collected from real industrial production can be fitted using more advanced ML algorithms. However, such models, especially deep neural networks, often face the problem of poor interpretability, known as the “black box” nature[191]. Finally, the applicability of various ML models in the field of biomass conversion has not been comprehensively studied, or the application of traditional theoretical models in the biomass conversion process is limited by their assumptions or insufficient sample sizes in the derivation process, which leads to a narrow range of applicability conditions for the models[192].

Based on this, there are several important factors that deserve careful attention regarding the future prospects of ML applications in biomass conversion:

1) Improvements in data collection, analysis, and adaptation: With the development of feature engineering techniques, such as data preprocessing, feature extraction, feature selection, and feature construction, more efficient methods for handling nonlinear, high-dimensional data in biomass conversion processes can be anticipated. These include improved missing value processing, data normalization, and data cleaning, as well as more advanced feature coding and textual feature extraction techniques. Future research may focus on developing more efficient feature generation algorithms, as well as automated interpretive methods that make automatically generated features more interpretable. This will help to deal with bias and imbalance in biomass conversion datasets and improve the quality of the datasets and the generalization ability of the models.

2) Improve model interpretability and expand model applicability: In order to solve the “black box” problem of models such as deep neural networks, explainable artificial intelligence (XAI) technology will become a hot spot for research. XAI technology facilitates deeper comprehension of model decision-making processes and significantly improves model transparency and credibility. In addition, through multi-core learning and multi-view learning, different sources and types of data can be integrated to improve the robustness and applicability of the model. This helps to overcome the limitations of traditional theoretical models in the biomass conversion process and broaden the application scope of the models.

3) Data security and ethical issues: With the development of ML and AI technology, data security and ethical issues will become the focus of research. In the field of biomass energy, this means that new technologies and methods need to be developed to protect data from misuse while ensuring the sustainable development of AI

technology.

6 Conclusions and perspectives

This review provides an in-depth analysis of the utilization of biomass and its wastes, systematically describes the advances in the application of biomass conversion technologies, including biochemical and thermochemical conversion, and explores the potential of biomass conversion technologies for the production of valuable products such as biofuels and biochar. Biomass can be converted into gaseous, liquid, and solid products through thermochemical and biochemical conversion processes, which have a wide range of applications in the fields of energy, chemical industry, and agriculture[193]. The development and application of these technologies are not only of great significance to environmental protection and energy security, but also provide a new impetus for the sustainable development of the economy. In addition, this paper explores the application of machine learning in the field of biomass conversion, especially its potential in optimizing the biomass conversion process, improving the accuracy of energy yield prediction, and enhancing process control.

In view of the important role of biomass conversion technology in solving energy and environmental problems, future research directions and development trends are particularly important. The following are a few key directions for development:

1) Technological innovation and integration: Future research should focus on the development of more efficient biomass conversion technologies, including the integrated optimization of biochemical and thermochemical conversion to increase energy yield and reduce costs. At the same time, the application of new catalysts and biotechnology should be explored to improve conversion efficiency and product selectivity. For example, the "coal-to-biomass" technology[194] can fundamentally change the energy and mass density properties of biomass and break the technical bottleneck.

2) Application of machine learning and artificial intelligence: Given the potential of machine learning in optimizing the biomass conversion process, future research could further explore how advanced data analytics can be used to predict and optimize the biomass conversion process to increase energy production and reduce environmental impact. Machine learning techniques have a wide range of application areas, including image recognition, natural language processing, recommender systems, and predictive analytics[195], which can provide innovative solutions in the field of biomass energy, such as assisting in decision making through intelligent analytics to improve the efficiency and economic benefits of biomass energy conversion.

3) Construction of a sustainable biomass supply chain: In order to ensure the sustainability of biomass energy, a stable and sustainable biomass supply chain needs to be constructed. This includes the optimization of the planting, collection, storage, and transportation of biomass feedstock. The construction of the supply chain can be combined with machine learning, which can help companies predict demand more accurately, optimize inventory levels, and reduce operating costs by analyzing historical data and real-time information, while improving the ability to respond to market changes. Intelligent algorithms can enable logistics optimization, reduce transportation time and costs, and improve overall efficiency. In the case of biomass feedstock transportation, this means that delays and costs during transportation can be reduced and the efficiency of feedstock transportation can be improved.

4) Environmental impact assessment and life cycle analysis: Future research should pay more attention to the environmental impact assessment of the whole process of biomass energy production, and assess the environmental sustainability of biomass energy through life cycle analysis (LCA). Exploring the mass and heat transfer of reaction and separation processes, exploring the kinetics and thermodynamics of complex conversion systems, and constructing equations of state and basic physical property databases with reliable theoretical foundations are essential for assessing the environmental impacts of biomass energy and optimizing the utilization of biomass energy.

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