Review Article

Journal of Environmental Nanotechnology

Advancing Bioenergy and Biofuels: Role of Nanotechnology in Sustainable Energy Systems

Zainab SH. Mohammed*

Department of Laser Physics, College of Science for Women, University of Babylon, Babil, Iraq

Received: 23.04.2025 Accepted: 07.06.2025 Published: 30.06.2025

*wsci.zainab.mohammed@uobabylon.edu.iq

ABSTRACT

The growing necessity to transition from fossil fuels to sustainable energy sources has driven extensive research into advanced technologies that can address the limitations of conventional biofuel production. In this context, nanotechnology has emerged as a transformative platform, offering substantial enhancements in catalytic activity, enzyme immobilization, microbial efficiency, and reaction kinetics. This review provides a critical assessment of recent developments in the application of nanomaterials including metal oxides, carbon-based nanostructures, and bimetallic nanoparticles in the production of bioethanol, biodiesel, biogas, and biohydrogen. Empirical findings demonstrate the potential of nanomaterials to support process intensification through improved biomass pretreatment, catalyst reusability, and improved substrate conversion. However, despite these advancements, challenges persist, particularly concerning nanoparticle toxicity, environmental sustainability, scalability, and the economic viability of nano-enabled biofuel systems.

Keywords: Nanotechnology; Biofuels; Nanomaterials; Bioethanol; Biohydrogen; Renewable energy

1. INTRODUCTION

Nanomaterials are materials with an external dimension or at least one dimension measured within the range of 1-100 nanometers. They have gained much attention due to their unique physical and chemical properties, which differ from their bulk counterparts (Hussein, 2015). The European Commission has formalized this size criterion for defining nanomaterials. Their novel characteristics make them highly applicable in various fields; including energy production. Among renewable energy alternatives; biofuels have emerged as a promising substitute for fossil fuels due to their compatibility with existing engines allowing up to 85% gasoline blending without requiring modifications (Cherian *et al.* 2015). Moreover, biofuels are environmentally friendly, renewable, and sustainable, offering a means to significantly reduce greenhouse gas emissions. Biofuel feedstocks can include agricultural waste, animal dung, vegetable oils, animal fats, and sugar crops. Techniques of production for such fuels include anaerobic digestion, fermentation, and transesterification (Pavlidis *et al.* 2012). However, manufacturing biofuels is usually a high-cost process. Further, the conversion efficiency remains rather low, and the whole process has several technical barriers (Lee *et al*. 2015). The aforesaid challenges in the production of biofuels and bioenergy make nanotechnology a practically deployable solution. Nano-electrodes and catalysts are useful for applications that range from building portable devices to automobiles. Innovations such as boundary-layer designs in nanostructured semiconductors and nanotube-based power lines make utilization of waste heat possible, thus decreasing energy loss while transmitting power (Guan *et al.* 2017). Furthermore, nanotechnology methods of superconducting material fabrication reduce conduction losses and provide feasible and effective options for wireless power transmission using lasers and microwaves. New nanomaterials can change the face of the energy economy through enhanced efficiency in various industries and also provide financial benefits to nations through the use of state-of-the-art energy technologies (Stellwagen *et al*. 2013).

Nanotechnology is emerging as a transformative tool in the field of renewable energy, particularly in enhancing the production processes and efficiency of biofuels. Its application spans multiple aspects of biofuel generation, from improving biomass conversion to optimizing fuel compatibility with conventional gasoline and diesel. Recent studies have demonstrated that the inclusion of nanomaterials such as nanomagnets, nanofibers, and nanodroplets significantly enhances catalytic performance due to their high surface area, exceptional stability, and recyclability (Pavlidis *et al.* 2012; Gardy *et al.* 2017). These unique physicochemical properties enable nanomaterials to play a major role in improving the yields of bioethanol, biodiesel, and biogas through various pathways. The integration of nanotechnology across the biofuel production cycle from biomass pretreatment and hydrolysis to transesterification and anaerobic digestion has opened new avenues for efficient and sustainable energy conversion. While the majority of these

applications are currently limited to laboratory and pilot scales, ongoing technological progress indicates strong potential for scaling up to industrial production (Masran *et al.* 2016; Chaudhary *et al.* 2025). For instance, innovations in nanocatalysts, bioreactor designs, and nanostructured enzyme supports are driving significant advancements toward cost-effective and scalable biofuel systems. A wide range of nanomaterials including metal oxides (e.g. TiO_2, ZnO, Fe_3O_4), carbon-based nanostructures (e.g. graphene, carbon nanotubes), ceramics, semiconductors, and polymers have demonstrated immense potential in bioenergy applications (Cherian *et al*. 2015; Rana and Prajapati, 2023). Among these, magnetic nanoparticles stand out due to their tunable surface chemistry, quantum effects, and ease of recovery from reaction media using external magnetic fields, all of which contribute to their superior catalytic efficiency (Kushwaha *et al.* 2018).

Despite these promising developments, certain technical and environmental challenges persist. The controlled synthesis of nanoparticles with specific size, shape, and chemical functionality is complex and cost-intensive. Moreover, concerns related to nanoparticle toxicity, bioaccumulation, and long-term interactions with biological macromolecules continue to raise questions about their environmental and health impacts (Hao *et al.* 2019). Therefore, sustainable production strategies, including green synthesis and lifecycle assessment of nanomaterials, are essential to maximize the benefits of nanotechnology in biofuel applications. As highlighted by Fayaz *et al*. (2022), Malaysia is actively exploring the integration of nanotechnology with biodiesel and solar energy as part of a broader renewable energy conversion. Similarly, Chaudhary *et al*. (2025) emphasized the synergistic benefits of combining nanotechnology with hybrid energy systems, artificial intelligence, and biotechnological advancements to align with circular economy principles. Such multidisciplinary approaches have been shown to reduce greenhouse gas emissions by up to 30 % and improve energy output by 15-37 %, highlighting the vital role of nanotechnology in future energy security.

Fig. 1 illustrates the multifaceted roles of nanomaterials in enhancing biogas, bioethanol, and biodiesel production. These enhancements include accelerated enzymatic hydrolysis, improved microbial activity, efficient substrate utilization, and optimized methanation processes. Table 1 further summarizes the utilization of various nanomaterials across feedstock types, showcasing their effectiveness in improving conversion efficiency and fuel yield (Rana and Prajapati, 2023; Kushwaha *et al.* 2018).

The paper investigates the possibility of nanotechnology to revolutionize bioenergy and biofuel production by addressing limitations in efficiency, scalability, and sustainability. This review focuses on the nanomaterials as catalysts, additives, and enhancers in key processes of biofuel production, and it also presents a road map for future developments.

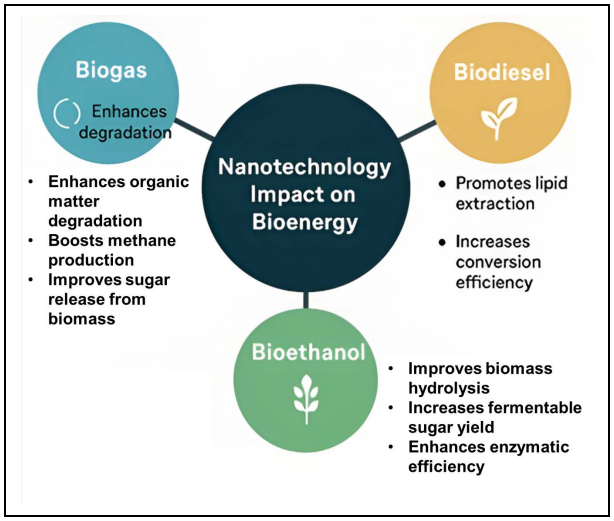


Fig. 1: Integration of nanotechnology into key processes for biofuel and bioenergy production adapted from Chaudhary *et al.* (2025)

Table 1. Nanotechnology applications in biofuel production from biomass (Kushawaha *et al.* 2018)

Product	Nanotechnology	Biomass Feedstock
Biodiesel (40.8%)	Nanoparticles of cobalt	*Camellia sinensis* waste tea
Bioethanol (95.7%)	Silica nanoparticles with physisorbed cellulase	Microcrystalline cellulose
Bioethanol (21.96%)	MnO_2-immobilized cellulase	Leaves from sugarcane and jackfruit waste
Bioethanol (5.31 g/L)	Magnetic nanoparticles enclosed in cellulose	*Sesbania aculeata*

2. LITERATURE SURVEY

2.1 Nanomaterial Preparation

Nanoparticles play a significant role in enhancing the biochemical processes involved in liquid fuel production, particularly through enzymatic pathways such as fermentation. Their application improves mass transfer rates, enzyme-substrate interactions, and catalytic conversions due to their high surface area-to-volume ratios and tunable surface functionalities (Ndaba *et al.* 2025; Togun *et al.* 2025).

2.1.1 Synthesis of Nickel Oxide Nanoparticles (NiO NPs)

Nickel oxide nanoparticles have gained increasing interest due to their favorable redox

properties, catalytic surface activity, and cost-effective synthesis protocols. In a typical preparation route, NiO NPs are synthesized by dissolving nickel(II) chloride hexahydrate ($NiCl_2.6H_2O$) in distilled water, followed by pH adjustment to 10 by adding NH_3 dropwise and subsequent microwave irradiation at 700 W for 180 seconds. The resulting green precipitate is then thoroughly washed and oven-dried for six hours (Sanusi *et al*. 2019). These NiO NPs exhibit strong potential to enhance biomass hydrolysis by improving the catalytic interface for enzyme-substrate interactions, thereby increasing the yield of fermentable sugars from lignocellulosic materials (Dutta *et al.* 2023). Recent developments have further expanded the application of nickel-based nanomaterials in bioenergy conversion. For example, Marimuthu *et al.* (2024) synthesized three-dimensional FeCoP nanosheets supported on NiO NPs, achieving outstanding catalytic performance in glucose oxidation due to their high electrochemically active surface area and long-term durability, an essential feature for biofuel cells. Moreover, Zahid *et al.* (2024) demonstrated that Ni-doped ZnO nanocatalysts could achieve a 90.1% biodiesel yield from neem oil transesterification under optimized thermal conditions, highlighting the efficiency of nickel-enhanced systems in liquid fuel production. In the context of sustainable synthesis, *Garcinia cambogia* seed powder was employed as a green fuel for synthesizing Ni-doped MoO_3 nanoparticles, which exhibited enhanced photocatalytic degradation under UV light emphazising the eco-friendliness of biofuel-compatible nanomaterials. Furthermore, immobilization of enzymes onto nickel ferrite-based carriers, such as $NiFe_2O_4$, has been shown to facilitate hydrocarbon production *via* light-driven enzymatic decarboxylation with excellent recovery and stability (Li *et al.* 2023). These findings confirm the versatile role of nickel-based nanomaterials across multiple bioenergy pathways, from enhanced saccharification to advanced electrocatalysis, and stress the need for continued innovation in nanoparticle design for scalable, and sustainable biofuel systems.

2.1.2 Synthesis of Iron(III) Oxide Nanoparticles (Fe_3O_4 NPs)

Magnetic iron oxide nanoparticles are increasingly utilized in sustainable bioenergy applications due to their biocompatibility, ease of recovery, surface functionalization potential, and ability to enhance enzymatic and microbial activity. A commonly employed synthesis route involves dissolving 1.0 g of ferrous sulfate heptahydrate ($FeSO_4.7H_2O$) in distilled water, followed by the gradual addition of 25 mL of NaOH and further dilution with distilled water. The pH is adjusted to approximately 12, and the mixture is irradiated using microwave synthesis at 700 W for 10 minutes, yielding a black Fe_3O_4 precipitate. This product is then washed and dried at 70°C (Aruwajoye *et al.* 2017). These nanoparticles have been shown to significantly improve reducing sugar recovery from lignocellulosic biomass during pretreatment and enzymatic hydrolysis phases (Ndaba *et al.* 2025; Vickram *et al.* 2023).

Recent developments highlight the use of biosynthesized Fe_3O_4 and its nanocomposites to further enhance catalytic activity. For instance, Fe_3O_4 coated with polyaniline (Fe_3O_4/PANI) nanocomposites synthesized *via in situ* polymerization demonstrated superior electron transfer rates and power output in microbial fuel cells, achieving a power density of 424.5 mW/m^2 over six times higher than conventional electrodes (Tesfaye *et al.* 2025). Moreover, green-synthesized Fe_2O_3 nanoparticles from *Salvia moocroftiana* leaf extract were effectively reused as nanocatalysts for biodiesel production from *Cupressus macrocarpa* seed oil, achieving 93% fatty acid methyl ester conversion under optimized conditions (Rozina *et al.* 2025).

In microalgae-based bioprocesses, tannin-functionalized Fe_3O_4 nanoparticles have also proven effective in harvesting *Chlorella sp*., offering over 92% harvesting efficiency and reusability across six cycles, highlighting their scalability and cost-effectiveness (Osman *et al.* 2024; Barizao *et al*. 2025). Additionally, magnetic Fe_3O_4 particles functionalized for enzyme immobilization, such as with Eversa Transform 2.0 lipase, have enabled efficient biodiesel production from oleic acid with conversion rates exceeding 88%, further confirming the catalytic and recovery benefits of Fe_3O_4 nanostructures (Dos *et al.* 2024).

2.2 Production of Bioethanol

Ethanol remains one of the most commercially viable renewable fuels due to its high octane number, lower greenhouse gas emissions, and compatibility with existing fuel infrastructure. Bioethanol, derived from lignocellulosic biomass, is of particular interest given its potential to be sustainably scaled through nanotechnology-assisted bioconversion processes (Chaudhary *et al.* 2025; Ndaba *et al.* 2025).

2.2.1 Production Process

Bioethanol production comprises three key steps: raw material pretreatment, enzymatic hydrolysis, and fermentation (Alvira *et al.* 2010). Pretreatment is essential to break down the lignin cellulose barrier and expose fermentable sugars such as glucose. However, conventional pretreatment is often energy-intensive and expensive.

The integration of nanomaterials, especially NiO and Fe_3O_4, has been shown to significantly improve the efficiency of this stage. These nanomaterials act as catalysts or co-factors in reducing biomass recalcitrance, enhancing enzyme accessibility, and lowering the severity of process conditions required (Ndaba *et al.* 2025; Togun *et al.* 2025). For instance, Fe_3O_4

nanoparticles have been shown to increase reducing sugar recovery by up to 60% in certain lignocellulosic feedstocks, directly boosting ethanol yields.

2.2.2 Immobilization of Enzymes

The immobilization of commercial enzymes (e.g. Cellic CTec3) onto nanoparticles has become a common approach to enhance the stability, reusability, and catalytic activity of hydrolytic enzymes. Various nanomaterials such as iron oxide, magnesium oxide, and silver oxide have been employed for enzyme immobilization *via* physical adsorption or covalent coupling techniques (Ivanova *et al.* 2011). Among these, β-glucosidase immobilized on magnetic supports exhibited superior hydrolysis efficiency and reusability. Polymer magnetic nanofiber supports have further demonstrated enhanced stability across multiple use cycles (Aruwajoye *et al.* 2017).

Nanomaterials like silicon dioxide, titanium dioxide, carbon nanotubes, fullerene, and graphene have also been used to support enzymes or microbial strains (e.g. *Saccharomyces cerevisiae*) during fermentation (Rai *et al.* 2019). These supports offer significant advantages due to their large surface area, functionalizability, and mechanical strength. The reduced diffusional limitations and increased local enzyme concentrations on nanosurfaces result in higher conversion rates and cost-effective bioethanol production compared to classical production process as shown in Fig. 2 (Ndaba *et al.* 2025; Razzaghi *et al.* 2022).

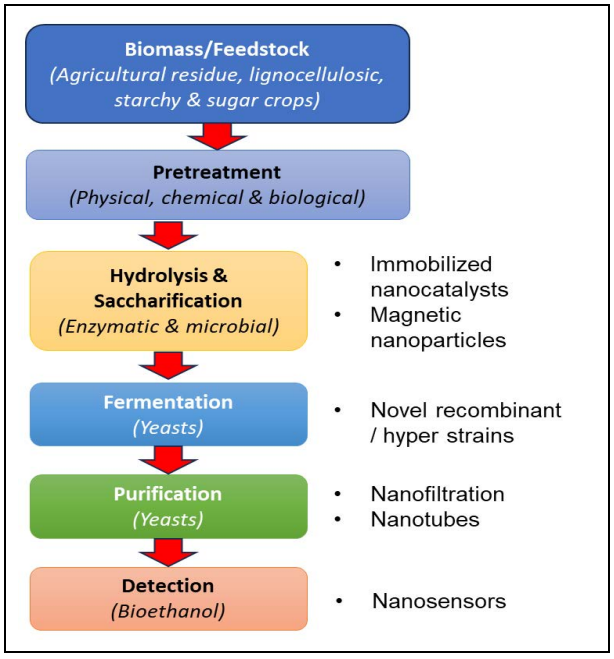


Fig. 2: Utilization of nanotechnology in bioethanol synthesis (Ndaba *et al.* 2025)

The catalytic efficiency and reusability of enzymes are significantly improved by immobilizing them on nanomaterials, particularly due to increased active surface area and stability under varied pH and thermal conditions. This also facilitates efficient substrate penetration and sugar extraction under mild operating environments (Verma *et al.* 2016). Notably recent findings suggest that Fe_3O_4-immobilized cellulase systems can be reused for more than 10 cycles with minimal loss in activity, providing both economic and operational advantages (Ndaba *et al.* 2025). Nanoparticle-enhanced immobilization strategies are thus key enablers for industrial-scale bioconversion.

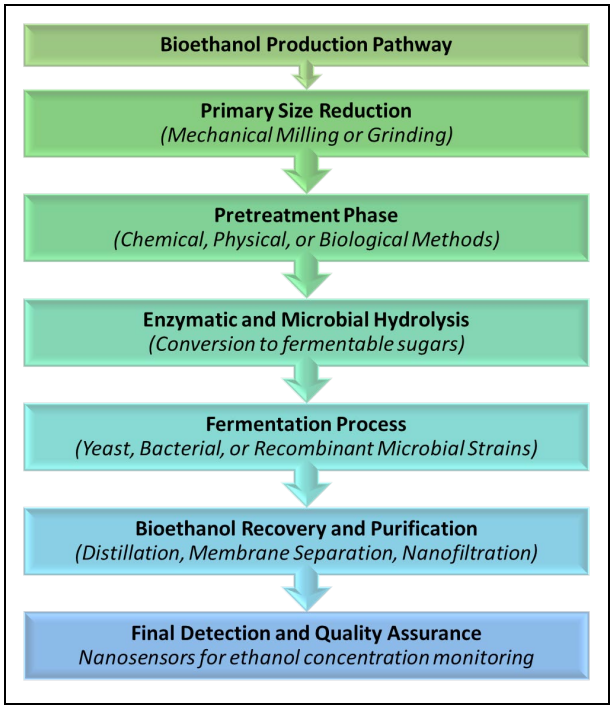


Fig. 3: Integrated bioethanol production from mixtures of lignocellulosic biomass (Source: Togun *et al.* 2025)

Nanomaterials possess extraordinary surface-area-to-volume ratios, high porosity, and chemical reactivity that make them highly suitable for enzyme immobilization and feedstock pretreatment, two critical steps in improving the economic feasibility of second-generation bioethanol production shown in Fig. 3 (Ndaba *et al.* 2025; Rai *et al.* 2019; Sharma *et al.* 2023). Enzyme immobilization using nanomaterials such as Fe_3O_4, SiO_2, and TiO_2 not only enhances enzymatic stability and substrate accessibility but also enables magnetic separation and reusability, significantly reducing operational costs. Techniques such as nano-encapsulation, covalent coupling, and adsorption have been widely adopted to immobilize enzymes like cellulase and β-glucosidase; leading to over 90% sugar yield and 10+ reuse cycles with sustained activity (Antunes *et al.* 2014; Razzaghi *et al.* 2022; Mehejabin *et al.* 2024).

In feedstock pretreatment, nanoparticles disrupt the rigid lignin-hemicellulose matrix of lignocellulosic

biomass, enhancing enzymatic hydrolysis under milder conditions. Metal oxides like ZnO, TiO_2, and NiO have shown high catalytic activity in facilitating delignification and increasing sugar recovery rates (Togun *et al.* 2025; Sher *et al.* 2024).

2.2.2 Nanotechnology-driven Advancements in Biodiesel Production

Nanotechnology plays a pivotal role across all stages of biodiesel production (Fig. 4) from feedstock pretreatment and lipid extraction to catalysis and fuel upgrading, enhancing process sustainability, conversion efficiency, and fuel quality (Kazemi *et al.* 2024; Bin *et al.* 2023). Traditional homogeneous catalysts suffer from drawbacks such as saponification, high water sensitivity, and limited reusability. Nanocatalysts particularly metal oxides (e.g. TiO_2, MgO, SrO), carbon-based nanomaterials (CNTs), biochar, and rare earth oxides (e.g. CeO_2, La_2O_3) offer enhanced activity, thermal stability, and durability (Sulaiman *et al.* 2025; Pandit *et al.* 2023). The yield of 90-95% with over 80% catalytic activity retained after multiple reuse cycles using CeO_2 and La_2O_3, especially when processing waste cooking oil (Sulaiman *et al.* 2025).

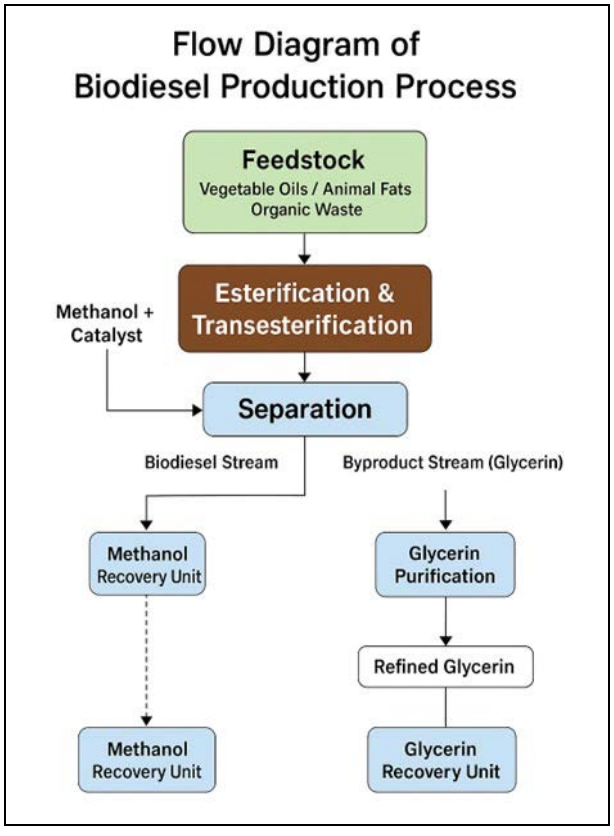


Fig. 4: Biodiesel production path from raw or refined plant oil or recycled greases (Sher *et al.* 2024)

In the case of marine microalga *Chlorella salina*, biodiesel yields reached 93.56 % using magnetic nanocatalyst-immobilized lipase (Liu *et al.* 2008). while TiO_2-based nanocatalysts have demonstrated consistent 95% yields across 10 reuse cycles (Sher *et al.* 2024). These catalysts also offer higher resistance to free fatty acids and water content that is common in low-grade or waste oils.

Microalgae are promising feedstocks for third-generation biodiesel due to their high lipid content, rapid growth, and non-reliance on arable land. Nanomaterials have been shown to improve algal cultivation (e.g. *via* enhanced light absorption), accelerate flocculation and harvesting, and improve lipid extraction (Akram *et al.* 2025; Awogbemi and Kallon, 2024). Moreover, green-synthesized nanoparticles such as ZnO and biochar have increased biomass yield and lipid productivity under controlled stress conditions (Hosseinzadeh *et al.* 2023).

Immobilized lipase on nanoparticles such as Fe_3O_4, CaO/Al_2O_3, or functionalized CNTs has emerged as a key strategy for sustainable biodiesel synthesis. These nanobiocatalysts allow biodiesel production under milder temperatures and pH conditions, maintain high conversion rates, and minimize post-reaction purification (Verma *et al.* 2013; Singh *et al.* 2025). Moreover, such systems contribute to reducing enzyme deactivation and increasing reusability, supporting green and circular bioeconomy models (Ezeorba *et al.* 2024; Garg *et al.* 2024)

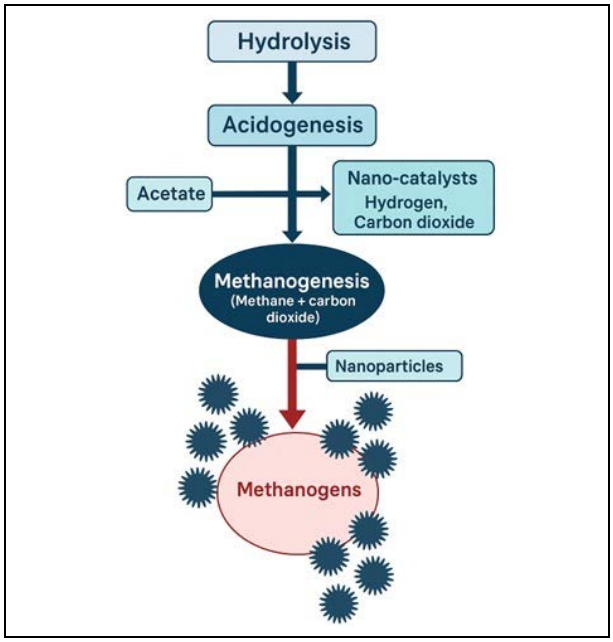


Fig. 5: Production of biogas through anaerobic digestion (Yadav *et al.* 2024)

2.2.3 Applications of Nanomaterials in Biogas Production

Biogas, a renewable energy source primarily composed of methane and carbon dioxide, generated through the anaerobic digestion (AD) of organic waste such as agricultural residues, livestock manure, food

waste, and human excreta (Abdelwahab *et al.* 2024). The AD process can be significantly enhanced through the strategic application of nanomaterials, which serve as bio-stimulants, catalysts, and electron shuttles. Fig. 5 illustrates the basic biogas generation pathway and its enhancement with nanomaterial additives (Yadav *et al.* 2024).

Recent advancements have shown that incorporating nanomaterials such as zero-valent iron (nZVI), magnetite (Fe_3O_4), graphene oxide, carbon nanotubes, and metal oxide composites can drastically enhance biogas yield and process stability. These nanomaterials improve microbial activity, facilitate direct interspecies electron transfer (DIET), and increase substrate degradation efficiency (Faisal *et al.* 2018; Ali *et al.* 2017). For example, Yadav *et al.* (2024) demonstrated that multiwalled carbon nanotubes (MWCNTs) and graphene nanoparticles enhanced biogas yield by up to 81.16% when added to food waste digestion systems. The study attributed this increase to improved DIET and enriched microbial diversity dominated by firmicutes and proteobacteria.

The use of metallic nanoparticles such as nZVI and magnetite has also been found effective in co-digestion systems. Yusuf *et al.* (2024) reported that nZVI outperformed magnetite in methane production during the co-digestion of fecal sludge and food waste under high-solid content conditions. The enhanced performance was attributed to the dual role of iron in hydrogen production and methanogen enrichment. Furthermore, Goodarzi *et al.* (2024) emphasized that the effect of nanomaterials on methane yield is highly pH-dependent, with magnetic reduced graphene oxide improving biochemical methane potential by 56% under neutral pH.

Nanotechnology has also influenced pretreatment strategies used indium vanadate-decorated titanium dioxide nanocomposites to photocatalytically pretreat rice husk, resulting in a 2.8-fold increase in biogas production compared to untreated feedstock (Rashid *et al.* 2014). Similarly Soliman *et al.* (2023) developed europium-doped yttrium titanate (Eu^{3+}:$Y_2Ti_2O_7$) nanomaterials for the simultaneous production of biogas and hydrogen from acetic acid, showcasing their role in dual-output energy systems.

However, the concentration and type of nanomaterials used remain critical. A meta-analysis by Castro *et al.* (2024) confirmed that while low concentrations of nanoparticles (typically <100 mg/L) can significantly boost biogas production, higher concentrations may lead to cytotoxicity and reduced methane yield. Hence, careful optimization is essential. Beyond technical enhancement, Gupta *et al.* (2024) emphasized the environmental synergy of using flower waste in AD, which can be valorized into nanomaterials for circular bioeconomy strategies, thereby integrating waste management with nanotechnology-based energy recovery.

Nanomaterials are increasingly recognized for their transformative potential in improving AD processes and maximizing biogas yields. Their unique surface area, electron transfer capabilities, and catalytic properties enable enhanced microbial activity and efficient conversion of organic matter into methane.

Zero-valent iron nanoparticles (nZVI) has been widely employed in AD systems due to its electron-donating properties, which facilitate DIET. Ambuchi *et al.* (2016) reported a 180% increase in biogas and a 234% increase in methane concentration using Fe_3O_4 nanoparticles. More recent studies have corroborated these effects, showing that iron-based nanomaterials not only stimulate methanogens but also improve the resilience of microbial communities (Khan *et al.* 2022; Mitra and Kaparaju, 2024).

Metal oxide nanoparticles (MONPs) such as Fe_2O_3, TiO_2, and ZnO enhance solubilization and hydrolysis processes during AD, resulting in higher methane yields and lower chemical oxygen demand levels. Abdelsalam *et al.* (2016) observed that these nanoparticles promote better contact between methanogens and substrates. Awogbemi *et al.* (2024) further emphasized the role of MONPs in stabilizing volatile fatty acid levels, thereby preventing process inhibition.

Materials like multi-walled carbon nanotubes and graphene oxide provide a highly stable matrix for microbial colonization and electron transport. Amen *et al.* (2018) demonstrated enhanced cumulative methane production in MWCNT reactors. Recent work by Mehejabin *et al.* (2024) supports the multifunctionality of these carbon-based nanomaterials in improving fermentation kinetics and reducing lag phases in biogas systems.

Copper-iron bimetallic nanoparticles (nZVI/Cu) have been utilized to enhance methane production in municipal sludge digestion. Their redox synergy accelerates hydrolysis and methanogenesis, though optimal concentrations must be determined to avoid toxicity (Khan *et al.* 2022; Baniamerian *et al.* 2019).

Nanoparticles facilitate multiple pathways of methanogenesis including acetotrophic and hydrogenotrophic routes by acting as electron shuttles, syntrophic relationships. Iron-based nanoparticles, for instance, maintain a stable microbial consortium while optimizing nutrient bioavailability (Holm *et al.* 2009; Markandan and Chai, 2022).

Additionally, the integration of food and garden organic wastes with nanomaterials in co-digestion setups

has led to increased biogas yields and reduced process instability (Mitra and Kaparaju, 2024). Nanotechnology has also been shown to reduce the required retention time and increase the methane yield per gram of volatile solids added (Pugazhendhi *et al.* 2024).

Despite the promising results; the deployment of nanomaterials in large-scale AD systems faces challenges related to nanoparticle toxicity, cost of synthesis, and environmental impact. Mehejabin *et al*. (2024) and Khan *et al*. (2022) have highlighted the need for biodegradable and biocompatible nanomaterials to ensure long-term sustainability. Further, retrieval of nanoparticles post-AD remains a critical bottleneck (Awogbemi *et al.* 2024). Research is now focusing on green synthesis methods and the use of biosourced nanomaterials,such as biochar-supported metal oxides, to mitigate these concerns (Sher *et al.* 2024; Tamta *et al.* 2024).

Despite the considerable promise of nanomaterials in enhancing biofuel production, their widespread industrial deployment is restrained by unresolved concerns related to environmental safety, process scalability, and microbial ecosystem stability. Long-term exposure of anaerobic digesters to nanoparticles such as ZnO and CuO has shown adverse impacts. For instance, ZnO nanoparticles have been linked to microbial toxicity due to the disruption of intracellular zinc homeostasis, damaging lysosomes and mitochondria (Feng *et al.* 2014). Similarly, prolonged CuO nanoparticle exposure inhibits methane generation compared to short-term exposure due to persistent microbial stress (Mehejabin *et al.* 2024; Feng *et al.* 2014).

Moreover, nanoparticle leaching, bioaccumulation, and non-reusability pose significant environmental and health risks (Bin *et al.* 2023; Khan *et al*. 2022). Issues of nanomaterial recovery post-digestion, especially in large-scale biogas systems, also remain unresolved (Mitra and Kaparaju, 2024; Baniamerian *et al*. 2019). Addressing these challenges requires the development of biodegradable nanostructures, green synthesis methods, and lifecycle risk assessments (Sher *et al.* 2024; Tamta *et al.* 2024). It is also crucial to balance enhancement effects with potential toxicity trade-offs, particularly when nanomaterials are introduced in anaerobic environments with sensitive microbial consortia (Awogbemi *et al*. 2024; Markandan and Chai, 2022).

2.2.4 Biohydrogen Production

Biohydrogen offers a clean, sustainable energy alternative with high gravimetric energy density. It is primarily produced through dark fermentation and photofermentation of organic substrates by bacteria. During dark fermentation, fermentative bacteria convert sugars and biowaste into hydrogen and organic acids under anaerobic conditions, while photofermentative organisms further metabolize these acids into hydrogen under light exposure (Verma *et al.* 2013; Patel *et al.* 2018).

While promising, dark fermentation is hindered by low hydrogen yields and process instability due to fluctuations in pH, substrate variability, and microbial competition. The formation of volatile fatty acids, for instance, can inhibit microbial hydrogenases and reduce gas productivity (Mitra and Kaparaju, 2024; Markandan and Chai, 2022). These issues call for strategic enhancement of microbial pathways and system stability through biotechnological interventions.

Recent advances in nanotechnology have significantly improved biohydrogen production efficiency by supporting enhanced microbial metabolism and increasing photocatalytic conversion rates. Inorganic nanoparticles such as Ag, Au, Ni, Fe, TiO_2, and carbon-based materials like CNTs and graphene oxide have demonstrated potential to enhance hydrogen yields from biowaste and sugar substrates (Pugazhendhi *et al.* 2024; Patel *et al.* 2018).

Nanoparticles improve biohydrogen production *via* multiple mechanisms (Fig. 6):

- Iron and palladium nanoparticles act as electron shuttles, enhancing interspecies electron transfer and stimulating hydrogenase activity (Mehejabin *et al.* 2024; Awogbemi *et al.* 2024).
- TiO_2 and CNTs serve as visible-light photocatalysts, promoting efficient energy conversion in photo-fermentative systems (Sharma *et al.* 2023; Patel *et al.* 2018).
- Pretreatment of algal and lignocellulosic biomass with nanomaterials improves substrate hydrolysis, making sugars more accessible to fermentative bacteria (Mitra and Kaparaju, 2024 Chakravorty *et al.* 2023).
- Nanostructures like carbon nanotubes and graphene oxide provide extensive surface area for microbial colonization and metabolic exchange (Khan *et al.* 2022 ; Pugazhendhi *et al.* 2024).

Despite these benefits, concerns regarding nanoparticle toxicity, reusability, and environmental impact must be addressed before large-scale deployment. Strategies such as using green-synthesized nanomaterials, exploring nano-bio hybrids, and integrating real-time biosensors for monitoring microbial health are emerging as critical avenues (Mehejabin *et al.* 2024; Sher *et al.* 2024). There is a growing consensus that

interdisciplinary efforts combining nanotechnology, systems biology, and bioengineering will be essential to unlock the full potential of biohydrogen as a sustainable energy vector.

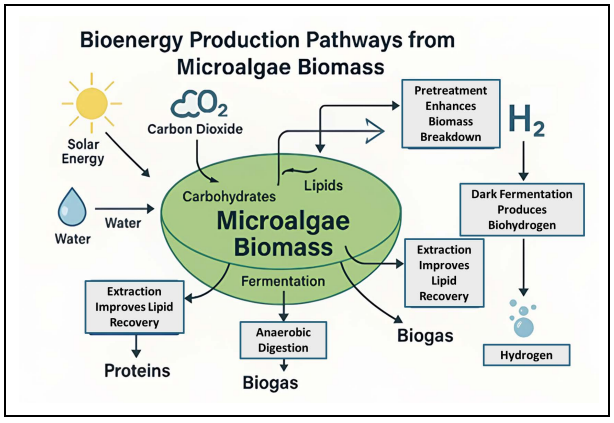


Fig. 6: Biohydrogen production *via* fermentation of pretreated microalgal biomass (Biswal *et al.* 2023)

3. INSIGHTS AND APPLICATIONS OF NANOTECHNOLOGY IN BIOENERGY PRODUCTION AND SUSTAINABILITY

3.1 Applications of Nanotechnology in Bioethanol Production

The integration of nanotechnology into bioethanol manufacturing has significantly improved biomass hydrolysis, enzymatic activity, and product yield. For instance, NiO and Fe_3O_4 nanoparticles, when applied during different stages of the integrated saccharification and fermentation of potato peels, notably enhanced ethanol productivity. NiO nanoparticles used during the pretreatment stage in the NSLISF (Nano + Soaking-Assisted Thermal Pre-treatment + Liquefaction + Instant Saccharification and Fermentation) mode yielded a peak concentration of 36.04 g/L, while Fe_3O_4 applied during both pretreatment and liquefaction in NSLISCF (Nano + Soaking-Assisted Thermal Pre-treatment + Liquefaction + Instant Saccharification and Co-Fermentation) and SNLISF (Soaking-Assisted Thermal Pre-treatment + Nano + Liquefaction + Instant Saccharification and Fermentation) modes, respectively, produced 23.99 g/L of bioethanol. The dual-nanoparticle strategy incorporating NiO and Fe_3O_4 resulted in the highest ethanol yield of 0.93 g/g (Awogbemi *et al.* 2024).

These findings align with broader trends showing that nanoparticle-assisted enzymatic immobilization and substrate modification can reduce processing severity and enhance sugar conversion efficiency (Ndaba *et al.* 2025; Togun *et al.* 2025; Abraham *et al.* 2014). In particular; metal oxide nanoparticles (e.g. Fe_3O_4, TiO_2) have been noted for their ability to accelerate saccharification while improving enzyme stability and reusability (Razzaghi *et al.* 2022; Mehejabin *et al.* 2024).

3.2 Applications of Nanotechnology in Biodiesel Production

Nanotechnology has advanced biodiesel synthesis through enhanced transesterification reactions, improved fuel properties, and engine combustion optimization. Nanofluids incorporated into diesel-biodiesel blends have shown the ability to increase flame propagation, reduce ignition delay, and improve atomization, thereby enhancing combustion efficiency (Le *et al.* 2024).

For instance, metal oxide nanocatalysts like TiO_2, CaO, MgO, and SrO have effectively accelerated biodiesel synthesis; while carbon-based nanocatalysts such as graphene oxide, carbon nanotubes, and biochar demonstrated enhanced reactivity and yield across various feedstocks (Sher *et al.* 2024; Pandit *et al.* 2023; Hussain *et al.* 2017). One example includes the transesterification of sunflower oil using magnetic Cs/Al/Fe_3O_4 nanoparticles, which achieved a biodiesel yield of 94.8% (Chisti *et al.* 2007; Zahid *et al.* 2024) also showed that using Ni-ZnO nanocatalysts in neem oil transesterification led to a 90.1% yield under optimized conditions.

The studies highlight the potential cytotoxicity of *in vivo* nanoparticles, risks of bioaccumulation, and unresolved questions related to life cycle assessment (LCA) and cost-benefit analysis (Kazemi *et al.* 2024; Pugazhendhi *et al.* 2024; Sekhon *et al.* 2014; Lee *et al.* 2015). Therefore, the widespread adoption of nano-enabled biodiesel solutions hinges on further research into their long-term ecological impact.

3.3 Applications of Nanotechnology in Biogas Production

The use of nanomaterials in anaerobic digestion has shown promising results in improving both biogas yield and process kinetics. Metal-based nanoparticles such as Fe_3O_4 and TiO_2 significantly enhance electron transfer processes, promoting microbial activity and methane production. Specifically, Fe_3O_4 nanoparticles have been associated with a 180% increase in biogas yield and 234% increase in methane concentration, attributed to their stimulation of enzymatic electron flow within methanogens (Ambuchi *et al.* 2016; Amen *et al.* 2018).

Recent studies also demonstrate that carbon-based nanomaterials (e.g. MWCNTs and graphene oxide) provide high surface areas that facilitate microbial colonization, reducing lag phases and boosting methane productivity (Khan *et al.* 2022; Mitra and Kaparaju, 2024; Yadav *et al.* 2024). The nanomaterials enhance

DIET, but noted cytotoxicity at higher doses. Moreover, Castro *et al*. (2024) and Yusuf *et al.* (2024) showed that nZVI and Fe_3O_4 dosing in high-solid digestion stabilizes AD and enriches methanogenic communities under harsh conditions.

Photocatalytic pretreatments using nanocomposites like $InVO_4TiO_2$ also significantly enhance substrate digestibility for biogas conversion, with yield improvements up to 2.8-fold in rice husk digestion (Rashid *et al.* 2023). Additional insights emphasize the importance of nanoparticle type, dosage, and system pH as key variables impacting methane yield (Goodarzi *et al.* 2024; Yusuf *et al.* 2024).

3.4 Applications of Nanotechnology in Biohydrogen Production

Biohydrogen production, particularly *via* dark fermentation and photobiological processes, has benefited from the catalytic and stimulatory effects of various nanomaterials. Inorganic nanoparticles such as Ag, Cu, Ni, and Fe, along with carbon-based nanostructures like CNTs and graphene oxide, have enhanced microbial hydrogenase activity, increased electron transfer rates, and improved substrate breakdown (Patel *et al.* 2018; Biswal *et al.* 2023).

For example, the incorporation of Fe and Cu nanoparticles in dark fermentation systems significantly boosted hydrogen yields by facilitating redox balance and microbial syntrophy. Kumar *et al.* (2019); Hsieh *et al.* (2016), Mao *et al.* (2012), and Patel *et al*. (2018) noted that TiO_2 and CNTs further contributed to light-assisted hydrogen generation through better photon harvesting and surface reactivity. Nanoparticle-modified membranes have also shown potential in enhancing H_2 separation efficiency, enabling continuous hydrogen recovery under milder conditions (Chakravorty *et al.* 2023).

3.5 Challenges Faced in the Use of Nanomaterials in Bioenergy Production

While the integration of nanotechnology into bioenergy systems offers numerous benefits, several critical challenges must be addressed to enable safe and scalable deployment:

- Heavy reliance on first-generation biomass raises concerns over food security, especially in resource-limited settings (Baniamerian *et al.* 2019; Zheng *et al.* 2022).
- Many nanoparticles have unknown or poorly studied toxicological profiles, especially concerning long-term environmental exposure and microbial biodiversity disruption (Feng *et al.* 2014).
- Despite promising lab-scale results, translating nanotechnologies to commercial-scale systems is hindered by issues like nanoparticle cost, stability, and synthesis scalability (Awogbemi and Kallon, 2024).
- Comprehensive LCA and techno-economic assessments remain scarce in existing studies, preventing policymakers and stakeholders from making informed decisions on nanotechnology adoption in biofuels (Mehejabin *et al.* 2024; Sher *et al.* 2024).

Overall, the integration of nanotechnology into bioenergy systems has demonstrated remarkable potential across diverse biofuel platforms such as bioethanol, biodiesel, biogas, and biohydrogen. Metal oxide nanoparticles (e.g. Fe_3O_4, ZnO, TiO_2) and carbon-based nanomaterials (e.g. graphene oxide, MWCNTs) have significantly improved catalytic activity, enzyme immobilization, and substrate accessibility, leading to enhanced conversion efficiencies and product yields (Abraham *et al.* 2014; Harun and Danquah, 2011; Hussain *et al.* 2017; Yadav *et al.* 2024; Lee *et al.* 2015; Palaniappan *et al.* 2017). In biodiesel and bioethanol production, doped and magnetic nanocatalysts have boosted transesterification and saccharification processes, while maintaining high thermal and operational stability (Razzaghi *et al.* 2022; Verziu *et al.* 2008; Zahid *et al.* 2024; Sekhon *et al*. 2014; Mao *et al*. 2012). In biogas systems, nanomaterials have enhanced microbial syntrophy and electron transfer mechanisms such as DIET, though care must be taken to avoid cytotoxicity and ensure compatibility with microbial consortia (Harun and Danquah, 2011; Rashid *et al.* 2023; Yadav *et al.* 2024; Farghali *et al.* 2019). Similarly, in biohydrogen production, nanoparticle-mediated enhancements in dark fermentation and photocatalytic processes have resulted in improved hydrogenase activity and light absorption (Hussain *et al.* 2017; Mao *et al.* 2012; Palaniappan *et al*. 2017). Despite these advancements, further studies on environmental toxicity, nanoparticle fate, and life cycle assessments are vital to guide large-scale deployment and policy regulation (Kim *et al.* 2013; Sabri *et al*. 2023; Sekhon *et al.* 2014; Farghali *et al.* 2019). Moving forward, the rational design of multifunctional, biodegradable, and cost-effective nanomaterials will be essential in realizing sustainable and commercially viable bioenergy solutions.

4. CONCLUSION

Bioenergy technologies are in a developmental stage and are closely associated with climate change and fossil fuel dependency. Nanotechnology thus becomes a game-changer and helps to make every step including pretreatment, enzymatic hydrolysis, fermentation, transesterification, and methane generation more efficient. In addition to improving energy storage and

conversion rates, the use of nanomaterials as catalysts and additives also helps in creating advanced biofuel production systems. Despite being renewable and environmentally-friendly, the production of biofuels calls for further innovation towards attaining sustainability, economic viability and scalability. This problem can be solved by nanotechnology which provides cost-effective, eco-friendly, and technologically upgraded ways of producing bioenergy and biofuel. The future will witness integration of nanotechnology into biofuel manufacture for a cleaner greener world energy future.

CONFLICTS OF INTEREST

The author declares that there is no conflict of interest regarding the publication of this paper.

FUNDING

This research received no specific grant from any funding agency in the public, commercial, or not-for-profit sectors.

COPYRIGHT

This article is an open-access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (http://creativecommons.org/licenses/by/4.0/).



REFERENCES

Abdelsalam, E., Samer, M., Attia, Y. A., Abdel, H. M. A., Hassan, H. E. and Badr, Y., Comparison of nanoparticles effects on biogas and methane production from anaerobic digestion of cattle dung slurry, *Renewable Energy.*, 87, 592–598(2016). https://doi.org/10.1016/j.renene.2015.10.053

Abdelwahab, T. A. M., Mohanty, M. K., Sahoo, P. K. and Behera, D., Application of nanoparticles for biogas production: Current status and perspectives, *Energy. Sources. Recovery. Util. Environ. Effects.*, 46(1), 8602–8614(2024). https://doi.org/10.1080/15567036.2020.1767730

Abraham, R. E., Verma, M. L., Barrow, C. J. and Puri, M., Suitability of magnetic nanoparticle immobilised cellulases in enhancing enzymatic saccharification of pretreated hemp biomass, *Biotechnol. Biofuels.*, 7(1), 90(2014). https://doi.org/10.1186/1754-6834-7-90

Akram, F., Aslam, H., Suhail, M., Fatima, T. and Ul, H. I., Divulging the future of sustainable energy, Innovations and challenges in algal biodiesel production for green energy, *Sustainable Energy. Technol.. Assess.*, 75, 104266(2025). https://doi.org/10.1016/j. seta.2025.104266

Ali, A., Mahar, R. B., Soomro, R. A. and Sherazi, S. T. H., Fe_3 O_4 nanoparticles facilitated anaerobic digestion of organic fraction of municipal solid waste for enhancement of methane production, *Energy. Sources. Recovery. Utilil. Environ.. Effects.*, 39(16), 1815–1822(2017). https://doi.org/10.1080/15567036.2017.1384866

Alvira, P., Tomas, P. E., Ballesteros, M. and Negro, M. J., Pretreatment technologies for an efficient bioethanol production process based on enzymatic hydrolysis, *Bioresour. Technol.*, 101(13), 4851–4861(2010). https://doi.org/10.1016/j.biortech.2009.11.093

Ambuchi, J. J., Zhaohan Z. and Yujie, F., Biogas Enhancement Using Iron Oxide Nanoparticles And Multi-Wall Carbon Nanotubes, 10(10), 1307-6892(2016). https://doi.org/10.5281/ZENODO.1127072

Amen, T. W. M., Eljamal, O., Khalil, A. M. E., Sugihara, Y. and Matsunaga, N., Methane yield enhancement by the addition of new novel of iron and copper-iron bimetallic nanoparticles, *Chem. Eng. Process. Intensif.*, 130, 253–261(2018). https://doi.org/10.1016/j.cep.2018.06.020

Antunes, F. A. F., Chandel, A. K., Milessi, T. S. S., Santos, J. C., Rosa, C. A. and Da Silva, S. S., Bioethanol Production from Sugarcane Bagasse by a Novel Brazilian Pentose Fermenting Yeast Scheffersomyces shehatae UFMG-HM Evaluation of Fermentation Medium, *Int. J. Chem. Eng.*, 20141–8(2014). https://doi.org/10.1155/2014/180681

Aruwajoye, G. S., Faloye, F. D. and Kana, E. G., Soaking assisted thermal pretreatment of cassava peels wastes for fermentable sugar production: Process modelling and optimization, *Energy. Convers. Manage.*, 150, 558–566(2017). https://doi.org/10.1016/j.enconman.2017.08.046

Awogbemi, O. and Kallon, D. V. V., Recent advances in the application of nanomaterials for improved biodiesel, biogas, biohydrogen, and bioethanol production, *Fuel.*, 358, 130261(2024). https://doi.org/10.1016/j.fuel.2023.130261

Awogbemi, O., Ojo, A. A. and Adeleye, S. A., Advancements in the application of metal oxide nanocatalysts for sustainable biodiesel production, *Discov. Appl. Sci.*, 6(5), 250(2024). https://doi.org/10.1007/s42452-024-05920-3

Baniamerian, H., Isfahani, P. G., Tsapekos, P., Alvarado, M. M., Shahrokhi, M., Vossoughi, M. and Angelidaki, I., Application of nano-structured materials in anaerobic digestion: Current status and perspectives, *Chemosphere.*, 229, 188–199(2019). https://doi.org/10.1016/j.chemosphere.2019.04.193

Bin, R. A., Utilization of Nanotechnology and Nanomaterials in Biodiesel Production and Property Enhancement, *J. Nanomater.*, 2023(1), 1–14(2023). https://doi.org/10.1155/2023/7054045

Biswal, T., Shadangi, K. P. and Sarangi, P. K., Application of Nanotechnology in the Production of Biohydrogen: A Review, *Chem. Eng. Technol.*, 46(2), 218–233(2023). https://doi.org/10.1002/ceat.202000565

Castro, J. C. D., Resende, E., Taveira, I., Enrich, P. A. and Abreu, F., Nanotechnology boosts the production of clean energy via nanoparticle addition in anaerobic digestion, *Front. Nanotechnol.*, 6, 1406344(2024). https://doi.org/10.3389/fnano.2024.1406344

Chakravorty, M., Nanda, M., Bisht, B., Sharma, R., Kumar, S., Mishra, A., Vlaskin, M. S., Chauhan, P. K. and Kumar, V., Heavy metal tolerance in microalgae: Detoxification mechanisms and applications, *Aquat. Toxicol.*, 260, 106555(2023). https://doi.org/10.1016/j. aquatox.2023.106555

Chaudhary, A., Rathour, R. K., Solanki, P., Mehta Kakkar, P., Pathania, S., Walia, A., Baadhe, R. R. and Bhatia, R. K., Recent technological advancements in biomass conversion to biofuels and bioenergy for circular economy roadmap, *Renew. Energy.*, 244, 122714(2025). https://doi.org/10.1016/j.renene.2025.122714

Cherian, E., Dharmendirakumar, M. and Baskar, G., Immobilization of cellulase onto MnO2 nanoparticles for bioethanol production by enhanced hydrolysis of agricultural waste, *Chin. J. Catal.*, 36(8), 1223–1229(2015). https://doi.org/10.1016/S1872-2067(15)60906-8

Chisti, Y., Biodiesel from microalgae, *Biotechnol. Adv.*, 25(3), 294–306(2007). https://doi.org/10.1016/j.biotechadv.2007.02.001

Barizao, D. L. A. C., Brandao, L. L., De, O. L. E., Goncalves, R. F., De, Ol. J. P. and Cassini, S. T., Optimizing magnetic flocculation of Chlorella sp. using magnetite nanoparticles functionalized with tannin from Rhizophora mangle, *Environ. Sc.i Pollut. Res.*, 32(11), 6750–6760(2025). https://doi.org/10.1007/s11356-025-36149-1

Dos, S, K. M., De França Serpa, J., De Castro Bizerra, V., Melo, R. L. F., Sousa Junior, P. G. D., Santos Alexandre, V., Da Fonseca, A. M., Fechine, P. B. A., Lomonaco, D., Sousa Dos Santos, J. C. and Martins De Souza, M. C., Enhanced Biodiesel Production with Eversa Transform 2.0 Lipase on Magnetic Nanoparticles, *Langmuir.*, 40(51), 26835–26851(2024). https://doi.org/10.1021/acs.langmuir.4c02542

Dutta, S., Saravanabhupathy, S., Anusha, A., Rajak, R. C., Banerjee, R., Dikshit, P. K., Padigala, C. T., Das, A. K. and Kim, B. S., Recent developments in lignocellulosic biofuel production with nanotechnological intervention: an emphasis on ethanol, *Catal.*, 13(11), 1439 (2023). https://doi.org/10.3390/catal13111439

Ezeorba, T. P. C., Okeke, E. S., Mayel, M. H., Nwuche, C. O. and Ezike, T. C., Recent advances in biotechnological valorization of agro-food wastes (AFW): Optimizing integrated approaches for sustainable biorefinery and circular bioeconomy, *Bioresour. Technol. Rep.*, 26, 101823(2024). https://doi.org/10.1016/j.biteb.2024.101823

Faisal, S., Yusuf, H. F., Zafar, Y., Majeed, S., Leng, X., Zhao, S., Saif, I., Malik, K. and Li, X., A Review on Nanoparticles as Boon for Biogas Producers—Nano Fuels and Biosensing Monitoring, *Appl. Sci.*, 9(1), 59(2018). https://doi.org/10.3390/app9010059

Farghali, M., Fetra, J. A., Ahmed, M. M., Kotb, S., Yamashiro, T., Iwasaki, M. and Umetsu, K., Impacts of iron oxide and titanium dioxide nanoparticles on biogas production: Hydrogen sulfide mitigation, process stability, and prospective challenges, *J. Environ. Manage.*, 240, 160–167(2019). https://doi.org/10.1016/j.jenvman.2019.03.089

Fayaz, H., Khan, S. A., Saleel, C. A., Shaik, S., Yusuf, A. A., Veza, I., Fattah, I. R., Rawi, N. F. M., Asyraf, M. R. M. and Alarifi, I. M., Developments in nanoparticles enhanced biofuels and solar energy in Malaysian perspective: a review of state of the art, *J. of Nanomater.*, 2022(1), 8091576 (2022). http://dx.doi.org/10.1155/2022/8091576

Feng, Y., Zhang, Y., Quan, X. and Chen, S., Enhanced anaerobic digestion of waste activated sludge digestion by the addition of zero valent iron, *Water. Res.*, 52, 242–250(2014). https://doi.org/10.1016/j.watres.2013.10.072

Gardy, J., Hassanpour, A., Lai, X., Ahmed, M. H. and Rehan, M., Biodiesel production from used cooking oil using a novel surface functionalised TiO2 nano-catalyst, *Appl. Catal. Environ.*,, 207, 297–310(2017). https://doi.org/10.1016/j.apcatb.2017.01.080

Garg, A., Basu, S., Shetti, N. P., Bhattu, M., Alodhayb, A. N. and Pandiaraj, S., Biowaste to bioenergy nexus: Fostering sustainability and circular economy, *Environ. Res.*, 250, 118503(2024). https://doi.org/10.1016/j.envres.2024.118503

Goodarzi, M., Arjmand, M. and Eskicioglu, C., Nanomaterial-amended anaerobic sludge digestion: Effect of pH as a game changer, *Environ. Res.*, 240, 117463(2024). https://doi.org/10.1016/j.envres.2023.117463

Guan, Q., Li, Y., Chen, Y., Shi, Y., Gu, J., Li, B., Miao, R., Chen, Q. and Ning, P., Sulfonated multi-walled carbon nanotubes for biodiesel production through triglycerides transesterification, *RSC. Adv.*, 7(12), 7250–7258(2017). https://doi.org/10.1039/C6RA28067F

Gupta, V. K., Kumar, R., Dhanker, R., Kamble, S. S. and Mohamed, H. I., Sustainable Management of Floral Waste to Reduce Environmental Pollution by Conversion to Value-Added Products and Their Applications in the Synthesizing of Nanomaterials: a Review, *Water. Air. Soil. Pollut.*, 235(7), 436(2024). https://doi.org/10.1007/s11270-024-07228-9

Hao, Y., Wang, Y., Ma, C., White, J. C., Zhao, Z., Duan, C., Zhang, Y., Adeel, M., Rui, Y., Li, G. and Xing, B., Carbon nanomaterials induce residue degradation and increase methane production from livestock manure in an anaerobic digestion system, *J. Cleaner. Prod.*, 240, 118257(2019). https://doi.org/10.1016/j.jclepro.2019.118257

Harun, R. and Danquah, M. K., Influence of acid pre-treatment on microalgal biomass for bioethanol production, *Process. Biochem.*, 46(1), 304–309(2011). https://doi.org/10.1016/j.procbio.2010.08.027

Holm, N. J. B., Al, T. and Oleskowicz-Popiel, P., The future of anaerobic digestion and biogas utilization, *Bioresour. Technol.*, 100(22), 5478–5484(2009). https://doi.org/10.1016/j.biortech.2008.12.046

Hosseinzadeh, B. H., Panahi H. K. S., Dehhaghi M., Orooji, Y., Shahbeik, H., Mahian, O., Karimi-Maleh, H., Sulaiman, A., Mei, C., Kiehbadroudinezhad, M., Abdul-Satter, N., Guillemin, G. G., Lam, S. S., Peng, W., Chen, X., Kim, K. H., Aghbashlo M. and Tabatabaei M. Nanomaterials and their role in advancing biodiesel feedstock production: A comprehensive review, *Biofuel. Res. J.,* 10(3) 1901–1932(2023). https://doi.org/10.18331/BRJ2023.10.3.4

Hsieh, P. H., Lai, Y. C., Chen, K. Y. and Hung, C. H., Explore the possible effect of TiO2 and magnetic hematite nanoparticle addition on biohydrogen production by Clostridium pasteurianum based on gene expression measurements, *Int. J. Hydrogen. Energy.*, 41(46), 21685–21691(2016). https://doi.org/10.1016/j.ijhydene.2016.06.197

Hussain, M., Ahmad, R., Liu, Y., Liu, B., He, M. and He, N., Applications of Nanomaterials and Biological Materials in Bioenergy, *J. nanosci. nanotechnol.*, 17(12), 8654–8666(2017). https://doi.org/10.1166/jnn.2017.14672

Hussein, A. K., Applications of nanotechnology in renewable energies—A comprehensive overview and understanding, *Renewable. Sustainable. Energy. Rev.*, 42, 460–476(2015). https://doi.org/10.1016/j.rser.2014.10.027

Ivanova, V., Petrova, P. and Hristov, J., Application in the Ethanol Fermentation of Immobilized Yeast Cells in Matrix of Alginate/Magnetic Nanoparticles, on Chitosan-Magnetite Microparticles and Cellulose-coated Magnetic Nanoparticles, *Int. Rev. Chem. Eng.*, 3(2), 289-299(2011). https://doi.org/10.48550/ARXIV.1105.0619

Kazemi, S. P. H., Hosseinzadeh, B. H., Dehhaghi, M., Orooji, Y., Mahian, O., Shahbeik, H., Kiehbadroudinezhad, M., Kalam, M. A., Karimi-Maleh, H., Salehi, J. G., Mei, C., Guillemin, G. G., Nizami, A. S., Wang, Y., Gupta, V. K., Lam, S. S., Pan, J., Kim, K. H., Peng, W., Aghbashlo, M. and Tabatabaei, M., Nanotechnology applications in biodiesel processing and production: A comprehensive review, *Renew. Sustain. Energy Rev.*, 192, 114219(2024). https://doi.org/10.1016/j.rser.2023.114219

Khan, S. Z., Zaidi, A. A., Naseer, M. N. and AlMohamadi, H., Nanomaterials for biogas augmentation towards renewable and sustainable energy production: A critical review, *Front. Bioeng. Biotechnol.*, 10, 868454(2022). https://doi.org/10.3389/fbioe.2022.868454

Kim, J., Yoo, G., Lee, H., Lim, J., Kim, K., Kim, C. W., Park, M. S. and Yang, J. W., Methods of downstream processing for the production of biodiesel from microalgae, *Biotechnol. Adv.*, 31(6), 862–876(2013). https://doi.org/10.1016/j.biotechadv.2013.04.006

Kumar, G., Mathimani, T., Rene, E. R. and Pugazhendhi, A., Application of nanotechnology in dark fermentation for enhanced biohydrogen production using inorganic nanoparticles, *Int. J. Hydrogen. Energy.*, 44(26), 13106–13113(2019). https://doi.org/10.1016/j.ijhydene.2019.03.131

Kushwaha, D., Upadhyay, S. N. and Mishra, P. K., Nanotechnology in bioethanol/biobutanol production, *Environ. Sci*., 115–127 (2018). https://doi.org/10.1007/978-3-319-75052-1_8

Le, T. T., Tran, M. H., Nguyen, Q. C., Le, H. C., Nguyen, V. Q., Cao, D. N. and Paramasivam, P., Nanotechnology-based biodiesel: A comprehensive review on production, and utilization in diesel engine as a substitute of diesel fuel, *Int. J. Renew. Energy. Dev.*, 13(3), 405–429(2024). https://doi.org/10.61435/ijred.2024.60126

Lee, Y. C., Lee, K. and Oh, Y. K., Recent nanoparticle engineering advances in microalgal cultivation and harvesting processes of biodiesel production: A review, *Bioresour. Technol.*, 184, 63–72(2015). https://doi.org/10.1016/j.biortech.2014.10.145

Liu, X., He, H., Wang, Y., Zhu, S. and Piao, X., Transesterification of soybean oil to biodiesel using CaO as a solid base catalyst, *Fuel.*, 87(2), 216–221(2008). https://doi.org/10.1016/j.fuel.2007.04.013

Mao, S. S., Shen, S. and Guo, L., Nanomaterials for renewable hydrogen production, storage and utilization, *Prog. Nat. Sci. Mater. Int.*, 22(6), 522–534(2012). https://doi.org/10.1016/j.pnsc.2012.12.003

Markandan, K. and Chai, W. S., Perspectives on Nanomaterials and Nanotechnology for Sustainable Bioenergy Generation, *Mater.*, 15(21), 7769(2022). https://doi.org/10.3390/ma15217769

Marimuthu, S., Anoopkumar, H. and Maduraiveeran, G., Three-dimensional iron-cobalt phosphide nanosheets on nickel oxide nanoparticles for improved glucose oxidation reaction, *New J. Chem*., 49(4), 1232–1241 (2024). https://doi.org/10.1039/D4NJ04220D

Masran, R., Zanirun, Z., Bahrin, E. K., Ibrahim, M. F., Lai Yee, P. and Abd, A. S., Harnessing the potential of ligninolytic enzymes for lignocellulosic biomass pretreatment, *Appl. Microbiol. Biotechnol.*, 100(12), 5231–5246(2016). https://doi.org/10.1007/s00253-016-7545-1

Mehejabin, F., Musharrat, A., Ahmed, S. F., Kabir, Z., Khan, T. M. Y. and Saleel, C. A., Sustainable Biofuel Production Utilizing Nanotechnology: Challenges and Potential Solutions, *GCB. Bioenergy.*, 16(10), 70001(2024). https://doi.org/10.1111/gcbb.70001

Mitra, S. and Kaparaju, P., Feasibility of Food Organics and Garden Organics as a Promising Source of Biomethane: A Review on Process Optimisation and Impact of Nanomaterials, *Energies.*, 17(16), 4198(2024). https://doi.org/10.3390/en17164198

Ndaba, B., Rama, H., Bingwa, N. and Roopnarain, A., Unravelling the role of nanoparticles during bioethanol production: A review on pretreatment, hydrolysis and fermentation, *Fuel.*, 396, 135336(2025). https://doi.org/10.1016/j. fuel.2025.135336

Osman, A. I., Zhang, Y., Farghali, M., Rashwan, A. K., Eltaweil, A. S., Abd El-Monaem, E. M. and Yap, P. S., Synthesis of green nanoparticles for energy, biomedical, environmental, agricultural, and food applications: A review, *Environ. Chem. Lett.*, 22(2), 841–887 (2024). https://doi.org/10.1007/s10311-023-01682-3

Palaniappan, K., An overview of applications of nanotechnology in biofuel production, *World. Appl. Sci.*, 35, 1305–1311(2017). https://doi.org/10.5829/IDOSI.WASJ.2017.1305.1311

Pandit, C., Banerjee, S., Pandit, S., Lahiri, D., Kumar, V., Chaubey, K. K., Al-Balushi, R., Al-Bahry, S. and Joshi, S. J., Recent advances and challenges in the utilization of nanomaterials in transesterification for biodiesel production, *Heliyon.*, 9(4), e15475(2023). https://doi.org/10.1016/j.heliyon.2023.e15475

Patel, S. K. S., Lee, J. K. and Kalia, V. C., Nanoparticles in Biological Hydrogen Production: An Overview, *Indian. J. Microbiol.*, 58(1), 8–18(2018). https://doi.org/10.1007/s12088-017-0678-9

Pavlidis, I. V., Vorhaben, T., Gournis, D., Papadopoulos, G. K., Bornscheuer, U. T. and Stamatis, H., Regulation of catalytic behaviour of hydrolases through interactions with functionalized carbon-based nanomaterials, *J. Nanopart. Res.*, 14(5), 842(2012). https://doi.org/10.1007/s11051-012-0842-4

Pugazhendhi, A., Kamarudin, S. K., Alshehri, M. A., Ganesan, R. and Brindhadevi, K., Nanomaterials – A promising solution for textile and fossil fuel generated pollutants, *Environ. Res.*, 258, 119427(2024). https://doi.org/10.1016/j.envres.2024.119427

Rai, M., Ingle, A. P., Pandit, R., Paralikar, P., Biswas, J. K. and Da Silva, S. S., Emerging role of nanobiocatalysts in hydrolysis of lignocellulosic biomass leading to sustainable bioethanol production, *Catal. Reviews.*, 61(1), 1–26(2019). https://doi.org/10.1080/01614940.2018.1479503

Rana, M. S. and Prajapati, S. K., Multifarious applications of nanoparticles in microalgae for bioenergy generation: State-of-the-art review, *J. Environ. Chem. Eng.*, 11(1), 109145(2023). https://doi.org/10.1016/j. jece.2022.109145

Rashid, J., Tufail, B. T., Hassan, M., Barakat, M. A., Kumar, R. and Xu, M., Enhancement in anaerobic biogas conversion by visible light photocatalytic Pre-treatment of rice husk with indium vanadate decorated titanium dioxide nanocomposite, *Fuel.*, 346, 128289(2023). https://doi.org/10.1016/j.fuel.2023.128289

Rashid, N., Ur, R, M. S., Sadiq, M., Mahmood, T. and Han, J. I., Current status, issues and developments in microalgae derived biodiesel production, *Renewable. Sustainable. Energy. Rev.*, 40, 760–778(2014). https://doi.org/10.1016/j. rser.2014.07.104

Razzaghi, M., Homaei, A., Vianello, F., Azad, T., Sharma, T., Nadda, A. K., Stevanato, R., Bilal, M. and Iqbal, H. M. N., Industrial applications of immobilized nano-biocatalysts, *Bioprocess. Biosyst. Eng.*, 45(2), 237–256(2022). https://doi.org/10.1007/s00449-021-02647-y

Rozina., Emmanuel, O., Ahmad, M., Duduyemi, A., Ahmad, S., Khan, A., Esiaba, R. and Elekwachi, C., Valorization of waste seed oil from Cupressus macrocarpa L. for biodiesel production via green-synthesized iron oxide nanoparticles: A sustainable approach toward decarbonization, *Next. Energy.*, 7, 100218(2025). https://doi.org/10.1016/j.nxener.2024.100218

Sabri, M. A., Bharath, G., Hai, A., Haija, M. A., Nogueira, R. P. and Banat, F., Highly efficient PdNiB decorated over carbon supports for the electrochemical valorization of furfural and 5-hydroxymethylfurfural into fuels, *Fuel.*, 353, 129241(2023). https://doi.org/10.1016/j.fuel.2023.129241

Sanusi, I. A., Faloye, F. D. and Gueguim, K. E. B., Impact of various metallic oxide nanoparticles on ethanol production by Saccharomyces cerevisiae BY4743: screening, kinetic study and validation on potato waste, *Catal. Lett.,* 149, 2015–2031 (2019). http://dx.doi.org /10.1007/s10562-019-02796-6

Sekhon, B., Nanotechnology in agri-food production, an overview, *NSA.*, 7, 31-53(2014). https://doi.org/10.2147/NSA. S39406

Sharma, Y., Manro, B., Thakur, P., Khera, A., Dey, P., Gupta, D., Khajuria, A., Jaiswal, P. K., Barnwal, R. P. and Singh, G., Nanotechnology as a vital science in accelerating biofuel production, a boon or bane, *Biofuels. Bioprod. Bioref.*, 17(3), 616–663(2023). https://doi.org/10.1002/bbb.2455

Sher, F., Ziani, I., Hameed, M., Ali, S. and Sulejmanović, J., Advanced nanomaterials design and synthesis for accelerating sustainable biofuels production – A review, *Curr. Opin. Green. Sustainable. Chem.*, 47, 100925(2024). https://doi.org/10.1016/j.cogsc.2024.100925

Singh, A., Gangwar, A. and Kumar, S., Prospects and limitations of existing biofuels and emerging trends in the utilization of nanoparticles for enhanced biofuel production and microbial fuel cell efficiency, *Biofuels.*, 16(5), 519–544(2025). https://doi.org/10.1080/17597269.2024.2431766

Soliman, H. A., Ali, L. I., Khaled, K. F., Hafez, H., Mbrouk, O. A., Saif, M. and Ibrahim, M. M., Eu^{3+} :Y_2 Ti_2 O_7 nanomaterials as efficient photocatalysts used for hydrogen and biogas production toward a sustainable environment, *Appl. Organom. Chemis.*, 37(12), e7280(2023). https://doi.org/10.1002/aoc.7280

Stellwagen, D. R., van der Klis, F., van Es, D. S., de Jong, K. P. and Bitter, J. H., Functionalized Carbon Nanofibers as Solid-Acid Catalysts for Transesterification, *ChemSusChem.*, 6(9), 1668–1672(2013). https://doi.org/10.1002/cssc.201300372

Sulaiman, N. F., Gunasekaran, S. S., Mohd Nashruddin, S. N. A., Mohd Nashruddin, S. N. A., Sofiah, A. G. N., Abd Mubin, M. H. and Lee, S. L., Advancements in transesterification of waste cooking oil to biodiesel using rare earth metal oxide catalysts: A bibliometric analysis and future prospects, *Fuel.*, 394, 135158(2025). https://doi.org/10.1016/j.fuel.2025.135158

Tamta, S., Vimal, V., Verma, S., Gupta, D., Verma, D. and Nangan, S., Recent development of nanobiomaterials in sustainable agriculture and agrowaste management, *Biocatal. Agric. Biotechnol.*, 56, 103050(2024). https://doi.org/10.1016/j.bcab.2024.103050

Tesfaye, T., Shuka, Y., Tadesse, S., Eyoel, T. and Mengesha, M., Improving the power production efficiency of microbial fuel cell by using biosynthesized polyanaline coated Fe3O4 as pencil graphite anode modifier, *Sci. Rep.*, 15(1), 587(2025). https://doi.org/10.1038/s41598-024-84311-5

Togun, H., Basem, A., Abdulrazzaq, T., Biswas, N., Abed, A. M., Dhabab, J. M., Mohammed, H. I., Sharma, B. K., Paul, D. and Barmavatu, P., Current developments in the use of nanotechnology to enhance the generation of sustainable bioenergy, *Sustainable. Mater. Technol.*, 43, e01266(2025). https://doi.org/10.1016/j.susmat.2025.e01266

Verma, M. L., Barrow, C. J. and Puri, M., Nanobiotechnology as a novel paradigm for enzyme immobilisation and stabilisation with potential applications in biodiesel production, *Appl. Microbiol. Biotechnol.*, 97(1), 23–39(2013). https://doi.org/10.1007/s00253-012-4535-9

Verma, M. L., Puri, M. and Barrow, C. J., Recent trends in nanomaterials immobilised enzymes for biofuel production, *Crit. Rev. Biotechnol.*, 36(1), 108–119(2016). https://doi.org/10.3109/07388551.2014.928811

Verziu, M., Cojocaru, B., Hu, J., Richards, R., Ciuculescu, C., Filip, P. and Parvulescu, V. I., Sunflower and rapeseed oil transesterification to biodiesel over different nanocrystalline MgO catalysts, *Green. Chem.*, 10(4), 373–381(2008). https://doi.org/10.1039/B712102D

Vickram, S., Manikandan, S., Deena, S. R., Mundike, J., Subbaiya, R., Karmegam, N., Jones, S., Kumar Yadav, K., Chang, S. W., Ravindran, B. and Kumar Awasthi, M., Advanced biofuel production, policy and technological implementation of nano-additives for sustainable environmental management – A critical review, *Bioresour. Technol.*, 387, 129660(2023). https://doi.org/10.1016/j.biortech.2023.129660

Yadav, N., Mohanakrishna, G., Gandu, R., Cahan, R. and Gandu, B., Enhancing anaerobic digestion of food waste for biogas production: Impact of graphene nanoparticles and multiwalled nanotubes on direct interspecies electron transfer mechanism, *Process. Saf. Environ. Prot.*, 191, 2335–2349(2024). https://doi.org/10.1016/j.psep.2024.09.089

Yusuf, H. H., Pan, X., Ye, Z. L., Cai, G., Appels, L., Cai, J., Lv, Z., Li, Y. and Ning, J., Revolutionizing sanitation: Valorizing fecal slags through co-digesting food waste at high-solid content and dosing metallic nanomaterials for anaerobic digestion stability, *J. Environ. Manage.*, 353, 120177(2024). https://doi.org/10.1016/j.jenvman.2024.120177

Zahid, A., Mukhtar, Z., Shahid, S., AlMasoud, N., Shariq, M., Almutib, E., Alasmari, A., Alshehri, K., Al-Gethami, W., Hassan, K. F., Alomar, T. S. and Qamar, M. A., Efficient Production of Biodiesel by the Transesterification of Neem Oil Using Ni-Doped ZnO Nanoparticles as Heterogeneous Catalysts, *Arab. J. Sc.i Eng.*, 49(7), 9323–9332(2024). https://doi.org/10.1007/s13369-023-08616-9

Zheng, B., Yu, S., Chen, Z. and Huo, Y.-X., A consolidated review of commercial-scale high-value products from lignocellulosic biomass, *Front. Microbiol.*, 13, 933882(2022). https://doi.org/10.3389/fmicb.2022.933882