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REVIEW ARTICLE

Comprehensive analysis of nanotechnology-driven advancements and outlines future directions for sustainable biofuel production

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Abstract

The global energy crisis, environmental degradation and diminishing fossil fuel reserves have amplified the demand for sustainable energy alternatives. Biofuels derived from renewable resources offer a promising solution; however, their large-scale adoption is limited by challenges such as high production costs, scalability issues and low efficiency. This review examines the role of nanotechnology in overcoming these barriers by enhancing biofuel production processes. Nanostructured materials, renowned for their high surface area and catalytic efficiency are employed to optimize critical stages such as the pre-treatment of biomass, enzymatic hydrolysis and transesterification. This review emphasizes the utilization of advanced nanomaterials, including metal oxides, magnetic nanoparticles, carbon nanotubes and acid-functionalized nanoparticles, in improving production efficiency and enabling the use of non-edible feedstocks. These innovations not only boost economic viability but also reduce environmental remediation. Although these advantages exist, concerns related to nanoparticle toxicity, environmental safety and economic feasibility remain significant, necessitating future research. The review offers a comprehensive comparison of nanomaterial types, evaluates their performance in various stages of biofuel production and highlights their potential for industrial-scale application-providing fresh insights for future development. In this review, we provide a comprehensive analysis of nanotechnology-driven advancements and outlines future directions for sustainable biofuel production.

Keywords: biofuel; energy efficiency; nanoparticles; nanotechnology; renewable energy; sustainability

Introduction

The global reliance on non-renewable energy sources has led to significant environmental, economic and energy security challenges, necessitating the search for sustainable alternatives. Biofuels, such as bioethanol and biodiesel, are emerging as viable substitutes for petroleum-based fuels due to their renewable nature and reduced environmental impacts (1). Ethanol, used either alone or blended with gasoline, serves as an effective alternative fuel for Otto cycle engines, particularly in countries like the United States and Brazil. Similarly, biodiesel, a renewable fuel for diesel engines, offers multiple advantages, including a higher flashpoint, biodegradability, natural lubrication properties and reduced exhaust emissions (2). Additionally, biodiesel production integrates seamlessly with the existing fuel distribution infrastructure, making it a practical solution for reducing dependence on petroleum. In a study using palm oil, transesterification aided by ZnO and NiO nanocatalysts significantly enhanced biodiesel yield, reaching 96.23 % with ZnO and 94.27 % with NiO. ZnO proved to be the more efficient catalyst, demonstrating its potential for optimizing biodiesel production (3).

Biofuels are typically produced from carbohydrates, animal fats and vegetable oils through fermentation and transesterification processes. However, these production methods face significant challenges, including high costs and technological barriers. Addressing these challenges requires innovative approaches and nanotechnology has emerged as a promising tool to enhance biofuel production efficiency and reduce either costs (4). Nanostructures are particularly effective in biodiesel production through the transesterification of lipids and oils and the synthesis of second

-generation ethanol. Their unique properties facilitate catalyst recovery and reuse, significantly improving process sustainability (5) .

Nanotechnology, the science and engineering of creating molecular-scale materials and devices, has garnered attention for its wide-ranging applications (6). Nanoparticles, typically ranging from 1 to 100 nm in size, exhibit distinctive characteristics that set them apart from both bulk materials and individual particles. These include a high specific surface area, elevated surface energy and quantum confinement effects. These properties enable nanoparticles to perform efficiently in various commercial applications, including biofuel production. For instance, nanostructured polymers derived from polyacrylates, polyoxides, polysaccharides, polyvinylics and polyethylenes, play a vital role in enhancing biofuel synthesis. Polymer nanomatrices, often composed of elements such as carbon, silicon and chromium are integral to these advancements (7).

The nanotechnology has emerged as a promising approach to overcome limitations in traditional biofuel production processes. Biofuels such as biohydrogen, biodiesel, bioethanol and biogas have been successfully synthesized with the aid of nanotechnology (8). Key processes, including esterification and transesterification, transform triglycerides into biofuels. Nano-catalysts such as nanotubes, nanosheets and nanoparticles, primarily sourced from microbial fuel cells are integral to these processes (9) .

In this review, we explore the integration of nanotechnology in biofuel production, highlighting its role in overcoming existing challenges, enhancing efficiency and enabling the development of sustainable energy solutions. (Fig. 1)

1. Biofuels

Biofuels, derived from renewable resources, offer a sustainable solution to the depletion of fossil fuels and present a greener alternative to non-renewable energy sources. The biofuel industry is categorized into first-generation, second-generation and third-generation biofuels (10, 11). First-generation biofuels rely on consumable feedstocks such as sugar, wheat and vegetable oils (12). However, limited availability of feedstock and the high production cost render first-generation biofuels less competitive compared to fossil fuels. Second-generation biofuels, produced from inedible feedstocks, address some of the challenges but remain costly (13). Third-generation biofuels, as illustrated in Fig. 2, primarily utilize lignocellulosic and algal biomass as raw materials (14). Despite the promising potential of algal biomass as a renewable feedstock for biofuel production, several critical limitations hinder its large-scale deployment. Algae cultivation particularly in open pond systems, demands significant land and water resources. Studies indicate that producing one litre of algal biodiesel may require up to 1944 litres of water, raising sustainability concerns, especially in water-scarce regions. Furthermore, large surface areas are needed to scale production, potentially leading to land-use conflicts with agriculture or natural ecosystems. Another significant challenge is the susceptibility of algal cultures to biological contamination. Open systems are prone to invasions by competing algal strains, bacteria and protozoa which can reduce biomass productivity and alters the biochemical composition. Additionally, maintaining the optimal nutrient levels often necessitates high inputs of nitrogen and phosphorus and without effective recycling strategies, this can result in nutrient runoff and environmental degradation such as eutrophication. These challenges implicates the importance of integrated approaches are closed photobioreactor systems, strain improvement and resource-efficient harvesting technologies to enhance the sustainability and resilience of algae-based biofuel systems (15).

Advancements across these generations have progressively reduced production costs and enhanced the efficiency of biofuel synthesis, thereby increasing the utilization of non-edible biomass.

Biodiesel has gained prominence in renewable and eco -friendly alternative to conventional fossil fuels, offering solutions to the global energy crisis and environmental challenges. Advanced methodologies, such as transesterification, enzymatic catalysis and the application of nanotechnology, have substantially improved biodiesel

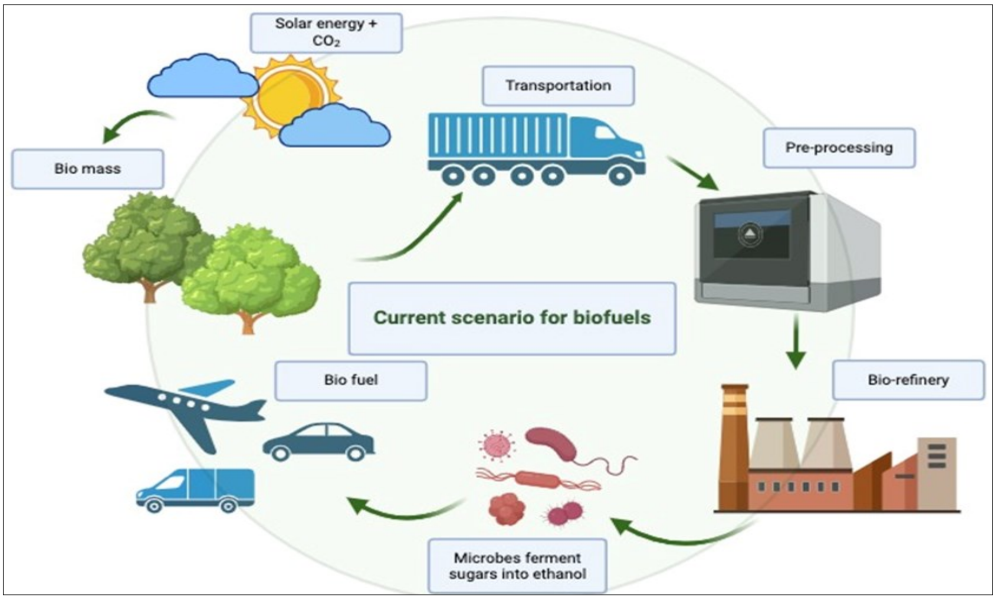

Fig. 1. Current applications of biofuels in sustainable energy.

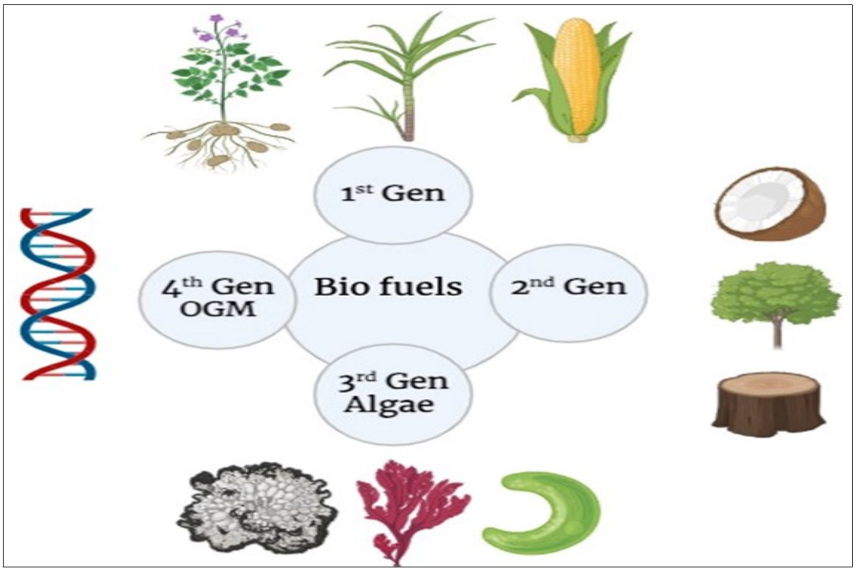

Fig. 2. Types of biofuels and the sources.

production efficiency and quality (16). In current studies, highlight the significance of heterogeneous and nano-catalysts, including metal oxides and carbon-based materials, in optimizing biodiesel synthesis. Furthermore, use of waste-derived oils and algal biomass has emerged as a promising sustainable strategy for biodiesel production (17). Comprehensive life-cycle assessments of biodiesel systems underline its ecological advantages, such as lower greenhouse gas emissions and enhanced biodegradability (8).

The current generation focuses on improving bioethanol production from lignocellulosic biomass, agricultural residues and non-edible feedstocks, reducing dependency on food crops. Advances in pretreatment techniques, enzymatic hydrolysis and microbial fermentation have enhanced production efficiency and yield (18). Integration of nanotechnology, such as use of nano catalysts and immobilized enzymes, has further revolutionized bioethanol production, offering higher reaction rates and cost-effectiveness (4). Moreover, innovative bioprocessing technologies, such as consolidated bioprocessing (CBP), are streamlining production by combining enzymatic hydrolysis and fermentation in a single step, significantly reducing costs (19).

Bio-methanol, a sustainable alternative to traditional methanol, was produced from biomass sources such as agricultural waste, forestry residues and municipal solid waste, aligning with global sustainability objectives. Advanced technologies like gasification and catalytic conversion of syngas have improved production efficiency while minimizing greenhouse gas emissions (20). Innovations in enzyme engineering and fermentation processes have facilitated the utilization of lignocellulosic feedstocks, enhancing the practicality of bio methanol production (21). Furthermore, integration of nanotechnology and advanced catalysts, including metal-organic frameworks (MOFs), has optimized conversion efficiency and reduced energy demands (22). However, current challenges such as high production costs and limited feedstock availability persist, necessitating continued research and technological advancements (20).

Biogas has emerged as a sustainable and renewable energy source derived from the anaerobic digestion of organic waste, biogas primarily consists of methane (CH_4) and carbon dioxide (CO_2). Its production offers dual benefits: reducing waste and mitigating greenhouse gas emissions (23). Recent advancements in biogas technology have focused on enhancing methane yield through the use of additives like nano-zero valent iron (nZVI), which significantly boosts microbial activity and enzymatic reactions (24). Moreover, co-digestion strategies combining agricultural residues and industrial waste have proven effective in improving biogas yield and substrate utilization efficiency (25).

The production of biohydrogen involves diverse biological processes such as dark fermentation, photo-fermentation and microbial electrolysis cells (MECs), each with its unique advantages and limitations (26). Recent advancements in nanotechnology have significantly enhanced the efficiency of biohydrogen production by improving microbial activity, enhancing enzyme stability and optimizing reaction kinetics (27). Moreover, the integration of nanomaterials such as iron oxide and carbon-based nanoparticles, into biohydrogen systems has demonstrated improved hydrogen yields by facilitating electron transfer processes (28).

2. Nanostructure in biofuel production

Nanostructure plays a crucial role in biofuel production due to their high surface area and unique physicochemical properties, which enhance catalytic activity, particle size and large surface -to-volume ratio, enabling better interaction with reactants, leading to improved reaction rates and product yields (29). One of the key applications of nanostructure in biofuel production is enzyme immobilization and recycling, which helps reduce operational costs and improve sustainability. Nano-catalysts, composed of different nanostructure, significantly enhance the biofuel production process by facilitating efficient biochemical reactions. For instance, carbon nanotubes (CNTs) are widely used as enzyme scaffolds, providing a stable support for enzymes involved in biofuel synthesis, thereby increasing their longevity and activity (30). Magnetic nanoparticles also play an essential role by allowing easy separation and recovery of enzymes or catalysts, making the process more cost-effective and environmentally friendly. Additionally, varieties of materials, including metals (such as gold and silver), metal oxides (titanium dioxide and zinc oxide), acid-functionalized substances and heterogeneous catalysts are commonly employed to optimize different stages of biofuel production. These nanoparticles contribute to feedstock pretreatment, transesterification and microbial fermentation, enhancing efficiency and yield. The integration of nanotechnology in biofuel production holds great promise for improving the economic and environmental viability of renewable energy sources (4).

2.1. Carbon nanotubes (CNTs)

CNTs play a crucial role in biofuel production due to their high surface area, stability and catalytic efficiency. Their cost-effectiveness and renewable nature enhance their application in biofuel synthesis (31). Studies have demonstrated that the addition of CNTs in anaerobic digestion systems improves biohydrogen production, enhances reactor performance and reduces initial time (32).

Co-immobilizing *Clostridium pasteurianum* CH_5 with carboxyl-functionalized multi-walled carbon nanotubes (MWCNT-COOH) has been shown to significantly enhance hydrogen production efficiency and glucose degradation rates compared to free-cell systems, presenting a promising strategy for sustainable biohydrogen generation (33). Additionally, enzyme immobilization on CNTs improves reusability and maintains catalytic activity, further enhancing biofuel production efficiency (34-36). Functionalizing MWCNTs with amino groups increases their thermal stability, making them suitable for biofuel applications (37) .

Catalytic studies on sulfonated multi-walled carbon nanotubes (s-MWCNTs) have highlighted their efficiency in biofuel synthesis. For instance, s-MWCNTs achieved a 95.12 % conversion of methanol to oleic acid at 210 °C, demonstrating their stability and efficiency in catalytic applications (36). A comparative study also showed that MWCNTs outperform single-walled carbon nanotubes (SWCNTs) in catalyst immobilization due to their superior structural compatibility, maintaining recyclability efficiency across multiple hydrolysis cycles (38, 39). The integration of CNTs in biofuel production significantly enhances process efficiency, enzyme stability and catalytic performance, making them a promising nanomaterial for sustainable energy applications.

2.2. Magnetic nanoparticles (MNPs)

MNPs have gained significant attention in biofuel production due to their ability to facilitate enzyme immobilization, enhance biomass hydrolysis and improve biofuel yields. Enzymes such as cellulases and lipases are commonly used in biofuel production processes and their immobilization on magnetic nanoparticles allows for enzyme reuse and process optimization (40, 37). The attachment of enzymes to a magnetic support matrix coated with nanomaterials enhances hydrolysis efficiency and biomass conversion (41). Additionally, the magnetic properties enable easy enzyme recovery and reuse, improving sustainability (42). Encapsulation of cellulase on magnetic nanoparticles has been shown to streamline biomass hydrolysis (43). Fig. 3 shows the production of biofuel using cellulase.

Magnetic nanoparticles have been explored for biodiesel production, as demonstrated in the use of $CaSO_4$/ Fe_2O_3-SiO_2 nanoparticles for converting *Jatropha curcas* oil into biodiesel. These nanoparticles, with a surface area of 391 m^2/g and a pore size of 90 nm, achieved a biodiesel yield of 94 % under optimal conditions. However, catalytic efficiency declined due to nanoparticle inactivation and pore blockage after multiple cycles (44). A magnetic nanocatalyst, $AlFe_2O_4$ functionalized with sulfonic acid groups ($AlFe_2O_4$@n-Pr@Et-SO_3H), has demonstrated high efficiency in biodiesel production from oleic acid via esterification, achieving up to 98 % yield under optimized conditions. This catalyst also exhibited excellent reusability over multiple cycles without significant loss in activity (45). Similarly, calcium-doped magnetic microferrites enhanced biodiesel yield by over 85 % when processing soybean cooking oils (46) .

Magnetic nanocomposites have also been utilized to improve bio-electrocatalytic activity. A polyaniline (PANI) framework nanocomposite, integrating Fe_3O_4-NH_2 with reduced graphene oxide (rGO), demonstrated superior bio-electrocatalytic activity for glucose oxidase. This nanocomposite significantly enhanced enzymatic biofuel cell (EBFC)

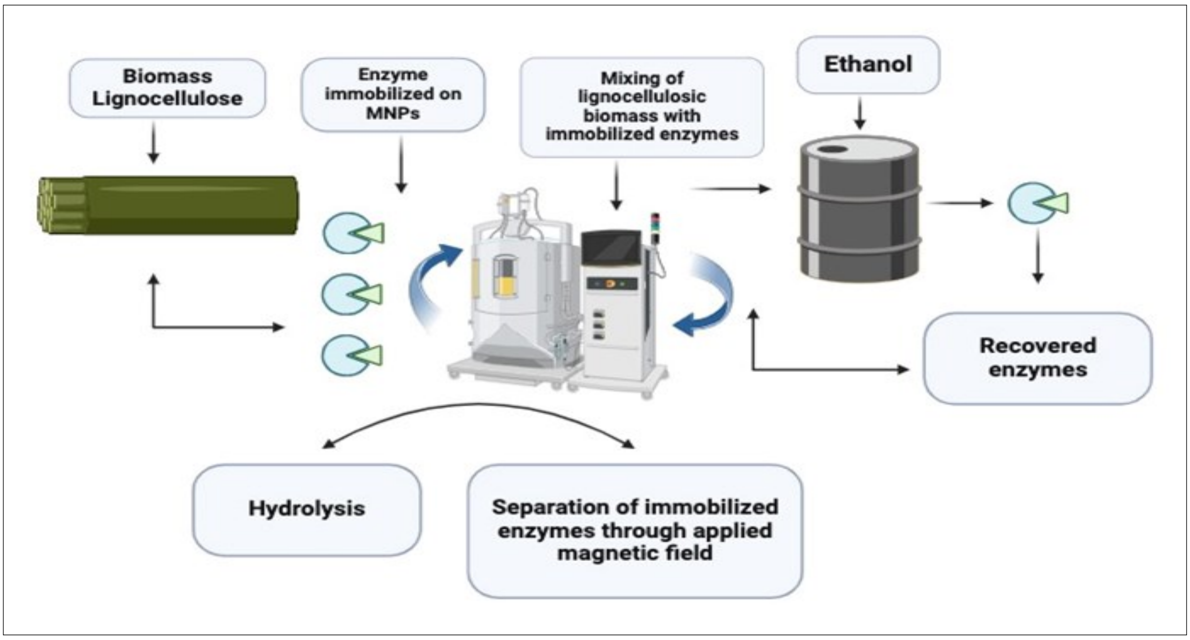

Fig. 3. Production of biofuel using cellulase integrated with magnetic nanoparticles to degrade the cellulose.

performance, achieving a maximum current density of 32.9 mA cm^{-2} in the presence of 50 mM glucose (47).

In bioethanol production, sugarcane leaves treated with MnO_2 nanoparticles improved enzyme binding efficiency and ethanol synthesis (48). Additionally, yeast cell immobilization on magnetic nanoparticles further enhanced ethanol yield (49, 50). The hydrolysis of microalgae cell walls using immobilized cellulase on magnetic nanoparticles facilitated lipid extraction for biofuel production (51).

Magnetic nanoparticles also play a role in biohydrogen and biogas production. Iron nanoparticles enhanced anaerobic digestion and hydrogen production from water hyacinth, yielding 57 mL/g of dry biomass (52). Research has also demonstrated that glucose as a substrate enhances hydrogen production (28, 53). Additionally, iron oxide nanoparticles (Fe_2O_3 and Fe_3O_4) and zero-valent nanoparticles have been investigated for biohydrogen production from glucose, wastewater and sugarcane bagasse (54-56).

The use of nano zero-valent iron (nZVI) and Fe_2O_3 nanoparticles in waste-activated sludge treatment has shown substantial increases in methane production, with 10 mg/g nZVI and 100 mg/g Fe_2O_3 leading to methane yield improvements of 120 % and 117 % respectively. These findings indicate that nanoparticles can enhance microbial growth, enzymatic activity and boosting methane generation (57).

2.3. Acid functionalized nanoparticles

Potential pre-treatment approaches for lignocellulosic biomass involve two approaches, acidic and basic methodologies. Acid-functionalized nanoparticles are believed to facilitate the hydrolysis of different biomasses, which are subsequently utilized for biofuel production. The transesterification process is typical for triglycerides, while esterification is common for fatty acids. However, acid-catalyzed reaction methods make use of biomass at a lower cost (27) (Table 1).

Biodiesel synthesis has reportedly employed sulfamic and sulfonic acid-assisted silica-coated Fe/Fe_3O_4 magnetic nanoparticles (58). Glyceryl trioleate and oleic acid were transesterified using magnetic nanoparticles functionalized with sulfonic acid and sulfamic acid respectively. Evidence indicates that esterification achieves a 100 % yield of oleic acid in just 4 hrs, whereas transesterification at 100 °C for 20 hrs converts 88 % of glyceryl trioleate with sulfonic acid functionalized and 100 % with sulfamic acid functionalized nanoparticles. In comparison, the sulfamic acid functionalized process attained a 95 % conversion rate in the fifth consecutive cycle, while the sulfonic acid functionalized catalyst managed only a 62 % conversion rate.

Recent studies have demonstrated the potential of nanotechnology by hydrolyzing cellobiose from lignocellulosic biomass using acid-functionalized magnetic nanoparticles (MNPs) as catalysts. The research discovered that acid-functionalized MNPs with a 6 % sulfur content converted cellobiose at a rate of 96 %, significantly higher than the typical 32.8 % conversion rate without the catalyst (59). These acid-functionalized MNPs have the potential to immobilize specific proteins more quickly, making them nano-catalysts that could accelerate hydrolysis. The high surface-to-volume ratio of these MNPs enhances the hydrolysis rate compared to chemical pre-treatment. It was found that sulfonate-supported silica MNPs could hydrolyze lignocellulosic biomass, making them a robust catalyst for hydrolysis. Furthermore, these nanoparticles are thermally stable and easy to separate from the reaction mixture (60). Enzymes used in bioethanol or biodiesel production can be immobilized on MNPs. Due to their strong magnetism and paramagnetic properties, MNPs are also suitable for biogas production during methanogenesis (61, 62).

2.4. Metallic nanoparticles

Despite the limited research, numerous studies have attempted to determine the efficacy of metallic nanoparticles in biofuel production. Due to their increased surface area and nanoscale dimensions, magnetic nanoparticles can enhance electron transport and form interactions with enzymes like oxidoreductase (63). The oxygen reduction and ion transfer rates of several catalytic nanoparticles have been engineered to be more significant. A biofuel cell with high loading capacity and efficient electron transfer rate might be developed by layering metallic nanoparticles (NPs) with the appropriate polymers and catalysts. This would improve the cell's electrocatalytic activity (64).

In one approach, hybrid nano-catalysts were developed by incorporating metallic nanoparticles of gold, platinum and Pt0.75-Tin0.25 into acid-functionalized Multi-Walled Carbon Nanotubes (MWCNTs). In another method, gold nanoparticles were encapsulated in a poly (amidoamine) (PAMAM) dendrimer structure. High-resolution transmission electron microscopy (HR-TEM) studies have demonstrated that dendrimer-encapsulated nanoparticles are highly organized and extremely efficient. The application of MWCNTs in biofuel

Table 1. Comparison of magnetic and ccid-functionalized nanoparticles in biodiesel production: efficiency, cost and reusability

Parameter	Magnetic Nanoparticles (MNPs)	Acid-Functionalized Nanoparticles (AFNPs)	References
Catalytic Efficiency	High efficiency in biodiesel transesterification; good mass transfer due to magnetic recovery (e.g., 85–95 % yield)	High efficiency, especially for biomass hydrolysis and esterification (e.g., 80–90 % yield)	(127-129)
Cost	Moderate to high (due to magnetic core materials like Fe_3O_4 and surface modifications)	Lower to moderate (based on silica, carbon, or metal oxides with sulfonic acid groups)	
Reusability	Excellent; can be recovered magnetically and reused up to 5–10 cycles with minimal activity loss	Good, but slightly less durable; tends to lose activity after 3–7 cycles depending on stability	
Separation Ease	Easy magnetic separation; reduces downstream processing cost	Requires filtration or centrifugation, increasing processing complexity	
Stability	Generally stable under mild reaction conditions	May degrade under extreme pH or temperature conditions	
Common Materials	Fe_3O_4, $CoFe_2O_4$, Fe_2O_3 with silica or polymer coatings	Sulfonated silica, carbon, TiO_2, or mesoporous materials	

cells has facilitated the support of Pt0.75-Tin0.25, gold and platinum. The electrical conductivity, biocompatibility and catalytic activity of gold nanoparticles (NPs) are exceptional. Ethanol exhibited high oxidation activity when paired with tin and platinum nanoparticles (65).

An alternative study employed laser ablation of an aqueous solution to synthesize gold nanoparticles, which demonstrated remarkable electrocatalytic efficiency and catalytic activity from the 10^{th} cycle onwards. Although the LA-Au nanoparticles were smaller in size, they outperformed their counterparts. Therefore, in the context of constructing biofuel cells, LA-Au nanoparticles are a robust choice (66).

Several types of nanomaterials have been employed to produce biohydrogen. The combination rate of biohydrogen increases by 46 % and the substrate utilization capacity by 56 % when 5 nm gold nanoparticles are used (26). Gold nanoparticles, due to their smaller size and larger surface area, facilitate biohydrogen production by attracting microorganisms to specific sites. The enzymatic activity of the apparatus involved is crucial for biohydrogen production and these nanoparticles enhance this activity. Researchers have shown that silver nanoparticles promote biohydrogen production by maximizing substrate utilization. These nanoparticles initiate the acidic reaction, the primary pathway for biohydrogen production, while reducing the lag phase of bacteria and algae growth. Nanoparticles enhance biohydrogen production in photosynthetic microorganisms. The addition of nanoparticles to the growth medium improves microbial growth, nitrogen metabolism, protein synthesis, physiological processes and photosynthetic efficiency. The optimal amounts of Ag and Au nanoparticles improved photosynthetic activity in *Chlorella vulgaris* (67). Biogas production from waste sources is enhanced by zerovalent iron nanoparticles (68, 69). The hydrogenation process converts glucose into sorbitol (70).

2.5. Metal oxide nanoparticles

The synthesis of metal oxide nanoparticles is essential for sustainable applications and solution-phase methods provide a high degree of control over the final product. Metal oxide nanoparticles are often organized using the sol-gel technique, which halts the reaction just before gelation. Precipitation methods are like this approach. The uniqueness of nanoparticles lies in the mechanisms involved in their creation, nucleation and aging processes.

Metal oxide nanoparticles are employed in various industries, including electronic materials, sensors, catalysis and environmental remediation. The use of metal oxides has enabled the transformation of vegetable oil into biofuel. Catalyzing the conversion of oil into organic liquid products is achievable with the help of metal oxides such as KOH, MoO_3, ZnO, V_2O_5, Co_3O_4 and NiO (71).

Metal oxides have been employed as supportive systems due to their strong catalytic activity and low selectivity. Biodiesel has been produced using nano-catalysts made of calcium oxide and aluminum oxide. The transesterification method can yield biodiesel with an output of 82.3 % using Jatropha oil as feedstock, along with methanol and oil (72).

The use of a combined feedstock of free fatty acids and soybean oil allows the metal oxide catalyst ZrO_2 to perform esterification and transesterification simultaneously. ZrO_2 is noted for its hardness, stability and both basic and acidic properties. Fatty acid methyl ester (FAME) yields of 89 % to 86 % have been achieved using both simultaneous methods. It has been observed that increasing the temperature of the ZrO_2 metal oxide catalyst results in higher FAME yields (73). The production of biofuel from used cooking oils has also been enhanced by the use of various NP catalysts, such as MeO-SBA-15, ZnO-SBA-15, La2O3-SBA-15 and others (74).

The production of biohydrogen has utilized silica (SiO_2) nanoparticles in the dark fermentation process. The nanocomposite formed by combining SiO_2 nanoparticles with Fe_3O_4 is gaining prominence in biohydrogen synthesis due to its enhanced stability and catalytic activity. These nanocomposites also offer various advantages, such as high-temperature stability and low toxicity (75-77). Adding Fe_3O_4/ZnMg(Al)O nanoparticles to biodiesel has reportedly increased its production.

3. Nanotechnology for biofuel generation

Biofuel has been regarded as a viable environmentally friendly substitute that might satisfy the world's energy needs. The lower production yields and greater costs of pretreatment techniques, biofuel production is still being prepared to compete with fossil fuels. Therefore, it was thought that applying nanobiotechnology will help the biofuel sector expand. Because nanomaterials have many benefits and structural diversity, their use in manufacturing can guarantee the goal of optimizing biofuel synthesis while maintaining it as a profitable business strategy (78). Excellent recyclability, significant sorption capacity, thermal stability and catalytic output were among the nanoparticles qualities.

3.1. Biodiesel production

Biodiesel is prized as a transportation biofuel due to its low carbon emissions, improved degradability and abundant raw materials. These materials include various inedible oils, both plant-based and animal-based, which are often considered waste. Because biodiesel production relies on these non-edible sources, it does not compromise food security. Fig. 4, outlines the process of biodiesel generation (79).

Multiple studies have explored incorporating nanomaterials to improve biodiesel production efficiency. One study utilized Fe_3O_4/ZnMg (Al)O to examine how nanoparticles (NPs) affect biodiesel synthesis. Their tests revealed the catalyst's impressive magnetic responsiveness and significant surface area. They also determined that the catalyst was reusable after seven cycles, with biodiesel yield remaining above 82 %. Another study investigated Ni-doped ZnO nanocatalysts impact on biodiesel production (80). With an 8:1 methanol-to-oil molar ratio, transesterification increased biodiesel output by 95.20 %. An optimal catalyst concentration of 11.07 % (w/w) was identified after a 60 min reaction and the nanocatalyst remained effective for three cycles. However, the data indicated that biodiesel production decreased when catalyst concentration exceeded 12 %-14 %.

Lanthanum titanate ($LaTiO_3$) nanoparticles, while effective catalysts for biofuel production, tend to aggregate over time, diminishing their efficiency. Applying a silica (SiO_2) coating can prevent this aggregation by acting as a physical

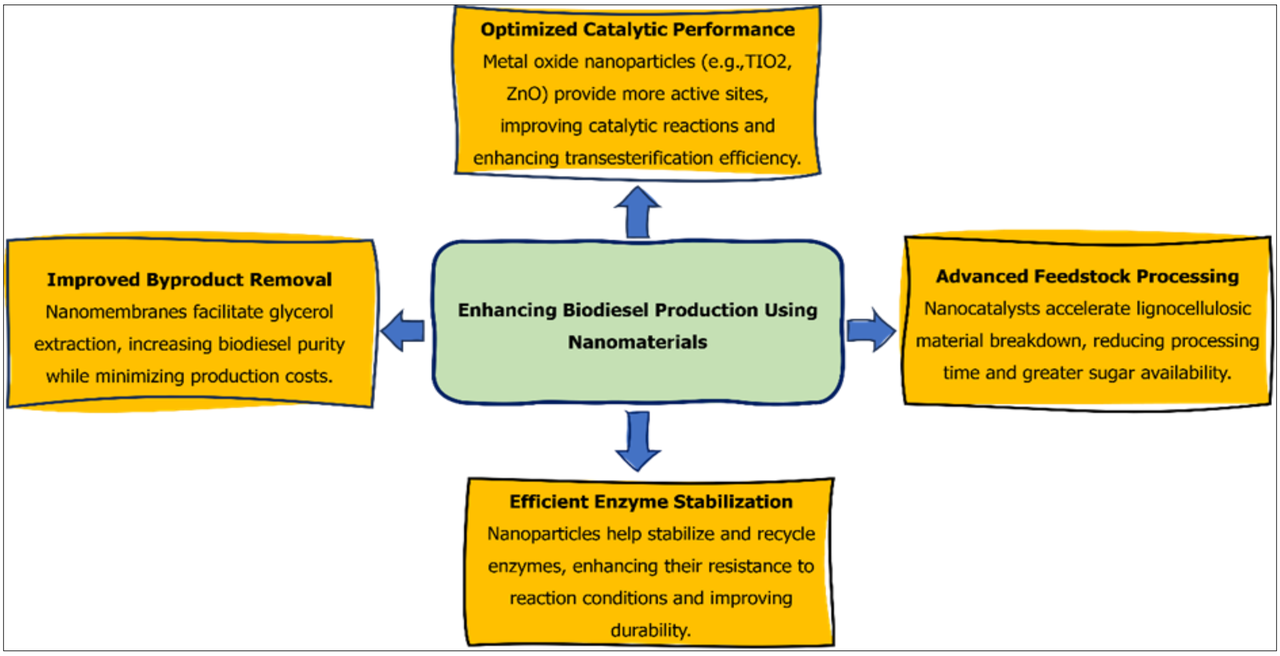

Fig. 4. Improving the production of biodiesel using nanomaterials.

barrier between particles. This coating maintains the nanoparticles' high surface area and catalytic activity, enhancing their stability and reusability in industrial applications. Such surface modification strategies are crucial for sustaining nanoparticle performance in large-scale biofuel production (81). Its acidic and alkaline properties were carefully analyzed to aid transesterification and esterification (82). The catalyst effectively produced biodiesel from sunflower seed oil, requiring less reaction time, fewer materials and easily achievable temperature settings. At a reaction temperature of 80 °C, the biodiesel yield reached 90 % within 60 min and the catalyst maintained a yield of 74 % even after eight cycles (81). Fig. 5 revealed that how incorporating nanomaterials in biofuel production enhances feedstock pretreatment, optimizes byproduct separation, aids enzyme immobilization and boosts catalytic efficiency. These mechanisms underscore the crucial role of nanotechnology in advancing renewable energy and improving the sustainability and cost-efficiency of biofuel production.

Incorporating nanomaterials into the enzymatic biodiesel synthesis process holds great potential. Nanoparticles (NPs) can immobilize lipase enzymes, making it easier to transesterify triglycerides into biodiesel. Immobilizing the enzyme enhances its resistance to harsh reaction conditions, improves stability and reusability and extends its operational lifespan (83). Studies have shown that mesoporous silica nanoparticles, serving as enzyme carriers, significantly boost biodiesel yield and maintain enzyme activity over multiple cycles. Nanotechnology also tackles the challenge of by-product separation in biodiesel production. Nanomembranes and nanoporous materials enhance the final biodiesel's quality and purity by selectively extracting glycerol, a significant by-product. These advanced separation techniques reduce downstream processing costs and boost the overall efficiency of the production process.

3.2. Biogas production

The biogas production process consists of four crucial stages. First, during hydrolysis, organic waste is decomposed into

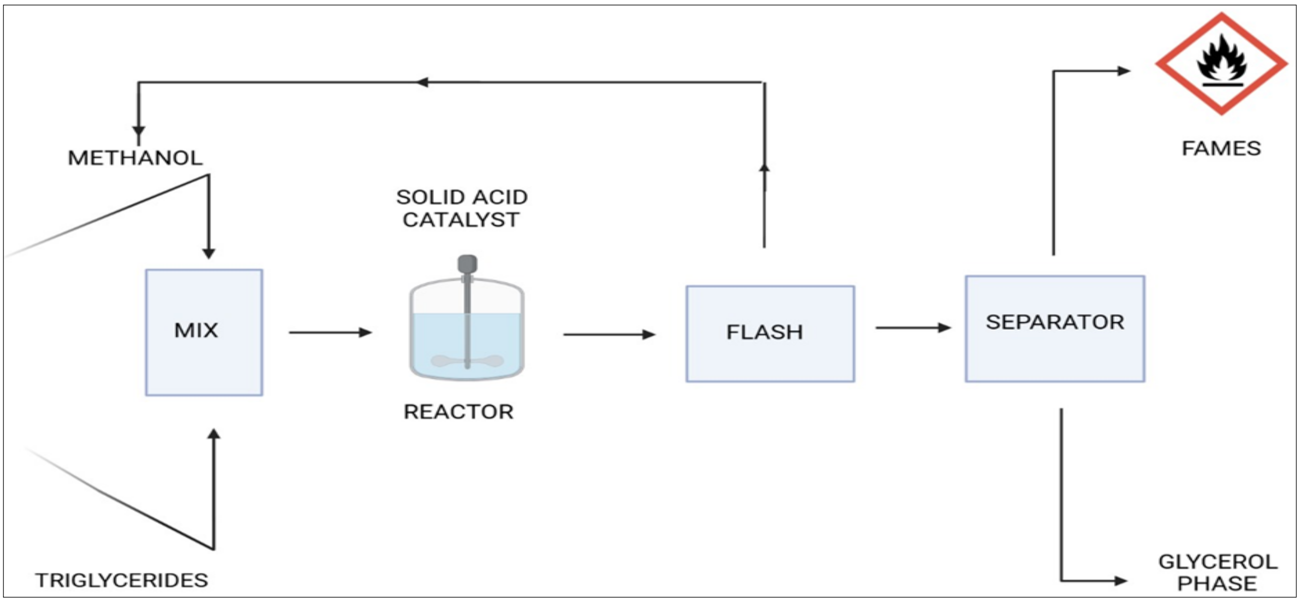

Fig. 5. Process flow diagram for the production of bio-diesel.

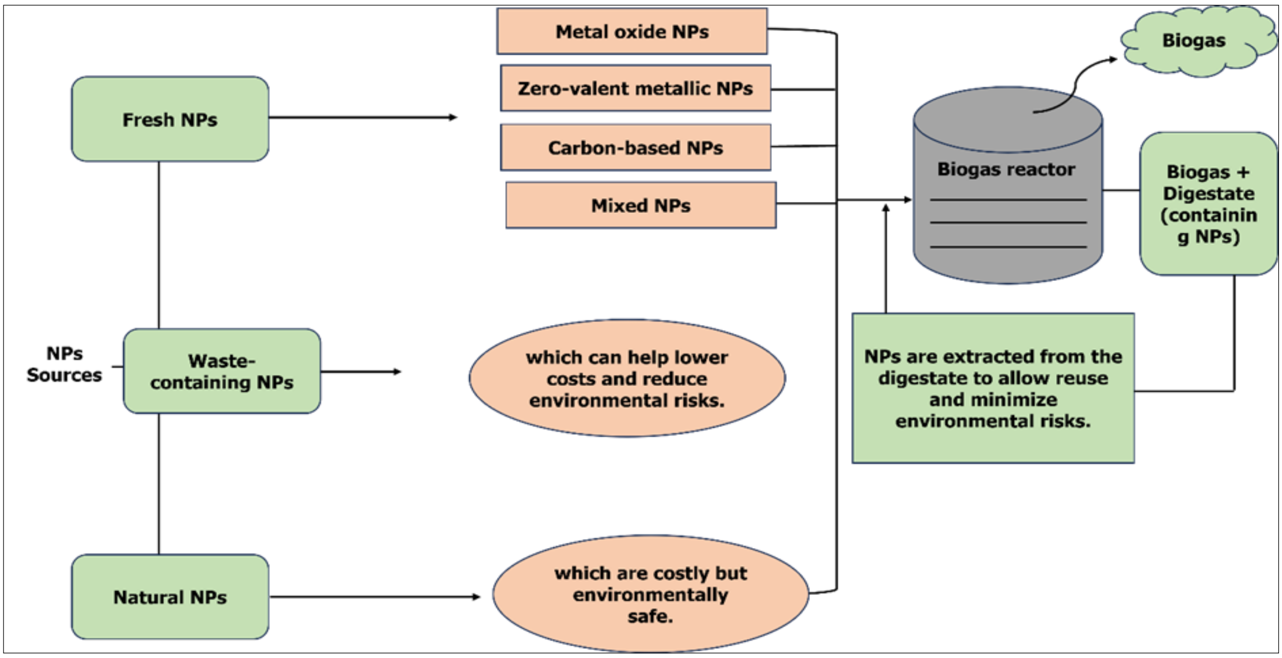

Fig. 6. Nanoparticle as additions for biogas production.

monomers or dimers. In the second stage, acidogenesis, the hydrolyzed products undergo fermentation. Acetogenesis then occurs, where acetate is synthesized from H_2 and CO_2. Finally, methanogenesis utilizes the newly produced acetate, water and CO_2 to generate methane (78). Fig. 6 illustrates the application of NPs as catalytic additives in biogas production. Various NPs, at different concentrations are employed to accelerate the production process and achieve maximum conversion rates more rapidly.

Scaling up nanoscale zero-valent iron (nZVI) from laboratory to industrial reactors presents significant challenges. Inadequate mixing at larger scales can lead to particle aggregation, reducing reactivity and efficiency. High flow rates in continuous reactors may cause nZVI to settle or passivate, diminishing its effectiveness. Innovative reactor designs, such as impinging stream-rotating packed bed reactors, have been developed to enhance mixing and maintain particle stability, thereby improving pollutant degradation rates. Additionally, the use of supports or stabilizers can prevent nZVI aggregation, ensuring consistent performance in industrial applications (84).

Several studies have proposed anaerobic digestion (AD) of waste to produce biogas. A study highlighted three NP types to mitigate pollutants in biogas and address related AD challenges (85). The experiment utilized metal oxide NPs, carbon -based NPs and zero-valent metallic NPs. Among these, zero-valent metallic NPs, particularly Ni and Co NPs, demonstrated exceptional catalytic activity by enhancing biogas output. Both beneficial and detrimental effects were observed with metal oxide NPs, influenced by their size, characteristics and concentration. The addition of carbon-based NPs to the AD process increased ammonia concentration and chemical oxygen demand. Recovery methods for NPs post-AD digestion could evaluate their potential environmental impact and the use of mixed NPs should be examined concerning contamination. Researchers examined the adverse impacts of NPs on waste-activated sludge (86). The study identified CuO NPs as the most hazardous in anaerobic digestion. Increasing CuO NP concentration led to an inhibition rate escalation from 5.8 % to 84 %, indicating a prolonged inhibition effect at 215.1 MgCuO per gTS. While Ag NPs caused a slight reduction in biogas production over time, they showed no short-term inhibitory effect. However, the inhibition was due to higher doses and prolonged exposure to Ag. In contrast, CeO_2 NPs enhanced methane production in the long term.

3.3. Bioethanol production

The utilization of bioethanol as a transportation fuel is becoming increasingly popular due to its cost-effectiveness and environmental advantages (87). Bioethanol is an excellent alternative for the transportation sector because of its broad flammability range, high octane rating (~108) and significant heat of vaporization (79). However, the traditional method of bioethanol production depends on edible crops such as corn, rice, sugarcane and oats, raising concerns about food security. Consequently, researchers are exploring non-edible feedstocks for bioethanol production (79). Fig. 7, illustrates the role of nanotechnology in the bioethanol production process.

Researchers are extensively investigating NPs to resolve enzyme immobilization issues caused by inhibitors. Researchers utilized MnO_2 NPs to immobilize cellulose for bioethanol production, resulting in increased bioethanol yield and improved enzymatic activity (48). Manganese dioxide (MnO_2) NPs mitigate inhibitor effects through various adsorption mechanisms. Their high surface area and surface hydroxyl groups facilitate electrostatic interactions and hydrogen bonding with inhibitors, enhancing adsorption efficiency. Additionally, MnO_2 NPs can undergo redox reactions, alter the chemical state of inhibitors and reducing their inhibitory effects. These combined mechanisms enable MnO_2 NPs to effectively counteract inhibitor-induced performance declines in catalytic and environmental applications.

After the process, NPs expanded by 25 nm and the immobilized cellulose retained 60 % of its catalytic capability after five cycles, enhancing reusability. Additionally,

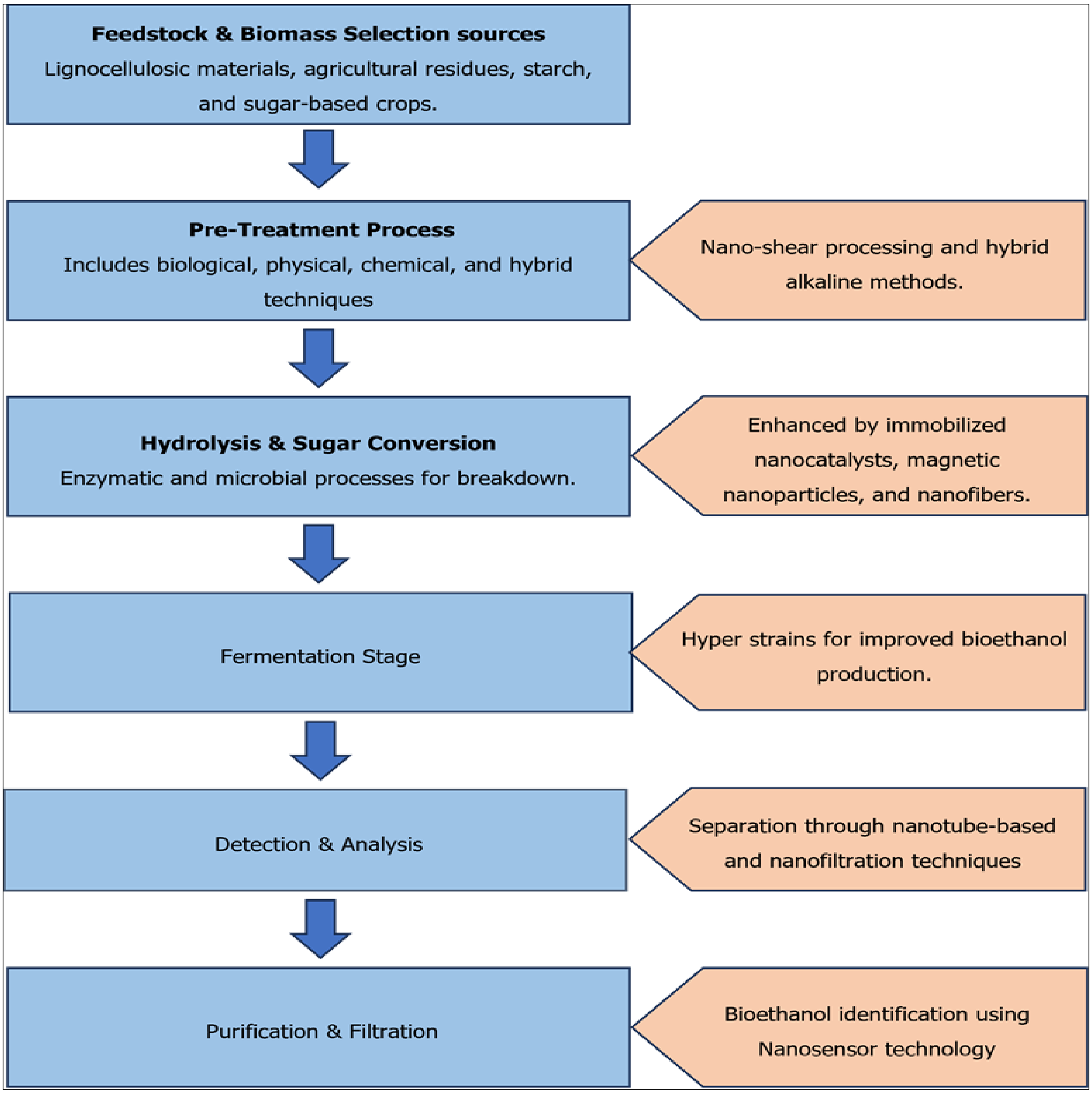

Fig. 7. Nanotechnology based bioethanol production techniques.

immobilized cellulose hydrolyzed cellulosic materials across a broad pH and temperature range, demonstrating superior thermal stability at 700 °C for 2 hrs. Research indicates that iron oxide NPs in acidic pretreatment, finding that NP and acid pretreatment combination increased glucose production by 13 -19 %compared to traditional methods (88). The Fe_3O_4-RGO-SO_3H nanocomposite was employed to create sugar, enhancing enzymatic hydrolysis and accelerating production.

3.4. Biohydrogen production

Biohydrogen production is viewed as a promising future alternative in the energy sector, potentially replacing multiple conventional energy sources (89, 27). Two primary methods exist for biohydrogen production: (i) photofermentation and (ii) dark fermentation. Photofermentation harnesses sunlight to drive photosynthesis, as outlined by (90). In contrast, dark fermentation relies on carbohydrate-rich green algae instead of light (91). These processes are described by the following equations (90).

3.4.1. Photo fermentation

$$16ATP + N_2 + 16H_2O + 10H^+ + 8e^- = 16ADP + 2NH_4^+ + 16pi + H_2 \quad (1)$$

3.4.2. Dark fermentation

$$C_6H_{12}O_6 + 6H_2O = 2CH_3COOH + 4H_2 + 2CO_2 \quad (2)$$

The major drawback of biohydrogen production is its relatively low yield compared to alternative solutions. NPs can enhance the fermentation process to address this issue (78). Fe_2O_3 nanoparticles were used to improve the yield of dark fermentation. Transmission electron microscopy revealed that NP internalization increased enzyme activity and yield in the bacteria. Increasing Fe_2O_3 content from 0 to 200 mg/L promoted biohydrogen production. However, glucose offered a higher biohydrogen yield (27.9 mL/g) (92). Adding NiO and Fe_2O_3 NPs increased hydrogenase enzyme activity, yielding 24 % more biohydrogen. Using CoO or NiO NPs also increased hydrogen production, with CoO NPs resulting in a 1.67fold yield increase and NiO NPs resulting in a 1.51fold increase compared to the traditional approach. Notably, a study emphasized that using CoO and NiO nano additives at 3.00 mg/ L required a supplemental toxicity evaluation to address potential risks to bacteria (93).

3.5. Hydrotreated vegetable oils (HVOs)

HVOs exhibit superior flow and combustion characteristics compared to biodiesel or fatty acids, consisting of paraffinic hydrocarbons devoid of aromatics and sulfur. Catalytic hydroprocessing of fatty acids represents a promising alternative to biodiesel (10). The lack of an appropriate catalyst impeded the exploitation of HVO's properties until the feasibility of using NPs was established. NPs have been shown to overcome limitations and enhance HVO yields (94). Carbon-based nanocatalysts derived biodiesel from Jatropha oil, with Ni-Co/MWCNT demonstrating superior selectivity without carbon deposition and Ni/MWCNT achieving high yield. Aluminum particles have been found to boost HVO's ignition capacity. Comparing pure HVO to HVO with aluminum NPs, the study conducted at 1100 °C in a drop tube furnace. Nanofuels exhibited higher ignition capacity than pure HVO. HVO with 40 nm aluminum particles demonstrated the highest burning rate, while 70 nm particles showed the lowest burning rate.

Conventional diesel engines still have the potential to emit harmful substances. Consequently, researchers investigated whether altering fuel composition could be a viable alternative to updating engine technology (95). The primary fuel for their experiment was B7 biodiesel from an old vehicle, enhanced with NPs and HVO. They found that adding NPs and HVO decreased CO and hydrocarbon emissions by up to 52 % and 47 % respectively. Specifically, a combination of CeO_2 NPs with 30 % HVO proved effective in reducing particulate matter (PM) emissions. Jatropha biodiesel enhanced with various NPs demonstrated potential in lowering pollutant emissions. It was shown that combining CeO_2 and aluminum nanoparticles reduced NO emissions by 30 % (96).

3.6. Fischer–Tropsch synthesis

Fischer-Tropsch synthesis (FTS) is highly used for the cost-effective production of sustainable transportation fuel from natural gas (97). Recently, the advantages and disadvantages of various reactor designs have been thoroughly examined. The FTS process typically involves converting syngas into liquid hydrocarbons, with significant technological advancements enabling heavy hydrocarbon production. Iron (Fe) is considered the optimal catalyst due to its high sulfur resistance and notable operational longevity (98). Although ruthenium (Ru) catalysts exhibit superior catalytic efficiency, their high-cost limits economic feasibility. The efficacy of the FTS largely depends on the catalyst structure, necessitating careful catalyst design and production (99). Cobalt-based NPs are used in FTS in their metallic state, providing active sites for the reaction. The catalyst's effectiveness is influenced by the availability of active sites, which is further affected by the catalyst’s reduction level. However, the reduction process generates high temperatures, making the catalyst prone to metal sintering. Metal cluster issues pose challenges for maintaining a stable reaction. Researchers have explored using noble metals as promoters for Co-based catalysts. The potential of using Pt, Re and Ru in cobalt catalysts, supported by alumina, demonstrated that promoters enhance catalytic performance (100). The study identified Pt as the best metal for improving reducibility.

To improve fuel selectivity, conventionalFTS requires additional post-processing of Fischer-Tropsch waxes. Recent advancements in catalyst design have addressed this issue, allowing for the direct conversion of syngas into three selective fuels: diesel, jet fuel and gasoline. This was achieved using Co/Ymeso, a bifunctional catalyst, where Co nanoparticles were loaded onto Ymeso zeolites. The inability of the Anderson-Schulz-Flory (ASF) model to predict product distribution with bifunctional catalysts led to the development of a new distribution model. This model accurately estimates the distribution of products, unlike the ASF model which does not align with C–C bond catalysis. The FTS fuel selectivity analysis revealed that jet fuel was highly effective, with 74 % selectivity (101). Table 2 lists the NPs used as catalysts in biofuel synthesis.

4. Potential nanotechnology based solutions to address biofuel production issues

Numerous answers to the challenges faced in the manufacture of biofuel are offered by nanotechnology. The biofuel industry may solve several issues by implementing nanotechnological solutions, which will improve the economic feasibility, sustainability and efficiency of biofuel manufacturing processes. As Table 3 illustrates, nanotechnology can make considerable progress in a number of important areas.

5. Challenges in biofuel production

Nanotechnology and NPs are regarded as transformative tools for developing sustainable and efficient biofuel. However, several significant challenges must be addressed for their full integration into the industry. One of the main concerns is the intrinsic toxicity of NPs, posing substantial risks to biological and environmental systems involved in biofuel production. For example, NPs used in processes such as catalysis or microbial cultivation are likely to be released into the environment, potentially contaminating water sources through interactions with aquatic ecosystems. These interactions can produce reactive oxygen species (ROS), which are highly toxic and can severely disrupt the biological processes of microalgae and microorganisms crucial for biofuel production (102). ROS-induced oxidative stress can inhibit the growth of these organisms, directly affecting biofuel yield and efficiency. Additionally, metal oxide NPs such as ZnO, CuO and Fe_2O_3 have been shown to exacerbate these effects, leading to reduced microalgal production essential for biofuel synthesis (103) (Table 4).

The potential health risks associated with the widespread use of NPs in biofuel production pose another significant challenge. Handling and processing NPs can lead to unintended atmospheric release, endangering the health of nearby residents and workers. Inhalation or ingestion of NPs can cause oxidative stress, cellular inflammation and even cell death, potentially leading to chronic illnesses such as cancer and heart disease (104). These concerns are exacerbated by the potential for NPs to damage DNA by generating ROS, with long-term health implications (105). These risks are particularly concerning in industrial settings where large-scale nanomaterial processing increases exposure likelihood.

Another challenge is the impact of nanomaterials on the soil ecosystem. During biofuel production, nanomaterials may

Table 2. Nanotechnology-based studies on the production of biofuel

Nanoparticles (NPs)	Objectives	Method	Feedstock	Findings	Scalability and potential applications	Remarks	References
ZnO nanocatalyst	Improve the biodiesel production	Ultrasonic- assisted catalytic transestterification	Cooking oil waste (WCO)	It was found that 1.5 weight percent was the ideal catalyst concentration	High scalability for decentralized biodiesel production using kitchen and industrial waste oils.	Density and viscosity were less than standard biodiesel. FAME productivity was up to 96 %	(119)
ZnO	Bioethanol production	-	Rice straw	Adding 200 mg/L NPs resulted in the maximum ethanol output of 0.0359 g/g (biomass weight).	Promising for agricultural waste valorization in rural bioethanol units.	Maximum yield was up to 0.0359 g/g of plant dry weight	(120)
SiO_2 and SiO_2-CH_3 NPs	To measure CO_2 gas-liquid mass transfer	Stober method	Chlorella vulgaris	The dry cell weight was 1.49 g/L and FAME generation was 1.005 g/L/day	Scalable in photobioreactor-based algal biodiesel production systems.	FAME productivity was increased 210 and 610 % Cost-effectiveness.	(121)
Zeolite, iron NP mixes and nanoscale zero-valent iron (nZVI) particles	Assess the complete anaerobic digestion	Anaerobic digestion	Domestic sludge	Adding nZVI coated zeolite (ICZ) 1000 particles maximizes methane generation.	Feasible for municipal wastewater-to-biogas systems.	Methane content stimulated up to 88 and 74 %	(122)
Fe^{2+} and magnetite NPs	To identify the dominant H_2 generating bacterium and Improve biohydrogen generation reaction conditions.	-	Hydrolyzed sugarcane bagasse	The results showed that magnetite NPs inhibited microorganisms less than Fe^{2+} and that *Clostridium spp.* produced the most H_2.	Potential in integrated biorefineries for H_2 fuel from agricultural residues.	Assessing the magnetite NP degradation resistance and ion discharge capacity can determine biohydrogen generating feasibility	(56)
Ni-Co/MWCNT	To produce biofuel by deoxygenation process	deoxygenation process	Uneatable *Jatropha curcas* oil	With steady hydrocarbon production, catalyst reuse is four times.	Suitable for advanced drop-in biofuel production in remote or arid zones.	Carbon-based nanotubes are widely available and cost-effective.	(94)

Table 3. Potential remedies for the challenges related to the production of biofuel by utilizing nanotechnology in a number of crucial fields

Challenge area	Potential solutions	Required technological improvements	References
Separation and purification	Advanced nanofiltration membranes for selective separation of biofuel molecules	Development of high-selectivity, chemically stable and fouling-resistant membranes	(102)
	Magnetic nanoparticles for efficient biofuel separation from biomass slurry	Optimizing synthesis for biocompatibility and robust magnetic response	(108)
Biomass pretreatment	Photocatalytic nanoparticles for biomass decomposition under light exposure	Enhancing stability across different environments and improving light-driven processes	(103)
	Nanoparticle-assisted breakdown of lignocellulose to improve processability	Designing energy-efficient nanoparticles for effective lignocellulose degradation	(107)
Energy storage and distribution	Nanomaterials for biobatteries to enhance energy storage	Research on biobattery nanomaterials with high storage capacity and durability	(106)
	Nanotechnology-enhanced biofuel fuel cells for efficient energy storage and distribution	Innovation in nanostructured catalysts and electrolytes to improve fuel cell efficiency	(123)
Catalysts for iomass conversion	Synergistic effects of nanoscale metal combinations for improved catalytic performance	Enhancing bimetallic nanoparticle synthesis for better surface area and catalytic synergy	(124)
	Nanocatalysts for biomass-to-biofuel conversion to increase reaction speed and selectivity	Development of thermally stable, recyclable nanocatalysts with improved selectivity	(104)
CO_2 utilization	Nanomaterials for CO_2 capture from fermentation and industrial emissions	Creation of nanomaterials with large surface areas to improve CO_2 adsorption and conversion	(102)
	Nanostructured photocatalysts utilizing sunlight for CO_2 conversion in biofuel production	Enhancing photocatalyst sensitivity to visible light for better efficiency	(107)
Waste reduction and valorisation	Nanomaterials for biofuel effluent treatment, enabling resource recovery and compliance	Development of multifunctional nanoparticles that recover valuable resources and remove pollutants	(103)
	Nanotechnology-assisted conversion of biofuel byproducts into valuable chemicals or fuels	Innovations in catalytic processes for transforming low-value byproducts into high-value outputs	(106)
Microalgae cultivation	Engineered nanoparticles improving microalgae resilience and productivity	Developing NP formulations that enhance microalgae stress tolerance and nutrient absorption	(123).
	Nutrient-loaded nanoparticles for enhanced lipid accumulation in microalgae	Creating nanoparticles that improve bioavailability and lipid production in microalgae	(108)
Enzyme efficiency	Nanoparticle-immobilized enzymes for stable and efficient biofuel production	Development of stable NP–enzyme conjugates with high catalytic activity for industrial applications	(124)

Table 4. Current research on the production of biofuel and the use of nanotechnology

Core analysis	Key insights	Results	Reference
Advances in nanotechnology for biofuel production and sustainability	Nanotechnology enhances biofuel production efficiency and supports environmental sustainability.	Using nanotechnology can improve biofuel yield, reduce environmental impact and promote sustainable development.	(31)
Role of nanoparticles in biofuel production	Nanoparticles help improve biofuel quality, lower costs and enhance production efficiency.	Nanoparticles play a crucial role in optimizing biofuel production and minimizing environmental effects.	(79)
Sustainable industrial wastewater treatment using nanotechnology	Nanotechnology offers effective solutions for wastewater treatment while meeting sustainability goals.	Nanotechnology provides an eco-friendly approach to treating industrial wastewater with potential applications in various sectors.	(125)
Biodiesel production from Fats, Oils and Grease (FOG)	Research suggests that FOG can be a valuable feedstock for biodiesel production.	FOG serves as a promising alternative to conventional biodiesel feedstocks, improving fuel sustainability.	(126)
Pretreatment methods for lignocellulosic biofuel production	Advanced pretreatment techniques significantly enhance the conversion of lignocellulosic biomass into biofuels.	Efficient pretreatment processes are vital for improving biofuel yields from lignocellulosic biomass.	(107)

inadvertently contaminate the soil, altering the microbial composition and reducing soil fertility. This is especially problematic for the growth of feedstock crops used in biofuel production, as a healthy, diverse microbiome is essential for maintaining soil nutrients. Declining soil productivity not only reduces crop yield but also threatens the long-term sustainability of biofuel production (106).

The financial implications of integrating nanotechnology into biofuel production is crucial. Utilizing nanomaterials, particularly nanocatalysts in converting lignocellulosic biomass, involves high operational costs. These nanocatalysts often require complex and expensive pretreatment processes to convert biomass into fermentable sugars effectively (107). While these materials can enhance biofuel production efficiency, their costs may hinder scalability, particularly in developing countries where cost-effectiveness is essential. The high capital and operating expenses associated with nanotechnology-based biofuel production could limit its large-scale adoption and growth (108). Although nanotechnology holds potential for advancing biofuel production, it is essential to address related economic, health and environmental concerns thoroughly.

Biofuel is emerging as a viable alternative for sectors reliant on petroleum, given its safety, environmental sustainability, renewability and reduced ecological footprint. Experts are exploring biofuels as potential replacements for petroleum-based fuels, which are experiencing price increases due to heightened demand and limited supply (109). Despite being more eco-friendly, biofuel production remains a complex process (110).

Biomass is the primary feedstock for biofuel production and can be sourced from plants, organic waste, agricultural residues, wood and municipal organic waste (MOSW). While there are significant opportunities for progress, numerous challenges exist in replacing commercially available petroleum -based fuels (111). Lignocellulosic biomass pre-treatment methods entail high operational costs. Algal biomass is also a promising feedstock for biodiesel due to its high oil content, carbon neutrality and rapid growth rate. Some suggest it could eventually replace fossil fuels in biodiesel production; however, algal biomass production is costly and lipid extraction is energy-intensive (112).

The full potential of using nanocatalysts for biofuel production has not yet been realized, as adapting nanotechnology to industrial-scale biofuel production is challenging. Researchers are working to improve biofuel production with available resources. Until now, most biofuels have been derived from edible crops such as sugarcane and corn (111). Biofuel production from non-edible sources remains lower than that from edible sources, but nanotechnology is accelerating and increasing output from non-edible feedstocks (113). Commercially available biofuel still faces high costs and requires supplemental fuels, preventing it from fully replacing petroleum-based fuels. Nonetheless, the prospect of using biofuel as an environmentally friendly energy source is becoming increasingly viable (114-116).

6. Current trends and future perspective

The primary requirement for biofuel production is biomass, which can be sourced from wood, plants, organic waste, agricultural residues and municipal solid waste. However, numerous challenges need to be addressed to make biofuels a competitive replacement for conventional petroleum-based fuels (117). Algal biomass, rich in oil content, carbon-neutral and fast-growing, is also being explored for biodiesel production, with the potential to replace fossil fuels. However, its cultivation is expensive and lipid extraction demands significant energy inputs (118). On the other hand, biofuels are the future of petroleum-dependent industries due to their eco-friendly, renewable and safer nature. The growing scarcity of petroleum and rising demand, leading to frequent price surges, has encouraged researchers to explore biofuels as a viable alternative (109). Despite their advantages, producing biofuels remains a complex process.

Establishing comprehensive regulatory frameworks is essential to bridge the gap between laboratory research and market application of nanoparticle-enhanced biofuels. Internationally, the Organisation for Economic Co-operation and Development (OECD) has developed guidelines to assist governments in implementing policies that ensure the responsible development of nanotechnologies, focusing on safety evaluation and assessment of manufactured nanomaterials. These guidelines promote international cooperation on the human health and environmental safety aspects of manufactured nanomaterials for regulatory purposes. In the European Union, the Registration, Evaluation, Authorisation and Restriction of Chemicals (REACH) regulation requires companies to register nanomaterials and assess their risks before they can be marketed, providing a structured approach for the classification, labelling and safety assessment of nanomaterials. In India, the Department of Biotechnology (DBT) and the Ministry of Environment, Forest and Climate Change (MoEFCC) oversee the regulation of nanotechnology-based agricultural products, encompassing biofuels. These agencies enforce guidelines and standards to assess the safety and efficacy of nanomaterials, facilitating their responsible use in biofuel production. Implementing such regulatory frameworks can enhance public confidence, ensure environmental and human safety and accelerate the commercialization of nanoparticle-based biofuels.

Scaling up biofuel production with the aid of nanotechnology presents another set of hurdles, as the application of nano-catalysts in this field is still in its infancy. Research continues to enhance biofuel production using various resources. Large-scale biofuel production has predominantly relied on edible crops like maize and sugarcane. Advances in nanotechnology are helping to increase biofuel yields from non-edible sources, yet replacing petroleum-based fuels remains challenging. Nonetheless, the potential of biofuels as a sustainable and green energy alternative is expected to grow significantly soon.

Nanotechnology is revolutionizing biofuel production by enhancing efficiency and sustainability. Here are some current trends and future perspectives in the biofuel production using nanomaterials:

1. **Nanocatalysts:** Metal, magnetic and metal oxide nanoparticles are being used to improve biofuel production. Their unique properties, such as high surface area and catalytic activity, make them effective additives.

2. **Enzyme immobilization:** Nanomaterials like carbon nanotubes and nanofibers are used to immobilize enzymes, enhancing biofuel synthesis.

3. **Feedstock pretreatment:** Nanotechnology improves the pretreatment of lignocellulosic biomass, making it easier to convert into biofuels.

4. **Process efficiency:** Nanomaterials help in reducing energy consumption and improving the overall efficiency of biofuel production processes.

Conclusion

The incorporation of nanoparticles in biofuel production has significantly enhanced efficiency due to their unique physicochemical properties, including a high surface-area-to-volume ratio, excellent reactivity and good dispersibility. Nanoparticles such as metal, metal oxide, magnetic and carbon-based materials have been effectively utilized to improve biofuel production from various substrates. They also enhance substrate digestibility during pretreatment, further boosting yields. However, for successful commercialization, challenges such as the synthesis of non-toxic, cost-effective and environmentally friendly nanoparticles must be addressed. Additionally, shifting from chemical to biological nanoparticle synthesis methods is essential to reduce operational stringency.

Nanomaterials, including nanocatalysts, have shown remarkable potential in improving biofuel production, such as biodiesel and biogas. Catalysts like Li/ZnO-Fe_3O_4, CaO/Al/Fe_3O_4

and MgO@CaO have demonstrated biodiesel yields exceeding 98 % and can be reused with minimal efficiency loss. The immobilization of enzymes on nanomaterials, such as magnetic nanomaterials, graphene oxide and silica nanoparticles, offers benefits like high stability, low toxicity and enhanced reusability. Moreover, nanoparticles like NZVI and Fe_3O_4 have proven effective for biodiesel and biogas production while reducing harmful emissions. As global energy demands rise, nanotechnology provides a promising path for sustainable biofuel production, offering an alternative to fossil fuels while mitigating environmental impact.

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Authors' contributions

Authors KAR and VG were responsible for designing the study, conducting the statistical analysis, developing the protocol and drafting the initial manuscript and remaining all authors are contributed and revised the manuscript.

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