Biomass Conversion through Nanotechnology and Circular Economy

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Abstract

We have seen a huge utilization of fossil fuels due to the rise of energy requirements in the last decade. Biomass fuel production is the best alternative to meet this requirement and to protect the environment from hazards created by conventional energy resources like fossil fuels. Biomass can be converted into biofuel through different methods like gasification, direct liquefication, and biological processes. Nowadays the commonly used method for biofuel production is a catalytic process. In this regard, nanocatalysts are significant due to their high-quality fuel production and optimal working conditions. Nanocatalysts are more advanced than heterogenous catalysts as the present solution to common issues like limited outcomes, time-consuming processes, *etc*. As a result, there has been an increasing trend in the development of novel nanocatalysts. This study centers on biofuels and addresses several areas including categorization, manufacturing techniques, and approaches to enhance productivity using nanocatalysts. Ultimately, the study analyzed the prospective prospects and obstacles associated with utilizing nanocatalysts in the conversion of biomass into biofuels

Keywords: Sustainable biofuel production, Green nanocatalyst, Catalytic nanotechnology Circular Economy

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Introduction

Fossil fuels, such as coal, oil, and gas, have emerged as the predominant options for meeting the growing energy needs. Conventional fossil fuels currently meet almost 80% of the total energy demand. However, they also have several disadvantages (Hou et al., 2017). Due to their non-renewable nature, fossil fuels will eventually be depleted, resulting in a significant energy crisis. The growing predominance of energy sources results in a corresponding rise in costs, posing a considerable economic challenge, especially in developing nations. The primary issue at hand is the irreversible ecological harm resulting from using these traditional fuels. Fossil fuel combustion leads to environmental problems that's why there is a need for alternatives that have a positive effect on the environment (Yao et al., 2011; Chen et al., 2018; Yang and Wang 2018). Biofuels are best in this regard as they are environment friendly and broad range of raw materials (Adegboye et al., 2021).

The Biofuel sector has been revolutionized with the application of nanotechnology. The ability of microorganisms to produce biofuel has been enhanced by assisting with nanomaterials like nano-sheets, nanotubes, etc. (Bhardwaj et al., 2021). There are different nanoparticles (NPs) are used in this process, each has its advantages like thermal stability. Catalysts can prevent or minimize the formation of detrimental byproducts during chemical reactions. NPs possess a significant surface area and exhibit strong reactivity, rendering them appropriate for utilization as catalysts or as supports for catalytic processes. The utilization of NPs in catalysts increases their durability, hence reducing the frequency of expensive and resource-intensive replacements or regeneration (Li et al., 2014; Morsi et al., 2018; Ndolomingo et al., 2020; Mishra et al., 2021).

The primary objective of using nanobiotechnology is to decrease the expenses associated with transporting feedstock and enhance the breakdown of feedstock, hence increasing the efficiency of bioenergy production (Abusweireh et al., 2022). Nanobiotechnology holds the capacity to enhance energy efficiency, mitigate environmental impacts, and establish economic viability for bioenergy in comparison to conventional fossil fuels. It can be incorporated into bioenergy research and production operations. Many biorefineries use coated NPs on their equipment to provide corrosion protection and thermal insulation (Thomas et al., 2022), resulting in a more environmentally friendly process. The utilization of nano-metals for energy generation can enhance the commercial feasibility of microorganisms. Nanoscale studies are conducted to investigate enzymatic activity, where the enzymes themselves function as nano-objects. The utilization of nanoscale technologies has also expanded into research and development (R&D) in other domains.

The objectives of the chapter are given below.

1. Present an outline of modern biofuel production techniques, highlighting the importance of nanotechnology in expanding the effectiveness and sustainability of these methods.
2. Investigate different nanomaterials and their applications in biomass conversion, highlighting their catalytic attributes and potential to increase productivity.
3. Review the challenges and opportunities of integrating nanocatalysts into biofuel production, focusing on the circular economy and environmental sustainability.
4. Assess the potential of agricultural biomass and microalgal biomass as feedstocks for biofuels, as the role of nanotechnology in improving bioenergy production.

What does BIOMASS mean?

Biomass is an organic material obtained from organisms and used for the production is renewable energy. There is a need to produce energy sources with minimal negative effects on the environment. Biomass energy is the only one that does not have any limitations in terms of supply and accessibility. Biomass pertains to the organic matter obtained from living organisms or those that have just ended life, encompassing both plant and animal sources (Asadi, 2020; Jareteg, 2020). Organic materials possess the potential to serve as an energy source through their combustion or conversion into biofuels. Typical instances of biomass encompass wood, remnants of crops, agricultural waste, and specifically cultivated energy crops such as switchgrass and willow. Biomass emerges as a noteworthy renewable energy source that offers potential as an alternative to enhance energy self-sufficiency instead of fossil fuels and mitigate environmental degradation. Biomass exhibits potential as an alternative fuel source that can be utilized as a backup to meet the power grid demands during instances of production losses resulting from the intermittent nature of other renewable sources, which are reliant on weather conditions. Thermochemical conversion methods, including torrefaction, pyrolysis, hydrothermal liquefaction, gasification, and combustion, can be employed to utilize biomass for the generation of energy, biofuels, or chemical compounds. All of these methods are promoted as solutions that have worked very well in changing different types of biomasses into solid, liquid, and gaseous forms that can then be used to make energy, biofuels, and chemicals (Klaas, 2020; Torres, 2020; Zalazar-Garcia, 2022).

Role of Nanotechnology in Biomass Conversion

The latest advancements in nanomaterials technology have attracted significant attention due to their ability to convert various forms of biomass into useful products. The term 'Nano' has its origins in the Greek prefix that is commonly connected with the notion of 'dwarf,' denoting a factor of one billionth (Hulla et al., 2015; Nasrollahzadeh et al., 2019). Nanomaterials are widely employed in several industries such as medical, cosmetics, packaging, nanofiber manufacturing, biosensors, and electronics. The amazing magnetic, catalytic, mechanical, optical, and electrical properties of these entities have generated great interest, making them a prominent area of focus in ongoing research efforts (Thanh et al., 2014; Titus et al., 2019).

Types of Nanomaterials

Nanomaterials can be categorized according to several parameters. One distinguishing factor is the composition of the materials they are made of. Depending on the diversity of the materials, they can be broadly grouped into the following categories as shown in figure 1

Trends in Agricultural Biomass and Current Conversion

Agriculture biomass has been used as a source of energy since 1830 when it was first used to produce ethanol in Ethiopia utilizing the *Euphorbia abyssinica* plant (Smil, 1999). Globally, massive amounts of biomass are produced, with straw of wheat, rice, corn, and bagasse of sugarcane (Sarkar et al., 2012). Sarkar et al. (2012) gathered data on the worldwide disposal of various agricultural ruins and discovered the topmost manufacture to be straw of wheat. Asia produces the most wheat and rice straw. Throughout the last 3 decades, research in the United Mexican States has revealed the highest average potential of 3203 PJ per annum (Aleman-Nava, 2014).

Lignocellulose molecules, which are plentiful in agricultural biomass, are a critical component in biofuel generation. Table 2 shows the configuration of the main agricultural biomass in weight % of dry matter (Ali et al., 2019). According to reports, around 950 million tonnes of biomass are formed yearly in Europe and can be secondhand to make 0.3 billion tonnes of oil equivalent fuel (Stout, 2012).

Conversion of Agricultural Biomass into Various Energy Products

1. Production of Ethanol from Agricultural Biomass

Agricultural biomass contains hemicellulose and cellulose, which can be renewed into bioethanol (Patzek, 2005). Poland is a forerunner in terms of utilizing agricultural-based ethanol additives in petroleum. Approximately 2.5 million tonnes of biomass will be cast off to make bioethanol in Poland (Champagne, 2007; Acharya, 2019). Canada is a world leader in bio-ethanol production with the capacity to produce 5336 million liters of bio-ethanol from agricultural biomass each year (Kim, 2004). The increased use of agricultural biomass to make biofuel reflects a substantial shift in policy and environmental goals, which will result in a big revolution in the fuel market. Global ethanol output was predicted to be more than 30GL (Giga Liters) in 2001, but it climbed to more than 94GL in 2015. The biggest contributors to ethanol production are the United States and Brazil, which account for around 85% of global ethanol output (WFEP, 2017).

2. Fuel Pellets of Agricultural Biomass

Dry leaves, tree bark, and tree pruning from agricultural land are sometimes used to make fuel pellets. The usage of fuel pellets in industrial boilers has increased by 13% (Lehtikangas, 2017). According to studies, logging residue pellets have higher thermal power and can be applied in ordinary boilers to create power (Swanston, 2005). Pradhan et al. (2018) manufactured comparable quality pellets from orchard biomass exclusive of the use of any binder. The combustion test confirmed the suitability of pellets for domestic cooking. A palletization prototype research was also carried out, which confirmed the feasibility of fuel pellets (Pradhan et al., 2018).

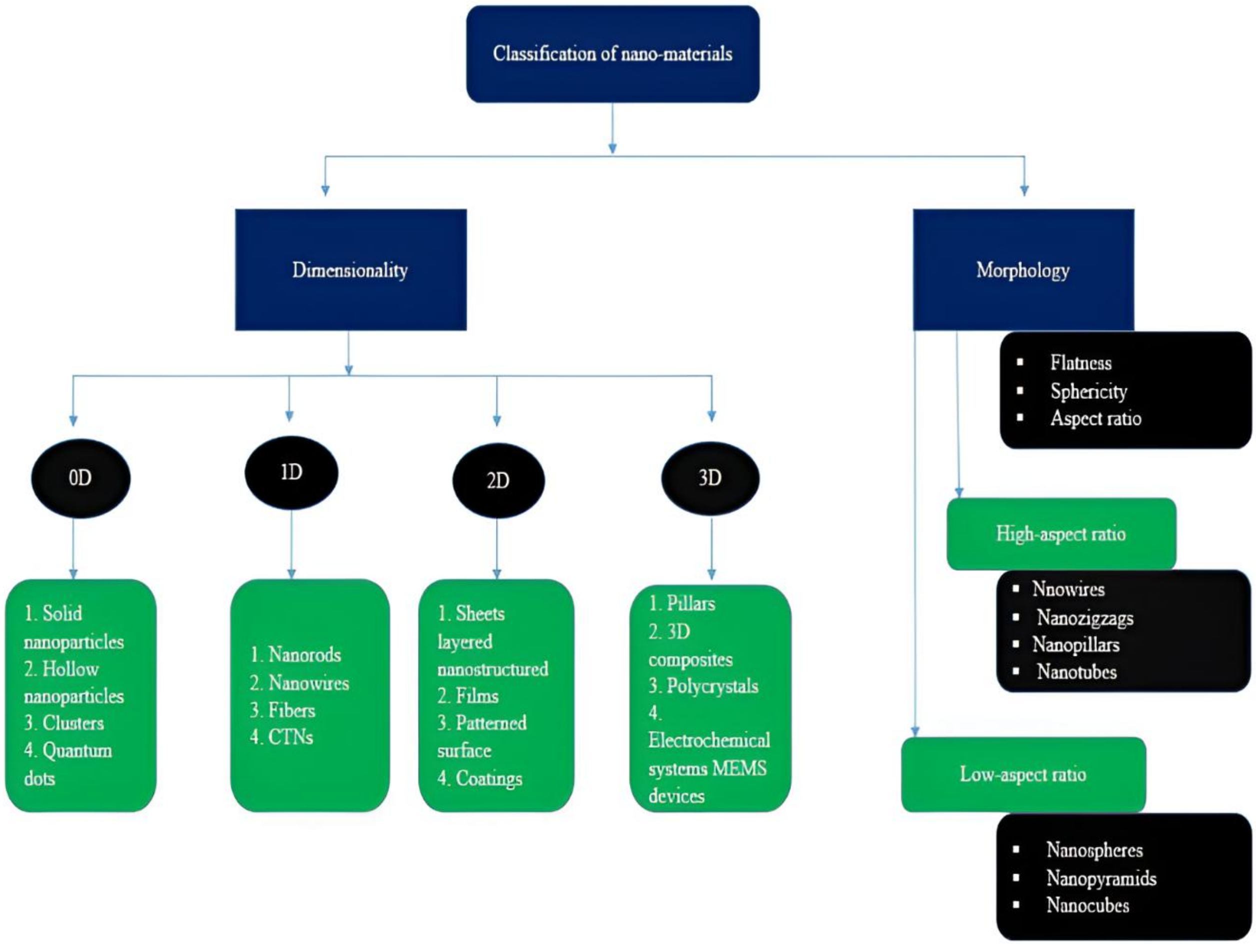

Fig. 1: Demonstrate the schematic classification of nano-materials

Table 1: Key agricultural wastes available globally (Sarkar et al., 2012)

Agricultural wastes	Quantity (million tons)
Rice's straw	731.3
Corn's stover	128.02
Sugarcane' sbagasse	180.73
Wheat straw	354.34

Table 2: Composition of major agriculture biomass

Crop waste types	Cellulose (%)	Hemicellulose (%)	(Lignin %)	Reference
Rice's straw	39.05	20.92	5.72	(Huang, 2010)
Rice's hull	33.48	21.04	18.81	(Mansaray, 1999)
Wheat's straw	43.3	34.2	22.01	(Alemdar, 2008)
Soya's hull	56.5	12.6	18.01	(Alemdar, 2008)
Corn's straw	42.7	21.4	8.3	(Sarkar et al., 2012).
Sugarcane's Bagasse	65.01	33.5	18.5	(Sarkar et al., 2012)
Sorghum's straw	32	24	13	(Saini, 2015)
Barley's straw	40	30	15	(Saini, 2015)
Coconut's husk	24.8	12.27	40.12	(Cabral, 2016)
Rapeseed's straw	32	16	18	(Thygesen, 2012)
Soybean's straw	35	17	21	(Martelli-Tosi, 2016)
Sunflower's straw	32	18	22	(Antonopoulou, 2015)
Peanut's shell	40.6	14.9	26.5	(Bharthare, 2014)

3. Biogas Production from Agricultural Biomass

Biogas is produced from agricultural biomass to meet the energy requirements for heating, cooking, and lighting, and thereafter, stored and transferred for residential utilization. An annual estimate indicates that gasoline consumption in Asia exceeds 3 Tg of methane (CH_4) (Einarsson, 2017). Approximately fifty percent of bio-methane facilities utilizing agricultural biomass are situated in Germany (Reijnders, 2008; McCormick, 2013). A potential application of straw is as a feedstock for biogas production, perhaps resulting in energy generation. Streets (2003) asserts that gasification methods might transform biomass in Poland into 1.5 billion m^3 of biogas.

Agricultural Biomass Conversion through Nano-Materials

Animal fats and a variety of other raw materials, including soybean, mustard, and sunflower, have been utilized to make biodiesel, which is currently a more environment-friendly and energy-efficient alternative. Nevertheless, their high cost and low yield have rendered them unsuitable for commercial use. Better substitutes are sustainable resources, such as microalgae with the highest lipid content and rate of growth. Oil is transformed into fatty acid methyl esters (FAME) or biodiesel via the trans-esterification process in the presence of alcohol. This reaction is catalyzed by acid/base/heterogeneous substances or enzymes the employment of enzymes makes the process more economical. By using NPs, this obstacle can be removed (Gebremariam and Marchetti, 2018; Khanna & Goyal, 2019; Verma and Rani, 2021). The cost of the raw materials plays the most influence in determining the cost of producing biodiesel, together with the facility's size and the value of the byproduct, glycerine. Depending on its source and what is easily accessible, waste, non-edible, and edible oil can all be categorized as feedstock. Producing biodiesel feedstocks from edible vegetable oils, such as soybean and palm oil, is dependable and financially advantageous. Lipases are produced by bacteria, fungi, plants, and animals. The primary issue with producing biodiesel by lipase catalysis is the high expense of the enzyme. Furthermore, there have been instances where immobilized lipases exhibit higher enzyme activity than free lipases. It is feasible to reduce the cost of enzyme use while increasing enzyme activity, stability, and reusability by employing nano-immobilized enzyme systems. During the biodiesel synthesis process, the immobilized lipases were disrupted by shear strain from the batch reaction stirring approach (Zhong et al., 2020).

With its β-1, 4 glycosidic links, cellulose is one of the most prevalent natural polymers in the world. Lignocellulose biomass is made up of 40–60% cellulose, 20–40% hemicellulose, and 10–25% lignin. Out of 181.5 billion tons, only 8.2 billion tons are used, and the remaining is lost as waste. The cellulosic content of lignocellulose can be used to produce bioenergy and it leads to waste degradation without harming the environment (Ashokkumar et al., 2022; Dahmen et al., 2019). Since biomass is a cheap substrate, cellulase, the biocatalytic enzyme, pays the greatest expense in this bioconversion process. The enzyme group known as cellulase is responsible for the production of oligosaccharide from random regions of cellulose by endoglucanase, cellobiose from the oligosaccharide by exoglucanase, and cellobiohydrolase, which converts cellobiose into glucose main products that serve as a precursor for biofuel (Rajnish et al., 2021).

A lignocellulosic biomass (LCB) biorefinery is a facility that uses dry, woody biomass or energy crops to produce bio-based fuels and biochemical products through biological or thermochemical processes (Singh et al., 2022). By enhancing efficiency, the use of nanotechnology in the biofuels production process can facilitate the process. Bioproduct production can be enhanced by using NPs as they improve biomass pretreatment and hydrolysis by chemical catalysts (Chandel et al., 2022). The name of this approach is the Nano Shear Hybrid Alkaline approach. Furthermore, NPs can be very important in the fermentation and enzymatic hydrolysis phases of the biofuel production process (Wang et al., 2013; Koo et al., 2017; Antunes et al., 2019).

Importance of Agricultural Biomass

1) Biofuels from Microalgal Biomass

Algal fuels are ecologically friendly since they help to reduce global carbon dioxide emissions. Plant-based biodiesel production involves the cultivation of oil-producing crops on cultivable land, and most governments limit biofuel feedstock supplies to avoid rivalry with food production on these lands. When compared to plants, algal biomass has a low percentage of lignin, which is one of the benefits that makes them good substrates for biofuels (Kavitha, 2023). Breaking down the tough cell wall that holds the soluble organics in place is the main problem with using algal biomass to make gasoline. Because different types of algae have different cell wall components, it is not possible to get a single pretreatment method that works for all of them. It is accurate to say that the production of biofuel from algal biomass has garnered considerable attention in recent years, the production process is complicated and challenging due to the unyielding and complex cell walls of algae. Algae biofuel production is still in its infancy despite advancements; this is primarily due to the energy and financial investment required for pretreatment (Kavitha, 2023). Further research should be devoted to the development of innovative, cost-effective biomass disintegration techniques.

2) Algal Biomass Conversion Through Nano-Materials

First, second, third, and fourth generations of biofuels are distinguished by their principal raw material sources. FAME is utilized in first-generation biofuels to transform vegetable oil, lipids, carbohydrates, and sugars into bio-alcohol (Vasantha et al., 2021). A wide range of feedstocks, including cereals, vegetable oils, sugar cane, and animal fats, can be used to create first-generation biofuels. Concerns have been voiced regarding these feedstocks' feasibility, nevertheless. Second-generation biofuels, on the other hand, seek to address the problem of carbon concentration by making use of nonfood feedstocks, particularly lignocellulosic biomass. In the worldwide biofuel development, this idea is gaining popularity (Boscaro et al., 2022).

Second-generation biofuels offer advantages, including the repurposing of waste resources; nevertheless, they also present disadvantages, such as high production costs and technological obstacles. Due to their elevated lipid content, algae are integral to the third and fourth phases of biofuel synthesis. Unlike third-generation biofuels that concentrate on algal production, fourth-generation biofuels utilize metabolic algae to generate carbon reservoirs (Khemthong et al., 2021).

The Department of Energy states that if algae were to entirely supplant petroleum as the fuel source for the United States, an area marginally larger than Maryland—approximately 17,000 square miles—would be necessary (Kushkevych et al., 2019).

Zaidi et al. (2018), study on the use of metals (Ni and Co) and metal oxide (Fe_3O_4 and MgO) NPs with green microalgae *Enteromorpha* to increase biogas generation. Geng et al, (2020) performed the BMP Test (biochemical methane potential test) and studied the incorporation of zerovalent iron (ZVI) in the anaerobic digestion of *Microcystis sp.* Sludge can boost methane production.

3) Trends in Forest Biomass Conversion

Current literature features continuous discussions over the significance of forest biomass in biomass utilization for energy generation (Plank et al., 2023; Raihan, 2023d). Raihan (2023e) and Siarudin et al. (2023) delineate two principal classifications of forest biomass: firewood and commercial roundwood. Direct combustion and conversion into bioenergy and biofuels are feasible methods for utilizing fuelwood obtained from forested regions (Manikandan et al., 2023; Raihan, 2023f). Thermochemical transformation, biological conversion, liquefaction, and gasification are conversion processes that can substantially benefit from utilizing fuelwood as a feedstock. According to Manikandan et al. (2023) and Raihan (2023g), this potential is derived from the increased concentrations of macromolecular carbohydrates, specifically cellulose and organic matter. Kalak (2023) suggests two possible approaches for investigating the utilization of forest biomass: first, as a co-combustion agent with fossil fuels; and second, as a standalone fuel source for power production devices, including boilers.

Limitations and Future Trends

Limitations and Challenges in Biofuel Cell Advancements

Despite the significant advancements made by several categories of nano-materials in the field of Biofuel Cells (BFCs), there remain numerous unresolved matters that need to be addressed to attain optimal performance in biochemical conversions. The current era is characterized by several significant problems, which include the attainment of optimal efficiency, effective cost management, the establishment of perfect operational circumstances, and the assurance of long-term technological durability. Presently focuses on the advancement of graphene-based bioanodes and biocathodes as alternative, highly efficient options for many applications. The formation of naturally existing macromolecular materials with porous characteristics. The successful incorporation of Carbon Nanotubes (CNTs) within the metallic structure. The investigation of inorganic biomass fuels. The bioelectrodes that have been recently developed, possess the capability to transform these possibilities into actuality in the coming times (Tawalbeh et al., 2022).

I. Economic Constraints in Biomass Conversion and Algal Biodiesel Production

The financial costs associated with pre-treatment methods of lingo-cellulosic biomass are substantial. It is believed that there exists an alternate method for converting fossil fuels into biodiesel throughout the production process. However, it should be noted that the cultivation of algal biomass for agricultural purposes experiences significant costs, while the extraction of lipids from these algae requires substantial allocation of resources (Assad et al., 2022).

II. The Role of Genetically Modified Microalgae and NPs in Future Bioeconomy

In future studies, it may be beneficial to explore the potential of utilizing genetically modified microalgae strains in conjunction with designed NPs in order to get enhanced and noteworthy outcomes. Therefore, NPs and microalgae possess the ability to serve as elementary components in the development of the bioeconomy characterized by renewable and sustainable opportunities (Dey et al., 2023).

III. Unexplored Avenues in Hydrogen Production Using Nano-Materials

The investigation of an integrated approach for biological hydrogen production with nano-materials remains an unexplored field of study. Regarding the creation of H_2 using nano electrocatalytic and nano photocatalytic processes, the advancement of two-dimensional nano-materials that possess hybrid structures and multifunctional capabilities presents a promising avenue for augmenting their potential in H_2 production by water splitting. The investigation of their production on a wide scale under controlled circumstances is also worthy of examination. There is a need to conduct a computational study on H_2 storage that takes into consideration practical and rigorous situations, as well as handles practical uncertainties. Moreover, there is a notable absence of comprehensive economic analysis on the various methods of H_2 storage in existing scholarly literature (Epelle et al., 2022).

IV. Advancing Biomass-Derived Carbon Electrochemical Sensors

There is a strong recommendation for more studies to look at the ability of biomass-derived nano-materials, particularly in terms of enhancing their inherent properties, hence leading to improved electrochemical performance. Consequently, it is conceivable that the advancement of research in this particular field could facilitate the development of portable electrochemical sensors capable of detecting harmful contaminants. Carbon-based electrochemical sensors made from biomass have gained significant popularity in recent years. However, they have not yet achieved the level of flexibility and portability required for use as detectors. The utilization of advanced technology such as 3D printing has the potential to facilitate the creation of rapid, cost-effective, and highly responsive sensing devices. Furthermore, there is potential for further development of this technology to produce intelligent functionalized devices that will establish the standard. The prevailing standard within this particular industry (Malode et al., 2023).

Conclusion

The transition to sustainable energy alternatives is crucial for addressing the environmental and economic challenges linked to fossil fuels. The conversion of biomass, improved through advancements in nanotechnology, offers a promising pathway to energy sustainability.

Nanocatalysts have transformed the biofuel industry through their remarkable efficiency and eco-friendly properties, enabling enhanced conversion rates, reduced energy consumption, and minimal environmental impact. This article highlights the potential of agricultural, algal, and forest biomass as abundant renewable resources for biofuel production and underscores the importance of nanotechnology in improving their utilization.

Despite significant advancements, challenges such as the high costs associated with nanocatalyst production and issues related to scalability continue to exist. Addressing these challenges requires continuous interdisciplinary research and innovation, as well as policies that support the circular economy. Facilitating collaborations among academia, industry, and government can transform biomass conversion through nanotechnology into a core element of sustainable energy systems

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