Progress in Biomass Energy Preparation and Conversion Technology Research

Siya Zhu *

Department of chemistry, Hong Kong University of Science and Technology, Hong Kong, China

* Corresponding Author Email: szhuay@connect.ust.hk

Abstract. Global energy demand is growing, while the overexploitation of fossil fuels has led to environmental pollution and climate change, triggering a global energy crisis. To meet this challenge, the development of renewable and sustainable clean energy has become a top priority. Biomass energy, as a renewable energy source, has the advantages of abundant resource reserves, strong sustainability, and environmental friendliness, which makes it an important direction for future energy development. This thesis discusses the characterization, preparation techniques, and storage methods of biomass energy, as well as the application of biomass energy modification technologies to improve energy storage efficiency. Thermochemical conversion technologies and biochemical conversion technologies are widely used to convert biomass into fuels, chemicals, or other useful products through high temperature and pressure conditions. As for storage methods, solid, liquid, and gaseous storage methods provide diverse options to increase the utilization efficiency and stability of biomass energy. Modification technologies play a key role in biomass energy storage, improving the storage efficiency and applicability of biomass energy through means such as surface modification and functionalized materials. The sustainable utilization and application of biomass energy cannot be separated from the integrated application of preparation technology, storage method, and modification technology, which provides an important reference for promoting clean energy and sustainable development.

Keywords: biomass energy, preparation technology, storage technology.

1. Introduction

As a renewable energy source, biomass energy has attracted much attention in the current context of global energy transition and environmental protection [1]. Biomass energy is derived from a variety of biomass resources, such as wood, herbaceous plants, and agricultural wastes, and is produced through a process of processing and conversion to produce biomass energy, including lignocellulose, bio-oil, and biogas. Lignocellulose is the main biomass energy component, consisting of hemicellulose, cellulose, and lignin [2]. Biomass energy source preparation technologies mainly include thermochemical conversion technology and biochemical conversion technology, in which thermochemical conversion technology converts biomass into fuels, chemicals, or other useful products utilizing high-temperature and pressure conditions to realize the reuse of resources. Biochemical conversion technology utilizes enzymes or microbial metabolic pathways in living organisms to convert organic wastes and biomass into useful chemicals, biofuels, or other organic products, which has the advantages of high efficiency, environmental protection, and sustainability. In addition to the traditional thermochemical and biochemical conversion technologies, photocatalytic technology, as an emerging biomass energy conversion technology, promotes chemical reactions by exciting electrons on the catalyst surface [3]. Meanwhile, storage of biomass energy is crucial for improving energy utilization efficiency and reducing energy loss. Traditional biomass energy storage methods include solid-state storage, liquid-state storage, and gas-state storage. Solid-state storage is the treatment of biomass feedstock into solid form to facilitate storage, transportation, and utilization. Liquid storage, on the other hand, is the conversion of biomass feedstock into liquid fuels with high energy density and portability. Gaseous storage is to convert biomass feedstock into gaseous fuel, which is suitable for a variety of energy conversion and utilization. To effectively improve energy utilization, the application of modification technology is crucial, and the storage efficiency and stability of biomass energy sources can be improved by surface modification and functionalized materials. In this paper, we will discuss in depth the characteristics of biomass energy sources, preparation technology, and storage methods, as well as the application of biomass energy source modification technology in improving energy storage efficiency, to provide theoretical support and technical guidance for the sustainable utilization and application of biomass energy source.

2. Characteristics of biomass energy

The focus of biomass energy preparation is on the processing and conversion of biomass resources (e.g., wood, herbaceous plants, agricultural wastes, etc.) through the utilization of biomass to produce biomass energy. The main components of lignocellulosic biomass are hemicellulose, cellulose, and lignin. The branch structure of hemocellulose is made up of various monosaccharide side groups, including xylose, mannose, glucose, and galactose, which makes it an amorphous heteropolymer. The heterogeneous structure of hemicellulose results in a low degree of crystallinity and therefore hemicellulose is capable of degradation at temperatures of 210-330 °C. Cellulose is the primary structural component of plant cell walls, composed of glucose units bound together by ß-(1-4) glucosidial bonds with a high degree of polymerization. Cellulose is impermeable to water in normal conditions and degrades at temperatures of approximately 300-380 °C. The chemical composition of lignin is heterogeneous and can be degraded at temperatures between 300-380 °C. Lignin is a biopolymer that contains complex aromatic compounds that make up 30% of all organic carbon on Earth, making it a viable source for aromatic chemicals in biomass. Three highly cross-linked phenylpropane units, p-coumarol, pinacol, and mustelol, are responsible for the formation of lignin, and the disordered repeating units are joined by ether or C-C bonds. The degradation temperature of lignin can vary widely between 150 and 1000 °C due to the irregular degree of polymerization.

Wood is usually rich in cellulose and has a high calorific value, making it suitable for combustion or gasification to prepare biomass energy. Herbaceous plants such as straw and reeds are rich in cellulose and have relatively low lignin content compared to other biomass materials, making them suitable for biomass ethanol production. Agricultural wastes such as rice husk and corn stover contain a large amount of cellulose, while hemicellulose is also an important component, which can be converted into biomass energy by pyrolysis or gasification [4].

3. Biomass energy preparation technology

3.1. Thermochemical conversion technology

Thermochemical conversion is a technology that converts organic matter, such as biomass, into fuels, chemicals, or other useful products under conditions of high temperature and pressure. In the thermochemical conversion process, biomass is heated to a high temperature so that it undergoes pyrolysis, gasification, cracking, and other chemical reactions to produce liquid fuels, gaseous fuels, biochar, and other products. Thermochemical conversion technology mainly includes biomass combustion, biomass gasification, biomass pyrolysis, and other methods, which can effectively utilize biomass resources to achieve energy conversion and resource utilization. This technology can reduce the dependence on traditional petroleum energy, reduce greenhouse gas emissions, and is conducive to environmental protection and sustainable development [5].

3.1.1. Combustion

Combustion is a process in which biomass or other organic matter is exposed to oxygen and heated so that it undergoes an oxidation reaction that releases heat energy and produces products such as carbon dioxide and water vapor. In thermochemical conversion technologies, combustion is typically used for direct combustion of biomass or as an additional step to other thermochemical conversion processes. Combustion is a common thermo-chemical conversion technology in which biomass is placed in a combustion plant and reacts with oxygen at high temperatures to release heat energy for generating steam, generating electricity, or providing thermal energy. During the combustion process, carbon, hydrogen, and other elements in biomass react with oxygen to generate carbon dioxide, water vapor, and other products, while releasing a large amount of heat. Biomass combustion not only realizes energy conversion, but also reduces the accumulation of waste, which is conducive to resource recycling and environmental protection.

The thermochemical transformation process that occurs in the presence of air is biomass combustion, which is the most fundamental. Heat, electricity, or cogeneration are the most common products that are burned directly from lignocellulosic biomass. The process involves a series of reactions that are both homogeneous and non-homogeneous. Depending on the particle size and nature of the feedstock, temperature, and combustion atmosphere, biomass combustion is achieved.

3.1.2. Gasification

Gasification is a process in which biomass or other carbonaceous materials are heated to high temperatures under oxygen-deficient or oxygen-restricted conditions so that they undergo pyrolysis, cracking, and gasification reactions to produce a combustible gas. During gasification, carbon, hydrogen, and other elements in biomass react with a gasifying agent (usually oxygen, water vapor, or carbon dioxide) to produce gaseous products such as carbon monoxide, hydrogen, methane, and other gaseous products, while at the same time releasing heat. It is a highly efficient biomass energy conversion technology that can convert biomass into syngas for power generation, fuel production, chemical feedstock, and other uses. The carbon monoxide and hydrogen in the syngas can be used to prepare liquid fuels (e.g., biodiesel, bioethanol), chemicals, or other energy products through further catalytic reactions.

Gasification is also known as an extension of pyrolysis, which is optimized to increase gaseous yields compared to liquid and solid phases. Oxygen is used instead of air as the gasification agent and nitrogen is removed as the diluent to produce high calorific value gas as the final product.

3.1.3. Pyrolysis

Pyrolysis is a process in which biomass or other organic materials are heated at high temperatures, without oxygen or with very low oxygen content, so that they undergo cracking and decomposition reactions to produce gases, liquids, and solid products. During pyrolysis, large organic molecules in biomass are heated to high temperatures and decomposed into small molecule gases (e.g., methane, carbon monoxide), liquid products (e.g., bio-oils), and solid residues (e.g., biochar). Pyrolysis is a common biomass energy conversion technology that can convert biomass into a variety of useful products. During pyrolysis, the type and yield of products can be regulated by controlling the temperature, reaction time, and reaction conditions to achieve efficient utilization of biomass resources. Biomass pyrolysis can produce bio-oil for the production of biofuels, chemicals, etc., bio-char can be used for applications such as soil improvement and carbon loading, and at the same time, the gas released through the pyrolysis process can be used for power generation, heating, and other purposes.

3.2. Biochemical conversion technologies

Biochemical conversion is a technology that utilizes enzymes or microbial metabolic pathways in living organisms to convert organic waste, biomass, or other biological feedstocks into useful chemicals, biofuels, or other organic products. In the biochemical conversion process, enzymes or microorganisms in organisms convert compounds in wastes or feedstocks into target products through catalysis, metabolism, or fermentation, thus realizing the resourceful utilization of wastes or the production of biomass energy. It involves a variety of reaction processes, such as enzymatic reactions, fermentation, metabolic pathways, etc., and can convert biowastes, agricultural wastes, wood fibers, etc., into biofuels (e.g., bioethanol, biodiesel), chemicals (e.g., organic acids, amino acids), pharmaceuticals, food additives, and other products. Utilizing biocatalysts in living organisms, this technology has the advantages of being highly efficient, environmentally friendly, and sustainable, helping to reduce dependence on fossil fuels, reduce waste emissions, and promote a circular economy and sustainable development. Biochemical conversion technology has a wide range of application prospects in the fields of bioenergy, biomedicine, and food industry. There are mainly two ways: anaerobic digestion and alcoholic fermentation [6].

3.2.1. Anaerobic digestion

Anaerobic digestion is the process by which microorganisms break down organic waste under anoxic conditions, producing gases such as methane and carbon dioxide while being converted into organic fertilizer and water. Anaerobic digestion is usually achieved through bioreactors or digestion tanks, where microorganisms metabolize under anaerobic or low-oxygen conditions, breaking down organic waste into simple organic compounds, which are then further converted into methane gas and carbon dioxide. This process, known as anaerobic digestion, produces methane gas that can be used for biogas or bioenergy production, and organic fertilizers that can be used for soil improvement and plant growth. Anaerobic digestion technology has the advantages of high efficiency, environmental protection and resource utilization, which can convert organic wastes into useful products, reduce waste emissions, reduce dependence on traditional fuels, and contribute to environmental protection and sustainable development. Anaerobic digestion has a wide range of applications in wastewater treatment plants, bioenergy production and agricultural waste treatment, etc.

3.2.2. Alcoholic fermentation

Alcoholic fermentation is a fermentative metabolic process through which microorganisms utilize carbohydrates as a source of energy, produce enzymes to break them down into simple organic matter, and then convert this organic matter into alcohol and carbon dioxide. Alcoholic fermentation has a wide range of applications in biochemical conversion technologies, including the winemaking industry and biofuel production. In winemaking, yeast converts glucose to alcohol and carbon dioxide through fermentation, resulting in the aroma and taste of alcohol. In biofuel production, alcoholic fermentation converts carbohydrates from plants into bioethanol, which can be used as a clean energy alternative to traditional fuels. Overall, through the process of alcoholic fermentation, carbohydrates can be converted into alcohol and carbon dioxide, enabling the conversion of waste resources and the production of biomass energy, helping to reduce dependence on traditional petroleum-based energy sources and promoting sustainable development and environmental protection.

3.3. Other technologies

In addition to thermochemical and biochemical conversion techniques, there are other preparation techniques such as photocatalysis. Photocatalysis is a process that uses light energy to excite electrons on the surface of a catalyst, thereby facilitating a chemical reaction [7]. In the conversion of biomass materials, photocatalysis can be applied in a variety of ways, such as photocatalytic degradation of biomass materials to produce useful compounds and photocatalytic conversion of biomass into biofuels or high-value-added chemicals. Photocatalysis can improve the conversion efficiency and selectivity of biomass materials, reduce energy consumption and chemical waste emissions, and be environmentally friendly. Photocatalytic technology has obvious advantages over traditional technologies

As far as temperature is concerned, photocatalysis allows biomass conversion under moderate conditions. Breaking multiple bonds necessitates heating to 150 °C. No stoichiometric reducing or oxidizing agents are employed to initiate biomass fragmentation. The heterogeneity of the process makes it easy to separate the products produced. Extracting and column separation are necessary to separate the generated products in many systems. In addition, recycling the photocatalyst is possible, which may reduce value-added costs on a large scale. The quality and yield of products obtained through photocatalysis may differ from those obtained through other technologies. Therefore, photocatalysis has the potential to compete with current methods for the production of specific products. Controlling the selectivity of the biomass value added is achievable through the design of the photocatalytic material. Reactive oxygen species (ROS) are a class of highly reactive oxidizing molecules produced in living organisms that act as oxidizing substrates, intermediates, or products in the photocatalytic process, selectively activating some specific bonds, which can be made difficult by technological advances. For example, O_2 reacts β radicals with C to form reactive peroxide intermediates [8].

In photocatalytic conversion technology, ROS plays an important role. Photocatalytic conversion is a process that uses light to stimulate the excited state electrons and holes generated on the surface of a catalyst to promote a chemical reaction. In this process, the generation and action of ROS can affect the reaction and the selectivity of the products.

4. Biomass energy storage technologies

4.1. Traditional storage technologies

In today's market, there are three main types of storage for biomass energy: solid storage, liquid storage, and gas storage [9]. Solid-state storage of biomass energy refers to the treatment of biomass feedstocks into solid forms, such as biomass pellets and biomass charcoal, to facilitate storage, transportation, and utilization. This type of storage improves the density, stability, and convenience of biomass energy, making it easier to apply to biomass fuels, biomass power generation, and other fields. Liquid storage of biomass energy refers to the process of converting biomass feedstock into liquid fuels through biomass conversion technology. The main forms of liquid storage include biodiesel and bioethanol. Liquid storage of biomass energy has high energy density and portability, and is suitable for transportation, heating, industrial production, and other fields. Through liquid storage, biomass energy can be more flexibly applied to different scenarios, promoting the development and utilization of renewable energy. Gaseous storage of biomass energy refers to the process of converting biomass feedstock into gaseous fuels through technologies such as gasification or fermentation. Biomass energy in gaseous storage has the characteristics of high energy density, portability, and flexibility, and is suitable for a variety of energy conversion and utilization methods. Through gaseous storage, biomass energy can be utilized more efficiently and promote the application and development of renewable energy in the field of energy supply. The characteristics of the three storage methods are summarized in Table 1.

Table 1. characteristics of the three storage methods

Storage mode	Storage efficiency	Storage cost	Security
Solid-state storage	The storage efficiency and energy density are lower	Relatively low storage costs for its simple handling and storage equipment	Relatively high safety, not easy to leak or cause fire
Liquid-state storage	The storage efficiency and energy density are rather high	Production processing and storage costs are high	Volatile and leakage, careful treatment is needed
Gas-state storage	The storage efficiency and energy density are high	Storage and compression costs are high	The storage pressure is high, and there are security risks of leakage. Strict control is required.

4.2. Modification techniques

With the development of society, the traditional storage methods can not meet the storage needs, through biomass energy modification technology to improve the efficiency of energy storage has become the mainstream direction of biomass energy storage. Modification technology refers to technology that utilizes physical, chemical, or biological methods to change the structure or properties of materials to improve their specific performance, increase added value, or expand application areas. In the field of energy, modification technology can be used to improve the utilization efficiency, stability, and applicability of energy materials and to promote the development and utilization of renewable energy. Modification techniques in biomass energy storage include surface modification, adding stabilizers, changing pore structure, reducing volatility, improving adsorption performance, reducing oxidation rate, functionalized materials, etc., of which functionalized materials and surface modification are the most common.

4.2.1. Functionalized materials

Functionalized materials are materials that are modified or treated to give them specific functions or properties, so that they have specific chemical, physical, or biological properties to meet the needs of specific applications. Such materials can be used in various fields, such as energy storage, sensors, catalysts, medical devices, etc., and have a wide range of application prospects. Functionalized adsorbents can be used in plants to improve the efficiency of storing and transporting biomass energy. For example, plants can use functionalized adsorbents, such as activated carbon or metal-organic framework materials, to adsorb and store biomass gases (e.g., methane, hydrogen, etc.). These functionalized adsorbents have higher adsorption capacity and selectivity, which can increase the storage density of biomass gases and reduce energy losses. By applying functionalized adsorbents in biomass energy storage plants, productivity can be increased, energy costs can be reduced, and environmental impacts can be reduced [10].

4.2.2. Surface modification

Surface modification is the process of changing the properties and performance of the surface of a material by introducing a new chemical composition, structure, or function to the surface. Such changes can be achieved by physical or chemical means and are aimed at enhancing specific properties of the material, such as surface wettability, corrosion resistance, abrasion resistance, biocompatibility, and so on. Surface modification can be applied to a variety of materials, including metals, polymers, ceramics, etc., and is widely used in industrial, medical, and electronic applications. Surface modification technology can be used to improve the utilization efficiency of biomass energy, reduce storage and transportation costs, and promote the sustainable development and application of biomass energy. For example, it is applied to materials such as biomass pellets or biomass charcoal to improve their storage and utilization efficiency. Through surface modification, the adsorption properties, stability, and renewability of biomass pellets can be improved, thus increasing their storage density and extending storage time. In addition, surface modification can enhance the adsorption capacity and electrical conductivity of biomass charcoal, making it more suitable for applications such as adsorption for hydrogen storage, adsorption for thermal storage, or electrochemical energy storage [11].

5. Summary

As a renewable energy source, biomass energy has abundant resources and broad application prospects. The utilization efficiency and environmental performance of biomass energy can be improved through the study of the characteristics, preparation technology, and storage methods of biomass energy. The modification technology of biomass energy sources is of great significance in improving the efficiency of energy storage and reducing energy loss, and it should be increased in research and application. Traditional solid, liquid, and gaseous storage methods provide the basis for the effective storage of biomass energy sources, while the application of modification technologies further improves storage efficiency and stability. The application of technologies such as surface modification and functionalized materials can improve the storage performance and applicability of biomass energy and promote the sustainable use of biomass energy. In the future, with the continuous innovation and development of technology, biomass energy will play a more important role in the energy field and contribute to the realization of clean energy and sustainable development. With the joint efforts of the government, industry, and academia, biomass energy will probably become an important pillar in the transformation of the energy structure, contributing to the building of a green and low-carbon society.

References

[1] Cihan Gokcol, Bahtiyar Dursun, Bora Alboyaci, et al. Importance of biomass energy as alternative to other sources in Turkey. Energy Policy, 2009, 37: 424-431.

[2] Sorek N, Yeats T H, Szemenyei H, et al. The Implications of Lignocellulosic Biomass Chemical Composition for the Production of Advanced Biofuels. BioScience, 2014, 64 (3): 192-201.

[3] Akhundi A. Photocatalytic reforming of biomass-derived feedstock to hydrogen production. Research on Chemical Intermediates, 2022, 48: 1793-1811.

[4] Serapiglia M J, Humiston M C, Xu H, et al. Enzymatic saccharification of shrub willow genotypes with differing biomass composition for biofuel production. Front Plant Sci, 2013, 25;4:57.

[5] Damartzis T, Zabaniotou A. Thermochemical conversion of biomass to second generation biofuels through integrated process design-A review. Renewable and Sustainable Energy Reviews, 2011, 15: 66-36.

[6] Maansi Aggarwal, Soumen Basu, Nagaraj Shetti, et al. Photocatalytic conversion of CO_2 into valuable products using emerging two-dimensional graphene-based nanomaterials: a step towards sustainability. Chemical Engineering Journal, 2021, 425: 131401.

[7] Shanmugam Poornima, Sivasubramanian Manikandan, Rajavel Prakash, et al. Muthusamy Govarthanan, Biofuel and biochemical production through biomass transformation using advanced thermochemical and biochemical processes - A review. Fuel, 2024, 372.

[8] Xinwei Sun, Kaiqi Xu, Athanasios Chatzitakis, et al. Photocatalytic generation of gas phase reactive oxygen species from adsorbed water: Remote action and electrochemical detection. Journal of Environmental Chemical Engineering, 2021, 9: 2.

[9] Yeon S H, Osswald S, Gogotsi Y, et al. Enhanced methane storage of chemically and physically activated carbide-derived carbon. Journal of Power Sources, 2009, 191 (2), 560-567.

[10] Kwadwo Mensah-Darkwa, Stefania Akromah, Ram K Gupta. Chapter 9-Advanced applications of biomass for energy storage. Elsevier, 2022, 171-209.

[11] Costa R, Pereira C M, Silva A F. Insight on the effect of surface modification by carbon materials on the ionic liquid electric double layer charge storage properties. Electrochimica Acta, 2015, 176: 880-886.

[12] Ridha Djellabi, Dominic Aboagye, Melissa Greta Galloni, et al. Combined conversion of lignocellulosic biomass into high-value products with ultrasonic cavitation and photocatalytically produced reactive oxygen species - A review. Bioresource Technology, 2023, 368.