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Recent Advances in ZnO Nanoparticle-Enhanced Neem Biodiesel: A Review of Its Interfacial Properties

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ABSTRACT

Due to the growing demand in sustainable energy sources, the neem biodiesel has been seen as a promising nonedible alternative to conventional petroleum diesel. This review examined recent advances in the application of ZnO nanoparticles for enhancing the interfacial properties of neem biodiesel. The reviewed literature demonstrates that nanoparticle incorporation has considerable potential to improve key fuel properties, including viscosity, flow behaviour, spray atomization and interfacial stability thereby enhancing biodiesel performance in energy and industrial applications. The review further revealed that, although numerous studies have investigated the use of metal oxide nanoparticle such as, ZnO TiO_2, $Al2O_3$, CeO_2, SiO_2, and CuO as catalysts and fuel additives, research specifically focusing on ZnO nanoparticle remains limited. Existing studies primarily emphasize biodiesel production, engine performance, and emission characteristics, while comparatively little attention has been given to understanding how ZnO nanoparticle influence the interfacial physics, and long team dispersion stability of neem biodiesel. These knowledge gaps restrict the wider adoption of nanoparticle enhanced biodiesel in advanced applications where physiochemical stability is essential.

Keywords: Interfacial properties, ZnO Nanoparticles, Neem Biodiesel, Neem Oil

1.0 INTRODUCTION

The global shift toward cleaner and more sustainable energy sources has placed biodiesel at the forefront of renewable fuel research (El-Araby, 2024). Unlike fossil fuels, biodiesel offers the advantages of biodegradability, lower emissions, and reduced environmental impact, making it an attractive option for energy and industrial applications (Neuphane 2023). Among the various non-edible oil feedstocks available in developing regions, neem (*Azadirachta indica*) oil stands out due to its abundance, affordability, and favourable chemical composition (Hamadou *et al.,* 2020). These attributes make it a promising candidate for the production of environmentally friendly biodiesel.

Biodiesel, derived from renewable feedstocks, has emerged as a promising substitute for conventional diesel (Perumal 2024). Among various biodiesel sources, neem oil, a non-edible and abundantly available feedstock offers significant potential due to its high yield and minimal competition with food crops (Fadairo *et al.,* 2024).

The growing concern over depleting fossil fuel reserves and escalating environmental pollution has accelerated the search for sustainable and eco-friendly alternatives (Hassan *et al.,* 2023). The rapid depletion of fossil fuel sources due to an increase in global energy demand has promoted the need for alternative resources (Esan *et al.,* 2020). However, the alternative fuel should be renewable, economically feasible, readily available, and have fewer environmental problems than conventional fuels (Maryam *et al.,* 2022). Fossil fuels are still produced today by subterranean heat and pressure; they are consumed faster than they are produced. Insufficient quantities or high cost of petroleum are major concerns, while renewable energy offers a promising alternative because it is clean and environmentally friendly (Zheng *et al.,* 2020).

The main advantage for biodiesel production is the availability of unlimited feedstocks (Hanif *et al.,* 2022). The most significant features of ideal feedstocks are high yield and low production cost (Callegari *et al.,* 2020). In the biodiesel industry, selection of raw material is very important, as 80% cost of biodiesel is associated with feedstock cost (Mhetras and Gokhale, 2025). Biofuel can be produced from edible feedstocks (like corn, rapeseed, palm oil and soybean) and non-edible feedstocks (like Karanja oil, Jatropha, and Mahua) (Lee *et al.,* 2020). The edible plants as feedstocks compete with human food, freshwater and require large areas of fertile lands (Abreu *et al.,* 2022). The production cost increases up to 70–92% due to increase in the cost of edible oils (Xue *et al.,* 2021). Therefore, low-cost waste oils have been receiving more attention for biodiesel production as an appropriate candidate to replace diesel fuel in recent times.

Due to its ready availability, 95% of biodiesel production comes from food sources only (Farouk, *et al.,* 2024). Poor planning on food resources reduces food spending and creates economic inequalities (Fanzo *et al.,* 2024). The high cost of raw materials, dependence on food prices, fertile land expropriation,

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deforestation, and sensitivity of edible plants to environmental conditions make biodiesel production from edible plants ultimately ineffective (Okpo *et al.,* 2025). In addition, there are extreme differences in feedstock sources, such as chicken fats, soybean oil, corn oil, and forest residues (Ahmed *et al.,* 2023). With increasing food restrictions, non-edible oil sources are the best alternative for the production of biofuels (Shaah *et al.,* 2022). The use of non-edible oils as feedstocks for biofuels can also reduce the market price of biodiesel (Roick *et al.,* 2021). To reduce the cost of production of biodiesel, researchers have also investigated macro- and micro-algae oils as feedstocks due to their huge biomass and rapid growth (Arshad *et al.,* 2023).

1.1 Background of the Study

The increasing global demand for sustainable and renewable energy solutions has intensified scientific interest in biodiesel as an alternative to petroleum-based fuels (Rajendran *et al.,* 2025). Neem oil has been widely recognized for its favourable fatty acid profile, biodegradability, and large-scale availability in many tropical regions (Ismaila *et al.,* 2022). These characteristics position neem biodiesel as a viable candidate for both energy generation and industrial applications (Shadi & Majid 2024). Biodiesel which is renewable and nontoxic, is usually derived from sustainable bioenergy sources, such as animal fats, edible and inedible sources of urban waste, and oil seed crops (Al-Muhtaseb *et al.,* 2022; Chuah *et al.,* 2022).

In the ideal scenario, biodiesel should possess interfacial properties that maximize its performance in combustion systems, such as a moderate viscosity to facilitate fluid flow and a low interfacial tension to promote atomization and prevent phase separation (Chen *et al.,* 2022). Moreover, colloidal stability is crucial for maintaining these properties over time and under varying operating conditions (Masudi *et al.,* 2023).

However, despite the aforementioned advantages, neem biodiesel still faces several challenges that limit its performance and broader utilization (Chhabra *et al.,* 2021). Key limitations stem from its fluid dynamics and spray behavior, where low interfacial stability reduces its suitability for advanced applications, particularly in high-voltage insulation systems, where stable dielectric and interfacial behaviour are crucial (Saleem and Akbar, 2022). Studies have reported that neem biodiesel typically exhibits higher viscosity, affecting its flow behaviour, and moderate oxidative stability, limiting its long-term performance (Rafiq *et al.,* 2020). These limitations are particularly critical in high-voltage insulation applications, where dielectric fluids must maintain stable interfacial behaviour under electrical stress. Studies have shown that its kinematic viscosity remains relatively high, posing challenges for injection and spray atomization (Chaudhari *et al.,* 2021). The density of neem biodiesel has also been measured to be slightly higher than petroleum diesel (Eberechi and Akhihiero, 2025), while its physicochemical properties (moisture content and free fatty acid content) can vary depending on seed origin (Zuhane *et al.,* 2025). These limitations create the need for scientific interventions that can enhance the interfacial properties of neem biodiesel without compromising its sustainability.

Nanotechnology has recently emerged as a powerful tool capable of addressing these challenges. Incorporating nanoparticles into biodiesel has shown promising improvements in fuel behaviour, surface interaction dynamics, and physicochemical stability (Hassan *et al.,* 2023).

To address these challenges, researchers have turned to nanofluid technology, which involves dispersing nanoparticles into base fluids to enhance their interfacial and physicochemical characteristics. Several investigations have demonstrated that nanoparticle doping can significantly improve biodiesel's viscosity, surface tension, and dielectric strength (Elkelawy *et al.,* 2023).

In particular, zinc oxide (ZnO) nanoparticles are attracting increasing attention because of their high surface energy and chemical stability (Raha and Ahmaruzzaman, 2022). Their interaction with the molecular structure of biodiesel can significantly influence interfacial dynamics, potentially improving critical properties such as viscosity, spray characteristics, and dielectric performance (Farade *et al.,* 2023). Among the various metal oxide nanoparticles studied, ZnO nanoparticles stand out due to their chemical inertness and high surface energy, which enable strong interactions with biodiesel molecules (Soudagar *et al.,* 2020). When dispersed in biodiesel, ZnO_2 nanoparticles can modify interfacial interactions and reduce molecular resistance, leading to measurable improvements in both interfacial and dielectric properties. Various strategies have been employed to improve biodiesel performance, including blending with alcohols, using surfactants, and introducing nanoparticle additives. Among these, ZnO nanoparticles show particular promise. El-Adawy (2023) demonstrated that adding ZnO to a biodiesel blend improved brake mean effective pressure (BMEP) and decreased specific fuel consumption in a CI engine.

Despite these advances, a significant gap remains. Specifically, there is insufficient mechanistic understanding of how ZnO nanoparticles modify the interfacial physics (e.g., surface and interfacial tension, wetting behaviour) of neem biodiesel. Furthermore, long-term stability (dispersion, agglomeration,

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sedimentation) under realistic conditions has not been comprehensively studied.

This research seeks to close this gap by systematically investigating the effects of varying concentrations of ZnO nanoparticles on the interfacial properties of neem biodiesel. The study will clarify the molecular-level interactions driving these changes and identify optimal nanoparticle loading and dispersion strategies to maximize performance enhancements while ensuring stability.

2.0 THEORETICAL REVIEW

Biodiesel is a renewable, biodegradable fuel produced from natural lipid sources, including vegetable oils, animal fats, and waste cooking oils (Randive *et al.,* 2024). Chemically, biodiesel primarily consists of fatty acid alkyl esters (FAAE), which contribute to its cleaner combustion characteristics compared to conventional diesel (Pradana *et al.,* 2024). Its favourable properties, such as low sulphur content, high lubricity, and reduced particulate emissions, make biodiesel a promising sustainable alternative to fossil-based diesel fuels (Narayana *et al.,* 2022).
Despite these advantages, biodiesel derived from non-edible feedstocks such as neem, castor, and jatropha is often limited by several physicochemical shortcomings. These include relatively high viscosity, poor volatility, higher pour points, and lower energy density compared to petroleum diesel (Yang *et al.,* 2024). Such limitations can negatively affect atomization, cold-start performance, fuel flow behaviour, and overall combustion efficiency. Consequently, blending or modification strategies are required before efficient use in diesel engines. Biodiesel, which is also known as fatty acid methyl ester, has been utilized as a viable alternative to fossil fuels for a considerable amount of time (Jeyakumar *et al.,* 2023). Biodiesel is better for internal combustion engines than syngas or biogas since it is easier to utilize and carry (Prabowoputra *et al.,* 2022).

Pure crude vegetable oils can be used as an alternative for diesel engines, but they suffer from high viscosity, cold start problems, deposition in the combustion chamber, piston ring wedging, and others. However, these undesirable properties of vegetable oils can be minimized/eliminated by a transesterification process, where the oil is converted into methyl esters (BD) (Manurung, *et al.,* 2025). Fatty Acid Alkyl Esters, which are produced through transesterification from long-chain fatty acids, are the basis components of biodiesel (Azami *et al.,* 2021).

In recent years, research efforts have been intensified toward improving biodiesel's interfacial characteristics. Among the emerging techniques, nanoparticle doping has shown strong potential for enhancing combustion behaviour and optimizing surface interactions within biodiesel fuels (Elkelawy *et al.,* 2023).

Bio-fuels derived from oils and fats are found to be the most promising alternative fuel to petroleum diesel. Bio-fuels can be employed in existing diesel engines with minor or no modifications, also it can extend the life of diesel engines because it is more lubricating than petroleum diesel fuel (Taiwo *et al.,* 2020). Neem (*Azadirachta indica*) leaves are widely recognized for their rich phytochemical content, including flavonoids, terpenoids, alkaloids, and polyphenols, which make them suitable for the green synthesis of copper nanoparticles (CuNPs) (Ujah *et al.,* 2021).

The synthesis of silver nanoparticles has traditionally been achieved through physical and chemical methods. However, these conventional methods often involve the use of toxic chemicals, high energy consumption, and produce hazardous by-products, which raises environmental and safety concerns (Sabzevar *et al.,* 2024).

2.1 Neem Oil as a Promising Biodiesel Feedstock

Neem (*Azadirachta indica*) is a widely available non-edible oil plant predominant in tropical and subtropical regions. Neem seed oil contains a high percentage of triglycerides, making it suitable for transesterification-based biodiesel production (Kichonge and Kivevele, 2024). Studies consistently report that neem biodiesel produces lower carbon monoxide, hydrocarbon, and smoke than petroleum diesel, reinforcing its potential as an environmentally friendly biofuel (Venkatachalam *et al.,* 2024).

Beyond its value as a feedstock, neem also plays an influential role in green nanotechnology. Neem leaves contain phytochemicals such as flavonoids, terpenoids, alkaloids, and polyphenols, which are effective reducing and stabilizing agents in the biosynthesis of metal oxide nanoparticles (Patil *et al.,* 2022). This dual functionality as both a biodiesel precursor and a green synthesis medium makes neem an important resource in sustainable energy and nanomaterial applications.

2.1.1 Biodiesel Production and the Emergence of Nanocatalysts

Transesterification remains the most widely used method for biodiesel production, involving the reaction of oils with short-chain alcohols in the presence of a catalyst to yield methyl esters and glycerol. While homogeneous alkaline catalysts such as sodium hydroxide (NaOH) and potassium hydroxide (KOH) are traditionally used, they are associated with issues such as soap formation and difficulties in catalyst recovery (Chanakaewsomboom *et al.,* 2023).

Nano catalysts have gained attention for overcoming these limitations. Due to their high surface area-to-volume ratio and enhanced catalytic activity, nanoparticles provide faster reaction kinetics, improved reaction yields, and better reusability (Basu and Binik, 2024).

Metal oxide nano catalysts, including zinc oxide (ZnO), copper oxide (CuO), iron oxide (Fe_2O_3), and nickel-doped zinc oxide (Ni–ZnO), have demonstrated excellent performance in biodiesel demonstrated excellent performance in biodiesel synthesis (Basu and Binik, 2024).

Metal oxide nanoparticles have been widely investigated as biodiesel additives due to their high surface area, catalytic activity, and surface modification capabilities. These properties enable nanoparticles to enhance biodiesel combustion and modify its interfacial behavior at relatively low concentrations (typically 20–100 ppm) (Fangyuan and Haeng 2024).

2.1.2 Zinc Oxide (ZnO) Nanoparticles

Zinc Oxide nanoparticles have attracted growing attention due to their catalytic activity, affordability, and ability to alter surface interactions (Saeed *et al.,* 2024). Several studies report improved combustion efficiency and controlled NO_x emissions in ZnO_2-doped biodiesel blends (Muniyappan, S., & Krishnaiah, R. 2025). However, research on zinc peroxide ZnO_2 nanoparticles is extremely limited. ZnO_2 possesses a higher oxygen content and stronger oxidative potential than ZnO_2, suggesting that it may further enhance biodiesel interfacial properties, yet this potential remains largely unexplored (Pambudi *et al.,* 2021).

Despite extensive studies on these metal oxide nanoparticles, comparative investigations focusing on interfacial physics are still limited, especially for non-edible biodiesels such as neem biodiesel. Furthermore, the lack of systematic studies on ZnO nanoparticle doping highlights a significant research gap that the present study aims to address.

2.1.3 Nanoparticles as Additives for Improving Biodiesel Properties

Nanoparticles are increasingly being incorporated directly into biodiesel as additives, where they improve combustion behaviour, enhance energy conversion, and modify the fuel's physicochemical characteristics. Metal oxides such as $\boldsymbol{TiO_2}$, $\boldsymbol{Al2O_3}$, $\boldsymbol{CeO_2}$, $\boldsymbol{SiO_2}$, and $\boldsymbol{CuO}$ are particularly effective due to their catalytic activity and ability to influence molecular-level interactions (Yasmin *et al.,* 2023).

Research reports that nanoparticle doping can have the following effects on biodiesel:

i. Reduce ignition delay and promote complete combustion.
ii. Lower viscosity and improve flow characteristics.
iii. Reduce surface tension, resulting in better fuel atomization.
iv. Minimize exhaust emissions such as CO, HC, and particulates (Khan *et al.,* 2022).
v.

2.2 Titanium Dioxide ($\boldsymbol{TiO_2}$)

Titanium is extensively reported as an effective combustion catalyst. Studies indicate that $\boldsymbol{TiO_2}$ doped biodiesel improves brake thermal efficiency and reduces ignition delay due to enhanced oxidation reactions during combustion (Partha, 2025).

2.2.1 Aluminium Oxide (Al_2O_3) Nanoparticles

Aluminium is primarily employed for fluid property enhancement. Its structural characteristics contribute to improved fuel atomization and spray characteristics, while its chemical stability makes it suitable for long-term fuel applications (Yıldızhan, Ş and Özcanlı M, 2022).

2.2.2 Cerium oxide ($\boldsymbol{CeO_2}$)

Cerium oxide is one of the most abundant rare-earth elements, which is commonly explored for various applications as a catalyst or catalyst support due to its unique nature and high oxygen storage capacity (OSC) (Sultana *et al.,* 2021). Biodiesel blends doped with $\boldsymbol{CeO_2}$ have demonstrated significant reductions in carbon monoxide (CO), unburnt hydrocarbons (HC), and particulate emissions (Mofijur *et al.,* 2024).

2.3 Non-edible Feedstocks Used for Biodiesel Production

2.3.1 Neem (*Azadirachta indica*)

Azadirachta indica, commonly known as Neem, belongs to the family Meliaceae (Adepoju *et al.,* 2020). The procedure of extracting oil from neem trees begins with collecting the seeds, which are then de-pulped, sun-dried, and crushed.

The high concentration of free fatty acids (FFAs) in neem oil makes it difficult to transform into bio lubricants without resorting to a two-stage transesterification procedure. The initial step in esterification is catalyzed by an alkali, like NaOH or KOH, which neutralizes the FFAs and stops soap from being formed (Rajak *et al.,* 2025).

The biodiesel derived from neem oil satisfies numerous conventional fuel parameters, including density, viscosity, and flash point, as outlined by ASTM standards, signifying its viability as an alternative fuel (Mallah and Sahito, 2020). Neem biodiesel exhibits reduced flammability compared to fossil fuels, which may enhance safety (Mustapha *et al.,* 2020). The production process may incorporate pretreatment

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measures to reduce free fatty acid concentration, thereby enhancing yield and quality (Rajak *et al.,* 2025; Rastogi *et al.,* 2021).

Agu *et al.* (2025) studied the use n-hexane in extracting neem seed oil, focusing on variations in time, temperature, and seed particle size. Yield improved with extended extraction duration, elevated temperature, and reduced particle size. At 55 ◦ C temperature, 150 min, and a particle size of 0.5 mm, an optimal yield of 54.14 % was reached. Due to the presence of saturated fatty acid content, this oil is well-suited for use in biodiesel synthesis, according to the physicochemical analysis and fatty acid composition.

2.3.2 Jatropha Curcas L.

Jatropha (*J. curcas L.*) is a big shrub or small tree belonging to the Euphorbiaceae family, producing seeds that contain oil. Originally from the Americas, this species has expanded its range to include the whole tropical and subtropical globe, including China, India, Southeast Asia, and Africa. Due to their remarkable adaptations to soil and extreme aridity, jatropha plants grow in semi-arid and arid areas characterized by elevated temperatures and little soil moisture (Karpagam *et al.,* 2020). It takes the plant 12 months to start producing seeds, and it takes 5 years to reach its peak production. Jatropha seeds contain around 300 to 400 g of oil per kg (Neupane *et al.,* 2021).

Reddy et al. (2020) reported a batch production method for converting Jatropha oil (JO) into biodiesel utilizing a catalyst that is functionalized with sulfonic acid (SAFACAM). SAFACAM, derived from glucose, presents a sustainable and economically viable solution. Under rigorously controlled circumstances (methanol-to-oil molar ratio 20:1, \$120^\circ\text{C}\$, 50 min, 9 wt% catalyst), a remarkable biodiesel conversion rate of \$98.7 \pm 0.6\%\$ was achieved by utilizing response surface methodology (RSM) combined with a central composite design (CCD) (Ruatpuia, *et al.,* 2023).

Zulfiqar *et al.* (2021) conducted a study using CaO-ZrO_2 catalyst derived from biomass and MOFs, to synthesize biodiesel from Jatropha curcas oil (JCO). The parameters for transesterification were optimized through RSM, achieving a biodiesel conversion of 97.12 ± 0.4 % at a temperature of 92.9 ◦C, with 68 mins of reaction time, a catalyst loading of 6.34 wt%, and an oil-to-methanol ratio of 1:18. Analyses of the biodiesel and catalyst were conducted using Gas Chromatography-Mass Spectrometry (GC–MS), Fourier Transform Infrared Spectroscopy (FT-IR) Brunauer – Emmett - Teller (BET), Scanning Electron Microscopy/Energy-Dispersive Spectroscopy (SEM-EDS), X-ray Diffraction (XRD), Thermogravimetric Analysis (TGA), Proton Nuclear Magnetic Resonance (1H NMR), Carbon-13 Nuclear Magnetic Resonance (13C NMR) techniques.

2.2.3 Karanja Oil (*Pongamia pinnata*)

Karanja belongs to the family tree named Leguminosae that is indigenous to India and Southernmost Asia (Soan *et al.,* 2023). With great tolerance to salty soil, tropical areas such as China, New Zealand, Australia, and the United States of America are also native to this tree. It is commonly seen in the Western Ghats region of India and may thrive in many soil types, ranging from clayey to sandy. Karanja flourishes in environments characterized by high humidity and subtropical climates, where the annual precipitation ranges from 500 to 2500 mm. The elliptical pod with thick walls holds a single seed about the size of an almond (Sami *et al.,* 2022).

Sudalai et al. (2024) produced biodiesel from *Pongamia pinnata* oil utilizing dolomite, a waste product from the healthcare industry, as an innovative catalyst. A biodiesel yield of 92.3% was obtained under optimized conditions.

2.4 Castor Oil (*Ricinus communis*)

Ricinus communis, commonly known as the castor oil plant, is a dwarf woody tree which belongs to the Euphorbiaceae family and may grow up to 6 m. Despite the fact that it originated in Africa, it is a species that is extensively found in warm climate regions all over the world. The USA, Japan, and Thailand are the top importers of castor beans, while India, China, and Brazil are leading manufacturers. With a content of 48% to 60% oil, its seeds may yield 500,000–10,000,000 mL of oil per acre, which is significantly higher potential than the majority of commonly used oil crops.

Sangeetha et al. (2023) processed castor seed oil, which has high FFA content, to produce biodiesel in one pot utilizing a basic ionic liquid catalyst. A biodiesel yield of 97.83% was achieved using optimal conditions. The activation energy for turning *Ricinus communis* seed oil into biodiesel is 37.60 kJ/mol.

Ahmad-Jan et al. (2022) used CaO nanoparticles to synthesize biodiesel from *Ricinus communis*. CaO was characterized by SEM and XRD. Biodiesel qualities were tested using ASTM and EN fuel property tests. The feedstock had 0.89 mg KOH/g FFA and 53.7% oil. The optimum yield of biodiesel was found to be 89% using optimal parameters. Characteristic peaks in NMR, GC–MS, and FT-IR verified biodiesel generation. The fuel meets ASTM and EN criteria, showing engine suitability and environmental friendliness.

2.4.1 Waste Cooking Oil (WCO)

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Research on the utilization of WCO for biodiesel production has seen considerable growth, especially in Asian countries such as Indonesia, Malaysia, Taiwan, and China, which a major producers and consumers of palm oil (Manfaati *et al.,* 2023). Attempts have been made to convert WCO into biofuel fractions using catalysts such as cobalt aluminate nanoparticles, achieving high conversion rates exceeding 90% (Kochaniec, *et el.,* 2023; Muthub, *et al.,* 2024). In addition, the reuse of WCO through fermentation processes has been explored to produce free fatty acids, contributing to a circular economy by reducing environmental pollution (Tsouko *et al.,* 2024; Hartini *et al.,* 2023). Historical data from previous studies pay more attention to the potential of WCO as biodiesel feedstock in various countries. Studies have shown that WCO can be efficiently converted into biodiesel using solid acid catalysts such as SO42—/ZNO-β-zeolite (Yusuf, *et al.,* 2023). Furthermore, the catalytic performance of supported potassium hydroxide on alumina for WCO transesterification has been investigated, achieving a biodiesel yield of 86.6% under optimized reaction conditions (Erwa *et al.,* 2023). Comparatively, biodiesel production from WCO and Palm Carnel Oil (PCO) has been evaluated, with PKO showing higher biodiesel yields and better characteristics, making it a promising alternative fuel (Kumar *et al.,* 2024). These studies collectively demonstrate the potential of WCO as a sustainable feedstock for biodiesel production in countries such as China, Taiwan, Indonesia, and Malaysia. Figure 1 shows a comparison of annual WCO production between China, Indonesia, Malaysia, and Taiwan, providing a clear picture of the difference in production scale in the region. China's significant production of 5 million tons of WCO per year (Zhao *et al.,* 2021) demonstrates its substantial potential to develop the WCO-based biodiesel industry. Various studies highlight the feasibility of utilizing WCO for biodiesel production, emphasizing environmental benefits and efficiency. In addition, the systematic review emphasized the importance of enablers such as government policies, financial support, and technological advances in promoting WCO-based biodiesel production (Shen, *et al.,* 2023). As an archipelagic country with a variety of food industries, Indonesia has the potential to optimize the use of WCO in renewable energy production (Yusuf, *et al.* ,2023). Malaysia, with a reported production of 0.54 million tons per annum, also shows active participation in the biodiesel market (Chen, *et al.,* 2021; Chang, *et al.,* 2020).
market (Chen, *et al.,* 2021; Chang, *et al.,* 2020).

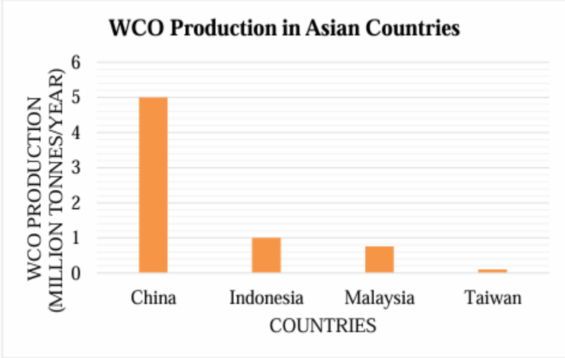

Fig. 1. WCO is produced in Asian countries

(Muhammad *et al.*, 2024)

2.5 Empirical Review

Several researchers have explored the use of various nanoparticles as catalysts in biodiesel production from Neem and waste cooking oils.

Noreen *et al.* (2021) synthesized Fe, Ni, and Cu doped ZnO nanocatalysts and employed them in biodiesel production from neem oil. Their study results revealed biodiesel yields of 95%, 80%, and 85% for Fe, Ni, and Cu respectively. Besides, results of analysis of produced biodiesel samples unveiled that the Fe, Ni, and Cu doped ZnO nanocatalysts are promising heterogeneous catalysts.

Zahid *et al.* (2024) Ni doped ZnO heterogeneous catalyst was used in conversion of neem oil to biodiesel by transesterification. A maximum biodiesel yield of 90.18%, under reaction conditions of 60 °C, 1:10 oil-to-methyl alcohol ratio, and 0.9g catalyst, was obtained.

Farokhi *et al*. (2021) used spinel type $Ni_xZn_{1-x}Fe_2O_4$ magnetic nano catalysts for conversion of neem oil into biodiesel via transesterification, and obtained a maximum biodiesel yield of 93%.

Opadoja *et al.* (2022) in their study on the fuel properties of biodiesel made from a blend of ackee and neem seed oils noted that the primary obstacles to using biodiesel directly in compression ignition (CI) engines are its excessive kinematic viscosity, particularly from Ackee seed biodiesel, as well as its lower volatility, higher pour point, higher boiling point, lower calorific value, and higher Free Fatty Acid (FFA). To mitigate these drawbacks, nanoparticles are crucial.

Opadoja *et al.* (2025). Titanium oxide was synthesis with green neem leaf using so-gel method. By adjusting the blended combination of neem biodiesel with different amounts of titanium oxide nanoparticle, the proper volumetric quantity of the nanoparticle (Titanium Oxide) was found till an ideal value was reached. Biodiesel was mixed with titanium oxide (TiO_2) nanoparticles to boost engine performance and its characteristics. Fuel manufacturers may develop a

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nano-fuel with increased fuel efficiency and lower emissions by mixing TiO2 nanoparticles with biodiesel, making it a more efficient and eco-friendly fuel choice.

Research continues to show that biodiesel products from several seed oils have fuel properties equivalent to those of diesel fuel, with lower harmful emissions (Abdullahi *et al.,* 2024).

The most widely used and recognized approach to producing biodiesel is the transesterification process, which consists of a catalytic reaction between renewable feedstocks such as vegetable oil or animal fats with methanol, producing glycerol as a by-product. (Anwar 2021).

It has been found that the addition of nanoparticles, either as a catalyst or as an additive, improves the trans-esterification process and some of the properties. Recently, many researchers have turned their attention to fuel formulation techniques to achieve better performance and emissions properties. Newer fuel additives for biodiesel contain nanoparticles as an additive. Biodiesel has emerged as a new promising fuel to achieve maximum performance increase and exhaust emission reduction (Mohadesi *et al.,* 2021).

The biodiesel can be obtained from edible and non-edible feedstocks. Possible developing countries like India are producing biodiesels such as mahua oil, neem oil, rice bran oil, Pongamia oil, soyabean oil, jatropha oil, etc., from non-edible oils (Abhijeet, *et al.,* 2024).

Ulakpa *et al.* (2022) contributed to biodiesel production from neem oil with the utilization of waste bone as a heterogeneous catalyst, achieving a 94% biodiesel yield.

Researchers have combined various feedstocks, including edible and nonedible oils, to address feedstock shortages and fuel quality issues.

Mujtaba *et al.* (2020) achieved a 96.61% biodiesel yield by transesterification equal parts of palm and sesame oils with methanol.

Adepoju *et al.* (2020) achieved a 98.03% biodiesel yield via a 60:40 blend of pig and neem seed oils. Another investigation by (Niju, *et al.,* (2019) achieved a 96.5% conversion rate by blending Calophyllum inophyllum oil with waste cooking oil (WCO).

Simbi *et al.* (2021) reported the synthesis of fatty acid methyl esters (FAME) from waste sunflower oil using a novel CaO/Al_2O_3 catalyst, achieving a yield of 98.23% at optimal conditions (2.5 wt% catalyst loading, 5-hour reaction time, and 60°C).

Abdul Hamid *at al.* (2025) investigated the use of antioxidant additives in sunflower biodiesel, which resulted in a 3.0% reduction in NOx emissions and a 4.4% reduction in smoke opacity compared to pure biodiesel. CO and HC emissions increased slightly but remained lower than those of petroleum diesel.

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Author (s), Year	**Feedstock/ Material**	**Nanoparticle/ Catalyst Used**	**Focus of Study**	**Key Findings /Outcomes**	**Identified Gaps /Limitations**
Adepoju *et al*., 2020	Pig + neem seed oil (60:40 blend)	Waste biomass catalysts	Optimization of biodiesel production	Achieved 98.03% biodiesel yield.	The study is largely laboratory based, with no explicit discussion on scalability, catalyst reusability, or long-term operational stability
Jeyakumar *et al*., 2020	Jatropha biodiesel	Moringa oleifera additive	Oxidation stability	Improved the storage stability of biodiesel.	Engine performance and long-term fuel degradation under real operating conditions were not explicitly evaluate
Mujtaba *et al*., 2020	Palm + sesame oil (1:1)	No nanoparticles	Process optimization	Achieved 96.61% biodiesel yield using ultrasound-assisted process.	The economic feasibility and energy requirements of ultrasound assisted production were not discussed
Prabowoputra *et al*., 2020	Castor oil	No nanoparticles	Influence of pressure/temperature on biodiesel	Identified optimal thermo-processing conditions for biodiesel production.	The study focuses on process conditions without validation through engine performance or large-scale application
Taiwo *et al*., 2020	Neem seed oil	No nanoparticles	Characterization of neem biodiesel	Neem biodiesel is viable but requires processing to reduce viscosity and improve stability.	Specific optimization strategies to address viscosity and stability challenges were not provide
Mohadesi *et al*., 2021	Various oils	Low-cost nanocatalysts	Microreactor biodiesel production	Nanocatalysts significantly improved fuel properties and production efficiency.	The scalability and economic viability of microreactor systems for industrial application were not explicitly addressed
Noreen *et al*., 2021	Neem oil	Fe-, Ni-, and Cu-doped ZnO	Nanocatalytic biodiesel production	Achieved biodiesel yields of 95% (Fe), 80% (Ni), 85% (Cu); doped ZnO catalysts are effective heterogeneous catalysts.	Catalyst recovery, recyclability, and environmental implications were not explicitly discussed
Ujah *et al*., 2021	Neem leaves	Green-synthesized Cu nanoparticles	Phytochemical-assisted nanoparticle synthesis	Neem phytochemicals suitable for green synthesis of metal nanoparticles.	The direct application of the synthesized nanoparticles in biodiesel production was not explored
Ulakpa *et al*., 2022	Neem oil	Waste bone-based catalyst	Transesterification	Achieved 94% biodiesel yield, showing waste catalysts are effective.	Variability in waste-derived catalyst composition and long-term usability were not clearly evaluated
Farokhi *et al*., 2021	Neem oil	$Ni_xZn_{1-x}Fe_2O_4$ magnetic nanocatalysts	Conversion of neem oil to biodiesel	Achieved 93% biodiesel yield using spinel-type magnetic nanoparticles.	The complexity of catalyst synthesis and cost implications were not explicitly
Abdullahi *et al*., 2024	Neem + Yellow	No nanoparticles	Engine performance with biodiesel blends	Biodiesel blends produced cleaner emissions than diesel; properties meet biodiesel standards.	The study does not incorporate nanoparticle enhancement or detailed optimization of blend ratios

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	Oleander oil blends				
Sabzevar *et al*., 2024	Haloxylon persicum extract	Ag nanoparticles	Antibacterial and green synthesis	Green synthesis avoids toxic chemicals; nanoparticles exhibit desirable antimicrobial properties.	The study is not directly linked to biodiesel production or fuel performance evaluation
Zahid *et al*., 2024	Neem oil	Ni-doped ZnO	Optimization of transesterification	Maximum biodiesel yield of 90.18% at 60°C, 1:10 oil-methanol ratio, 0.9 g catalyst.	Optimization is limited to specific conditions; engine performance and lifecycle assessment were not reporte
Manurung *et al*., 2025	Vegetable oils	No nanoparticles	Review of fatty acid composition	Fatty acid profile strongly influences biodiesel properties (viscosity, cold flow, etc.).	As a review, it lacks experimental validation and does not integrate nanotechnology-based enhancement

Salmasi *et al.* (2020) produced biodiesel using a K2CO3 catalyst derived from talc, achieving a 98.4% yield at 338 K, with 4 wt% catalyst loading and a 6:1 methanol-to-oil molar ratio.

The methanol-to-oil molar ratio and transesterification temperature are critical factors in biodiesel production as they influence the efficiency of the transesterification reaction and the quality of the resulting biodiesel Kumar *et al.,*2025).

The reviewed literature shows increasing global interest in biodiesel as a sustainable alternative fuel, with neem oil emerging as a viable non-edible feedstock. Nanoparticles, whether used as catalysts or fuel additives, offer substantial improvements in biodiesel production efficiency and combustion quality. However, the physicochemical and interfacial behaviour of neem biodiesel modified with ZnO_2 nanoparticles has not been sufficiently explored.

This study will contribute to filling this research gap by examining the interfacial enhancements associated with ZnO_2 nanoparticle doping, thereby advancing the understanding of fuel behaviour within the fields of interfacial physics and surface engineering.

3.0 CONCLUSION

The growing demand for sustainable and environmentally friendly energy sources has positioned neem biodiesel as a promising non edible alternative to conventional petroleum diesel. This review examined recent advances in the application of ZnO nanoparticles for enhancing the interfacial properties of neem biodiesel. The reviewed literature demonstrates that nanoparticle incorporation has considerable potential to improve key fuel properties, including viscosity, flow behaviour, spray atomization and interfacial stability thereby enhancing biodiesel performance in energy and industrial applications.

The review further revealed that, although numerous studies have investigated the use of metal oxide nanoparticle such as, ZnO $TiO_{2,}$ $Al2O_3$, $CeO_{2,}$ $SiO_{2,}$ and CuO as catalysts and fuel additives, research specifically focusing on ZnO nanoparticle remains limited. Existing studies primarily emphasize biodiesel production, engine performance, and emission characteristics, while comparatively little attention has been given to understanding how ZnO nanoparticle influence the interfacial physics, and long team dispersion stability of neem biodiesel. These knowledge gaps restrict the wider adoption of nanoparticle enhanced biodiesel in advanced applications where physiochemical stability is essential.

However, the available literature indicates that $\boldsymbol{ZnO}$ nanoparticles possess significate potential to improve the performance of neem biodiesel owing to their chemical stability, and strong surface interactions.

Moreover, further systematic investigations are required to establish the relationships between nanoparticle concentration, dispersion techniques, interfacial characteristics, and long-term stability under practical operating condition. Addressing these challenges will contribute to the development of high performance, sustainable biodiesel formulations and advance the application of nanoparticle enhanced biofuels in the future energy system.

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