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Biofuel Production: A Nanotechnological Approach

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ABSTRACT

The need for renewable energy resources continues to rise, rendering the switch to biofuels as a sustainable substitute for fossil fuels increasingly important. The synthesis of biofuels still confronts many challenges in spite of this urgency, such as a lack of feedstocks, high production costs, and environmental issues. Nanotechnology offers promising and effective solutions to improve both the reliability and efficiency of biofuel manufacturing methods, which resolve the production barriers. This review discusses the recent development of nanotechnology and its role in biofuel production. The significance of nanotechnology in addressing important issues in biofuel production, such as feedstock conversion, enzyme efficiency, and process optimization, has also been discussed. Moreover, the factors affecting nanomaterials in biofuel production are reported. Numerous types of nanoparticles (NPs), including metal, metal-oxide, magnetic, core-shell, hybrid, and carbon-based, have found extensive application in the generation of biofuel. The synthesis process of nanomaterials and their characterization techniques was explored. Environmental and health concerns of NPs have also been discussed. Even with its progress, nanotechnology still faces many challenges, including the toxicity of NPs, excessive expenses, and technical limitations, which are intended to be addressed through innovative solutions.

Keywords: Biofuel production, Nanotechnology, Nanocatalysts, Enzyme immobilization, Transesterification

Highlights

- The rising need for renewable energy makes biofuels a crucial alternative to fossil fuels.
- Nanotechnology enhances biofuel production by improving feedstock conversion, enzyme efficiency, and process optimization.
- Various nanoparticles, i.e., metal, metal-oxide, magnetic, core-shell, hybrid, and carbon-based, are widely used in biofuel generation.
- Despite progress, nanotechnology still faces challenges like toxicity, excessive costs, and practical limitations.

Introduction

The declining abundance of fossil fuels and the polluting of the natural environment spurred on by them highlight the urgent need for alternative energy sources, as these fuels currently supply more than 80% of global energy demand.[1] The worldwide consumption of fossil fuels is expected to double by 2035 and triple by 2055 due to the increased energy demand brought on by population expansion, endangering future supply.[2] The development of nanoparticles (NPs) began with Paul Ehrlich's early work, followed by Ursula Scheffel and colleagues' first attempts, and further advancements by Professor Peter Speiser's group at ETH Zürich in the late 1960s and early 1970s.[3] Special attention is given to the period between 1970 and the early 1980s. Key innovations include NPs for drug delivery across the blood-brain barrier and PEGylated NPs for prolonged blood circulation. The use of monolithic magnets, for instance, originated in atomic submarines during the 1950s. Post-1999, European oil law affected emissions and energy production. The shift in focus toward nanotechnology in Europe has made it a mainstream field, significantly enhancing catalytic efficiency and revolutionizing various disciplines, including nanobiotechnology. American Fiber and Finishing in Tifton, Georgia, produces 19,800 million aluminum oxide NPs annually at $450 per ton, boosting nanotechnology's role in biofuel efficiency and sustainability.

The continued use of this fuel drives greenhouse gas emissions and global warming, which threatens ecosystems and public health.[4,5] Biofuel offers a sustainable alternative, derived from renewable sources like animal waste, crop residues, and microbial feedstock through biological processes.[1,6] Its low carbon footprint results in lower CO_2 emissions compared to fossil fuels.[6,7] Transesterification of triglycerides with alcohol is the process that yields biodiesel. Its composition primarily consists of various fatty acids, making it renewable, biodegradable, non-toxic, and low in sulfur. When blended with conventional diesel, biodiesel helps reduce emissions and environmental pollutants.

First-generation biofuels come from plants that can be eaten, like corn, wheat, and sugarcane. Second-generation biofuels, on the other hand, come from plants that cannot be eaten, like straw and grass. First-generation bioenergy originated from various edible crops like wheat, corn, and sugarcane, while second-generation bioenergy is derived from non-edible sources, mainly agricultural and forestry waste such as lignocellulosic biomass, straw, and grass. Third-generation biofuels are produced from algal biomass or utilize carbon dioxide as feedstock to create biogas, biohydrogen, or biodiesel. Second- and third-generation biofuels are more appropriate for large-scale production than first-generation biofuels due to their ability to reduce environmental and food security risks.[8] However, their commercialization depends on factors like conversion efficiency, feedstock cost, and process optimization to enhance carbon and energy utilization. Biofuel from foodstuffs is an economically viable and trustworthy alternative to petroleum fuels, usable directly or blended with conventional diesel. The availability of feedstock, production prices, and process difficulty are major obstacles. Prominent methods of bioenergy production include transesterification, pyrolysis, and the supercritical fluid process.[9]

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Nanotechnology has gained significant attention recently, with engineered nanomaterials or NPs used across industries such as drug delivery, cosmetics, food, bioremediation, crop production, and materials science. NPs are widely used across various industries, including medicine, electronics, agriculture, and energy. In medicine, they serve as drug delivery systems, enhancing the bioavailability and targeting of drugs. In electronics, NPs are used in sensors and displays, offering improved performance. Agricultural applications include pesticide delivery and soil improvement. When comparing products, NP often outperforms conventional materials in efficiency and functionality. However, their production cost can be higher due to specialized manufacturing processes. The cost varies depending on the type of NP and its application, with some advanced NPs, such as those used in drug delivery, being particularly expensive to produce.

In biodiesel production, nanotechnology shows great potential to reduce costs and improve efficiency. Nanotechnology has improved the production of biodiesel using nanocatalysts, which decreased the catalyst weight, reaction temperature, and oil-to-alcohol ratio while improving output and quality and reducing reaction time.[10] Nanocatalysts accelerate reaction rates, reduce activation energy, and remain undamaged during the process. Nanomaterials are revolutionizing the generation of biofuel by increasing substrate digestibility due to their high surface-area-to-volume ratio, great dispersibility, and increased activation.[11] Functionalized graphene and graphene oxide (GO) are the two forms of graphene-based catalysts that exhibit promise in the generation of biodiesel. GO catalysts modified with metal (e.g., with aluminum or ferric) effectively raise the yield of methyl hexadecanoic acid while lowering the amount of free fatty acids. Moreover, metal-organic frameworks (MOFs) are also effective in oil-to-biodiesel conversion, with ongoing research optimizing their performance.[12] Moreover, carbon nanotube (CNT) catalysts, particularly sulfonated CNTs, offer stability, reusability, and high catalytic activity in esterification and transesterification reactions. Copper-doped zinc oxide and sodium zinc silicate are two instances of nanomaterials that improve the synthesis of biodiesel from used cooking oil and spirulina algae oil. In under 30 minutes, microbubble-mediated mass transfer technology achieved a 92% conversion rate in microalgae oil esterification, enhancing gas-liquid interaction.[13]

The large inter-facial surface area, porosity, selectivity, active sites, chemical stability, and catalytic effectiveness of nanomaterials (1–100 nm) are highly prized.[14] They are extensively utilized in areas including the delivery of drugs, biological sensing, water purification, cancer treatment, and the generation of bioenergy. There are five categories of nanomaterials: carbon-based (i.e., CNT, GO) nanomaterials, biomolecules, enzymes/biocatalysts, metallic/metal oxides, and non-metal oxides (i.e., Al_2O_3, Fe_3O_4).[15] They play a crucial role in energy optimization and improving biofuel yields, with studies showing significant advancements in nanomaterial-assisted biofuel systems over the past decade. Biofuel production from different generations of biomass and nanomaterials-assistance synthesis steps enhances the yield and overall quality of the biofuel and are displayed in Figure 1a–d.

Nanomaterials in biofuels enhance catalytic activity, electron transfer, and microbial performance while reducing inhibitors. Precise control over their size, shape, and geometry is crucial for their effectiveness and stability. Many researchers have extensively investigated the utilizations of nanotechnology and nanomaterials-assisted biodiesel production and its efficiency toward the synthesis process.[1–6] Hence, this review explores the recent developments of different nanomaterials used in biodiesel production and emphasizes the significance of nanotechnology in biodiesel production. The synthesis methods of nanomaterials, characterizing techniques, and factors affecting NPs efficiency in biofuel production have been discussed. Moreover, this review discusses the benefits and challenges of using nanotechnology at different process stages.

Nanotechnology for Enhancing Biofuel Efficiency and Sustainability

Nanotechnology in terms of nanomaterials or NPs has gained significant attention in recent years for the nanomaterials' special characteristics and potential role in biofuel production, owing to their nanoscopic particle size and novel optical, magnetic, electrical, chemical, and mechanical capabilities. In biofuel production, nanotechnology has been successfully applied to crop oil transesterification, ethanol production, and biodiesel synthesis from vegetable fats.[17] Their use enhances catalyst recovery and reuse, improving process efficiency. Numerous NPs, including nanofibers, nanocomposites, metals, metal oxides, non-metallics, hybrids, CNTs, GOs, etc., have been employed in the conversation processes, offering versatile benefits.[18] These nanomaterials have proven effective in enhancing biomass to bioenergy conversion rates from sources like vegetable and non-vegetable wastes, microalgae, and lignocellulose.[19]

Nanomaterials are effective in overcoming the challenges of biofuel production, including lower conversion rates, feedstock limitations, primitive technologies, and catalytic activity. Nanomaterials such as carbon-based, metal, and metal-based oxide have been explored for improving mass transfer processes. According to research, NP-assisted compounds improve mass and heat transmission via Brownian motion and diffusiophoresis. Different types of nanomaterials used for biofuel production are shown in Table 1.

Various geometries of NPs, such as nanocage, cubic, ring, spherical, nanotube, and nanowire, can be produced based on the reaction circumstances and precursor. Biofuel production has significant grow potential with hybrid and core-shell systems. Variable oxidation states of d-block elements enable novel reaction pathways for intermediate complexes. The catalytic, enzyme-immobilized, pretreatment, and byproduct separation performance of different nanomaterials are widely used in biofuel production. NPs catalyze various biofuel production processes effectively, as found in Figure 2a.[7] Functionalized NPs and nanocatalysts are used to pretreat biomass and improve the production process of fuel, as shown in Figure 2b.[7] Figure 2c shows that various heterogeneous nanocatalysts are being widely used to produce biofuel. The catalytic activity of nanomaterials is influenced by structure, electronic fluctuations, and surface defects. Transition metals exhibit large coordination numbers and electronic fluctuations, enhancing catalytic performance. Hydrogen evolution reaction activity improves with higher electronegativity and principal quantum numbers of non-metals. Metal and non-metal oxides are thermally stable at elevated temperatures, while metallic NPs are oxidation-sensitive but stabilize when supported on SiO_2 or Al_2O_3. CNTs remain stable at high temperatures.[20] CNTs enhance anaerobic digestion, enzyme immobilization, and hydrogen production, offering cost-effective and efficient alternatives for renewable energy applications due to their unique properties and synthesis methods. Due to the low cost, CNTs are considered a promising nanomaterial. MWCNTs enhance

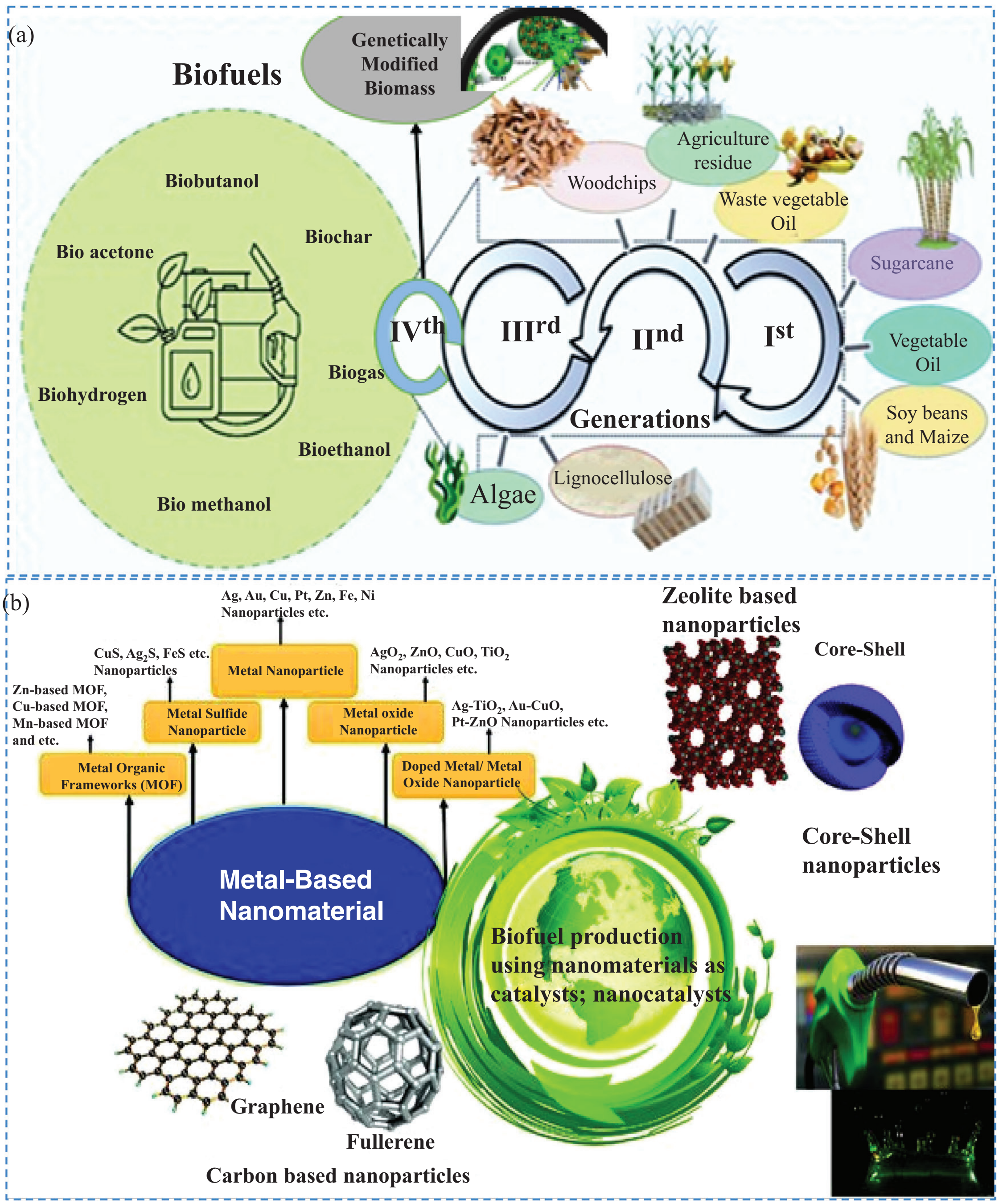
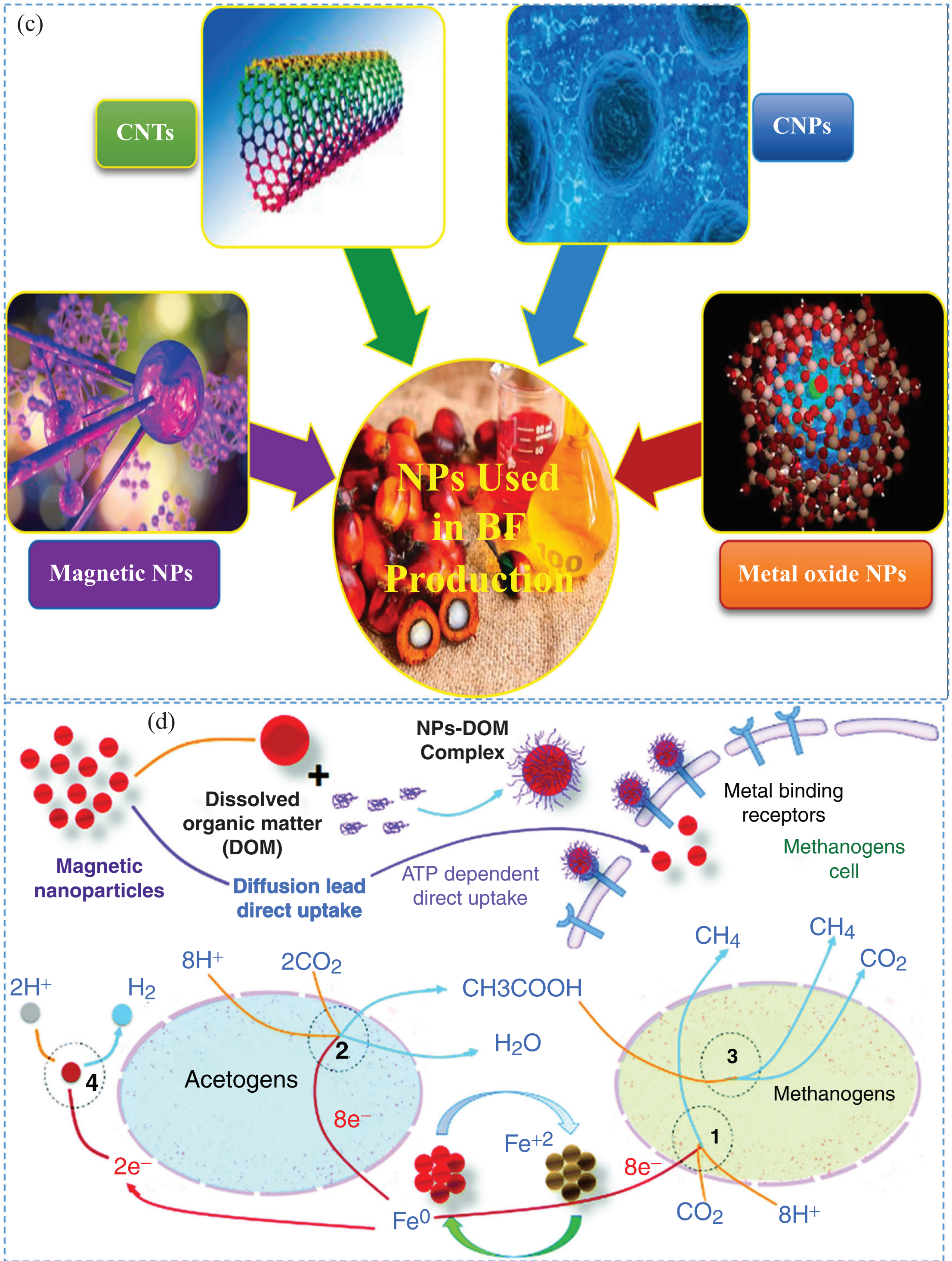


Fig 1 | (a) The production of biofuels from fourth generations of biomass,[15] (b) & (c) Biofuel production enhance using various NPs,[1,6] and (d) Optimization of biogas (Methane, hydrogen, and acetone) yield using iron-assisted nanomaterials[16]



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diesel engine efficiency and biodiesel-diesel blending efficiency with cost-effectiveness. Its metallic (i.e., Fe, Mg, Al, Si, Ag, Au, Cu, B) oxides (i.e., TiO_2, CuO, ZnO, Al_2O_3), and hybrid forms (i.e., Ni-Co, Mg-Al, Pd-Ni) enhance fuel properties and performance in biofuel production. Metals and metal oxides exhibit high catalytic activity and stability. These NPs act as heterogeneous catalysts, facilitating transesterification reactions with improved yields and shorter reaction times. Recent studies highlight the use of doped metal oxides to further enhance catalytic performance.

The ability to efficiently detach and reuse catalysts based on magnetic NPs is a major plus for large-scale biodiesel production from a financial perspective.

Table 1 | Various types of nanomaterials are used to produce biofuel

Types of NPs	Typical NPs	Performance
Metal NPs	Fe, Al, Mn, Au, Pd, Mg, Cu, B, Pt, Si, Ni, Ag, Rh,	Stable at medium temperature with higher catalytic performance
Metal-oxide NPs	Al_2O_3, Co_3O_4, cerium oxide (CeO_2), CuO, ZrO_2, Fe_3O_4, ZnO, CaO	Melting point and thermal stability are higher.
Non-metal-oxide NPs	SiO_2, titanium dioxide (TiO_2), GO	Thermal stability and melting point are higher.
Core-shell NPs	ZnO/SiO_2, Au/SiO_2, Ag/SiO_2, Au/TiO_2, Fe_3O_4/SiO_2, Fe/C, FeNi/SiO_2,	Multifunctional activity of higher stability.
Carbon-based NPs	Graphene, GO, Carbon Quantum Dots, Fullerene, CNTs, Multi-walled CNTs (MWCNTs), Activated Carbon.	Greater stability and thermal conductivity and inert.
Magnetic NPs	Fe, Ni, Co	Small size and a high ratio of surface area to volume.
Hybrid NPs	Ni-Co, Mg-Al, Pd-Ni, Fe-Mo, Cu-Mo, CaO-CeO_2, CaO-Al_2O_3, TiO_2-MgO, MgO-ZnO, CaO-ZrO_2.	Synergetic types catalytic activity.

Magnetic microferrites doped with calcium have been found to have a notable impact on biodiesel synthesis, increasing the yield from soybean cooking oils by over 85%. Separating immobilized enzymes using magnetic NPs, which have a super magnetic property, can increase their reusability.[21] Immobilizing cellulose on magnetic NPs for biomass hydrolysis has been the subject of numerous such endeavors. The development of efficient catalysts is currently the focus of research into magnetic nanostructure materials of several kinds. The synergistic effects of two or more metals in a bimetallic nanocatalyst enhance the selectivity and reaction rates. There has been improved catalytic performance in biodiesel generation when NPs like Pt-Ni and Co-Cu are combined. Catalysts in the biodiesel manufacturing process include graphene, GO, and reduced GO. One example of a nanobiocatalyst is GO used in conjunction with immobilized lipase to produce biodiesel.[22] It has been demonstrated that a nanocomposite of nickel and graphene can enhance the biohydrogen generation process from wastewater.[23] After four cycles of hydrolysis, cellulase immobilized on Fe_3O_4/GO/chitosan maintained 99% activity, according to research by John et al.[24] The enzyme also showed excellent thermal stability. Catalytic activity is high, and sugar liberation from lignocellulosic biomass is increased when NPs are acid-functionalized.[25,26] Additionally, functionalized NPs facilitate the conversion of algal oil into biodiesel and serve as a catalyst in the process. Functionalized NPs and nanocatalysts are used to pretreat biomass and improve the production process, as shown in Figure 2b, c.

The use of enzymes like lipases as biocatalysts in the biodiesel synthesis process is highly encouraging. Another intriguing application of nanotechnology in biofuel production is the immobilization of biocatalysts inside lipase-catalyzed biodiesel and cellulosic ethanol-generating procedures, as seen in Figure 2d.[16] An intriguing technique for improving mechanical procedures, enzyme immobilization involves placing a biocatalyst in a biocompatible and passive environment. It has a few advantages over free biocatalysts, including improved filling and activity of the catalyst, stability of temperature and pH, recovery, and biocatalyst reusability. Protein immobilization using NPs has several potential applications, including nanoencapsulation, frame-up with silanization, and adsorption, all of which have the potential to lower the costs of biofuel production. Nanostructured reactors, such as microchannel reactors incorporating nanomaterials, improve mass transfer and heat distribution during biodiesel synthesis. These reactors enable continuous processing, reducing production time and energy requirements. The various forms of nanomaterial used in biofuel production are shown in Figure 3a. Figure 3b depicts a cobalt (II)-chelated immobilization of *Pseudomonas fluorescens* lipase biocatalyst that achieved a 95% biodiesel yield from waste cooking oil and retained stability, with only a 12% yield reduction after ten reuse cycles.

Nanoadditives enhance biofuel quality by reducing CO emissions, thus mitigating the global warming effect, though they may increase CO_2 emissions. This is made feasible by enhancing the combustion rate, braking thermal efficiency, and fuel consumption particular to the brakes. Metallic NPs boost combustion by enhancing lean premixed combustion, atomization rate, fuel oxygen content, and heat transfer. Biofuel atomization and combustion efficiency are improved by microexplosions in fuel droplets containing CeO_2 NPs (Figure 3c, d).[27] Developing non-toxic, affordable NPs, resolving environmental issues, and reducing possible dangers to the ecosystem and human health are problems in ensuring sustainability. Thus, the sustainable use of nanomaterials requires careful investigation, risk analyses, and appropriate waste management techniques. Table 2 summarizes the reusability and performance of various nanocatalysts in biodiesel production, demonstrating their ability to be reused multiple times without significant loss in biodiesel yield.[30]

As an excellent catalyst, sulfonic-acid-functionalized MOF, UiO-66-SO_3H, demonstrated outstanding activity with a 98.30% conversion rate and is being employed for next-generation nanomaterials.[32] Under optimized conditions, the Na_2SiO_3/Ni-MOF catalyst led to biodiesel production yields reaching 98.4% for soybean oil and up to 94.5% during repeated cycles using spent bleaching clay oil. The transesterification process using GO and sulfonated GO as catalysts results in biodiesel production efficiencies of 84.6–99% from wet microalgae biomass.[33] Recent discoveries in catalyst design and process methods emphasize the necessity of developing innovative solutions to create sustainable biodiesel manufacturing techniques.

In summary, nanotechnology provides a promising solution to economic and environmental challenges, with NPs offering advantages in biofuel production processes like the transesterification of oils and fats for biodiesel. Catalyst recovery and reuse are also enhanced. Nanomaterials are considered ideal for improving biofuel and bioenergy production efficiency. NPs aid biomass degradation for second-generation biofuels and offer process-efficient methods to enhance production. They improve fuel properties, maintain consistent chemical reactions, reduce production costs, and increase efficiency in biofuel generation. The unique features of nanomaterials enable their use as crucial elements to boost sustainability alongside the increased pace of biofuel conversion rates. Nanotechnology enhances biomass degradation along with transesterification reactions and catalyst recovery operations, thus supporting the production of ethanol and bioenergy effectively. Research shows that NPs reduce manufacturing expenses while upgrading petroleum attributes and performing reliable chemical sequences, which leads to improved economic and operational efficiency of biofuel production. Ultrathin particles, through biomaterial

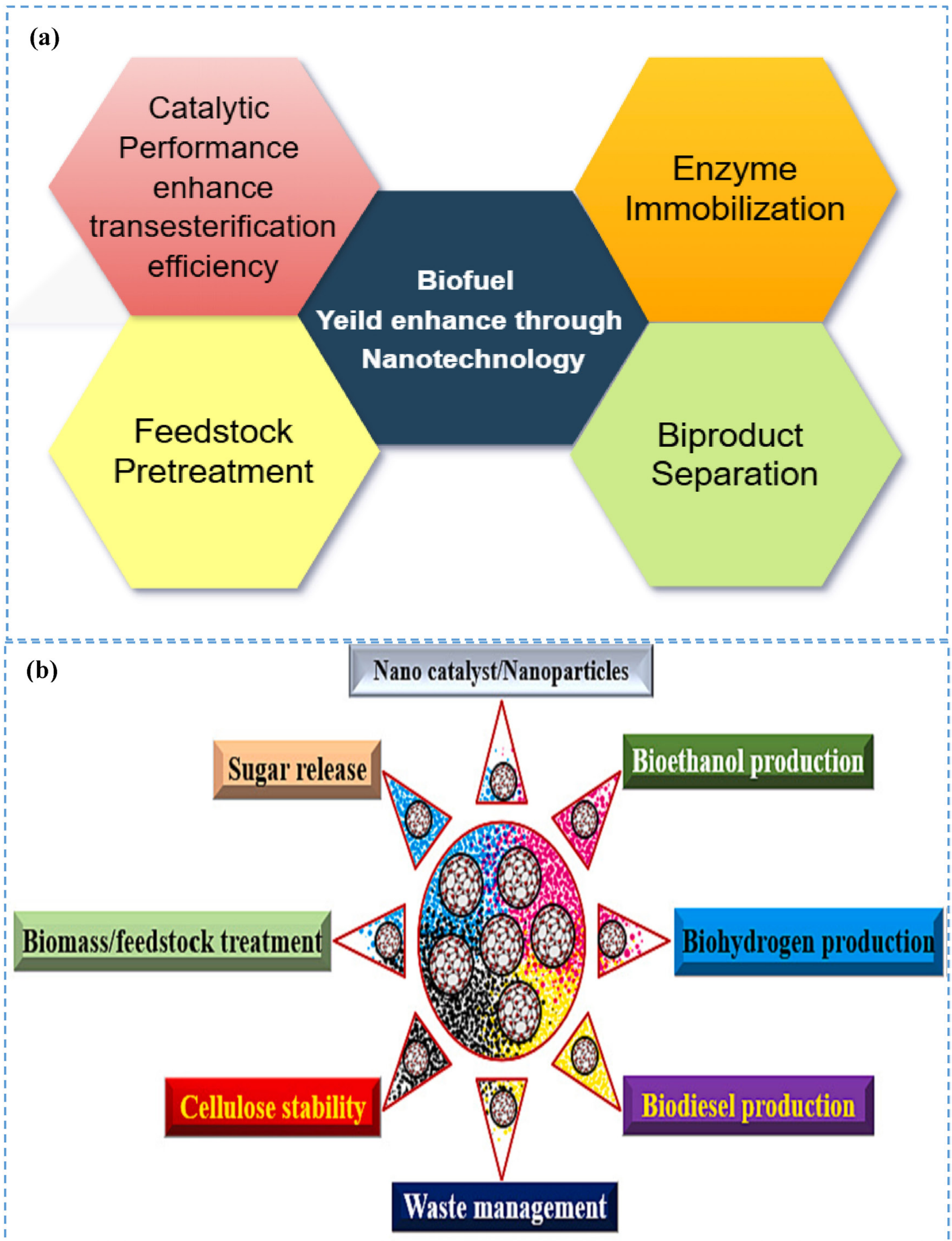
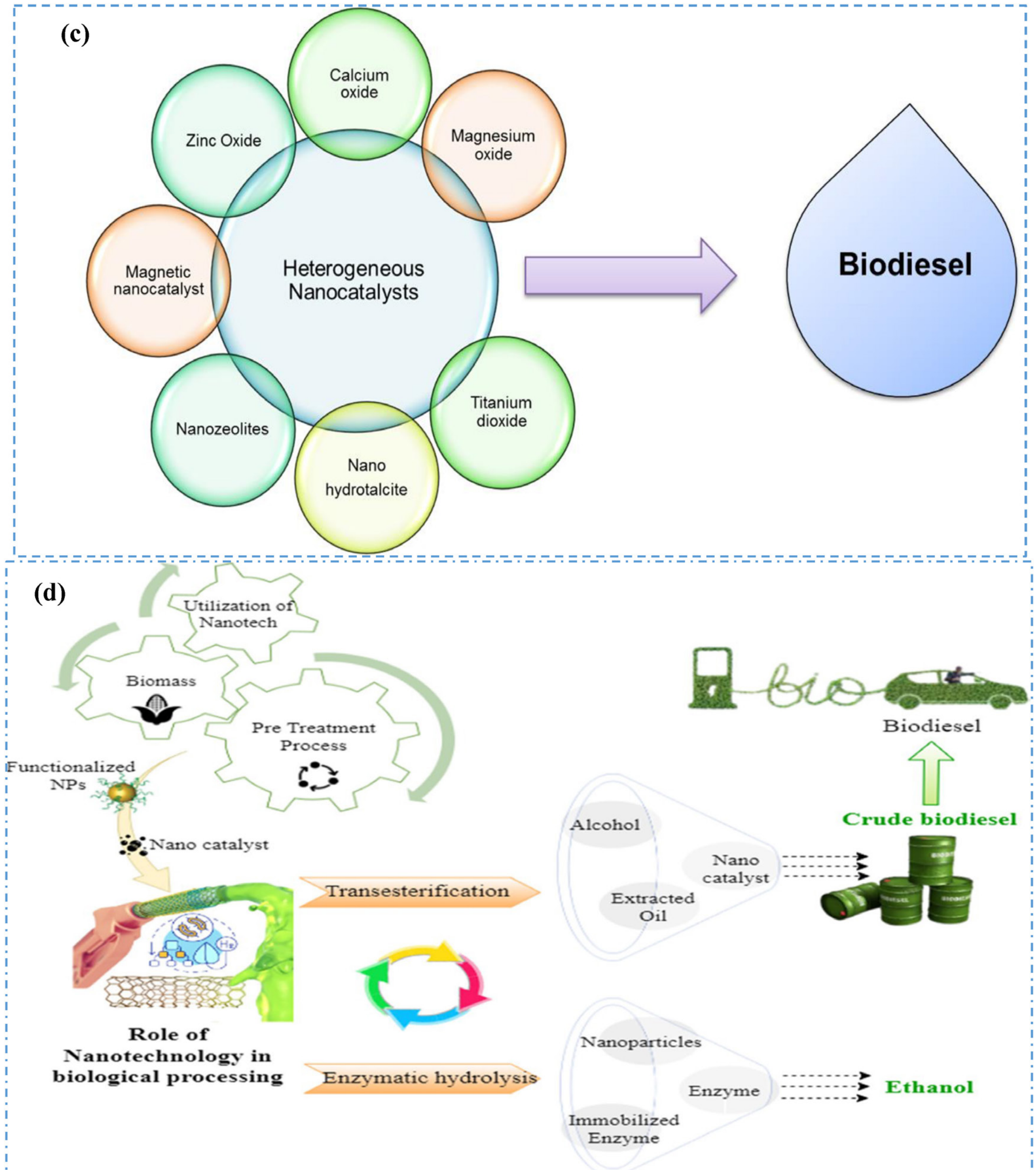


Fig 2 | (a) Biofuel yield enhanced through various forms of NPs, (b) Utilizations of NPs as nanocatalysts in diverse phases of biofuel industries,[6] (c) Biodiesel production via heterogeneous nanocatalysts[19] and (d) The mechanism of enzymatic hydrolysis and transesterification using nanotechnology for biofuel generation[15]



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conversion, solve issues that enable the production of second-generation biofuels. The development of nanomaterials represents a revolutionary technology for sustainable biofuel solutions because they allow more productive production processes while resolving economic and environmental barriers.

Nanomaterials vary in efficiency, cost, and environmental impact. CNTs and graphene offer high conductivity and strength but are expensive to produce.[34,35] Metal NPs, like silver and gold, are effective in catalysis and medicine but pose toxicity risks. Silica and cellulose nanomaterials are cost-effective and environmentally friendly. While nanomaterials enhance performance across industries, concerns over resource use, toxicity, and recyclability highlight the need for sustainable production methods. Some typical nanomaterials, along with their performance, cost, and environmental effects, are shown in Table 3.

Factors Influencing the Effectiveness of NPs

The effectiveness of NPs in biofuel generation is dependent on their size, shape, surface area, catalytic activity, and synthesis process conditions such as pH value, temperature, pressure, and so on.[1,2] Moreover, the functionalization and composites of NPs enhance the stability and enzyme immobilization. It is highly recommended to adopt biological synthesis methods because they employ safe, sustainable substances that have very little effect on biocatalysts when producing biofuel.[43] The synthesis medium of pH has been found to vary the effectiveness of metallic NPs, i.e., Ag, Zn, Fe, Au, and others. This confirmed the variation of pH value during NPs synthesis is highly affected by the size, shape, structure, and morphology of the NPs, which in turn affects their stability and reactivity. Understanding these relationships is important for optimizing the synthesis process and tailoring the properties of NPs for bioenergy production. Therefore, the standard synthesis method confirms stability and minimizes toxicity, which makes NPs crucial for enhancing biofuel yield and process efficiency.

The size of NPs also affects the production of biofuel, and it has been found to yield better in acidic media than in basic media.[44,45] Biofuel conversion, as well as catalytic activity, increases because of higher surface-area-to-volume ratios in small NPs. However, effectiveness suffers when NPs become too small because this leads to aggregation between particles. Biofuel production reaches its highest yields when different shapes of NPs (spherical, rod, and cubic) are used since they affect surface reactivity, enzyme immobilization, and substrate interaction rates.[46] The production of biofuels becomes more efficient through structures such as core-shell and porous or hollow shapes that provide benefits for thermal stability, recyclability, and substrate access. The thermal and chemical stability of NPs improves the reaction efficiency of bioenergy conversion.

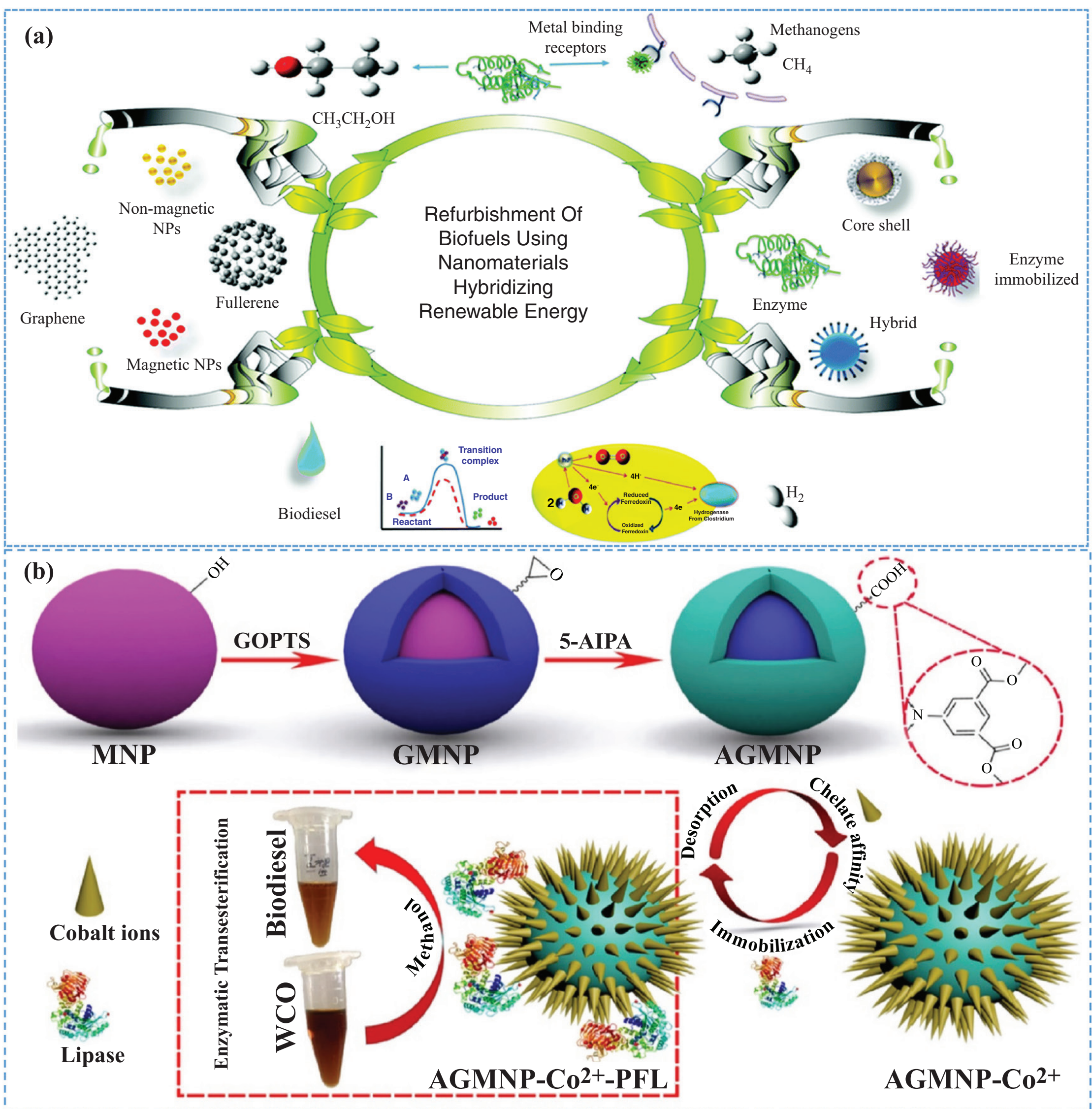

Fig 3 | (a) The various forms of nanomaterial used in biofuel production,[16] (b) Preparation of reversible lipase immobilization from cobalt (II)-chelated metal NPs,[27] (c) Fuel-encapsulated CeO_2 nanoadditives: microexplosion,[28] and (d) The harmful consequences and protective effects of carbon monoxide (CO) after inhalation[29]

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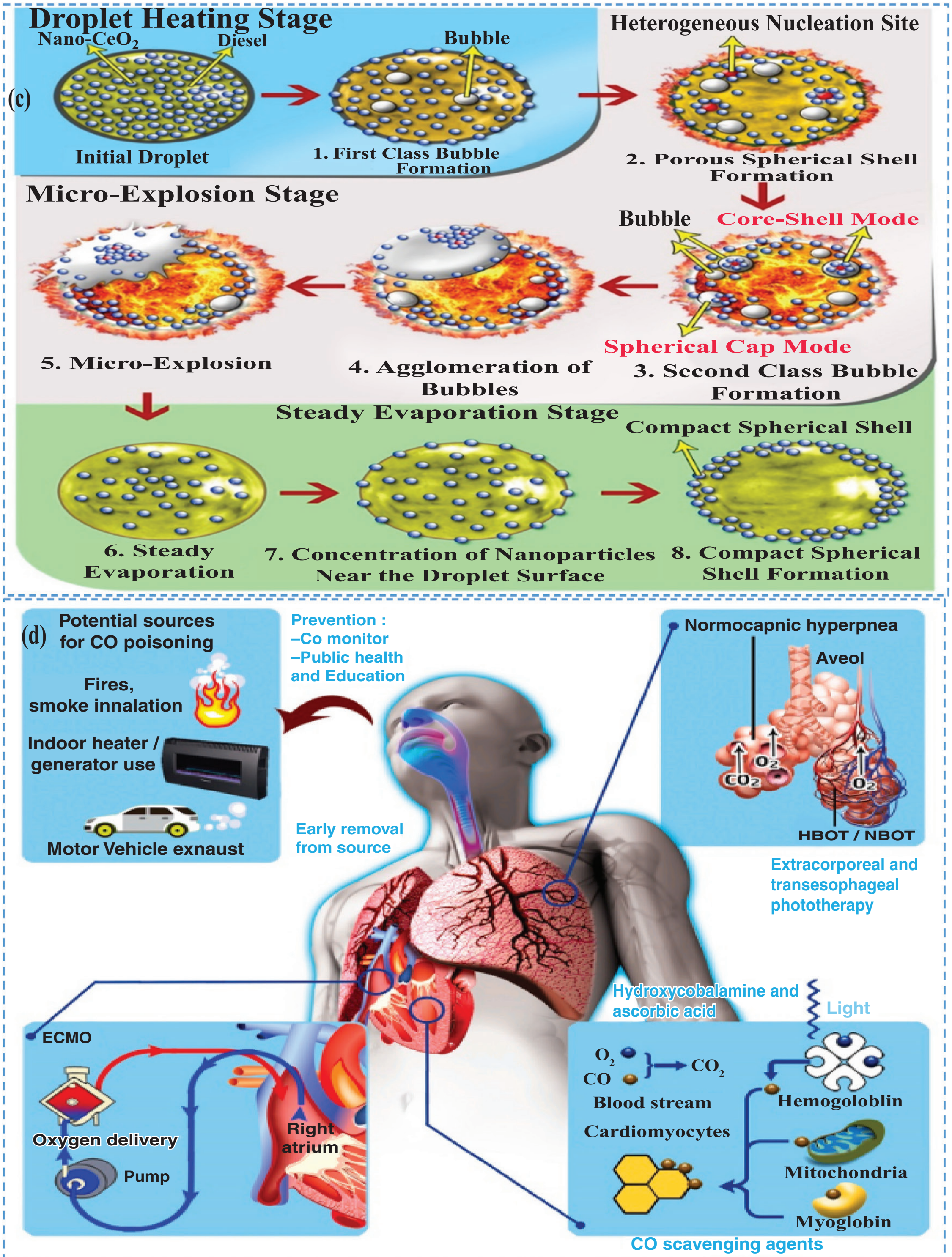

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Synthesis and Characterization Techniques of Nanomaterials

The top-down and bottom-up method have been widely used to synthesize the nanomaterial. Top-down approaches are ideal for materials with macroscopic connections and long-range order, while bottom-up methods excel at short-range order on the nanoscale. Bottom-up strategies offer effective control over size and geometry but yield small quantities. The top-down approach is known as a destructive method in which

Table 2 | Different nanocatalysts and their reusability conversion yield (%) to produce biofuel[31]

Types of Nanocatalyst	Yield of Biodiesel (%)	Source of Oil	Conversion Yield for Reusability (%)	Cycle Numbers
CaO	98.54	Crude jatropha	95.8	6
CaO-Au	97.00	Sunflower	89	10
$Fe\text{-}Mn\text{-}SO_4/ZrO_2$	96.60	Tannery	›90	4
SiO_2/ZrO_2	96.40	Soybean	84.1	6
$KF/CaO\text{-}Fe_3O_4$	95.00	Stillingia	›90	14
$Ni_{0.5}Zn_{0.5}Fe_2O_4$	99.54	Soybean	98.45	3
$MgO/MgFe_2O_4$	91.20	Sunflower	82.4	5

Table 3 | The Efficiency, costs, and environmental impacts relative to different nanomaterials

Types of NPs	Efficiency	Cost/Per Gram	Environmental Impact	References
Silver NPs	High antimicrobial properties, effective in wound healing and water purification and bioenergy production.	High: $500–$1000	Potential toxicity to aquatic life, bioaccumulation concerns.	34,35
TiO_2 NPs	High in photocatalysis, solar energy applications and bioenergy production.	Moderate: $10–$100	Non-toxic, biodegradable; minimal environmental impact.	36,37
Silicon NPs	Efficient in electronics and battery applications.	Moderate: $50–$200	Relatively low environmental impact; non-toxic in most cases.	38,39
Gold NPs	Highly effective in drug delivery, biofuel production, and diagnostics.	Very high: $1000–$5000	Biocompatible, but excessive use can lead to accumulation in organisms.	40
CNTs	High strength-to-weight ratio, efficient in structural applications and bioenergy production.	Moderate: $20–$500	Concerns about toxicity and bioaccumulation, potential respiratory hazards.	41
Magnetic NPs	Highly efficient in targeted drug delivery, MRI imaging, and biofuel production.	Moderate: $100–$300	Biodegradable, low toxicity; risk of bioaccumulation.	42

larger molecules are broken up into smaller units and further transformed into NPs. Usually, it uses mechanical or physical methods such as grinding, chemical etching, milling, sputtering, cutting, laser ablation, electrolysis, and spraying. Using ceramic balls for milling, Bello et al. prepared coconut shell NPs.[47] They saw a gradual decrease in size and a fading brown hue, which suggested changes in the material's properties at the nanoscale.

Using the bottom-up method, NPs are produced through chemical or biochemical reactions, laser evaporation, electrical evaporation, chemical vapor deposition, sol–gel, hydrothermal, supercritical fluid synthesis, and magnetron sputtering. This process is capable of controlling the particle size, shape, and composition of NPs, which makes it ideal for application in energy, catalysis, medicine, and electronics. Through the photocatalytic degradation of methylene blue, Mogilevsky et al. synthesize titanium anatase NPs with graphene support using titanium isopropoxide and alizarin.[48] Research shows that both top-down and bottom-up methods can be used to manufacture metallic NPs such as Fe, Cu, Ag, and Bi.[49] X-ray diffraction, Fourier transform infrared spectroscopy, X-ray photoelectron spectroscopy, dynamic light scattering, electron backscatter diffraction, small-angle X-ray scattering, Brunauer–Emmett–Teller analysis, transmission electron microscopy, field emission-scanning electron microscopy, and inductively coupled plasma mass/atomic emission spectroscopy are some of several characterization techniques that are frequently employed in NPs characterization.[50] Structural, morphological, and electrical properties, including size, shape, surface area, structure, and elemental composition of NPs, are evaluated by these characterization techniques. Typical Fe_3O_4 NPs have been synthesized and characterized through FE-SEM, XRD, and FT-IR. FE-SEM analysis revealed that Fe_3O_4 NPs and their nanocatalysts exhibit spherical shapes with nanoscale dimensions, retaining their morphology after silica and organic compound coatings (Figure 4a, b). TEM images confirmed a core-shell structure with silica fixed onto Fe_3O_4 NPs (Figure 4c, d). The particle size distribution ranged between 45 and 55 nm (Figure 4e), validating the successful synthesis and preservation of the nanostructure features.

Environmental and Health Concerns

Nanotechnology offers solutions to environmental issues, prevention strategies for future challenges, and insights into NP risks.[51,52] While expanding research and investment, its implementation raises concerns about regulation, safety, and ethics. Growing demand in healthcare, electronics, and agriculture drives NP production, necessitating urgent assessment of their environmental and human impacts. Metal-oxide NPs pose potential toxicity risks to plants, affecting growth, metabolism, and nutrient absorption. Their release into water sources contributes to pollution, altering aquatic ecosystems and bioaccumulating in organisms. Human exposure, through inhalation or ingestion, raises concerns about cellular toxicity and long-term health effects. Further research is needed to understand these impacts and develop safer, environmentally friendly nanomaterials to minimize ecological and health risks. The toxicity of NPs is influenced by multiple factors, as shown in Figure 5. NPs in the environment cannot remain as bare particles due to their reactive surfaces. Proteins form a "corona" around the particle, with varying residence times based on surface affinity.[53] Physical interactions can cause membrane rupture and protein aggregation, while chemical interactions lead to oxidative damage through reactive oxygen species (ROS).[54] Environmental factors further complicate NP toxicity evaluation.[55] NPs can be emitted at any stage of their life cycle, with the most complex consequences occurring during consumer use. Transformations in their physicochemical properties can alter their environmental impact. Toxicity studies should consider these changes, as most methods focus on oxidative stress pathways, leading to ROS production and cell damage. In vitro and in vivo studies have

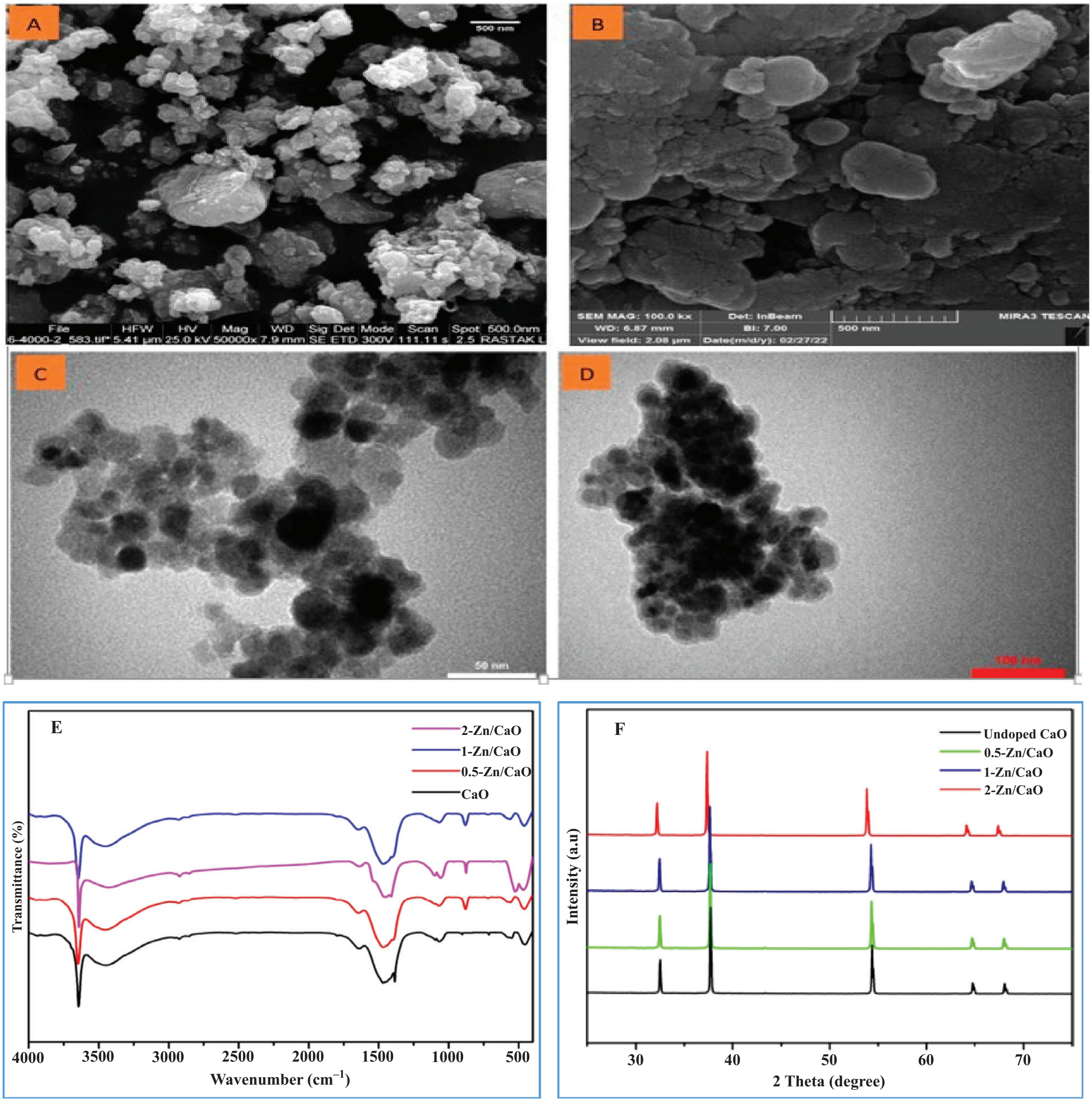

Fig 4 | (a) FE-SEM images of Fe_3O_4,[41] (b) FE-SEM images of the as-prepared nanocatalyst,[41] (c) TEM images of Fe_3O_4,[41] (d) TEM images of the as-prepared nanocatalyst,[41] (e) FT-IR spectra of undoped and Zn-doped CaO nanocatalysts,[41] and (f) XRD patterns of undoped and Zn-doped CaO nanocatalysts[41]

shown diverse toxic effects across various organisms, with impacts varying by nanomaterial properties and target species.

Despite their many advantages, NPs also have negative environmental impacts. NPs dissolve slowly, leading to potential long-term concerns regarding their persistence and bioaccumulation. Their interactions with ecosystems remain an active research area, necessitating careful studies on toxicity, degradation, and accumulation over time. Additionally, NPs can enter organisms through inhalation, ingestion, or absorption, posing potential risks to biological systems. For example, studies suggest that certain NPs, such as silver and TiO_2, may disrupt microbial ecosystems or impact insect populations. Addressing these risks requires a multidisciplinary approach involving biologists, chemists, and physicists to evaluate and mitigate their environmental effects. NPs also play a crucial role in toxin and pesticide applications, enhancing reliability and effectiveness. Their boundary weight influences environmental interactions, affecting dispersion, stability, and bioavailability. Heavier NPs tend to settle faster, reducing airborne contamination, whereas lighter ones remain suspended longer, increasing exposure risks. Understanding these factors is essential for optimizing NP applications in agriculture and medicine while minimizing ecological risks and ensuring safety in environmental use.[57]

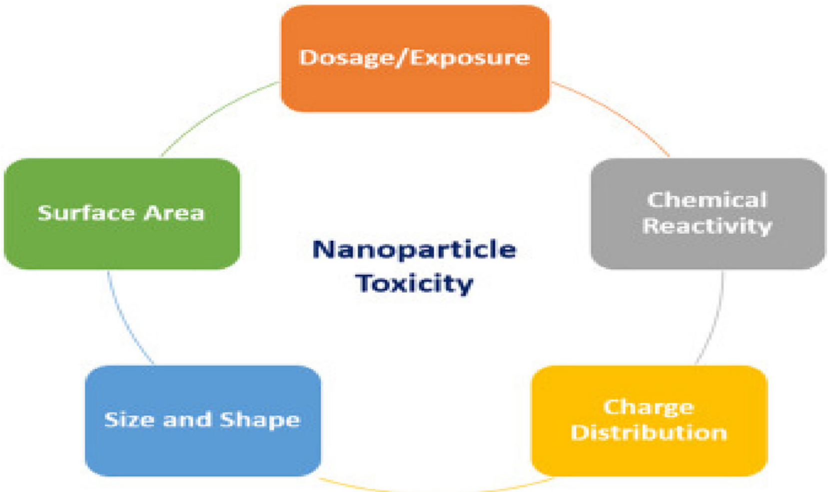

Fig 5 | Different aspects which might alter an NP's overall toxicity[56]

Metal-oxide NPs pose potential toxicity risks to plants by affecting growth, metabolism, and nutrient absorption. Their release into water sources contributes to pollution, altering aquatic ecosystems and bioaccumulating in organisms. Human exposure through inhalation or ingestion raises concerns about cellular toxicity and long-term health effects. Further research is needed to understand these impacts and develop safer, environmentally friendly nanomaterials to minimize ecological and health risks.[3]

Challenges and Prospects

Biofuel production could reach a transformative phase through nanotechnology because the technology improves output rates, minimizes energy utilization, and optimizes production protocols. The successful development of nanomaterials in biofuel production demands the resolution of three major barriers: excessive product costs, scalability problems, and environmental and health-related dangers associated with metal-oxide NPs. To improve both nanocatalysts and enzyme efficiency and increase biomass conversion, researchers need to conduct more advanced studies. The research must focus on developing environmentally friendly NPs, as well as using nanomaterials for reaction monitoring and finding economic approaches for NP production. Commercialization faces three main barriers: intellectual property matters alongside market segmentation requirements and funding constraints. NPs offer significant benefits but pose challenges in terms of environmental impact, toxicity, health concerns, cost, and effectiveness. Their high surface area enhances performance in medicine, agriculture, and industry, yet slow degradation raises bioaccumulation risks. Certain NPs, like metal oxides, can harm ecosystems and human health through inhalation or ingestion. High production costs limit widespread use, while regulatory uncertainties hinder adoption. However, advancements in green synthesis and biodegradable NPs offer promising prospects. Developing cost-effective, eco-friendly alternatives and conducting long-term toxicity studies are crucial to balancing innovation with sustainability, ensuring safe and efficient NP applications across various fields.

The promotion of sustainability happens when nanotechnology integrates circular economy principles and enables researchers to work closely with stakeholders. The future of biofuel production shows promise because newly developed nanobiocatalysts combined with nanostructured membranes, while utilizing carbon-based nanomaterials, offer additional effective solutions. The combination of better waste-fuel conversion methods with advanced process controls would improve both the efficiency and economic feasibility of biofuel production. Technology expansion demands the resolution of mass transfer limitations, as well as high energy consumption issues. Excellent research combined with policy backing and industry alliances will make nanotechnology drive biofuel adoption instead of fossil fuels, which creates sustainable energy pathways.

Conclusions

Nanotechnology is turning into a transformative technique for increasing the production of biofuels by increasing sustainability, yield, and efficiency. Significant advancements in biomass conversion, enzyme activity optimization, and process scalability have been made possible using nanocatalysts, nanomaterials, and biocatalyst immobilization approaches. In addition to improving the production of biofuels like biodiesel, bioethanol, and biogas, these technologies help diminish their adverse effects on the environment by using less energy and producing less waste. Various forms of NPs, such as metal, metal-oxide, magnetic, core-shell, hybrid, and carbon-based, have been widely used in biofuel production. Metal-based and metal-oxide NPs were the most successful of them, producing an astounding 96.5–98.54% biodiesel yield. Sulfonic-acid-functionalized MOF has recently been employed as an effective catalyst that showed remarkable activity with a 98.30% conversion rate for next-generation nanomaterials. A number of NP characteristics, including size, shape, pH, synthesis method, and others, must be taken into consideration when producing biofuel. The top-down and bottom-up method has been followed to synthesize NPs. NPs enhance feedstock operations and make biofuel conversion rate faster while producing better quality end products. NPs offer immense potential but raise concerns regarding environmental impact, toxicity, health risks, and cost. While their effectiveness drives advancements, issues like bioaccumulation and regulatory challenges persist. Though nanotechnology shows potential for biofuel production, it faces challenges in large-scale development because of material expenses and safety concerns. More combined research efforts in nanotechnology and green synthesis methods with sufficient investment will make its effective use wider across many areas. The future of energy sustainability depends on biofuel production through nanotechnology, which reduces fossil fuel use and fights climate change. Research should prioritize eco-friendly synthesis, safety, and cost reduction for sustainable NP applications.

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