Available online at www.sciencedirect.com

ScienceDirect

Current Opinion in
Green and Sustainable Chemistry

Advanced nanomaterials design and synthesis for accelerating sustainable biofuels production – A review

Farooq Sher[1], Imane Ziani[2,3], Mariam Hameed[3,4], Salman Ali[3] and Jasmina Sulejmanović[3,5]

Abstract

The utilization of nanomaterials in biofuel production has garnered considerable attention owing to their distinctive characteristics, including a high surface-area-to-volume ratio, strong dispersibility, and enhanced reactivity. This review delves into the transformative role played by nanomaterials, specifically graphene-based catalysts, metal–organic frameworks, biomass waste materials, and carbon nanotubes, in augmenting various facets of biofuel production. Noteworthy examples include the application of metal-modified graphene oxide composite catalysts, incorporating aluminium and ferric, revealing a significant 25% reduction in free fatty acid content and a remarkable 15% increase in methyl hexadecanoic yield. Furthermore, the eco-friendly synthesis of TiO_2 nanoparticles showcased consistently high biodiesel yields, reaching 95% over 10 cycles, underscoring its economic advantages and stability. However, it is essential to acknowledge the potential drawbacks associated with nanomaterial utilization in biofuel production. Environmental concerns, such as nanoparticle release during production processes and their impact on ecosystems as well as safety issues related to exposure to nanoparticles, require careful consideration. This comprehensive overview encompasses recent studies on green synthesis, hydrothermal-assisted carbonization, gold nanoparticles in biomass hydrolysis, and the impact of nano-fuel technology on engine characteristics. Innovations in catalysts and processes, such as sulfonic acid functionalized metal–organic frameworks and magnetic MOF-derived materials, are scrutinized for their sustainability. The review culminates with a thorough analysis of the environmental and economic impacts, accentuating both the potential benefits and challenges entailed in the seamless integration of nanotechnology into biofuel production.

Addresses

[1] Department of Engineering, School of Science and Technology, Nottingham Trent University, Nottingham NG11 8NS, United Kingdom
[2] Laboratory of Applied Chemistry and Environment, Department of Chemistry, Faculty of Sciences, Mohammed First University, Oujda 60000, Morocco
[3] International Society of Engineering Science and Technology, Nottingham, United Kingdom
[4] School of Chemistry, University of the Punjab, Lahore 54590, Pakistan
[5] Department of Chemistry, Faculty of Science, University of Sarajevo, Sarajevo 71000, Bosnia and Herzegovina

Corresponding authors: Sher, Farooq. (Farooq.Sher@ntu.ac.uk); Sulejmanović, Jasmina (Jasmina.Sulejmanovic@pmf.unsa.ba)

Current Opinion in Green and Sustainable Chemistry 2024, **47:**100925

This review comes from a themed issue on **New Synthetic Methods (2024)**

Edited by **Mariam Ameen** and **Suzana Yusup**

Available online 25 April 2024

For complete overview of the section, please refer the article collection - New Synthetic Methods (2024)

https://doi.org/10.1016/j.cogsc.2024.100925

Keywords

Renewable energy, Biofuel production, Graphene-based catalysts, Environment, Carbon dioxide, Green synthesis, Greenhouse gas emissions and economic impacts.

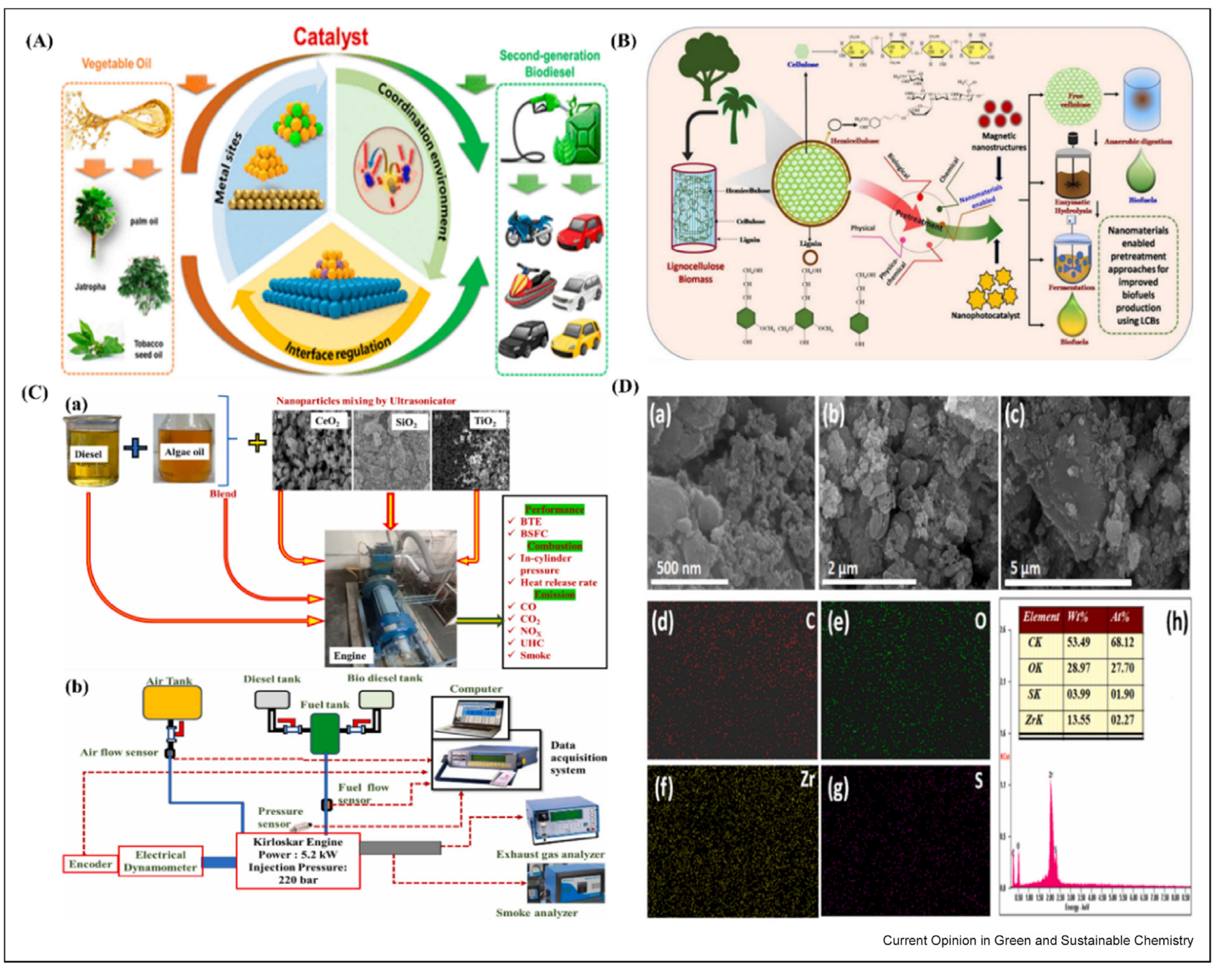
Introduction

The growing interest in utilizing nanomaterials for biofuel production signifies their unique characteristics that have the potential to revolutionize production processes [1]. Nanomaterials exhibit features such as a high surface-area-to-volume ratio [2], strong dispersibility [3], and enhanced reactivity, positioning them to transform biofuel production by improving substrate digestibility [4], increasing biofuel yields, and fostering better microalgal growth [5]. Notably, graphene-based catalysts, including exfoliated functionalized graphene and graphene oxide, show promise in biodiesel production [6]. Metal-modified graphene oxide composite catalysts, incorporating metals like aluminium and ferric, exhibit efficiency in reducing free fatty acid content and increasing methyl hexadecanoic yield. Furthermore, metal−organic frameworks (MOFs) [7], combining metals and organic frameworks, serve as catalysts for oil conversion into biodiesel, with ongoing studies focusing on optimization for enhanced performance [8].

Biomass waste materials, serving as catalysts, offer eco-friendly alternatives with recyclability and compatibility across diverse feedstocks. Carbon nanotube (CNT) catalysts [9], especially sulfonated carbon nanotubes, demonstrate stability, catalytic activity, and reusability in esterification and transesterification reactions [10]. Recent advancements in engineering techniques have significantly improved the efficiency of biofuel production from microalgae biomass. Nanomaterials, such as copper-doped zinc oxide nanocomposites and sodium zinc-silicate, serve as effective heterogeneous catalysts, enhancing biodiesel production from waste cooking oil and Spirulina algae oil [11]. Additionally, microbubble-mediated mass transfer technology has been employed to enhance gas and liquid mass transfer, thereby improving biofuel production efficiency. By providing a larger surface area for reactant interaction, microbubbles facilitate faster reaction rates and higher conversion yields [12], achieving a remarkable 92% conversion rate in microalgae oil esterification for biodiesel production within just 30 min.

To visually complement the exploration of nanomaterial applications in biofuels within this review, Figure 1(A) provides an overview of the use of nanomaterials for pretreatment of lignocellulosic biomass (LCBs) in biofuels production [13]. This figure highlights the potential of magnetic nanostructures and nanocatalysts in improving the efficiency of LCBs pretreatment. Additionally, Figure 1(B) illustrates design of catalysts used in the process of catalytic deoxygenation of vegetable oils to produce second-generation biodiesel [14]. The development and application of various nanomaterials, metal oxides, and microalgae for biofuel production indeed present promising avenues, yet they are accompanied by significant challenges that warrant acknowledgement. Carbon nanomaterials, for instance, confront hurdles in material selection and design due to uncertainties surrounding enzymatic electron transfer

Fig. 1



(A) Strategies for designing catalysts to deoxygenate vegetable oils for the production of second-generation biodiesel. (B) The influence of nanomaterials on environmentally friendly pretreatment methods for lignocellulosic biomass in biofuel manufacturing. (C) (a) Experimental sequence involving engine parameters tested with various fuels and (b) Configuration of the experimental engine with data acquisition and emission measurement systems. (D) Illustrative scanning electron micrographs, (a–c) Showcasing UiO-66-SO_3H catalyst, (d) Elemental mapping of carbon, (e) Oxygen, (f) Zirconium, (g) Sulfur and (h) EDS spectrum. Edited with permission from Refs. [13,15–17], Copyright ACS ©2023, Elsevier ©2023 and ©2022.

kinetics and synthesizing heteroatom-doped carbon nanomaterials.

Additionally, concerns regarding the mechanical strength required for practical device applications and time-consuming nature of hazardous surface functionalization processes hinder progress in this domain. Similarly, metal oxide catalysts face obstacles such as maintaining stability under harsh conditions, the potential for leaching, and environmental impacts [18]. Despite these challenges, they offer scalability potential, albeit necessitating optimization for high catalytic activity and selectivity. Transitioning to microalgae-based biofuels also presents challenges, including addressing cost efficiency, water and nutrient requirements, cultivation complexities, and harvesting difficulties [19]. Although microalgae offer scalability and environmental benefits, optimizing their utilization and addressing resource competition remains crucial. Additionally, the utilization of nanoparticles introduces concerns regarding toxicity, cost, feasibility, environmental impact, and regulatory compliance, highlighting the need for safety measures and exploration of alternative approaches for economic viability and sustainability.

This review emphasizes the most significant developments in the field over past two years, offering a comprehensive exploration of the practical applications of designed nanomaterials in biofuel production. Covering catalytic enhancement, increased biodiesel yield, free fatty acid reduction, utilization of biomass waste materials, and improved oil conversion efficiency, these nanomaterials provide sustainable and eco-friendly approaches to biodiesel production across diverse feedstocks. This focus on recent advancements positions review at the forefront of current progress, offering valuable insights into the evolving landscape of nanomaterial applications in biofuels.

Nanocatalysts driving progress in sustainable biofuel production

The integration of state-of-the-art nanosynthesis and advanced technologies presents a promising avenue towards sustainable biofuel production. In a groundbreaking study by Qamar et al. [20], the potential of green synthesis utilizing microorganisms and common plants to produce cost-effective TiO_2 nanoparticles (NPs) for biodiesel manufacturing was highlighted [20]. Their work introduced $SO_4/Fe{-}Al{-}TiO_2$ catalyst, designed for biodiesel production from waste cooking oil, which exhibited exceptional superparamagnetic properties and a high tolerance for free fatty acids [20], ensuring both efficiency and sustainability. This catalyst maintained a consistent biodiesel yield of 95% over 10 cycles [13]. However, a significant challenge arises as TiO_2 nanoparticles lose catalytic activity and selectivity when exposed to high temperatures during sintering process. Overcoming this limitation necessitates the use of supported TiO_2-based nanocatalysts, albeit at a higher production cost due to increased methanol usage and involvement of hazardous chemicals in synthetic methods [21].

Meanwhile, Alagumalai et al. [22] explored hydrothermal-assisted carbonization for biofuel production, achieving a remarkable 96.4% biodiesel yield. The study introduced a catalyst derived from palm kernel shells, enhancing performance as a support for synthesized nanocatalysts. Coupled with the use of empty fruit bunches in hydrothermal carbonization, this innovative approach offers a biofuel yield exceeding 97%, showcasing commercialization potential [22]. Metal-based catalysts, including zinc chloride and iron (III) chloride, contribute to improved hydrothermal carbonization efficiency, affirming the viability of this method for sustainable and commercially viable biofuel production [22]. Nevertheless, challenges persist in hydrothermal-assisted carbonization, notably in conversion efficiency and biocrude quality. To address these challenges, researchers have focused on catalytic approaches, aiming to accelerate reactions and improve biocrude quality by optimizing catalyst formulations and increasing the quantity of catalytically active sites [22].

The transformative role of nanomaterials is exemplified in Aarti et al. [23]'s work, where gold nanoparticles (AuNPs) enhance efficiency and cost-effectiveness in biomass hydrolysis and bioethanol production. Leveraging bacterial cellulase for AuNP synthesis, immobilized yeast cells achieved substantial ethanol yields from NaOH pre-treated biomass of *A. philoxeroides* (45.09%) and *B. mutica* (50.1%). These findings position bacterial cellulase-assisted-synthesized AuNPs as promising catalysts for cost-effective bioethanol production from aquatic weed biomass [23]. The use of AuNPs provides a large surface area for cellulase attachment, leading to higher enzyme loading per unit mass of nanoparticles. This suggests that the use of AuNPs in biofuel production offers scalability benefits, because immobilization process can be scaled up for industrial applications, making it cost-effective and efficient [24].

Furthermore, AuNPs exhibit high chemical stability, reducing the amount of catalyst needed and allowing for environmentally friendly synthesis methods [24]. Meanwhile, Jegan et al. [15] explored nano fuel technology, incorporating metallic oxide nanoparticles (CeO_2, SiO_2, and TiO_2) to elevate algae oil biodiesel production as illustrated in Figure 1(C). $B_{25}TiO_2$ blend showcases remarkable enhancements, registering the highest in−cylinder pressure at 72.2 bars, a peak heat release rate of 63.2 J/°CA, and superior Brake Thermal Efficiency (BTE) of 33.8% at 2500 rpm, outperforming other fuels [15]. Incorporating metallic oxide nanoparticles in algae oil biodiesel production can yield both positive and negative environmental impacts. While these nanoparticles can enhance microalgae growth and lipid content, potentially increasing biofuel production, their production and disposal may contribute to pollution and environmental harm [25]. Additionally, the long-term ecological effects remain uncertain, necessitating careful assessment. Despite their potential scalability benefits, further research is crucial to fully understand their environmental implications [25]. Nonetheless, nanoparticles offer potential for catalyst recovery and reuse, promoting sustainability with responsible practices.

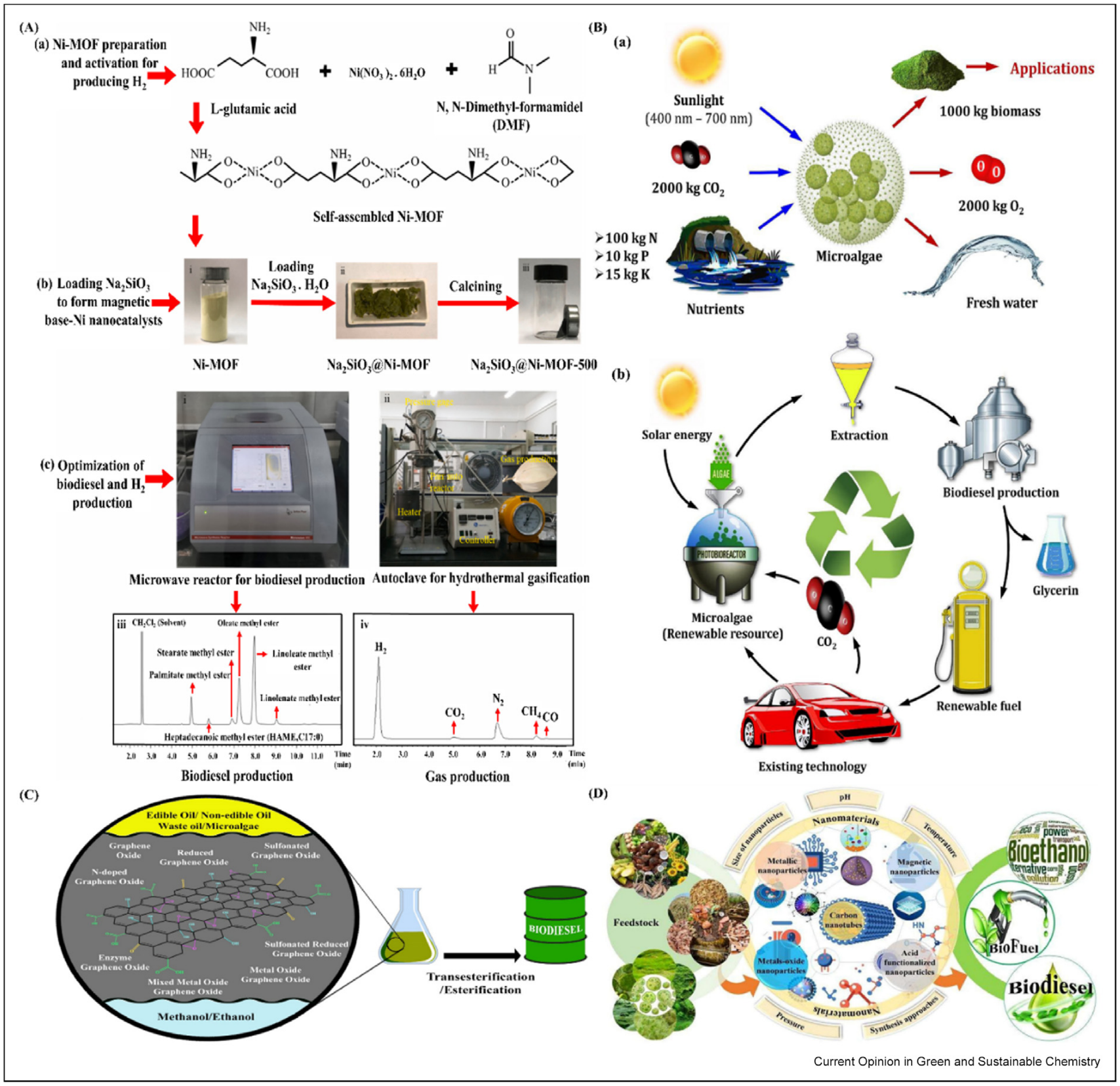
Sawaira et al. [26] explored the potential of newly synthesized green nanocatalysts, specifically Bi_2O_3, and Cannabis oil seed for future energy sustainability. Focused on the transesterification process of *Cannabis sativa* biodiesel, the study reveals efficient application results of green Bi_2O_3 nanoparticles. Under optimal conditions, including a 1.5% w/w catalyst weight, 1:12 oil to methanol molar ratio, and 92 °C reaction temperature, a biodiesel yield of 92% was achieved [26]. The produced Cannabis biodiesel met fuel quality standards, displaying a low sulfur content of 0.00047% for reduced emissions. Thermodynamic parameters indicated an unspontaneous and endergonic reaction catalyzed by Bi_2O_3 nanoparticles, positioning them as a promising catalyst for sustainable and economically viable biodiesel production [26]. Moreover, this study provides valuable insights into the scalability of the process by exploring optimal conditions for transesterification, such as oil-to-methanol ratio, reaction temperature, and catalyst concentration [26]. Understanding these parameters is crucial for scaling up production volumes while maintaining high biodiesel yields. Additionally, the study highlights reusability and recyclability of the catalyst, essential for cost-effective and sustainable biodiesel production on a larger scale [26]. However, challenges such as active site deactivation and catalyst effectiveness decline over multiple cycles should be addressed to ensure continuous efficiency in large-scale production. Furthermore, further investigation into morphological features and mechanical properties of the membrane used in membrane reactor is necessary to optimize its performance for industrial applications [26].

Next generation nanomaterial synthesis for biofuel advancements

Exploring cutting-edge innovations in biodiesel production, recent studies have illuminated promising avenues for sustainable and efficient methodologies. Gouda et al. [16] conducted a comprehensive study on the synthesis and characterization of a sulfonic acid functionalized metal–organic framework, UiO-66-SO_3H, aiming to assess its efficacy in oleic acid esterification to biodiesel [16]. The successful sulfonation of UiO-66 MOF resulted in UiO-66-SO_3H catalyst, with a 1.92 nm diameter (Figure 1(D)), exhibiting exceptional activity with a 98.30% conversion rate [16]. Optimized conditions, including a 20:1 methanol:oleic acid molar ratio, 8 wt% catalyst loading, 100 °C reaction temperature, and 1-h reaction time under microwave irradiation, contributed to this efficiency [16]. The UiO-66-SO_3H catalyst demonstrated commendable reusability over 5 consecutive cycles, positioning it as a promising and reusable option for sustainable biodiesel production [16]. However, to provide a broader perspective on the implications of these innovations, it's essential to compare efficacy of UiO-66-SO_3H with other conventional methods such as pyrolysis, ultrasonic, microwave, hydrodynamic cavitation and microfluidic reactors. Transesterification stands out as the most successful method in biodiesel production for several reasons. Firstly, it is the most commonly employed technique, benefiting from extensive study and optimization. Secondly, transesterification offers higher conversion rates and faster reaction times compared to alternative methods [27]. Additionally, it boasts flexibility in production, accommodating both catalytic and non-catalytic processes. Furthermore, transesterification enables the utilization of a wide range of feedstocks, including vegetable oils, waste cooking oils, and animal fats, rendering it a versatile and cost-effective approach for biodiesel production. These attributes collectively position transesterification as a preferred choice in biodiesel industry, ensuring its continued prominence amid emerging technologies.

In a related study, Cong et al. [28] focused on a green process co-producing biodiesel and hydrogen from waste oils using magnetic MOF-derived materials. The synthesis process of Na_2SiO_3/Ni-MOF catalysts is depicted in Figure 2(A), where steps (a), (b), and (c) illustrate initial preparation of Ni-MOF powders, loading of Ni-MOF powders with Na_2SiO_3 to form catalysts, and subsequent calcination process at varying temperatures, respectively. Notably, Na_2SiO_3/Ni-MOF-400 catalyst achieved a remarkable 98.4% yield from soybean oil and 94.5% (at sixth cycle) from spent bleaching clay oil under optimized conditions [28]. Stable and reusable performance with a 95% biodiesel yield after six cycles highlighted catalyst's efficacy. For hydrogen production, Ni-MOF-500 exhibited an impressive 126.8% yield from crude glycerol, with notable stability even after deactivation, emphasizing the effectiveness, stability, and reusability of Na_2SiO_3/Ni-MOF catalysts in co-producing biodiesel and hydrogen [28]. Furthermore, the long-term performance of co-producing biodiesel using magnetic MOF-derived materials was evaluated, demonstrating high activity and efficiency. Biodiesel yields reached 95.3%, while hydrogen yields reached 102.6% [28]. These nanoparticles were magnetically separable and could be recycled for multiple cycles, maintaining a biodiesel yield of 95%. Additionally, deactivated catalysts were repurposed for hydrothermal gasification, resulting

Figure 2



(A) A comprehensive workflow for fabrication of magnetic metal–organic framework (MOF)-supported base catalysts applied in biodiesel and hydrogen production. (B) Utilizing microalgae for the generation of biofuels; (a) Photosynthetic process of microalgae and (b) Their significance in the context of future renewable energy generation through carbon dioxide capture. (C) Implementation of graphene-based catalysts in biodiesel production process. (D) Application of nanomaterial stimulants in the production and utilization of biofuels. Edited with permission from Refs. [6,28,29,31,32], Copyright Elsevier ©2023 and ©2022.

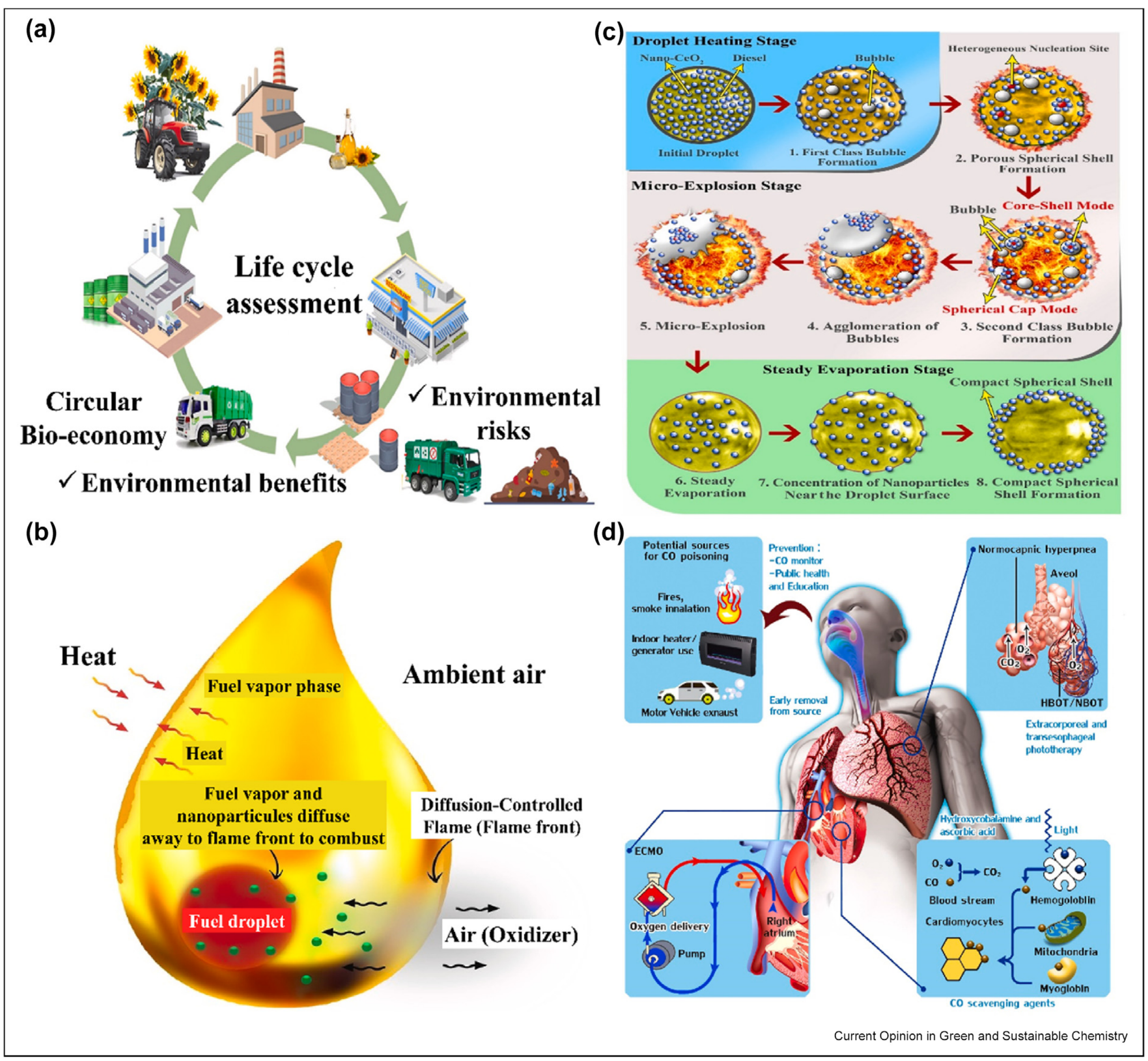
in a 50% increase in hydrogen yield [28]. This comprehensive evaluation showcases the effectiveness and recyclability of magnetic MOF-derived materials for co-producing biodiesel and hydrogen from waste oils, underlining their long-term performance and potential for sustainable energy production. Indeed, Figure 2(B) provides an insightful overview of microalgae's diverse contributions to biofuels generation. Panel (a) vividly illustrates how microalgae efficiently utilize sunlight, CO_2, and water in the process of photosynthesis, ultimately producing biofuels. This depiction emphasizes pivotal role of microalgae in renewable energy production. Meanwhile, panel (b) shines a light on another crucial aspect: microalgae's remarkable ability to capture CO_2, highlighting their dual significance in both biofuel production and carbon mitigation endeavors. Moving to Graphene-based catalysts (Figure 2(C)), known for their high efficiency in biodiesel production, exhibiting impressive transesterification/esterification yields, ranging from 84.6 to 99% [29]. Graphene oxide (GO) and sulfonated graphene oxide (SGO) emerge as particularly efficient catalysts for biodiesel production from wet microalgae biomass [29]. Despite their promising features, further research is imperative to explore full spectrum of recoverability, reusability, and enzyme support potential of graphene-based catalysts in biodiesel production under various conditions [30].

Environmental and economic significance

The integration of nanomaterials (Figure 2(D)) into biofuel production represents a transformative venture with dual-edged impacts [6], entwining both environmental and economic considerations (Figure 3(a)), as elucidated in Table 1. Nanomaterials leverage their unique properties to revolutionize biofuel production by enhancing substrate digestibility and increasing yields, thereby contributing to economic benefits through heightened efficiency and productivity [33]. Furthermore, nanotechnology offers tantalizing prospect of using non-edible feedstocks [34], reducing costs [35], and decreasing dependence on traditional food crops [36]. The significant surface-area-to-volume ratio and reactivity of nanoparticles play a pivotal role in amplifying biofuel production efficiency, underscoring their economic significance [34].

However, this promising landscape is marred by substantial technical challenges that must be overcome before nanotechnology in biofuel production achieves widespread commercialization. For instance, Figure 3(b) illustrates phenomenon of micro-explosion observed when fuel droplets containing cerium oxide (CeO_2)

Figure 3



(a) Evaluation of environmental impact throughout the life cycle of biodiesel production. (b) Flame diffusion in a fuel droplet with nanoparticles. (c) Inhalation consequences including CO's protective and harmful impacts. (d) Micro-explosion phenomenon induced by fuel-encapsulated CeO_2 nano-additives. Edited with permission from Refs. [31,37], Copyright Elsevier ©2022 and ©2023.

Table 1

Comprehensive assessment of environmental dimensions in nanomaterial-integrated biofuel production.

Critical aspect	Environmental implications	Positive aspects	Negative aspects	Reference
Corrosive effects	Nanoparticles in biodiesel fuels can cause damage to various parts of diesel engines. Continuous exposure to nanoparticle-laden fuels should be investigated.	Potential improvement in biofuel production efficiency	Risk of environmental impact	[38]
Engine performance and emissions	Long-term use of nanoparticle-doped biodiesel fuels can lead to deposits on engine components, impacting performance.	Improved fuel combustion efficiency may lead to reduced emissions	Potential harm to engine components and increased emissions	[39]
Toxicity	Concerns about toxic effects on organisms and ecosystems, particularly with carbon nanotubes and zinc oxide nanoparticles.	Improved efficiency in biofuel production may reduce overall environmental impact	Potential harm to aquatic organisms and ecosystems	[40]
Biodiversity	Potential changes in biodiversity due to widespread application of synthetic nanomaterials.	Increased yields in biofuel production may contribute to resource efficiency	Disruption of ecosystems	[41]
Environmental fate	Uncertainty about the fate of nanomaterials in environment, including bioaccumulation, persistence, and transport.	Potential improvement in biofuel production efficiency may offset environmental concerns	Risk of environmental impact	[42]
Manufacturing and disposal	Environmental implications in manufacturing process, energy-intensive methods, release of pollutants, and the need for proper disposal methods.	Enhanced substrate digestibility and increased biofuel yields may contribute to cleaner energy	Environmental pollution	[43]
Utilization of non-edible feedstocks	–	Reduced costs and dependence on traditional food crops	Initial investment challenges and technical obstacles	[44]
Investment and economic feasibility	Need for expertise and careful consideration of economic factors.	Potential economic benefits	Costs associated with research and development and potential market uncertainties	[45]

nano-additives are ignited [31]. The micro-explosion results from rapid vaporization of nanoparticles within fuel droplets, leading to efficient fuel atomization and improved combustion (Figure 3(c)). Overcoming these hurdles involves developing non-toxic and cost-effective nanoparticles while adapting chemical synthesis methods for biological nanoparticle synthesis. Addressing environmental concerns, particularly risk of releasing nanoparticles during biofuel production, is paramount for ensuring long-term sustainability [46]. Additionally, use of nanoparticles may have unknown effects on ecosystems and health impacts (Figure 3(d)), potentially contributing to environmental pollution if not properly managed [47]. Therefore, thorough research and assessments are crucial to understand potential risks and ensure the sustainable use of nanomaterials. Proper waste management and disposal strategies should be implemented to minimize any potential negative effects.

In assessing economic viability of investing nanotechnology into biofuel production, it's essential to weigh the cost-effectiveness of nanoparticle production against its potential benefits [36]. This involves analyzing not only expenses associated with nanoparticle synthesis, including raw materials and energy requirements but also considering enhanced catalytic activity and increased biofuel yield nanoparticles could offer. The variable cost of nanoparticles, ranging from £3−500 to £0.5−108 per kg [6], underscores the need for judicious evaluation of economic feasibility and cost-effectiveness in broader context of addressing global energy challenges. To ensure the long-term sustainability of biofuel production using nanoparticles, rigorous testing and evaluation of potential impacts on ecosystems and human health are essential, as well as adherence to regulatory guidelines and standards [48]. Collaboration between scientists, policymakers, and industry stakeholders is crucial to establish best practices for nanoparticle use in biofuel production and minimize environmental impact. Additionally, continuous research and innovation are necessary to improve the efficiency and effectiveness of nanoparticle-based biofuel production, thereby maximizing sustainability and minimizing environmental impact.

Conclusion

The integration of nanomaterials into biofuel production holds immense promise for efficiency, transforming the industry by enhancing efficiency, productivity, and sustainability. Across various biofuel production processes, significant advancements have been achieved with diverse nanomaterial catalysts, showcasing their potential. Innovative methodologies, such as green synthesis and hydrothermal-assisted carbonization, underscore ongoing exploration of sustainable approaches. Notably, studies exploring hydrothermal-assisted carbonization, particularly with metal-based catalysts like zinc chloride and iron (III) chloride, resulted in an impressive biodiesel yield of 96.4%, highlighting the method's effectiveness in achieving sustainable and commercially viable biofuel production. Moreover, the integration of gold nanoparticles in biomass hydrolysis yielded substantial ethanol outputs of 45.09% and 50.1%, emphasizing cost-effectiveness and efficiency of this approach. The transformative role of nanomaterials in enhancing engine characteristics and combustion performance underscores their positive impact on biofuels landscape. However, challenges such as technical hurdles, environmental concerns, and economic considerations must be addressed for widespread commercialization. Industry stakeholders and researchers play a pivotal role in overcoming these challenges. Collaborative efforts are essential to identify cost-effective solutions, prioritize sustainable practices, and drive innovation in research and development. By pooling expertise and resources, stakeholders can navigate technical complexities and optimize processes for nanomaterial integration. Moreover, fostering collaboration ensures that sustainability remains a core focus, mitigating environmental impacts and promoting responsible use of resources throughout biofuel production lifecycle. Through concerted efforts, industry can overcome barriers and ensure the successful integration of nanomaterials into biofuel production. This collective endeavour paves the way for a more efficient and sustainable energy future, where nanotechnology contributes significantly to meeting global energy demands while minimizing environmental footprint. This review positions itself at the forefront of current progress, offering valuable insights into evolving landscape of nanomaterial applications in biofuels.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Acknowledgement

The authors are thankful for financial support from the International Society of Engineering Science and Technology (ISEST) UK.

References

[1]. Jayaprabakar J, Sri Hari NS, Badreenath M, Anish M, Joy N, Prabhu A, Rajasimman M, Kumar JA: **Nano materials for green hydrogen production: technical insights on nano material selection, properties, production routes and commercial applications**. *Int J Hydrogen Energy* 2023, **52**:674–686. https://doi.org/10.1016/j.ijhydene.2023.06.109.

This paper examines how nanomaterials contribute to hydrogen production, storage, and commercial applications, offering insights to enhance green hydrogen synthesis and future research directions.

[2]. Ye J, Lu J, Wen D: **Engineering carbon nanomaterials toward high-efficiency bioelectrocatalysis for enzymatic biofuel cells: a review**. *Mater Chem Front* 2023. https://doi.org/10.1039/D3QM00615H.

This paper discusses the use of carbon nanomaterials to improve enzymatic biofuel cell (EBFC) efficiency, exploring strategies like morphological regulation and surface functionalization to enhance performance and address practical challenges.

[3]. Ethiraj J, Wagh D, Manyar H: **Advances in upgrading biomass to biofuels and oxygenated fuel additives using metal oxide catalysts**. *Energy Fuels* 2022, **36**:1189–1204. https://doi.org/10.1021/acs.energyfuels.1c03346.

This paper explores how metal oxide catalysts are utilized in synthesizing biomass-derived oxygenated fuel additives, optimizing their catalytic activity for various organic transformations in biorefinery processes.

[4]. Cheruvathoor Poulose A, Medveď M, Bakuru VR, Sharma A, Singh D, Kalidindi SB, Bares H, Otyepka M, Jayaramulu K, Bakandritsos A: **Acidic graphene organocatalyst for the superior transformation of wastes into high-added-value chemicals**. *Nat Commun* 2023, **14**:1373. https://doi.org/10.1038/s41467-023-36602-0.

This study introduces a graphene catalyst (G-ASA) functionalized with taurine for converting glycerol to high-value chemicals, including biodiesel, surpassing industrial catalysts and demonstrating potential for circular carbon economy applications.

[5]. Almomani F, Hosseinzadeh-Bandbafha H, Aghbashlo M, Omar A, Joo S-W, Vasseghian Y, Karimi-Maleh H, Lam SS, Tabatabaei M, Rezania S: **Comprehensive insights into conversion of microalgae to feed, food, and biofuels: current status and key challenges towards implementation of sustainable biorefineries**. *Chem. Eng. J.* 2023, **455**, 140588. https://doi.org/10.1016/j.cej.2022.140588.

This review underscores microalgae's biofuel potential using nutrient-rich wastewater, addressing conversion pathways and biomass harvesting techniques, urging future research to enhance yield, quality, and economic viability.

[6]. Ahmed SF, Debnath JC, Mehejabin F, Islam N, Tripura R, Mofijur M, Hoang AT, Rasul MG, Vo D-VN: **Utilization of nanomaterials in accelerating the production process of sustainable biofuels**. *Sustain Energy Technol Assessments* 2023, **55**, 102894. https://doi.org/10.1016/j.seta.2022.102894.

This study reviews how nanotechnology can improve biofuel production from non-edible sources, emphasizing factors affecting nanomaterial performance, cost-effectiveness, toxicity concerns, and future research needs.

[7]. Javed F, Zimmerman WB, Fazal T, Hafeez A, Mustafa M, Rashid N, Rehman F: **Green synthesis of biodiesel from microalgae cultivated in industrial wastewater via microbubble induced esterification using bio-MOF-based heterogeneous catalyst**. *Chem Eng Res Des* 2023, **189**:707–720. https://doi.org/10.1016/j.cherd.2022.12.004.
This study introduces a new catalyst, [HMIM][HSO4]/Bio-MOF, enhancing biodiesel production from microalgae oil with improved reactivity and conversion. Its stability over cycles and lower energy requirements highlights its potential for sustainable biofuel synthesis.

[8]. Yuan X, Cao Y, Li J, Patel AK, Dong C-D, Jin X, Gu C, Yip ACK, Tsang DCW, Ok YS: **Recent advancements and challenges in emerging applications of biochar-based catalysts**. *Biotechnol Adv* 2023, 108181. https://doi.org/10.1016/j.biotechadv.2023.108181.
This review emphasizes biochar-based catalysts' role in promoting carbon neutrality and circular economy through biomass waste utilization. It discusses synthesis routes, catalytic performance, and machine learning predictions for sustainable biorefineries and environmental protection, aiming to meet United Nations goals.

[9]. Sher F, Ziani I, Smith M, Chugreeva G, Hashimzada SZ, Prola LDT, Sulejmanović J, Sher EK: **Carbon quantum dots conjugated with metal hybrid nanoparticles as advanced electrocatalyst for energy applications–A review**. *Coord Chem Rev* 2024, **500**, 215499. https://doi.org/10.1016/j.ccr.2023.215499.
Nanomaterial advances suggest carbon quantum dots' (CQDs) potential as water-splitting electrocatalysts, with studies hinting at enhanced commercial applications through CQD/metal alloy nanoparticle conjugation, pending validation.

[10]. Ahranjani PJ, Saei SF, El-Hiti GA, Yadav KK, Cho J, Rezania S: **Magnetic carbon nanotubes doped cadmium oxide as heterogeneous catalyst for biodiesel from waste cooking oil**. *Chem Eng Res Des* 2024, **201**:176–184. https://doi.org/10.1016/j.cherd.2023.11.059.
This study introduces a novel nanocatalyst, MCNT@CdO, for efficient biodiesel production from Waste Cooking Oil (WCO), demonstrating high catalytic efficiency (>92%) under optimized conditions.

[11]. Rajpoot AS, Choudhary T, Chelladurai H, Verma TN, Pugazhendhi A: **Sustainability analysis of spirulina biodiesel and their bends on a diesel engine with energy, exergy and emission (3E's) parameters**. *Fuel* 2023, **349**, 128637. https://doi.org/10.1016/j.fuel.2023.128637.
This study supports spirulina microalgae biodiesel as a sustainable diesel alternative, showing significant emission reductions and comparable energy efficiency, promoting its broader use in sustainable energy solutions.

[12]. Diao Y, Gong X, Xu D, Duan P, Wang S, Guo Y: **From culture, harvest to pretreatment of microalgae and its high-value utilization**. *Algal Res* 2024, **78**, 103405. https://doi.org/10.1016/j.algal.2024.103405.
This study optimizes microalgae-based biomass fuel production by exploring high-value utilization and refining processing techniques, enhancing both environmental and economic sustainability.

[13]. Lin D, Mao Z, Shang J, Zhu H, Liu T, Wu Y, Li HZ, Peng C, Feng X: **Catalyst design strategies for deoxygenation of vegetable oils to produce second-generation biodiesel**. *Ind Eng Chem Res* 2023, **62**:12462–12481. https://doi.org/10.1021/acs.iecr.3c01542.
This review emphasizes catalyst design strategies for efficient deoxygenation of vegetable oils, crucial for second-generation biodiesel production, offering insights into fundamental mechanisms to guide catalyst synthesis and industrialization processes.

[14]. Srivastava N, Singh R, Srivastava M, Mohammad A, Harakeh S, Singh RP, Pal DB, Haque S, Tayeb HH, Moulay M: **Impact of nanomaterials on sustainable pretreatment of lignocellulosic biomass for biofuels production: an advanced approach**. *Bioresour Technol* 2023, **369**, 128471. https://doi.org/10.1016/j.biortech.2022.128471.
This review explores how nanomaterials can address challenges in pretreatment processes for lignocellulosic biomass (LCBs) in biofuels production, focusing on magnetic, carbon-based nanostructures, and nanophotocatalysts to enhance efficiency and sustainability.

[15]. Jegan CD, Selvakumaran T, Karthe M, Hemachandu P, Gopinathan R, Sathish T, Ağbulut Ü: **Influences of various metal oxide-based nanosized particles-added algae biodiesel on engine characteristics**. *Energy* 2023, **284**, 128633. https://doi.org/10.1016/j.energy.2023.128633.
This investigation improves algae oil biodiesel with nano fuel technology, incorporating CeO2, SiO2, and TiO2 nanoparticles. Characterized nano fuels like B25TiO2 enhance diesel engine performance, reducing emissions and improving efficiency compared to conventional diesel fuel.

[16]. Gouda SP, Ngaosuwan K, Assabumrungrat S, Selvaraj M, Halder G, Rokhum SL: **Microwave assisted biodiesel production using sulfonic acid-functionalized metal-organic frameworks UiO-66 as a heterogeneous catalyst**. *Renew Energy* 2022, **197**:161–169. https://doi.org/10.1016/j.renene.2022.07.061.
This study is pivotal for biodiesel production, highlighting the effectiveness of sulfonated UiO-66 catalyst under microwave irradiation in converting oleic acid to methyl oleate, thus promoting sustainable energy practices.

[17]. Srivastava N, Singh R, Srivastava M, Mohammad A, Harakeh S, Pratap Singh R, Pal DB, Haque S, Tayeb HH, Moulay M, Kumar Gupta V: **Impact of nanomaterials on sustainable pretreatment of lignocellulosic biomass for biofuels production: an advanced approach**. *Bioresour Technol* 2023, **369**, 128471. https://doi.org/10.1016/j.biortech.2022.128471.
This paper highlights lignocellulosic biomass (LCB) for energy production via anaerobic digestion (AD) with carbon capture, reviewing recent pretreatment methods for methane production, providing insights for sustainable AD systems.

[18]. Kim JK, Kim S, Kim S, Kim HJ, Kim K, Jung W, Han JW: **Dynamic surface evolution of metal oxides for autonomous adaptation to catalytic reaction environments**. *Adv. Mater.* 2023, **35**, 2203370. https://doi.org/10.1002/adma.202203370.
This review explores how metal oxides undergo dynamic surface reorganization during reactions, shedding light on their influence on catalytic material activity and stability, pivotal for advanced heterogeneous catalysis design.

[19]. Sahu S, Kaur A, Singh G, Arya SK: **Harnessing the potential of microalgae-bacteria interaction for eco-friendly wastewater treatment: a review on new strategies involving machine learning and artificial intelligence**. *J. Environ. Manage.* 2023, **346**, 119004. https://doi.org/10.1016/j.jenvman.2023.119004.
This analysis underscores the transformative role of artificial intelligence and machine learning in optimizing processes for microalgae-bacteria symbiosis, advancing wastewater treatment and biomass production towards sustainable solutions.

[20]. Qamar OA, Jamil F, Hussain M, Bae S, Inayat A, Shah NS, Waris A, Akhter P, Kwon EE, Park Y-K: **Advances in synthesis of TiO2 nanoparticles and their application to biodiesel production: a review**. *Chem. Eng. J.* 2023, **460**, 141734. https://doi.org/10.1016/j.cej.2023.141734.
This review promotes green synthesis of TiO2 nanoparticles (NPs) using microorganisms and plants to mitigate environmental and health concerns. It underscores TiO2 NPs' role as biodiesel catalysts, urging their adoption to address economic and environmental challenges.

[21]. Kanakaraju D, Chandrasekaran A: **Recent advances in TiO2/ZnS-based binary and ternary photocatalysts for the degradation of organic pollutants**. *Sci Total Environ* 2023, **868**, 161525. https://doi.org/10.1016/j.scitotenv.2023.161525.
This review explores enhancing photoefficiency for organic pollutant degradation in wastewater treatment via binary TiO2/ZnS and modified ternary photocatalysts (TiO2/ZnS-X), suggesting further research avenues

[22]. Alagumalai A, Devarajan B, Song H: **Unlocking the potential of catalysts in thermochemical energy conversion processes**. *Catal Sci Technol* 2023. https://doi.org/10.1039/D3CY00848G.
This review emphasizes catalysts' crucial role in thermochemical energy conversion processes and recent advancements in the field, offering insights for energy sector professionals and researchers.

[23]. Aarti C, Khusro A, Agastian P, Kuppusamy P, Al Farraj DA: **Synthesis of gold nanoparticles using bacterial cellulase and its role in saccharification and bioethanol production from aquatic weeds**. *J King Saud Univ* 2022, **34**, 101974. https://doi.org/10.1016/j.jksus.2022.101974.

The paper investigates the efficacy of gold nanoparticles synthesized with cellulase in saccharifying pre-treated aquatic weeds biomass for bioethanol production, suggesting a cost-effective approach for biofuel generation.

[24]. Gupta D, Thakur A, Gupta TK: **Green and sustainable synthesis of nanomaterials: recent advancements and limitations**. *Environ Res* 2023, 116316. https://doi.org/10.1016/j.envres.2023.116316.
This review underscores the significance of environmentally friendly green synthesis of nanoparticles, using natural reagents to produce materials with diverse applications, advocating for its pivotal role in promoting sustainable development across industries.

[25]. Ali HEA, El-fayoumy EA, Soliman RM, Elkhatat A, Al-Meer S, Elsaid K, Hussein HA, Rozaini MZH, Abdullah MA: **Nanoparticle applications in Algal-biorefinery for biofuel production**. *Renew Sustain Energy Rev* 2024, **192**, 114267. https://doi.org/10.1016/j.rser.2023.114267.
This review highlights multifunctional nanoparticles' role in advancing algal-based biofuels' commercial viability while addressing challenges and future trends.

[26]. Alsaiari M, Ahmad M, Munir M, Zafar M, Sultana S, Dawood S, Almohana AI, Mh A-MH, Alharbi AF, Ahmad Z: **Efficient application of newly synthesized green Bi2O3 nanoparticles for sustainable biodiesel production via membrane reactor**. *Chemosphere* 2023, **310**, 136838. https://doi.org/10.1016/j.chemosphere.2022.136838.
This study introduces green bismuth oxide nanoparticles synthesized from Euphorbia royealeana leaves for efficient biofuel production from *Cannabis sativa* seed oil, yielding 92% FAMEs under optimized conditions, affirming their potential for large-scale biodiesel production.

[27]. Das A, Li H, Kataki R, Agrawal PS, Moyon NS, Gurunathan B, Rokhum SL: **Terminalia arjuna bark–A highly efficient renewable heterogeneous base catalyst for biodiesel production**. *Renew Energy* 2023, **212**:185–196. https://doi.org/10.1016/j.renene.2023.05.066.
This study highlights TABCA's efficacy as a renewable alkaline catalyst for soybean oil biodiesel synthesis under microwave irradiation, ensuring high yields meeting engine standards.

[28]. jie Cong W, Yang J, Zhang J, Fang Z, diao Miao Z: **A green process for biodiesel and hydrogen coproduction from waste oils with a magnetic metal-organic framework derived material**. *Biomass Bioenergy* 2023, **175**, 106871. https://doi.org/10.1016/j.biombioe.2023.106871.
This paper highlights the potential of magnetic self-assembly metal–organic frameworks (MOFs) for simultaneous biodiesel and hydrogen production from waste oils, offering a sustainable pathway for biofuel synthesis.

[29]. Nazloo EK, Moheimani NR, Ennaceri H: **Graphene-based catalysts for biodiesel production: characteristics and performance**. *Sci Total Environ* 2023, **859**, 160000. https://doi.org/10.1016/j.scitotenv.2022.160000.
This paper examines the potential of graphene-based nano-catalysts for biodiesel production, particularly from wet microalgae, offering insights into their efficiency, recoverability, and economic viability as sustainable alternatives to conventional methods.

[30]. Pan H, Xia Q, Wang Y, Shen Z, Huang H, Ge Z, Li X, He J, Wang X, Li L: **Recent advances in biodiesel production using functional carbon materials as acid/base catalysts**. *Fuel Process Technol* 2022, **237**, 107421. https://doi.org/10.1016/j.fuproc.2022.107421.
This review summarizes recent advances in using carbon-based catalysts to convert renewable oil into biodiesel, covering feedstocks, synthesis methods, catalytic activities, and catalyst reusability, offering insights for future research

[31]. Hosseinzadeh-Bandbafha H, Panahi HKS, Dehhaghi M, Orooji Y, Shahbeik H, Mahian O, Karimi-Maleh H, Kalam MA, Jouzani GS, Mei C, Kazemi Shariat Panahi H, Dehhaghi M, Orooji Y, Shahbeik H, Mahian O, Karimi-Maleh H, Kalam MA, Salehi Jouzani G, Mei C, Nizami AS, Guillemin GG, Gupta VK, Lam SS, Yang Y, Peng W, Pan J, Kim KH, Aghbashlo M, Tabatabaei M: **Applications of nanotechnology in biodiesel combustion and post-combustion stages**. *Renew Sustain Energy Rev* 2023, **182**, 113414. https://doi.org/10.1016/j.rser.2023.113414.
The paper discusses how nanotechnology can enhance biodiesel combustion efficiency and reduce emissions, while also highlighting challenges such as toxicity, cost, and standardization that need to be addressed for safe and effective nanoparticle integration.

[32]. Ali SS, Mastropetros SG, Schagerl M, Sakarika M, Elsamahy T, El-Sheekh M, Sun J, Kornaros M: **Recent advances in wastewater microalgae-based biofuels production: a state-of-the-art review**. *Energy Rep* 2022, **8**:13253–13280. https://doi.org/10.1016/j.egyr.2022.09.143.
The integration of microalgae processes for wastewater treatment and biofuel production offers practical and cost-effective solutions, promising economic and environmental benefits.

[33]. Mohamed EA, Betiha MA, Negm NA: **Insight into the recent advances in sustainable biodiesel production by catalytic conversion of vegetable oils: current trends, challenges, and prospects**. *Energy Fuels* 2023, **37**:2631–2647. https://doi.org/10.1021/acs.energyfuels.2c03887.
Recent advances in creating efficient, low-cost heterogeneous catalysts for biodiesel production have focused on seven types of catalysts, offering high efficiency and low production costs, contributing to more applicable, effective, and eco-friendly biofuel production.

[34]. Khan S, Ul-Islam M, Ahmad MW, Khan MS, Imran M, Siyal SH, Javed MS: **Synthetic methodologies and energy storage/conversion applications of porous carbon nanosheets: a systematic review**. *Energy Fuels* 2022, **36**:3420–3442. https://doi.org/10.1021/acs.energyfuels.2c00077.
Research on 2D porous carbon materials, especially 2D PCNS, focuses on their unique properties and applications in energy storage and catalysis. This review covers synthetic methods, porous morphologies, applications in energy devices, and future prospects

[35]. Gu C, Gai P, Li F: **Construction of biofuel cells-based self-powered biosensors via design of nanocatalytic system**. *Nano Energy* 2022, **93**, 106806. https://doi.org/10.1016/j.nanoen.2021.106806.
Research focuses on improving BFC stability and output using novel nanomaterials and strategies.

[36]. Vickram S, Manikandan S, Deena SR, Mundike J, Subbaiya R, Karmegam N, Jones S, Yadav KK, woong Chang S, Ravindran B: **Advanced biofuel production, policy and technological implementation of nano-additives for sustainable environmental management–A critical review**. *Bioresour Technol* 2023, **387**, 129660. https://doi.org/10.1016/j.biortech.2023.129660.
This review examines advanced biofuel production methods for sustainability and environmental impact reduction, highlighting the integration of technologies like nanotechnology and enzymatic processes to enhance productivity and environmental performance, fostering a greener future.

[37]. Hosseinzadeh-Bandbafha H, Nizami A-S, Kalogirou SA, Gupta VK, Park Y-K, Fallahi A, Sulaiman A, Ranjbari M, Rahnama H, Aghbashlo M: **Environmental life cycle assessment of biodiesel production from waste cooking oil: a systematic review**. *Renew Sustain Energy Rev* 2022, **161**, 112411. https://doi.org/10.1016/j.rser.2022.112411.
This review discusses using waste cooking oil (WCO) for biodiesel production and highlights the importance of advanced environmental assessment tools like life cycle assessment (LCA) to optimize processes and address uncertainties.

[38]. Gad MS, Ağbulut Ü, Afzal A, Panchal H, Jayaraj S, Qasem NAA, El-Shafay AS: **A comprehensive review on the usage of the nano-sized particles along with diesel/biofuel blends and their impacts on engine behaviors**. *Fuel* 2023, **339**, 127364. https://doi.org/10.1016/j.fuel.2022.127364.
This review explores the potential of nanoparticle additives in improving the properties and performance of biodiesel fuels, addressing challenges such as poor atomization and high emissions associated with their use in diesel engines.

[39]. Ramalingam S, Babu MN, Devarajan Y, Babu MD, Varuvel EG: **Environmental and energy valuation of waste-derived Cymbopogon Martinii Methyl Ester combined with multi-walled carbon (MWCNTs) additives in hydrogen-enriched dual fuel engine**. *Int J Hydrogen Energy* 2023, **48**:39641–39657. https://doi.org/10.1016/j.ijhydene.2023.08.006.
This study investigates the impact of hydrogen enrichment and multi-walled multi-additive nanotubes (MWCNT) on dual-fuel engine performance, demonstrating improved combustion and reduced emissions

with hydrogen addition, and enhanced efficiency with MWCNT blending.

[40]. El-Kady MM, Ansari I, Arora C, Rai N, Soni S, Verma DK, Singh P, Mahmoud AED: **Nanomaterials: a comprehensive review of applications, toxicity, impact, and fate to environment**. *J Mol Liq* 2023, **370**, 121046. https://doi.org/10.1016/j.molliq.2022.121046.
This review evaluates the applications and potential risks of nanomaterials, stressing the importance of safe nanotechnology for sustainable development.

[41]. Okeke ES, Olisah C, Malloum A, Adegoke KA, Ighalo JO, Conradie J, Ohoro CR, Amaku JF, Oyedotun KO, Maxakato NW, Akpomie KG: **Ecotoxicological impact of dinotefuran insecticide and its metabolites on non-targets in agroecosystem: harnessing nanotechnology-and bio-based management strategies to reduce its impact on non-target ecosystems**. *Environ Res* 2023, **243**, 117870. https://doi.org/10.1016/j.envres.2023.117870.
This review discusses neonicotinoid insecticides, focusing on dinotefuran, their widespread use, ecological impacts, and potential mitigation strategies, suggesting future research directions for responsible application.

[42]. Mofijur M, Hasan MM, Ahmed SF, Djavanroodi F, Fattah IMR, Silitonga AS, Kalam MA, Zhou JL, Khan TMY: **Advances in identifying and managing emerging contaminants in aquatic ecosystems: analytical approaches, toxicity assessment, transformation pathways, environmental fate, and remediation strategies**. *Environ. Pollut.* 2023, 122889. https://doi.org/10.1016/j.envpol.2023.122889.
This review examines advanced analytical methods, like mass spectrometry, for detecting emerging contaminants (ECs) and understanding their environmental impact. It emphasizes the need for proactive monitoring and policy development to manage ECs effectively.

[43]. Arias DM, García-Valladares O, Besagni G, Markides CN: **A vision of renewable thermal technologies for drying, biofuels production and industrial waste, gas or water recovery**. *Appl Therm Eng* 2023, **223**, 120022. https://doi.org/10.1016/j.applthermaleng.2023.120022.
This review highlights thermal technologies' role in renewable energy, emphasizing solar drying, waste heat recovery, and biomass conversion, aiming to address cost and environmental challenges while promoting sustainability.

[44]. Sudalai S, Rupesh KJ, Devanesan MG, Arumugam A: **A critical review of Madhuca indica as an efficient biodiesel producer: towards sustainability**. *Renew Sustain Energy Rev* 2023, **188**, 113811. https://doi.org/10.1016/j.rser.2023.113811.
This review outlines its production, properties, and economic potential.

[45]. Acaroğlu H, Márquez FPG: **Economic viability assessments of high voltage direct current for wind energy systems**. *Sustain Energy Technol Assessments* 2023, **56**, 102948. https://doi.org/10.1016/j.seta.2022.102948.
This study evaluates the economic viability of HVDC technology for wind energy transmission in Turkey, focusing on a 1000 km line between Canakkale and Samsun-Bafra, employing life-cycle cost scenarios and cash flow analysis to assess profitability with government subsidies.

[46]. Wang L, Gopalan S, Naidu R: **Advancements in nanotechnological approaches to VOC detection and separation**. *Curr. Opin. Environ. Sci. Heal.* 2023, 100528. https://doi.org/10.1016/j.coesh.2023.100528.
This review discusses gas sensing advancements and challenges, emphasizing nanotechnology integration and future perspectives on efficient regeneration techniques and addressing biocompatibility concerns.

[47]. Kazemi Shariat Panahi H, Hosseinzadeh-Bandbafha H, Dehhaghi M, Orooji Y, Mahian O, Shahbeik H, Kiehbadroudinezhad M, Kalam MA, Karimi-Maleh H, Salehi Jouzani G, Mei C, Guillemin GG, Nizami A-S, Wang Y, Gupta VK, Lam SS, Pan J, Kim K-H, Peng W, Aghbashlo M, Tabatabaei M, Panahi HKS, Hosseinzadeh-Bandbafha H, Dehhaghi M, Orooji Y, Mahian O, Shahbeik H, Kiehbadroudinezhad M, Kalam MA, Karimi-Maleh H, Jouzani GS: **Nanotechnology applications in biodiesel processing and production: a comprehensive review**. *Renew Sustain Energy Rev* 2024, **192**, 114219. https://doi.org/10.1016/j.rser.2023.114219.
This review underscores biodiesel's potential as a sustainable alternative to fossil diesel, particularly through transesterification with nanocatalysts, which offer improved efficiency and environmental benefits, yet safety concerns necessitate further exploration.

[48]. Feder-Kubis J, Wirwis A, Policht M, Singh J, Kim K-H: **Principles and practice of greener ionic liquid−nanoparticles biosystem**. *Green Chem* 2024. https://doi.org/10.1039/D3GC04387H.
This review highlights the key role of ionic liquids (ILs) in synthesizing precise nanoparticles (NPs), aligning with green chemistry principles and advancing biotechnology and biomedicine.