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Nanomaterials for Bioenergy Production: Advances in Biodiesel, Bioethanol, Microbial Fuel Cells, and Biomass Conversion Technologies

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Abstract

The growing demand for sustainable energy and concerns regarding fossil fuel depletion have accelerated research into bioenergy production technologies. However, conventional bioenergy processes often suffer from low conversion efficiencies, high energy requirements, and limited catalyst performance. Nanotechnology has emerged as a promising approach to overcome these challenges through the application of nanomaterials and nanocatalysts with high surface area, enhanced catalytic activity, and superior electron transfer properties. Nanocatalysts improve biodiesel production by increasing transesterification efficiency and facilitating catalyst recovery. In bioethanol production, nanomaterials enhance biomass pretreatment, enzyme immobilization, and fermentation processes. Nanostructured materials also improve microbial fuel cell performance by promoting electron transfer and increasing power generation. Furthermore, nanotechnology enhances biomass conversion technologies such as pyrolysis, gasification, and hydrothermal liquefaction, leading to higher fuel yields and improved product quality. This review discusses the historical development, applications, advantages, challenges, and future prospects of nanomaterials in bioenergy production, highlighting their potential for sustainable and efficient renewable energy generation.

Keywords: Nanomaterials, Bioenergy Production, Nanocatalysts, Biodiesel, Bioethanol, Microbial Fuel Cells.

1. Introduction

The increasing demand for energy, depletion of fossil fuel reserves, and growing environmental concerns have accelerated the search for sustainable and renewable energy sources. Fossil fuels continue to dominate global energy production, but their extensive use has resulted in greenhouse gas emissions, climate change, and environmental degradation. Consequently, renewable energy technologies have gained considerable attention worldwide. Among these, bioenergy has emerged as a promising alternative due to its renewability, carbon-neutral nature, and the abundance of biomass resources available for energy generation.

Bioenergy is produced from biological materials such as agricultural residues, forestry wastes, animal manure, algae, municipal solid waste, and dedicated energy crops. These feedstocks can be converted into various forms of energy, including biodiesel, bioethanol, biogas, biohydrogen, and bioelectricity through biochemical and thermochemical processes. In addition to providing renewable energy, bioenergy contributes to waste management, reduction of greenhouse gas emissions, and rural economic development. Despite these advantages, conventional bioenergy production technologies face several limitations. Traditional catalysts used in biodiesel production often exhibit poor reusability and require complex separation procedures. Similarly, lignocellulosic bioethanol production involves expensive pretreatment and enzymatic hydrolysis processes due to the rigid structure of biomass. Microbial fuel cells commonly suffer from low power output because of inefficient electron transfer, while biomass conversion processes such as pyrolysis and gasification often show limited efficiency and product selectivity. These challenges have encouraged the development of advanced technologies to improve bioenergy production. Nanotechnology has emerged as a powerful tool for enhancing renewable energy systems. Nanomaterials are materials with dimensions ranging from 1 to 100 nm and possess unique physical, chemical, and catalytic properties. Their high surface area-to-volume ratio, enhanced reactivity, and tunable surface characteristics make them particularly suitable for bioenergy applications. In recent years, nanomaterials have been widely investigated for improving biodiesel production, bioethanol generation, microbial fuel cells, and biomass conversion technologies. Metal nanoparticles, metal oxide nanoparticles, carbon nanotubes, graphene, magnetic nanoparticles, and nanocomposites have shown significant potential in enhancing catalytic activity, reaction kinetics, and process efficiency. In biodiesel production, nanocatalysts provide a larger number of active sites, resulting in higher conversion efficiency, shorter reaction times, and improved catalyst recovery. In bioethanol production, nanomaterials facilitate biomass pretreatment, enzyme immobilization, and fermentation processes, leading to increased ethanol yields. Nanostructured materials have also improved the performance of microbial fuel cells by enhancing electron transfer and increasing electricity generation. Furthermore, nanocatalysts have significantly enhanced biomass conversion processes such as pyrolysis, gasification, and hydrothermal liquefaction by improving product selectivity and fuel quality.

Although nanomaterials offer numerous advantages, challenges related to production costs, environmental safety, and large-scale implementation need to be addressed. Continued research is therefore necessary to develop cost-effective and sustainable nanotechnology-based solutions. This review focuses on the role of nanomaterials in bioenergy production, particularly their applications in biodiesel production, bioethanol generation, microbial fuel cells, and biomass conversion technologies.

2. History of Bioenergy Production Using Nanomaterials

The development of bioenergy technologies has progressed from conventional biomass utilization to advanced nanotechnology-assisted energy production systems. Early bioenergy production relied primarily on the direct combustion of biomass such as wood, agricultural residues, and animal wastes for heating and cooking purposes. Although renewable, these methods were characterized by low efficiency and significant environmental pollution [1].

The modern bioenergy era emerged during the oil crises of the 1970s, when concerns regarding fossil fuel depletion and energy security stimulated interest in alternative fuels such as biodiesel and bioethanol. Research focused on converting vegetable oils, agricultural feedstocks, and lignocellulosic biomass into liquid fuels through biochemical and thermochemical processes. However, conventional production methods often suffered from low catalyst efficiency, high energy requirements, and poor conversion rates [2] .

The emergence of nanotechnology in the late 1980s and early 1990s created new opportunities for improving energy conversion processes. The discovery of advanced nanomaterials such as carbon nanotubes and graphene significantly expanded their potential applications in renewable energy systems [3]. Initially developed for electronic and materials science applications, these materials soon attracted attention for bioenergy production because of their unique catalytic and surface properties.

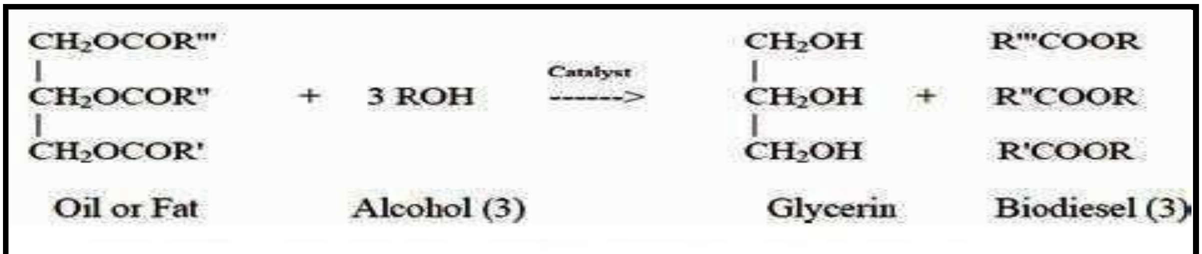
During the early 2000s, researchers began investigating metal oxide nanoparticles as catalysts for biodiesel production. Nanostructured catalysts such as CaO, MgO, TiO_2, and ZnO demonstrated superior catalytic activity and improved biodiesel yields compared with conventional catalysts [4]. Around the same period, nanomaterials were applied in bioethanol production for biomass pretreatment, enzyme immobilization, and fermentation enhancement [5].

The integration of nanomaterials into microbial fuel cells (MFCs) gained momentum during the mid-2000s. Carbon nanotubes, graphene, and metal oxide nanoparticles significantly improved electrode conductivity and electron transfer, resulting in enhanced electricity generation [6]. In recent years, nanotechnology has also advanced biomass conversion technologies, including pyrolysis, gasification, and hydrothermal liquefaction, through the development of highly efficient nanocatalysts [7].

Today, nanomaterials play an important role in biodiesel production, bioethanol generation, microbial fuel cells, and biomass conversion technologies. Their ability to improve process efficiency, product yield, and catalyst reusability has established nanotechnology as a key component of modern sustainable bioenergy production systems.

3.1 Nanocatalysts in Biodiesel Production

Biodiesel is a renewable, biodegradable, and environmentally friendly fuel produced primarily through the transesterification of vegetable oils, animal fats, and waste cooking oils with short-chain alcohols such as methanol or ethanol. Conventional biodiesel production typically employs homogeneous acid or alkaline catalysts, including sulfuric acid, sodium hydroxide, and potassium hydroxide. Although these catalysts provide high reaction rates, they suffer from several drawbacks, including soap formation, catalyst loss, corrosion, difficulty in catalyst recovery, and generation of large volumes of wastewater during purification [1]. To overcome these limitations, nanocatalysts have emerged as promising alternatives for enhancing biodiesel production efficiency.



Transesterification of oils

Nanocatalysts possess unique physicochemical properties due to their nanoscale dimensions. Their exceptionally high surface area-to-volume ratio provides a larger number of active catalytic sites, resulting in enhanced catalytic activity and improved reaction kinetics [4]. Furthermore, nanocatalysts exhibit superior thermal stability, mechanical strength, and reusability compared with conventional catalysts. These characteristics contribute to higher biodiesel yields, shorter reaction times, and reduced operating costs.

Among various nanocatalysts, metal oxide nanoparticles have received considerable attention. Calcium oxide (CaO) nanoparticles are widely used because of their strong basicity, low cost, and environmental compatibility. Studies have demonstrated that nanosized CaO catalysts can achieve biodiesel yields exceeding 90% under optimized reaction conditions [8]. Similarly, magnesium oxide (MgO), zinc oxide (ZnO), titanium dioxide (TiO_2), and zirconium dioxide (ZrO_2) nanoparticles have been investigated for transesterification reactions due to their high catalytic efficiency and stability [2].

Magnetic nanocatalysts represent another important advancement in biodiesel production. These catalysts typically consist of magnetic cores such as Fe_3O_4 coated with catalytic materials. After completion of the reaction, the catalyst can be easily separated from the reaction mixture using an external magnetic field, eliminating the need for complex filtration and centrifugation processes. This feature significantly reduces processing costs and facilitates catalyst recycling [2].

Carbon-based nanomaterials such as carbon nanotubes (CNTs), graphene oxide, and activated carbon nanocomposites have also been employed as catalyst supports. Their high surface area and excellent chemical stability enhance catalyst dispersion and improve accessibility of active sites. In many cases, metal nanoparticles immobilized on carbon nanostructures exhibit superior catalytic performance compared with unsupported catalysts [6].

Nanocatalysts also play a significant role in the utilization of low-quality feedstocks containing high levels of free fatty acids. Conventional alkaline catalysts often experience reduced efficiency under such conditions due to soap formation. In contrast, specially designed bifunctional nanocatalysts containing both acidic and basic active sites can simultaneously catalyse esterification and transesterification reactions, enabling efficient conversion of low-cost feedstocks into biodiesel [2].

The advantages of nanocatalysts extend beyond improved biodiesel yield. Reduced catalyst consumption, lower reaction temperatures, shorter processing times, and enhanced catalyst recyclability contribute to greater economic feasibility and environmental sustainability. Moreover, the development of green synthesis methods for nanoparticle production further enhances the environmental compatibility of nanotechnology-assisted biodiesel production systems.

Despite these benefits, challenges remain regarding large-scale implementation. Issues such as nanoparticle aggregation, catalyst deactivation, production costs, and environmental safety require further investigation. Nevertheless, continuous advancements in nanomaterial design and synthesis are expected to facilitate commercialization of nanocatalyst-based biodiesel technologies. The integration of nanotechnology into biodiesel production represents a significant step toward achieving sustainable and efficient renewable fuel generation.

3.2 Nanomaterials for Bioethanol Production

Bioethanol is one of the most widely used renewable biofuels and is primarily produced through the fermentation of sugars obtained from sugar crops, starch-rich feedstocks, and lignocellulosic biomass. The increasing demand for sustainable transportation fuels has stimulated extensive research into improving bioethanol production processes. Although conventional bioethanol production technologies are well established, challenges such as inefficient biomass pretreatment, high enzyme costs, incomplete hydrolysis, and low fermentation efficiency continue to limit large-scale commercialization [9]. Nanotechnology has emerged as a promising approach to address these limitations and enhance the overall efficiency of bioethanol production.

$$\underset{\text{Starch}}{(C_6H_{10}O_5)_x} \xrightarrow{\text{enzymes}} \underset{\text{Glucose}}{C_6H_{12}O_6} \xrightarrow{\text{enzymes}} \underset{\text{Ethanol}}{2CH_3CH_2OH} + 2CO_2$$

Lignocellulosic biomass, including agricultural residues, forestry wastes, and energy crops, is considered an abundant and sustainable feedstock for bioethanol production. However, the complex structure of lignocellulose, composed of cellulose, hemicellulose, and lignin, makes it resistant to enzymatic degradation. Effective pretreatment is therefore essential to improve biomass accessibility and increase sugar release. Nanomaterials have been successfully employed in biomass pretreatment processes due to their high surface area, catalytic activity, and unique physicochemical properties [5]. Metal oxide nanoparticles such as TiO_2, ZnO, and Fe_3O_4 have demonstrated the ability to disrupt lignocellulosic structures and enhance enzymatic hydrolysis efficiency.

One of the most significant applications of nanotechnology in bioethanol production is enzyme immobilization. Enzymes such as cellulases and hemicellulases play a crucial role in converting cellulose and hemicellulose into fermentable sugars. However, free enzymes are often expensive, unstable, and difficult to recover after use. Nanoparticles provide excellent support materials for enzyme immobilization because of their large surface area and tunable surface chemistry. Immobilized enzymes exhibit improved stability, enhanced catalytic activity, and greater resistance to environmental changes compared to free enzymes [10].

Magnetic nanoparticles have gained particular attention in enzyme immobilization systems. Enzymes attached to magnetic nanoparticles can be easily separated from reaction mixtures using an external magnetic field and subsequently reused in multiple production cycles. This capability significantly reduces enzyme consumption and operational costs while improving process sustainability. Studies have shown that magnetic nanoparticle-supported cellulases maintain high catalytic activity even after repeated use, making them attractive for industrial bioethanol production [10].

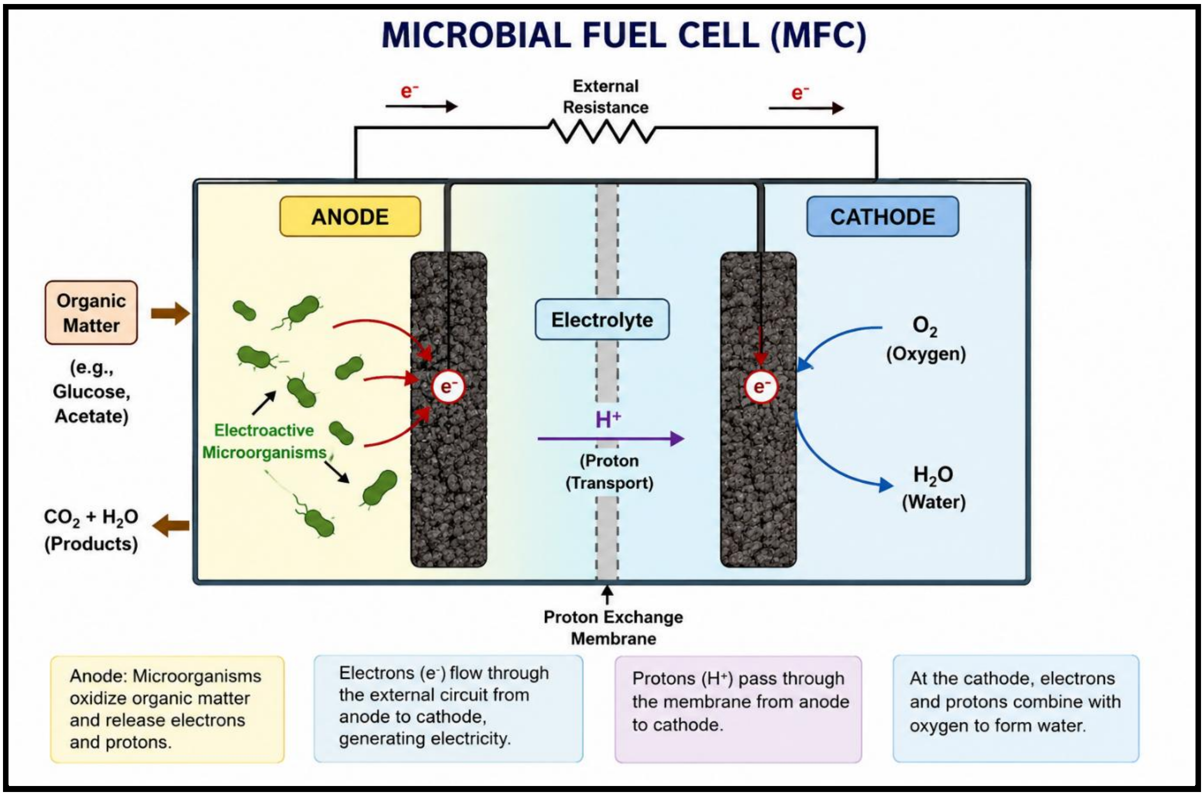
Nanomaterials also contribute to improved fermentation processes. Certain nanoparticles enhance microbial growth and metabolic activity by facilitating nutrient transport and cellular interactions. Carbon nanotubes, graphene derivatives, and nanocomposite materials have been investigated for their ability to improve fermentation performance and ethanol productivity [11]. Additionally, nanosensors have been developed for real-time monitoring of fermentation parameters such as glucose concentration, pH, and ethanol content, enabling better process control and optimization.

Recent advances have focused on integrating nanotechnology into consolidated bioprocessing systems, where pretreatment, hydrolysis, and fermentation occur simultaneously. Nanostructured catalysts and multifunctional nanocomposites can improve process integration, reduce energy requirements, and increase overall ethanol yields. Furthermore, green synthesis approaches for producing biocompatible nanoparticles are being explored to minimize environmental concerns associated with nanoparticle use.

Despite significant progress, challenges such as nanoparticle toxicity, recovery efficiency, large-scale production costs, and regulatory issues remain important considerations. Nevertheless, the incorporation of nanomaterials into bioethanol production offers substantial opportunities for improving conversion efficiency, reducing production costs, and enhancing the sustainability of renewable fuel generation. Continued research and technological development are expected to accelerate the commercial implementation of nanotechnology-assisted bioethanol production systems.

3.3 Nanomaterials for Microbial Fuel Cells

Microbial fuel cells (MFCs) are innovative bioelectrochemical systems that directly convert the chemical energy stored in organic matter into electrical energy through the metabolic activities of microorganisms while simultaneously treating organic waste streams. Their sustainable nature has attracted significant attention; however, conventional MFCs often exhibit low power output, limited electron transfer efficiency, high internal resistance, and poor electrode performance. The incorporation of nanomaterials has emerged as an effective strategy to overcome these limitations and significantly enhance system performance [12].



A typical MFC (Figure1) consists of an anode, cathode, electrolyte, and electroactive microorganisms. During operation, microorganisms oxidize organic substrates at the anode, releasing electrons and protons. The electrons are transferred to the anode and flow through an external circuit to the cathode, generating electrical current. The overall efficiency depends largely on the effectiveness of electron transfer between microbial cells and electrode surfaces [5].

Carbon-based nanomaterials, including carbon nanotubes (CNTs), graphene, graphene oxide, and carbon nanofibers, are widely used as electrode materials because of their exceptional electrical conductivity, high surface area, mechanical strength, and chemical stability. These properties promote microbial attachment, biofilm formation, and efficient electron transfer, leading to enhanced power generation [10]. Graphene-based electrodes provide extensive surface area for microbial colonization and rapid electron transport, resulting in higher current density, power density, and coulombic efficiency than conventional carbon electrodes. Similarly, CNTs form conductive networks that reduce internal resistance and improve electrical conductivity throughout the electrode structure [9].

Metal and metal oxide nanoparticles such as iron oxide (Fe_3O_4), manganese dioxide (MnO_2), titanium dioxide (TiO_2), and platinum nanoparticles further enhance MFC performance by improving cathode catalytic activity and oxygen reduction reactions, thereby increasing electricity generation efficiency [11]. Nanocomposites combining carbon nanostructures with metal oxide nanoparticles integrate superior conductivity, enhanced catalytic activity, and improved durability, promoting microbial adhesion, biofilm development, and efficient electron transport.

Beyond electricity generation, nanomaterial-enhanced MFCs are valuable for wastewater treatment, biosensing, environmental monitoring, and resource recovery by simultaneously removing organic pollutants and producing renewable energy. Although challenges such as high nanomaterial costs, potential nanoparticle toxicity, long-term stability, and large-scale implementation remain, ongoing research on low-cost, environmentally friendly nanomaterials and optimized electrode architectures is expected to establish nanomaterial-based MFCs as key technologies for sustainable bioenergy and environmental remediation.

3.4 Nanomaterials in Biomass Conversion Technologies

Biomass conversion technologies are essential for transforming renewable biological resources into fuels, chemicals, and energy products. Biomass feedstocks such as agricultural residues, forestry wastes, algae, municipal solid wastes, and energy crops contain substantial organic carbon that can be converted into biofuels through thermochemical, biochemical, and physicochemical processes. However, conventional conversion methods often face limitations such as low efficiency, high energy consumption, poor product selectivity, and catalyst deactivation. The incorporation of nanomaterials has emerged as an effective strategy to overcome these challenges and improve biomass conversion performance [13].

Among thermochemical processes, pyrolysis, gasification, and hydrothermal liquefaction (HTL) are widely used. Pyrolysis involves the thermal decomposition of biomass in the absence of oxygen to produce bio-oil, biochar, and syngas. Nanocatalysts enhance pyrolysis by promoting selective cracking reactions and reducing unwanted by-products. Metal nanoparticles such as nickel (Ni), cobalt (Co), iron (Fe), and their oxides have shown excellent catalytic activity, resulting in improved bio-oil yields and fuel quality [14].

Gasification converts biomass into synthesis gas (syngas) composed mainly of hydrogen, carbon monoxide, and methane. Nanocatalysts improve gasification efficiency by accelerating biomass decomposition, enhancing syngas quality, and reducing tar formation. Their high surface area and reactivity facilitate rapid catalytic reactions, leading to increased hydrogen production and lower energy requirements.

Hydrothermal liquefaction is particularly suitable for wet biomass and operates under high-temperature and high-pressure conditions to produce bio-crude oil. Nanocatalysts such as TiO_2, CeO_2, and ZrO_2 nanoparticles promote depolymerization and deoxygenation reactions, increasing bio-crude yield, carbon recovery, and fuel quality while reducing oxygen content [7].

Nanotechnology also supports the catalytic upgrading of biomass-derived products. Since raw bio-oils often exhibit high oxygen content, acidity, and instability, nanostructured catalysts are employed for hydrodeoxygenation, cracking, reforming, and hydrogenation reactions. Materials such as zeolite nanoparticles, metal-supported catalysts, carbon nanotubes, graphene-based materials, mesoporous silica nanoparticles, and metal-organic frameworks (MOFs) provide high surface areas and tunable structures that improve reaction efficiency and product selectivity. Magnetic nanocatalysts further enable easy catalyst recovery and reuse [15].

In addition to enhancing conversion efficiency, nanomaterials reduce environmental impacts by lowering energy consumption, greenhouse gas emissions, and waste generation. Nevertheless, challenges related to catalyst stability, nanoparticle recovery, production costs, and environmental safety remain. Future research should focus on developing economical, environmentally friendly, and recyclable nanocatalysts for large-scale biomass conversion, thereby improving the sustainability and commercial viability of bioenergy production systems.

4. Comparison of Traditional Bioenergy Production Methods and Nanomaterial-Assisted Bioenergy Production

Bioenergy production has traditionally relied on biochemical and thermochemical processes to convert biomass into fuels and energy products. Although these conventional technologies have contributed significantly to renewable energy development, they often suffer from limitations such as low conversion efficiency, high energy consumption, poor catalyst recovery, and reduced product quality. The incorporation of nanotechnology has introduced innovative solutions that significantly improve the performance and sustainability of bioenergy systems. Comparison of traditional and nanomaterial-assisted bioenergy production methods is given in table1.

One of the major differences between traditional and nanomaterial-assisted bioenergy production is catalytic efficiency. Conventional biodiesel production commonly uses homogeneous acid or alkaline catalysts such as sulfuric acid, sodium hydroxide, and potassium hydroxide. While effective, these catalysts are difficult to recover and reuse. Nanocatalysts possess exceptionally high surface area-to-volume ratios, providing more active sites for chemical reactions. As a result, they enable faster transesterification, higher biodiesel yields, and easier catalyst recovery, especially when magnetic nanoparticles are employed.

In bioethanol production, traditional methods require extensive pretreatment of lignocellulosic biomass and large quantities of enzymes. The resistant structure of lignocellulose limits sugar release and ethanol productivity. Nanomaterials enhance pretreatment efficiency and serve as effective supports for enzyme immobilization. Immobilized enzymes exhibit improved stability, reusability, and catalytic activity, reducing enzyme consumption and operational costs while increasing ethanol yields.

Nanotechnology has also improved microbial fuel cells. Conventional systems often experience low power densities because of inefficient electron transfer between microorganisms and electrodes. Nanomaterial-based electrodes such as graphene, carbon nanotubes, and metal oxide nanocomposites provide superior conductivity, larger surface areas, and enhanced microbial adhesion, resulting in significantly improved electricity generation.

Similarly, biomass conversion processes including pyrolysis, gasification, and hydrothermal liquefaction benefit from nanocatalysts. Compared with conventional catalysts, nanocatalysts improve reaction rates, enhance product selectivity, reduce energy requirements, and facilitate bio-oil upgrading through deoxygenation and hydrogenation reactions.

From environmental and economic perspectives, nanomaterial-assisted systems offer several advantages, including reduced energy consumption, lower waste generation, improved catalyst reuse, higher product yields, and longer catalyst lifetimes. However, challenges related to nanoparticle production costs, potential toxicity, environmental safety, and regulatory compliance remain. Overall, nanomaterial-assisted bioenergy production provides enhanced catalytic efficiency, improved energy conversion, superior product quality, and greater sustainability, making it a promising approach for future bioenergy development.

Table 1. Comparison of Traditional and Nanomaterial-Assisted Bioenergy Production

Parameter	Traditional Bioenergy Production	Nanomaterial-Assisted Bioenergy Production
Catalyst Activity	Moderate	Very high
Biodiesel Yield	Moderate to high	High to very high
Enzyme Stability	Limited	Enhanced through immobilization
Catalyst Recovery	Difficult	Easy, especially with magnetic nanoparticles
Reaction Time	Longer	Shorter
Energy Consumption	Higher	Lower
Bioethanol Production Efficiency	Moderate	High
Microbial fuel cell Power Density	Low	High
Biomass Conversion Efficiency	Moderate	Improved
Fuel Quality	Moderate	Superior
Waste Generation	Higher	Lower
Reusability of Catalyst	Limited	Excellent
Environmental Impact	Moderate	Reduced
Commercialization Challenges	Established technology	Cost and safety considerations

5. Conclusion

Nanotechnology has emerged as a powerful tool for enhancing the efficiency, sustainability, and economic viability of bioenergy production systems. Owing to their high surface area, superior catalytic activity, and excellent electrical conductivity, nanomaterials have significantly improved various bioenergy technologies. Nanocatalysts enhance biodiesel production by increasing reaction rates and catalyst reusability, while nanomaterials improve bioethanol production through efficient biomass pretreatment and enzyme immobilization. In microbial fuel cells, nanostructured electrodes facilitate better electron transfer and higher power generation. Similarly, advanced nanocatalysts improve biomass conversion processes such as pyrolysis, gasification, and hydrothermal liquefaction. Compared with conventional methods, nanomaterial-assisted systems provide higher conversion efficiencies, improved product quality, lower energy consumption, and reduced environmental impacts. Despite challenges related to cost, scalability, and safety, continued advancements are expected to support sustainable and renewable energy development.

Declaration of Conflicting Interests

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References

1. Demirbas A. Energy Conversion and Management, 2001, 42(11), 1357–1378.
2. Lam M.K., Lee K.T., Mohamed A.R. "Homogeneous, heterogeneous and enzymatic catalysis for transesterification of high free fatty acid oil." Biotechnology Advances, 2010, 28(4), 500–518.
3. Geim A.K., Novoselov K.S. "The rise of graphene." Nature Materials, 2007, 6(3), 183–191.
4. Lee, A. F., Bennett, J. A., Manayil, J. C., & Wilson, K. (2014). Heterogeneous catalysis for sustainable biodiesel production via esterification and transesterification. Chemical Society Reviews, 43(22), 7887–7916.
5. Mosier N., Wyman C., Dale B., Elander R., Lee Y.Y., Holtzapple M., Ladisch M. "Features of promising technologies for pretreatment of lignocellulosic biomass." Bioresource Technology, 2005, 96(6), 673–686
6. Logan B.E. "Exoelectrogenic bacteria that power microbial fuel cells." Nature Reviews Microbiology, 2009, 7(5), 375–381.
7. Elliott D.C., Biller P., Ross A.B., Schmidt A.J., Jones S.B. "Hydrothermal liquefaction of biomass: Developments from batch to continuous process." Bioresource Technology, 2015, 178, 147–156.
8. Atadashi I.M., Aroua M.K., Aziz A.A. "High quality biodiesel and its diesel engine application: A review." Renewable and Sustainable Energy Reviews, 2010, 14(7), 1999–2008
9. Sun Y., Cheng J. "Hydrolysis of lignocellulosic materials for ethanol production: A review." Bioresource Technology, 2002, 83(1), 1–11.
10. Verma, M. L., Barrow, C. J., & Puri, M. (2013). Nanobiotechnology as a novel paradigm for enzyme immobilisation and stabilisation with potential applications in biodiesel production. Applied Microbiology and Biotechnology, 97(1), 23–39.
11. Kim T.H., Lee Y.Y. "Pretreatment of corn stover by soaking in aqueous ammonia at moderate temperatures." Applied Biochemistry and Biotechnology, 2007, 137, 81–92.
12. Logan B.E., Hamelers B., Rozendal R., Schröder U., Keller J., Freguia S., Aelterman P., Verstraete W., Rabaey K. "Microbial fuel cells: Methodology and technology." Environmental Science & Technology, 2006, 40(17), 5181–5192.
13. Huber G.W., Iborra S., Corma A. "Synthesis of transportation fuels from biomass: Chemistry, catalysts, and engineering." Chemical Reviews, 2006, 106(9), 4044–4098.
14. Bridgwater A.V. "Review of fast pyrolysis of biomass and product upgrading." Biomass and Bioenergy, 2012, 38, 68–94.
15. Schröder U. "Anodic electron transfer mechanisms in microbial fuel cells and their energy efficiency." Physical Chemistry Chemical Physics, 2007, 9(21), 2619–2629.