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The Role of Biomass Energy in Zero-Carbon Development: A Review on Bioethanol, Biochar, and Biogas

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Abstract. To meet the global requirements for carbon peaking and carbon neutrality, there is a growing interest in biomass energy as a clean energy source on a global scale. This review organizes the current research status of bioethanol, biochar, and biogas. It summarizes the energy ratios and CO_2 equivalents of these three types of biomass energy under different raw materials. Compared with traditional and other clean energies, biomass energy has unique advantages in energy saving, emission reduction, and economic benefits. In the future, research on biomass energy will refine the comprehensive utilization of biomass, reasonably and objectively estimating the potential of biomass energy. Moreover, related studies will continuously focus on improving manufacturing materials. In the future, biomass energy should focus on transitioning to non-grain raw materials and then to microbial raw materials, seeking effective ways for large-scale and efficient production, thus making significant contributions to the world's zero-carbon development.

Keywords: Bioethanol, Biochar, Biogas, Energy Ratio, CO_2 Equivalent.

1. Introduction

Climate warming has brought extensive and profound impacts on the Earth's ecosystem, human society, and economic development. Controlling greenhouse gas emissions is a major global challenge faced by all humanity. By the end of 2023, more than 150 countries worldwide have proposed carbon neutrality targets. Biomass energy, owing to its renewable nature, minimal environmental impact, vast availability, abundant resource base, and its capability to achieve carbon neutrality, has garnered increasing international attention as a viable and clean energy alternative.

Biomass energy is the stored chemical energy within organic matter, which is ultimately sourced from solar radiation. As a prominent energy source, it ranks fourth globally, trailing coal, oil, and natural gas, yet plays a vital role in the broader energy structure. It is predicted that from 2023 to 2028, the demand for biofuels will increase by 38 billion liters, nearly a 30% growth compared to the past five years. In fact, by 2028, the total demand for biofuels will grow by 23%, reaching 200 billion liters; by 2030, biogas production will quadruple from the 2022 baseline of 1.6 EJ [1].

Against the backdrop of the growing demand for biomass energy, evaluating the environmental benefits of biomass energy has become a research hotspot among scholars. Based on extensive research by international scholars, this paper reviews the current research status on the impact of three widely used biomass products—bioethanol, biochar, and biogas—on greenhouse gas emissions.

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2. Main Text

2.1. Current Research Status of Bioethanol

Bioethanol refers to a type of renewable energy that converts various biomass into fuel alcohol through microbial fermentation, which is the most widely used biofuel globally. It not only has environmental and sustainable properties but can also be used as automotive fuel either alone or blended with gasoline to make ethanol gasoline.

The "2023 Biofuel Ethanol Industry Outlook" report reveals that the United States witnessed a surge in biofuel ethanol production, reaching 15.4 billion gallons in 2022. Notably, this biofuel ethanol now comprises a record-high 10.4% of gasoline consumption in the country. According to data released by Argus Media, Brazil's total ethanol production in 2023 was 2.558 billion liters.

Bioethanol is primarily derived from materials rich in sugar and starch. In the United States, corn is the primary feedstock for bioethanol production, while Brazil utilizes sugarcane for this purpose.

Table 1. Energy Ratios and Greenhouse Gas Emissions of Bioethanol from Diverse Feedstocks.

Year	Country	Raw Material	E Output/E Input	Greenhouse Gas Emissions
2011[2]	Brazil	Sugarcane	12.5	21.3gCO_2eq/MJ
2012[3]	USA	Sugarcane	4.32	45gCO_2eq/MJ
2019[4]	Brazil	Sugarcane	—	16-45gCO_2eq/MJ
2012[3]	USA	Corn	1.61	76gCO_2eq/MJ
2013[5]	USA	Corn	9.20	58.8gCO_2eq/MJ
2019[4]	Brazil	Corn	—	43-62gCO_2eq/MJ
2012[3]	USA	Corn Stalks	4.77	23gCO_2eq/MJ
2021[6]	EU	Wheat, Corn Stalks	—	19.4-19.6gCO_2eq/MJ

As shown in Table 1, generally speaking, among the three types of raw materials for producing bioethanol—sugarcane, corn, and crop stalks—crop stalk-based bioethanol has certain advantages in terms of energy savings and greenhouse gas emissions.

To align with sustainability benchmarks and address greenhouse gas emission regulations, the production of bioethanol is undergoing a transition from first-generation methods, which rely on food crops as feedstocks, to second-generation products that utilize non-food biomass sources.

Second-generation bioethanol primarily uses lignocellulosic biomass as raw material. This type of raw material is abundant in many countries and regions but is currently underutilized. In many cases, it does not require fertile land or intensive management to produce, so the potential environmental and social impacts of biofuel systems are expected to be significantly reduced. However, second-generation bioethanol production is still in its infancy and requires the use of LCA (Life Cycle Assessment) to compare the advantages of various potential routes brought by technological developments. Specifically, optimizing parameters at each production stage (such as water usage, total energy consumption, total production costs, and waste generated) can produce the desired amount of ethanol.

2.2. Current Research Status of Biochar

Biochar is a carbon-rich, charcoal-like substance created through the process of anaerobic pyrolysis. It is a more stable form of carbon. Its carbon sequestration benefits arise from the transfer of carbon from the atmospheric-biospheric cycle to a slower microbial degradation process[7]. The environmental benefits of biochar are mainly influenced by the thermal conversion method, preparation temperature, and production raw materials.

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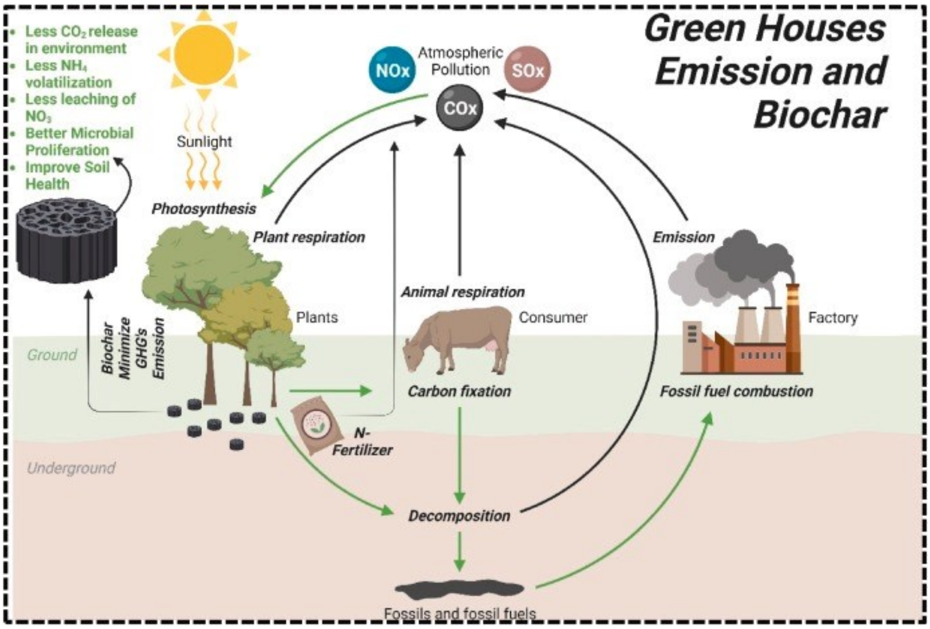

Figure 1. Greenhouse Gas Emissions and Potential Benefits of Biochar Applications.

Slow pyrolysis, a thermal decomposition process carried out within a temperature range of 300-700°C, efficiently converts biomass into biochar, producing minimal quantities of condensed bio-oil and syngas as byproducts, thereby maximizing the yield of biochar. This is a simple, robust process with cost and environmental benefits.

In biomass fuels obtained from fast pyrolysis, bio-oil yield is high, enhancing overall energy efficiency. However, the yield of biochar produced by this method is relatively low. In addition, biochar from fast pyrolysis, due to the presence of more moist products and physicochemical properties beneficial to microorganisms, emits more CO_2 than biochar from slow pyrolysis.

Table 2. Reaction Conditions and Product Distribution of Various Pyrolysis Modes.

Process	Temperature(℃)	Residence time	Yields (%)		
			Biochar	Bio-oil	Syngas
Slow pyrolysis	300-700	Hour-days	35	30	35
Intermediate pyrolysis	~500	10-20s	20	50	30
Fast pyrolysis	500-1000	<2s	12	75	13
gasification	~750-900	10-20s	10	5	85
Hydrothermal carbonization	180-300	1-16h	50-80	5-20	2-5
torrefaction	~290	~10-60min	80	0	20

In evaluating the ultimate stability of biochar in soil systems, Kurt A. Spokas[7] proposes utilizing the oxygen-to-carbon (O:C) molar ratio as an indicator to predict biochar properties. His findings indicate that as pyrolysis temperatures rise, the O:C ratio decreases, and conversely, a higher O:C ratio correlates with a shorter half-life for biochar. An increase in the relative carbon content within biochar may contribute to a higher graphite content, which resembles graphene's structure of flat, single-layer polycyclic aromatic hydrocarbon carbon atoms. This graphene-like structure endows biochar with exceptional stability and resistance to degradation, favoring its long-term preservation.

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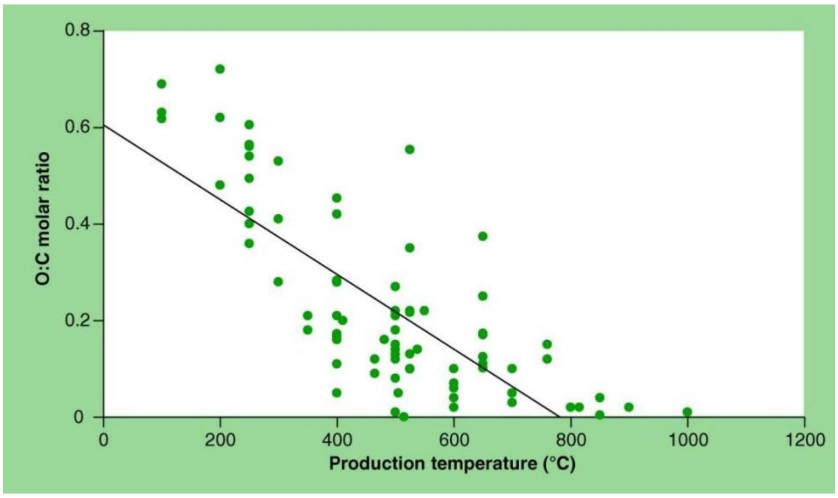

Figure 2. General Relationship Between Pyrolysis Production Temperature and Oxygen-to-Carbon (O:C) Molar Ratio of Synthetic.

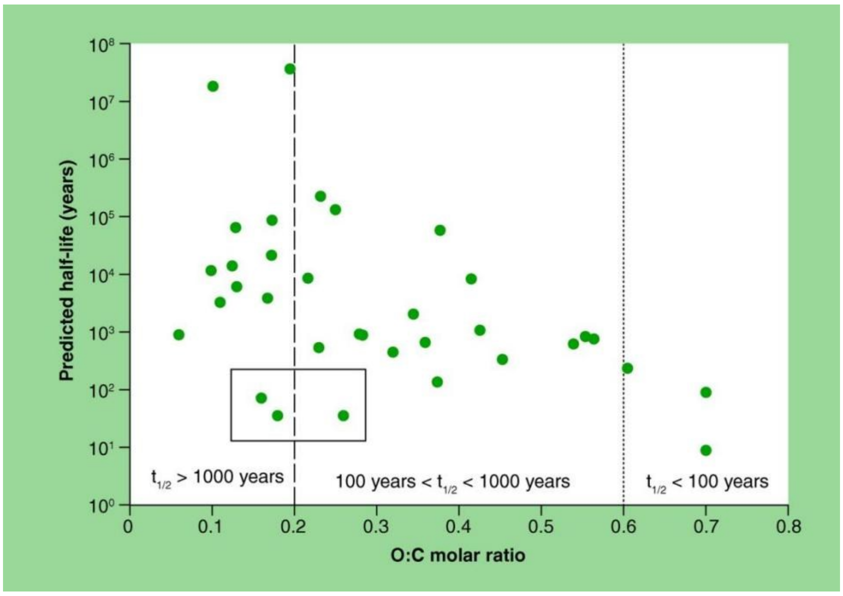

Figure 3. Correlation Between Oxygen-to-Carbon (O:C) Molar Ratio and Predicted Half-Life of Synthetic Biochar in Various Laboratory Incubations[7].

In the research on the impact of raw materials on biochar preparation, Roberts et al.[8] assessed the energy efficiency and environmental impact, particularly in terms of climate change emissions, of slow pyrolysis applied to diverse biomass feedstocks including late stover, early stover, switchgrass, and yard waste. Their results, presented in Figure 4, demonstrate that the system achieves a positive net energy balance, signifying a net gain in energy output over input. Regarding greenhouse gas emissions, except for an increase in net emissions for switchgrass B, the others are negative emissions. The article also specifically mentions that when biochar is applied to the soil, greenhouse gas emissions are reduced by 29%.

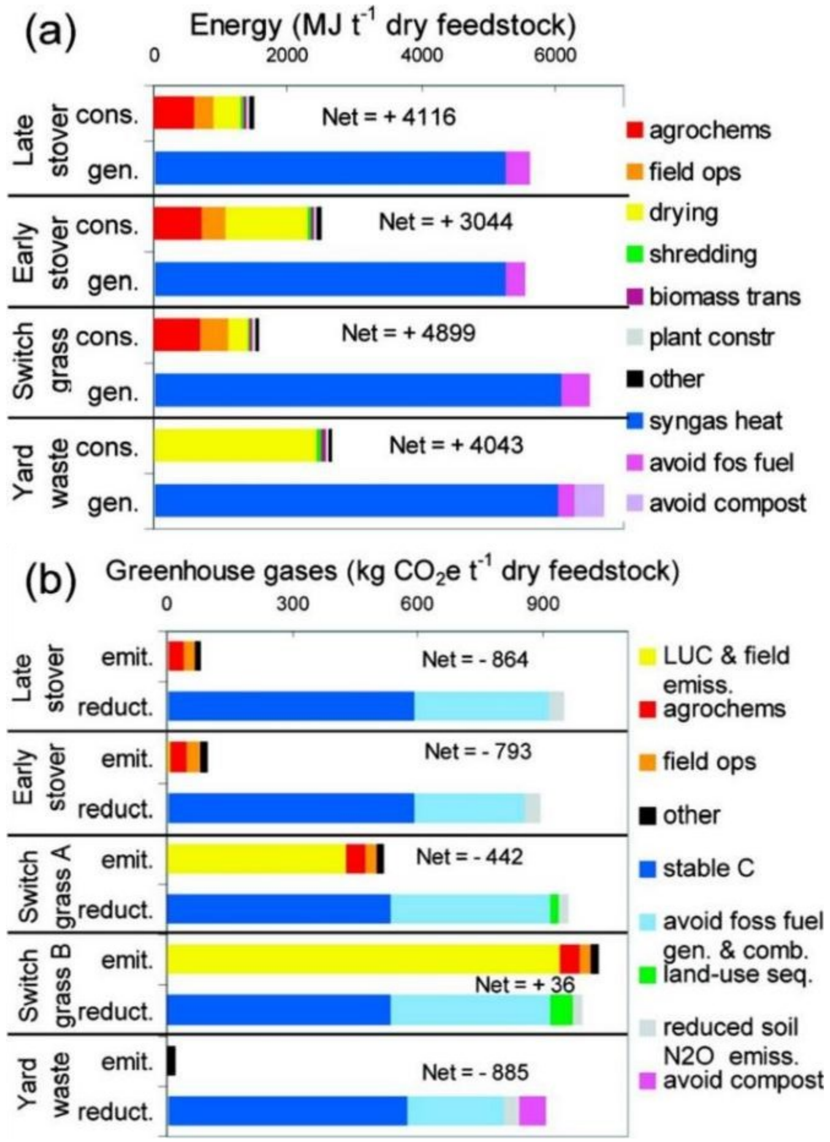

Figure 4. (a) Net Energy per Dry Ton of Biomass Feedstock in Biochar Systems with Bioenergy Production and (b) Net Climate Change Impact[8].

2.3. Biogas

Biogas production began to increase in the 1990s and has continued to rise. The International Energy Agency (IEA) included a dedicated section on biogas for the first time in its Renewable Energy Market Report 2023. Firstly, biogas, as a local energy resource, can enhance energy security and autonomy for many countries. Secondly, countries are increasingly viewing biogas as a ready-to-use technology for accelerated decarbonization. Additionally, biogas can help decarbonize sectors in transportation and industry that are difficult to electrify. Its role in rural economic development is also noteworthy[1].

The production of biogas and biomethane starts with anaerobic digestion (AD) of organic waste, which is primarily composed of a mixture of CH4 and CO2. After purification, the biogas can yield gas containing 95-98% CH4.

In biogas production, Pål Börjesson et al.[9] assessed six biogas crop feedstocks (Hemp, Sugar Beet, Maize, Triticale, Ley Crops, Wheat (grain)). They found that Ley Crops had the lowest greenhouse gas emissions, with emissions of 4.1 kg CO_2-eq·GJ^{-1} biomass under 100% mineral fertilizer (NPK) conditions, and even a negative emission of -4.2 kg CO_2-eq·GJ^{-1} biomass with the combination of digestate and mineral fertilizer (dig+NPK). In terms of energy balance, Hemp performed the best, with an input-output ratio of 9.9% under NPK conditions and 5.8% under dig+NPK conditions.

As research continues to expand, there has been a notable increase in studies exploring the co-digestion of multiple substrates for biogas generation. Wang et al. [10] conducted laboratory-based experiments and discovered that the combined digestion of pig manure, corn stover, and fruit and vegetable waste led to a significant enhancement of 39.5% in biogas production, when compared to the anaerobic digestion of pig manure as a standalone substrate. Additionally, the DOC (dissolved organic carbon) degradation rate was higher. In their subsequent research, they added enzymes (cellulase, amylase, protease) to the co-digestion system (cow manure and corn stover) to improve the production process. The experimental results showed that the gas production in the groups with added cellulase and milk powder enzyme was doubled compared to the untreated control groups.

Through specific research cases, it is evident that the environmental and energy benefits of the three types of biomass energy differ significantly due to the variations in raw materials used in production. Therefore, aside from making full use of various biomass resources, determining the optimal energy crop for large-scale production is of significant importance for each type of biomass energy. Additionally, for processes requiring microbial involvement, finding and cultivating suitable strains of microorganisms is also a key focus of current research.

3. Advantages of Biomass Energy in Greenhouse Gas Emission Reduction

CThe importance of biomass energy in mitigating greenhouse gas emissions is universally acknowledged, as it offers a viable alternative to fossil fuels. According to the article authored by Harish K et al., when excluding the influence of land use changes, the global warming potential (GWP) associated with biofuels is generally lower than that of fossil fuels, highlighting their environmental advantages [11].

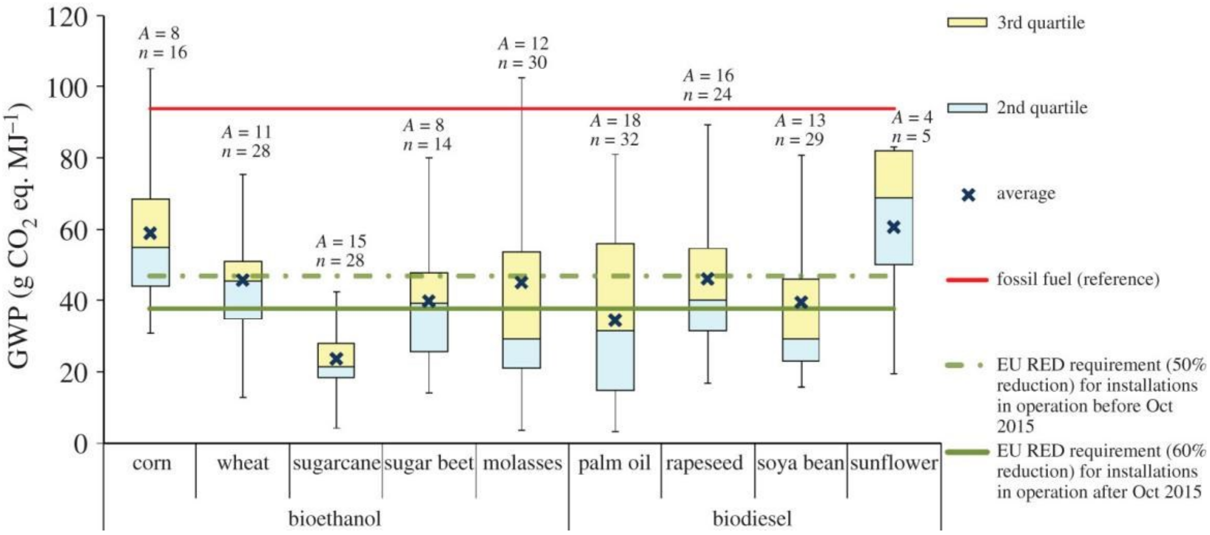

Figure 5. GWP of Biofuels without Considering Land Use Change Impacts [11].

Furthermore, biofuels exhibit distinct advantages in terms of energy efficiency. The majority of research suggests that the fossil energy consumed in the production of both first-generation and second-generation biofuels is minimal, estimated to be less than 0.5 MJ per MJ of biofuel produced, emphasizing their superior energy balance.

Compared to other clean energy sources, biofuels also have substantial competitiveness.

Hydrogen has a high heating value and does not produce pollutants when burned, making it a rare, highly efficient, and green clean energy source. However, the high production cost remains a major barrier. Additionally, current hydrogen production technologies are not yet mature. Steam Methane Reforming (SMR) is the main method for hydrogen supply in Europe, with a benchmark for the SMR

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hydrogen production process set at only 91 gCO2eq/MJ. In terms of greenhouse gas emissions, this is still notably inferior to biomass fuels.

Photovoltaic (PV) systems are also a clean and sustainable energy source with good emission reduction benefits. Their carbon footprint ranges from 50.4 to 262.8 g CO2-eq/MJ [12]. However, Muhammad Tawalbeh et al. [12] summarize in the literature that the use of solar energy in photovoltaic systems instead of traditional energy sources impacts the environment in as many as 32 ways. The environmental impact of these systems can vary depending on their installation locations, which encompass diverse ecosystems including forests, deserts, grasslands, and farmlands.

In conclusion, different clean energy sources have their respective suitable scenarios. Considering the existing technological constraints faced by various clean energy sources, the development of biomass fuels holds significant potential.

Yang et al. [13] project that harnessing merely 33% of China's crop residues for biochar production and its subsequent application in practical settings could lead to a substantial reduction of 54.27 Mt CO2-eq emissions annually. Envisioning a scenario where China employs its advanced Biomass Intermediate Pyrolysis Coproduction (BIPP) technology to convert 73% of crop residues into biochar and biofuels from 2020 to 2030, and subsequently integrates bioenergy with carbon capture and storage (BECCS) after 2030, the cumulative greenhouse gas reduction by 2050 could potentially soar to 8620 million tonnes of CO2. Notably, this reduction by 2050 is projected to contribute significantly, accounting for 13% to 31% of the global greenhouse gas mitigation target set by BECCS.

Europe, leading the industry with over 50% of the biogas market share, is expected to produce over 380 TWh of biogas by 2030. This figure will exceed 10% of the EU’s natural gas consumption in 2023. Furthermore, the industry’s growth is projected to create over 420,000 jobs in Europe by 2030 [14].

From the perspectives of Global Warming Potential (GWP) and the market potential of biochar, bioethanol, and biogas, it is evident that biomass energy not only has significant advantages in energy conservation and emission reduction but also plays an important role in promoting employment and economic development globally.

4. Summary

Biomass energy holds significant importance and role in the global context of carbon neutrality. As a crucial component of renewable energy and one of the key sources of zero-carbon energy, the development of biomass energy will contribute to optimizing and upgrading the global energy structure and promoting sustainable economic and social development. This review summarizes the current research status of biomass energy represented by bioethanol, biochar, and biogas. Compared to traditional energy sources, biomass energy performs well in terms of energy efficiency, environmental benefits, and economic advantages; and it also has unique advantages compared to other clean energy sources. Future research should refine the considerations of integrated biomass utilization and objectively and appropriately estimate the potential of biomass energy. Additionally, in future research directions, biomass energy should focus on transitioning from food-based raw materials to non-food-based raw materials, and then to microbial-based raw materials, exploring effective pathways for large-scale and efficient production.

5. Conclusion

Biomass energy products exhibit strong performance in energy efficiency, environmental benefits, and economic advantages, and have garnered widespread attention from scientists. However, there are still some shortcomings in the related research.

Currently, existing studies often overlook the fact that biomass has already been utilized extensively, lacking competitive analysis of other utilization pathways. Although there may be a significant amount of biomass available in different countries, a considerable portion may have already been effectively utilized by various sectors, such as the furniture industry, paper industry, and fertilizer industry. Ignoring this fact could seriously overestimate the potential yield of various biomass products and their contributions to mitigating climate change. Furthermore, policies promoting biomass industry development based on "overestimation" could potentially encroach upon the survival space of other industrial sectors. More indirect land use changes may also arise, such as importing biomass from other regions. Equally important is the issue with research tools; many Life Cycle Assessment (LCA) models have their own problems, including outdated default data, missing inventory data, and different utilization methods for by-products. These factors can impact the effectiveness of biomass product assessments.

In terms of future research directions, biomass energy is expected to transition from food-based raw materials to non-food-based raw materials and then to microbial-based raw materials. Although first-generation biofuels are more productive and cost-effective, they require food or oil crops as raw materials. This can lead to changes in land use types and affect global food supply. Second-generation biofuels mainly use agricultural and forestry residues. While they do not threaten food security, they still impact resources such as arable land, water, and pesticides. Moreover, second-generation products primarily utilize components such as cellulose, hemicellulose, and lignin, which require additional chemical processes and enzymatic hydrolysis. Third-generation biomass products are algal biofuels. They are characterized by high productivity, ease of processing, and strong greenhouse gas absorption and conversion capabilities. Importantly, algae can grow in seawater and wastewater, thus avoiding competition with food crops for freshwater or soil resources. Fourth-generation biofuels include algae, cyanobacteria, fungi, and genetically modified microorganisms [15]. Fourth-generation biomass fuels employ more diverse and complex methods and approaches to enhance energy conversion efficiency, including gene editing technologies, genetic engineering techniques, synthetic biology methods, computational biology methods, and some common processing methods such as biochemical methods and pyrolysis methods. Microbial-based biofuels also have the potential for large-scale industrial production. Using open ponds and tubular photobioreactor systems allows for more efficient production.

Overall, in current research on biomass energy, there is a need to strengthen the objective evaluation of its potential, considering the utilization of biomass raw materials by other production sectors. Additionally, further research should focus on the variety of energy raw materials, exploring the efficient preparation of large-scale biomass energy from microbial sources.

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