

Review

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A comprehensive review of the influences of nanoparticles as a fuel additive in an internal combustion engine (ICE)

<https://doi.org/10.1515/ntrev-2020-0104>

received August 17, 2020; accepted December 6, 2020

Abstract: Nanofluid is a colloidal mixture consisting of nano-sized particles dispersed in a liquid medium. It improves heat transfer properties and promotes high energy efficiency in a wide spectrum of engineering applications. In recent years, particularly in the automotive industry, the addition of nanofluid in diesel/biodiesel as an additive for ICE has become an attractive approach to promote enhanced combustion efficiency and emission reduction due to their superior thermophysical properties. Many researchers have previously demonstrated that the addition of nanoparticles in diesel/biodiesel fuel improved the overall engine combustion characteristics. As a whole, this study aims to summarize the recent research findings related to the effect of nanoparticles on the fuel properties and engine combustion efficiency. Furthermore, different types of additive blended with varying fuel properties are also compared and discussed. Lastly, the advantages and prospects of using nanofluid as an additive fuel are summarized for future research opportunities.

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Keywords: nanoparticles, ICE, diesel/biodiesel, fuel properties, combustion efficiency, emission control

1 Introduction

Global warming is expected to be the biggest challenge of the twenty-first century. The average temperature of the Earth increased by about 0.4–0.8°C in the past 10 decades [1,2]. Recently, the scientists from the Intergovernmental Panel on Climate Change have estimated that the average global temperatures will continue to rise by 1.4–5.8°C by the year 2100 [3]. Carbon dioxide (CO₂), water vapour, methane (CH₄), sulphur dioxide (SO₂), chlorofluorocarbon, and nitrogen dioxide (NO_x) are well known as the major contributors to the greenhouse effects.

Recently, many researchers have focused on developing a wide spectrum of renewable energies including oxygenated fuels, biofuel (*n*-butanol), fuel cell, and solar technologies to reduce the consumption of fossil fuels and control the emission of greenhouse gases (GHGs) to the atmosphere [4–7]. One of the most effective methods in controlling the emission of GHGs is to reduce the emission of CO₂ by reducing fossil fuel consumption [8–11]. CO₂ is directly related to the carbon content of the fuel and the amount of fuel consumption [11]. The production and combustion of transportation fuels also release CH₄ and nitrous oxide (N₂O) other than CO₂ which contributed to the emission of GHGs. Other than using clean fuel alternatives, novel automotive engines with post-combustion emission control devices should be developed to reduce the GHG emissions and improve the efficiency of energy systems [12–14]. The application of biodiesel engine in transportation and power generation sectors has shown development in the past decades, and the latest research development trend is seeking a novel ICE with low emission [15–17], energy savings [18,19], and high-efficiency performance [20–22].

Biodiesel engines have an excellent reputation for low fuel consumption, high reliability, and high durability due to their high thermal brake performance, high compression ratio, and lower air-fuel mix [19,23,24]. However, both diesel and biodiesel fuels have their respective limitations in producing a higher NO_x , which leads to poor combustion performance [25–27]. Thus, to overcome these limitations, the addition of fuel additives is gaining much attention to improve the oxidation characteristics of biodiesel. The blending of diesel/biodiesel with fuel additives could improve combustion performance and reduce GHG emissions effectively. Nanofluid is a potential fuel-additive candidate and the pioneer researcher who suggested it was Choi [28]. Nanofluid is a two-phase colloidal mixture consisting of nano-sized particles (nanoparticles) dispersing in a base liquid. Nanoparticles are generally known as particles with sizes approximately between 1 and 100 nm. Rheological behaviour and thermophysical properties of the base fluid would be significantly affected when nanoparticles are dispersed into the base fluid.

This study presents recent research findings of the properties of nanoparticles as an additive in diesel/biodiesel fuels. The present study compares the combustion performance and emission characteristics of ICEs with different types of diesel/biodiesel-nanoparticle blends. Currently, metal oxides like cerium oxide (CeO_2), aluminium oxide (Al_2O_3), copper oxide (CuO), silver oxide (Ag_2O), iron oxide (Fe_2O_3), titanium oxide (TiO_2), silicon (Si), zinc oxide (ZnO), and magnesium (Mg) and non-metal oxides like carbon nanotubes (CNTs), multiwall CNTs (MWCNTs), graphene oxide (GO), etc. are among the most widely used fuel-additive nanoparticles in diesel/biodiesel fuel.

The concentration of nanoparticles required for a stable dispersion is also considered in this article. It is well known that the use of different types of nanoparticles in different diesel/biodiesel mixtures can yield different results. For example, it will affect the engine performances, including brake-specific fuel consumption (BSFC), brake power (BP), brake heat efficiency (BTE), engine torque, and toxic gas emissions including CO, NO_x , and particulate matter (PM). To the best of the author's knowledge, very few review papers were published on the fuel consumption and combustion performance of diesel/biodiesel with the addition of nanoparticle-based fuel additives in an ICE.

Hence, the authors aim to provide an extensive review by comparing the combustion, emission, and performance characteristics of the nanofuel additives diesel/biodiesel blends. First, the renewable energies to control GHGs were briefed in the introduction section. This was

followed by a brief review of the stability of nanoparticles in a base fluid. Third, reports the effect of different types of additives blended on the fuel properties and engine performance using the most widely used nanoparticles. That is, metal oxides, such as CeO_2 , Al_2O_3 , CuO , Ag_2O , Fe_2O_3 , TiO_2 , Si, ZnO , and Mg, and non-metal oxides, such as CNT, MWCNT, and GO, were reviewed as potential additives in fuels. The research works of literature were sourced from Elsevier's ScienceDirect, Google Scholar, and ISI Web of Science. For sourcing information, many keywords have been used. The keywords include nanoparticles, ICE, diesel/biodiesel, fuel properties, combustion efficiency, and emission control. In identifying the possible articles, more than two of the keywords were used. The select literature included peer-reviewed studies, which contributed significantly to the field of study. Elsevier's Mendeley reference management programme was also used to gather references from the selected articles. All of the findings obtained from these articles are presented in a tabular form. As a whole, this review article will help the researchers from the nanotechnology field and industrial engine manufacturers to gather a quick report on the emission issues and engine performance of different diesel/biodiesel fuel blends.

2 Stability of nanoparticles in a base fluid

Generally, nanofluid has high surface energy owing to its large surface area, which tends to promote agglomeration and form micro-sized particles before deposition. For both scientific and practical applications, a stable and homogeneous nanofluid suspension is a crucial phenomenon. Stability plays a vital role in the production of nanofluid as it will affect its performance as a heat carrier and thermophysical properties. To promote a better stability of nanoparticles in a base fluid, many methods have been reported in the literature including ultrasonication, surface modification, the addition of surfactants, and pH control.

From the literature, several previous studies investigated the effectiveness of ultrasonic dispersion in promoting and improving the stability of nanoparticles. A study by Hong et al. [29] reported that the stability of nanofluids can be enhanced with longer sonication time. From their results, it was revealed that prolonging the sonication time helps to reduce the agglomeration of

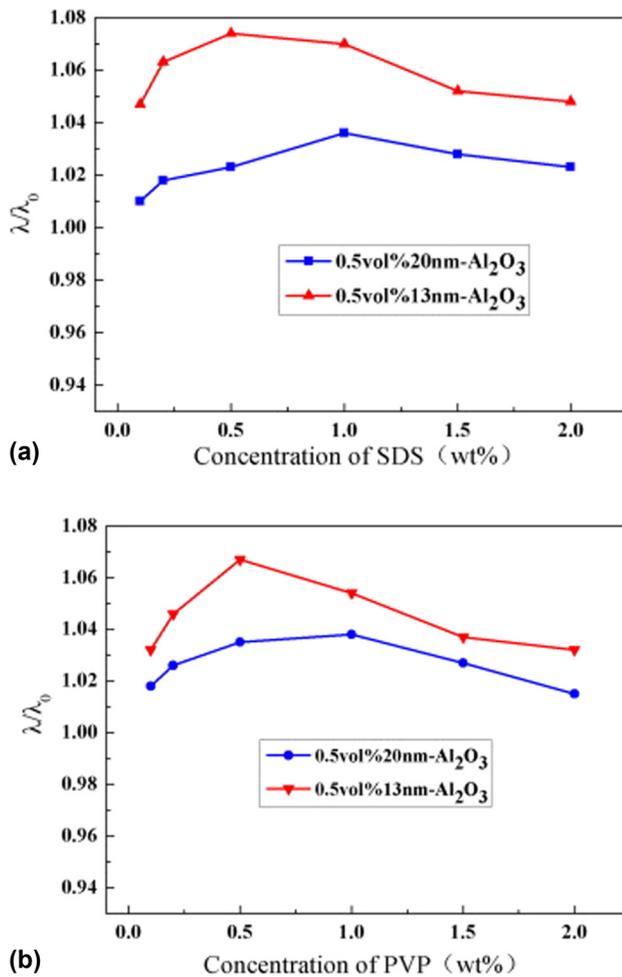


Figure 2: Influence of (a) SDS and (b) PVP concentration on the thermal conductivity of Al_2O_3 /de-ionized nanofluids with different particle size under room temperature [41].

nanofluids operating under high temperatures due to the possible bond breakdown between the surfactant and nanoparticles [43,44]. Chen et al. [45] studied the stability and thermal conductivity properties of CNT nanofluids stabilized by a cationic Gemini surfactant. From their finding, it was concluded that a high concentration of surfactants did not improve the thermal conductivity of nanofluids. Besides, the addition of surfactants increased the thermal resistance of the nanoparticle in the base fluids, which led to a poor thermal conductivity performance [43].

3 Effect of nanoparticles on fuel properties

The fuel properties are one of the significant factors that determine the quality of the fuel mixing and combustion

process. Recently, the addition of nanoparticles has been considered as an advantageous approach in enhancing the fuel properties. Numerous researchers have tested fuel properties by adding different types of nanoparticles in various diesel/biodiesel fuels [37,46–56]. Furthermore, the quality of the fuel mixing and combustion process was evaluated by studying their effects on different features including kinematic viscosity, calorific value, flash point, density, number of cetane, etc. Table 1 compares the physical properties of diesel/biodiesel blend with and without nano-additives.

An experimental investigation of NO_x reduction in a rapeseed oil biodiesel-fuelled CI engine was performed by Praveena et al. [46,47]. From their study, two different types of nano-additives, namely, CeO_2 and ZnO , were used to test the physical properties of the fuel under the American Society for Testing and Materials (ASTM) code. The calorific value of ZnO was found to be higher than that of CeO_2 . The low calorific values of CeO_2 caused an increase in BSFC. No significant effect was found in the density, pour, cloud points, and kinematic viscosity due to the addition of CeO_2 nanoparticles in the rapeseed oil biodiesel fuel. The experimental results were in good agreement with that obtained by Karthikeyan et al. [48] who also investigated the addition of CeO_2 (50 and 100 nm) nanoparticles in a rapeseed oil biodiesel fuel. However, there was a slight improvement in the flash-point and calorific value between Praveena [46,47] and Karthikeyan [48]. As a result, the addition of CeO_2 nanoparticles' additive exhibited a significant improvement in the performance of and a reduction in harmful emissions as compared to the B20 (20% biodiesel + 80% diesel).

Ang et al. [49] prepared the diesel fuel blends by using Al_2O_3 , CNT, and SiO_2 nanoparticles with dosing levels of 25, 50, and 100 ppm. The physical fuel properties were tested with the engine loads of 0%, 25%, 50%, 75%, and 100% using ASTM code under a constant engine speed of 1,800 rpm. It was observed that the addition of Al_2O_3 nanoparticles increased the density and calorific value of the blend with a viscosity reduction in DA25 (diesel fuel 1 kg + Al_2O_3 25 mg). As expected, a significant increment in the viscosity was observed when the concentration of nanoparticles increased. On the contrary, the addition of CNT did not affect the fuel density substantially and showed a reduction in viscosity due to the lubricity of carbon atoms. Yet, the calorific value was found to be increased due to the higher carbon content. Meanwhile, the SiO_2 blends displayed a lower fuel density with no significant change in the calorific value as compared to diesel fuel with a lower viscosity characteristic.

In a different study, Rolvin et al. [52] prepared the diesel fuel blend from TiO_2 nanoparticles with a dosing level

Table 1: Comparison between fuel properties of nanoparticles doped in diesel/biodiesel

| Authors | Base fuel | Nanoparticles | Fuel properties | | | | |
|---------------------------------|---------------------------------|------------------------------------|-----------------|-----------------|-------------------------|------------------------------|------------|
| | | | Viscosity (cSt) | Flashpoint (°C) | Calorific value (MJ/kg) | Density (kg/m ³) | Cetane No. |
| 1 Praveena et al. [46] | Grapeseed oil biodiesel (GSO) | — | 4.06 | — | 39.07 | — | 55 |
| | | CeO ₂ 100 | 4.47 | — | 38.76 | — | 57 |
| | | ZnO 100 | 4.42 | — | 38.9 | — | 59 |
| 2 Praveena et al. [47] | GSO biodiesel | — | 4.06 | — | 39.07 | 845 | 55 |
| | | ZnO 50 | 4.40 | — | 38.78 | 849 | 58 |
| | | ZnO 100 | 4.42 | — | 38.9 | 850 | 59 |
| | | CeO ₂ 50 | 4.45 | — | 38.55 | 852 | 56 |
| | | CeO ₂ 100 | 4.47 | — | 38.76 | 853 | 57 |
| 3 Karthikeyan et al. [48] | GSO biodiesel | — | 5.554 | 38 | 37.02 | 841 | — |
| | | CeO ₂ 50 | 5.556 | 39 | 38.38 | 843 | — |
| | | CeO ₂ 100 | 5.559 | 39 | 38.96 | 846 | — |
| 4 Ang et al. [49] | Diesel fuel | — | 4.56 | — | 48.58 | 841 | 56.0 |
| | | Al ₂ O ₃ 25 | 3.70 | — | 48.20 | 853 | 55.4 |
| | | Al ₂ O ₃ 50 | 3.81 | — | 49.32 | 856 | 55.3 |
| | | Al ₂ O ₃ 100 | 4.12 | — | 49.77 | 873 | 55.4 |
| | | CNT 25 | 3.99 | — | 49.09 | 841 | 54.7 |
| | | CNT 50 | 3.86 | — | 50.18 | 846 | 54.8 |
| | | CNT 100 | 3.83 | — | 51.27 | 850 | 54.9 |
| | | SiO ₂ 25 | 4.26 | — | 47.31 | 845 | 55.0 |
| | | SiO ₂ 50 | 3.98 | — | 47.78 | 835 | 55.2 |
| 5 Gumus et al. [50] | Diesel fuel | — | 3.6 | 60 | — | 833.5 | 53.8 |
| | | CuO 50 | 3.5 | 66 | — | 834.1 | 54.5 |
| | | Al ₂ O ₃ 50 | 3.5 | 68 | — | 834.3 | 54.4 |
| | | — | 3.6 | 60 | 42 | 833 | — |
| 6 Sahoo and Jain [51] | Diesel fuel | — | 3.6 | 60 | 42 | 833 | — |
| | | CuO | 3.5 | 66 | 42.43 | 834.1 | — |
| 7 Rolvin et al. [52] | Diesel fuel | — | 2.981 | 51 | 41.794 | 697.2 | — |
| | | TiO ₂ | 3.165 | 72 | 42.042 | 700.2 | — |
| 8 Devarajan et al. [53] | Palm stearin biodiesel | — | 4.28 | 140 | 37.51 | 844 | — |
| | | AgO 5 | 3.86 | 134 | 38.35 | 804 | — |
| | | AgO 10 | 3.71 | 132 | 38.54 | 797 | — |
| 9 Perumal and Ilangkumaran [54] | Pongamia biodiesel | — | 3.02 | 69 | 43.68 | 824 | — |
| | | CuO 50 | 4.79 | 67 | 43.78 | 835 | — |
| | | CuO 100 | 4.85 | 66 | 43.82 | 846 | — |
| 10 Sajin et al. [55] | Mango seed biodiesel | — | 3.8 | 165 | 38.125 | 880 | 58 |
| | | ZnO (20 nm) | 3.7 | 168 | 38.25 | 820 | 58 |
| | | ZnO (40 nm) | 3.6 | 171 | 38.75 | 790 | 59 |
| 11 Lenin et al. [56] | Diesel fuel | — | 2.7 | 48 | — | — | — |
| | | MnO | 2.53 | 44 | — | — | — |
| | | CuO | 2.24 | 40 | — | — | — |
| 12 Tewari et al. [57] | Honge oil methyl ester | — | 5.6 | 170 | 36.016 | — | — |
| | | CNT25 | 5.7 | 166 | 34.56 | — | — |
| | | CNT50 | 5.8 | 164 | 35.1 | — | — |
| 13 Narasiman et al. [58] | Sardine oil methyl ester (SOME) | — | 4.5 | 58 | 37.405 | 890 | 45 |
| | | CeO ₂ 25 ppm | 5.6 | 191 | 45.365 | 894 | 56 |
| 14 Sathiyamoorthi et al. [59] | Neem oil biodiesel | — | 3.74 | 65 | 41.9 | 828 | 43.5 |
| | | CeO ₂ 50 ppm | 3.71 | 66 | 41.94 | 830 | 43.7 |
| 15 Ghareghani et al. [60] | Diesel–biodiesel fuel blend | — | 2.9 | 82 | 44.572 | — | — |
| | | 7% water | 3.92 | 74 | 42.488 | — | — |
| | | CeO ₂ 90 ppm | 3.88 | 77 | 42.382 | — | — |
| 16 Annamalai et al. [61] | Lemongrass oil emulsion fuel | — | 4.6 | 55 | 37 | 905 | 48 |
| | | 5% water | 4.67 | 74 | 35.8 | 906 | 46.3 |

Table 1: Continued

| Authors | Base fuel | Nanoparticles | Fuel properties | | | | |
|----------------------------|---|---------------------------------------|-----------------|-----------------|-------------------------|------------------------------|------------|
| | | | Viscosity (cSt) | Flashpoint (°C) | Calorific value (MJ/kg) | Density (kg/m ³) | Cetane No. |
| 17 Nanthagopal et al. [62] | <i>Calophyllum inophyllum</i> biodiesel | CeO ₂ 30 ppm | 4.99 | 67 | 36.2 | 916.4 | 48.8 |
| | | — | 4.72 | 122 | 38 | 868.6 | 52 |
| | | ZnO 50 ppm | 4.76 | 123 | 37.02 | 871.1 | 54 |
| | | ZnO 100 ppm | 4.78 | 126 | 37.32 | 872.4 | 56 |
| | | TiO ₂ 50 ppm | 4.73 | 123 | 37.12 | 869.2 | 53 |
| 18 Anchupogu et al. [63] | <i>Calophyllum inophyllum</i> biodiesel | TiO ₂ 100 ppm | 4.75 | 124 | 37.54 | 870.4 | 55 |
| | | — | 3.56 | 69 | 40.92 | 843.3 | 53.85 |
| | | Al ₂ O ₃ 40 ppm | 3.64 | 64 | 41.435 | 858 | 54.58 |
| 18 Nithya et al. [64] | Canola biodiesel | — | 4.8 | — | — | 915 | 42 |
| | | TiO ₂ 300 ppm | 3.4 | — | — | 840 | 56 |
| 19 Najafi [65] | Diesel–biodiesel fuel blend | — | 4.24 | — | 45.72 | 835 | 46 |
| | | Ag 40 ppm | 4.36 | — | 46.44 | 854.7 | 47 |
| | | Ag 80 ppm | 4.4 | — | 46.68 | 855.3 | 48 |
| | | Ag 120 ppm | 4.49 | — | 46.92 | 858.8 | 50 |
| | | CNT 40 ppm | 4.74 | — | 47.12 | 879.9 | 57 |
| | | CNT 80 ppm | 4.82 | — | 48.02 | 884.3 | 59 |
| CNT 120 ppm | 4.91 | — | 48.68 | 891.6 | 61 | | |

of 500 ppm. The results demonstrated that the addition of nanoparticles to the base fuel improved the fuel properties including fire point, viscosity, density, and calorific value. Gumus et al. [50] and Sahoo and Jain [51] also concluded that the nanoparticle additives possessed better fuel characteristics like flash point and calorific value. A lower BSFC was attributed to the higher calorific value [62].

From an experimental investigation performed by Sajin et al. [55], the influence of the size of ZnO nanoparticles on the physical properties of mango seed biodiesel was investigated. From the results, the biodiesel blended with 40 nm ZnO nanoparticles had a higher calorific value and cetane value and the addition of nanoparticles in the biodiesel promoted better combustion performance.

4 Effects of metal oxide nanoparticles as additives in diesel/biodiesel fuel on the performance, combustion, and emission characteristics

The main purposes of adding nanoparticles into the diesel/biodiesel fuel are to promote a high surface-to-volume ratio and increase the number of reactive surfaces. It allows the

nanoparticles to act as an effective chemical catalyst which improves the mixing pattern of fuel with air and the fuel combustion performance, subsequently leading to a fully combusted chemical catalyst.

4.1 CeO₂

CeO₂ can be served as an oxygen buffer to simultaneously induce the oxidation of hydrocarbons (HCs) and reduction of nitrogen oxide emission [66,67]. Several studies and reviews have explored the effects of CeO₂ nanofuel additives on the performance, combustion, and emission characteristics of CI engine.

In 2015, Narasiman et al. [58] investigated the effects of CeO₂ nanoparticle's additive in diesel and sardine oil methyl ester (SOME). The mass fraction of nanoparticles used was 25 ppm. Throughout the experiments, a single four-stroke diesel engine was used at different loads under a constant speed. From the test, it was revealed that the nanoparticles could be used as an additive in diesel and biodiesel to induce complete fuel combustion and significantly improve the exhaust emissions.

Sathiyamoorthi et al. [59] investigated the performance, emission, and combustion characteristics of a single cylinder with two modified fuel blends: BN20 (biodiesel from neem oil) and CeO₂ nanoparticle's additive blended in BN20. Ultrasonicator was used to mix CeO₂

nano-additives with BN20 to promote better colloidal stability. The addition of nanoparticle additives promoted a higher BSFC and BTE as compared to the standard diesel fuel. The emissions of NO_x , smoke, HC, and CO were found to significantly decrease after the nanoparticle's additive was added into the BN20 fuel. Experimental results also revealed that a higher amount of cylinder pressure and heat were released when CeO_2 nanoparticles were added into BN20 fuel.

A significant study by Ghareghani *et al.* [60] included the effect of water and CeO_2 nanoparticles on engine performance, combustion, and emission characteristics of diesel/biodiesel fuels. The influence of water and nano-additive in diesel/biodiesel fuel was found to improve the overall combustion quality. The experimental results were in good agreement with that obtained by Khalife *et al.* [68] and Mei *et al.* [69].

Sathiyamoorthi *et al.* [70] conducted a novel study to evaluate the performance, combustion, and emission characteristics of neat lemongrass oil biodiesel. The entire research was performed in the diesel engine using emulsified LGO25 (75% diesel volume and 25% lemongrass oil volume), a mixture of CeO_2 -emulsified LGO25, and a mixture of diethyl ether (DEE)-emulsified LGO25 with an exhaust gas recirculation (EGR). All of the nano-fluid blends were compared to the standard diesel and LGO25 fuel. From the results, a significant improvement in NO_x and smoke emission was observed in the mixture of DEE-emulsified LGO25 and EGR. The NO_x and smoke emissions were found to be reduced by 30.72 and 11.2%, respectively. In the context of HC and CO emissions, both were reduced by 18.18 and 33.31%, respectively, whereas the BTE and BSFC increased by 2.87 and 10.8%, respectively. The combustion characteristics such as cylinder pressure and heat release rate increased by 4.46 and 3.29%, respectively, as compared to the emulsified LGO25. These findings are in line with those found in the literature and the nano-additive was demonstrated as an oxygen buffer to promote a better combustion and emission control efficiency [71].

Pandey *et al.* [72,73] investigated the effect of CeO_2 nanoparticles on the combustion performance and emission of Karanja oil biodiesel. From the results, Karanja oil biodiesel with 5 wt% of nano-additive demonstrated enhanced engine performance with a substantial reduction in particulate emissions including lower emissions of NO_x (14–25%) and PM as compared to diesel fuel. Besides, the addition of nano-additive to Karanja oil biodiesel caused a slower heat release rate as compared to the standard diesel. It possessed a higher cetane number than diesel [66] and thus had a shorter delay in the

ignition as compared to petrol. Apart from that, their results were in good agreement with that reported by Babu and Praneeth [74].

Ananda *et al.* [75] demonstrated the emission reduction of an ethanol–gasoline blend using CeO_2 nanoparticles as a fuel additive. From the results, the thermal brake performance of nanoparticle mixtures was found to be improved. In the CO emission test, the CO_2 , HC, and NO_x emissions reduced significantly with a substantial increment in O_2 concentration in all blends. From the combustion analysis, the gas pressure of nanoparticle blends was higher as compared to that of the pristine fuel.

Recently, Janakiraman *et al.* [76] examined the combustion performance and emissions of CeO_2 , ZrO_2 , and TiO_2 as nanoparticle additives. It was observed that the HC of TiO_2 , CeO_2 , and ZrO_2 blended with B20 (20% *Garcinia gummi-gutta* biodiesel + 80% diesel) were lower than the neat B20 by 6.39, 3.99, and 5.64%, respectively, under maximum load condition. Furthermore, B20 blend with TiO_2 had a better combustion efficiency, lower CO, unburned HC (UBHC), smoke, and diesel fuel combustion. The addition of nanoparticles into the blends was found to contribute a declining trend in the HC emissions due to the high availability of oxygen content and lower activation energy discharged by the nanoparticles [55,69,77–80]. All the nanoparticle blends exhibited a lower brake specific energy consumption (BSEC) as compared to B100 by 23.42, 22.11, and 19.8%, under the maximum load condition. The reduction of fuel blends in BSEF is shown in Figure 3. The study from Senthil and Ramesh [80] evaluated the effect of ginger grass oil biodiesel on the performance, combustion, and emission characteristics using CeO_2 as a fuel additive. It was found out that the HC content increased with a higher concentration of ginger grass oil in the blends.

Thangavelu *et al.* [81] explored the potential of CeO_2 nanoparticles as a fuel additive in a four-stroke single-cylinder water-cooled compression ignition engine with the volumetric proportions of 5, 10, 15, and 20%. From the study, a significant reduction in the emission of HC by 3%, smoke by 7.7%, and CO by 1.33% was found as compared to that of the conventional diesel. It was concluded that B5D85 + CeO_2 (100 ppm) fuel blend had the best fuel ratio for a CI engine due to the high engine efficiency, low particle emission, and better combustion. Thus, it can be served as a suitable alternative fuel for the CI engine.

CeO_2 nanoparticles and iron dope (10 and 20% iron) were added into the waste cooking oil biodiesel–diesel blend in the study by Hawi *et al.* [82]. From the results, the NO_x emission was reduced by 15.7% with no

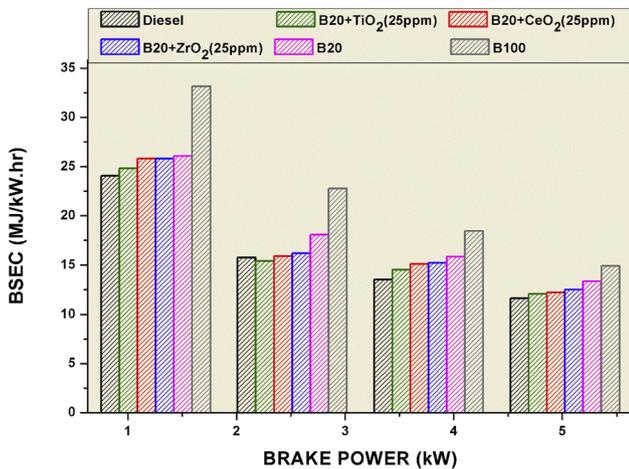


Figure 3: The BSEC for fuel blends with nanoparticles [76].

significant change in the HC emissions. At the same time, CO emission was reduced by 24.6% for B30 and 15.4% for B30 with nano-additives. From low to medium loads, a lower BSFC was found for the B30 fuel mixture with 10% FeCeO₂ nanoparticles and comparable to D100 at high loads. In contrast, BTE improved with an increase in engine load. Akram et al. [83] also conducted a study using waste cooking oil diesel/biodiesel. However, in their research, the emission reduction potential in CO, NO_x, and UBHC was investigated using different concentrations of CeO₂ nanoparticles and Ce_{0.5}Co_{0.5} nanocomposite oxide under full engine load. It was found that CO, NO_x, and UBHC emissions reduced by 18.27, 6.57, and 23.46%, respectively, when CeO₂ (100 ppm) was used. On the contrary, when Ce_{0.5}Co_{0.5} nanocomposite oxide (100 ppm) was used, CO, NO_x, and UBHC emissions reduced by 24.18, 13.96, and 40.74%, respectively. It was observed that the addition of CeO₂ nanoparticles led to an increase in the viscosity index of the biodiesel owing to the high catalytic activity [84,85].

Table 2 summarizes the effect of CeO₂ nanoparticles in diesel/biodiesel fuel on the performance, combustion, and emission characteristics of the ICE with some undiscussed research works.

4.2 Al₂O₃

In the following section, the effect of Al₂O₃ nanoparticles as a fuel additive in diesel/biodiesel blend on the engine performance, combustion, and emission characteristics of the ICE are reviewed and discussed. Nassir and Shahad [87] attempted to examine the impact of Al₂O₃ and TiO₂ nanoparticles on the combustion phasing of

diesel fuel. The addition of nanoparticles improved the fuel properties. For instance, the cetane number enhanced from 51.6 to 54.3 with the addition of 150 ppm Al₂O₃ nanoparticles. The effect of nanoparticles on the delay time and fractioning of heat release (premix and diffusion) was noticeable. From the results, the delay period decreased with higher nanoparticle concentration. The effect of Al₂O₃ nanoparticles on viscosity, temperatures, and the cetane number was more prominent than the effect of TiO₂. Nevertheless, TiO₂ nanoparticles contributed to the most significant reduction in the delay period, which can be attributed to the higher viscosity of Al₂O₃.

Sathiamurthi et al. [88] added 50 nm Al₂O₃ nanoparticles into the diesel fuel and evaluated the combustion performance and emission characteristics of the diesel blend in a four-stroke, single-cylinder diesel engine under different load conditions and fuel blends (0.5 g and 1 g of 50 nm Al₂O₃ nanoparticles were blended into 1 L of diesel fuel). The results obtained were similar to the study done by Venkatesan and Kadiresh [89] even though they used a smaller size of nanoparticles (40 nm) and different fuel rate (1 and 1.5 g/L). These results indicate that particle size has a significant effect on ignition and combustion. The smaller particle sizes showed a greater intensity of reaction. Furthermore, the addition of nanoparticle was found to improve the combustion characteristics and enhanced the surface to volume ratio. Thus, the burning efficiency of the test fuels was promoted as more diesel fuels reacted with the oxidizer. From the results, a significant increase in BTE and a considerable reduction in the NO_x and UBHC contents of all loads were observed as compared to pure diesel fuel. This could be due to the improved combustion characteristics of nanoparticles and the enhanced air mixing ratio.

Basha [90] also studied the combustion performance of diesel fuel blend with Al₂O₃ nanoparticles. The result of the analysis revealed that a significant increase in BTE and a marginal reduction in harmful pollutants including NO_x, CO, and smoke were observed with the diesel fuel blend in contrast to the pure diesel fuel. The addition of Al₂O₃ nanoparticles in diesel fuels boosted the combustion efficiency of the diesel engine. However, many research works are still ongoing to capture potential nanoparticles released from the exhaust to avoid environmental pollution. Kao et al. [91] conducted an experimental investigation in a single-cylinder horizontal diesel engine using Al₂O₃ additive diesel fuel with different percentages of water (3–6%). A significant reduction in the BSFC and harmful pollutants was observed. The addition of Al₂O₃ nanoparticles to the diesel fuel provided a large surface area for interaction between water molecules and

Table 2: Summary of CeO₂ nanoparticle studies as an additive in diesel/biodiesel fuel

| Authors | Base fuel | Nanoparticles | Mass fraction of nanoparticles |
|---|----------------------------------|--|--------------------------------|
| 1 Praveena et al. [46] | Grapeseed oil biodiesel | CeO ₂ and ZnO | 100 ppm |
| Engine performance: BTE of CeO ₂ and ZnO increased by 1.4 and 1.71% from 28.8. BSFC of CeO ₂ decreased to 0.30 kg/kW h and BSFC of ZnO reduced to 0.29 kg/kW h | | | |
| Harmful emission: NO _x emissions of CeO ₂ and ZnO were reduced by 74.16 and 80.06%, respectively | | | |
| 2 Praveena et al. [47] | Grapeseed oil biodiesel | CeO ₂ and ZnO | 50 and 100 ppm |
| Engine performance: Improved BTE. Reduced BTE by 29.34 and 29.23% for GSD ZnO100 and GSD CeO ₂ 100. BSFC improved to 0.31 kg kW ⁻¹ h ⁻¹ | | | |
| Harmful emission: NO _x , HC, and CO emissions reduced | | | |
| 3 Karthikeyan et al. [48] | GSO biodiesel | CeO ₂ | 50 and 100 ppm |
| Engine performance: Higher BTE and lower BSFC | | | |
| Harmful emission: Reduction in harmful emission | | | |
| 4 Narasiman et al. [58] | SOME biodiesel and diesel | CeO ₂ | 25 ppm |
| Engine performance: Lower BTE than B20 | | | |
| Harmful emission: Increase in NO _x emission and a significant decrease in HC emission | | | |
| 5 Sathiyamoorthi et al. [59] | Neem oil biodiesel | CeO ₂ | 50 ppm |
| Engine performance: Higher BTE and BSFC as compared to B20 | | | |
| Harmful emission: NO _x , Smoke, HC, and CO emissions significantly reduced | | | |
| 6 Ghareghani et al. [60] | Diesel–biodiesel fuel (B5) | CeO ₂ | 90 ppm |
| Engine performance: BTE for B5W7m (B5 containing 7% water and nanoparticle) was increased by more than 13.5 and 6% compared to B5W7 and B5. BSFC was reduced by 8 and 23% | | | |
| Harmful emission: CO emission for B5W7m reduced by 42 and 3% as compared to B5W7 and B5, respectively | | | |
| 7 Khalife et al. [68] | Biodiesel/diesel fuel blend (B5) | CeO ₂ | 90 ppm |
| Engine performance: BSFC reduced by 16%. BTE was increased by 11% | | | |
| Harmful emission: CO, HC, and NO _x emissions reduced by 51, 45, and 27%, respectively, as compared to those of neat biodiesel/diesel fuel | | | |
| 8 Mei et al. [69] | Diesel | CeO ₂ | 50 and 100 ppm |
| Engine performance: Higher BTE and slight decreased in BSFC | | | |
| Harmful emission: Harmful pollutants including HC, CO, and NO _x decreased | | | |
| 9 Sathiyamoorthi et al. [70] | Neat lemongrass oil biodiesel | CeO ₂ | 50 ppm |
| Engine performance: Higher BTE and BSFC as compared to B20 | | | |
| Harmful emission: NO _x , Smoke, HC, and CO emissions significantly reduced | | | |
| 10 Annamalai et al. [61] | Neat lemongrass oil biodiesel | CeO ₂ | 30 ppm |
| Engine performance: Higher BTE and lower BSFC | | | |
| Harmful emission: UBHC and CO emission reduced by 35.5 and 16.03%. NO _x reduced by 24.8 and 20.3% and smoke by 6.4 and 19.8% as compared to neat LGO and neat diesel fuel | | | |
| 11 Pandey et al. [72] | Karanja oil biodiesel | CeO ₂ | 30, 40, 45, 50, and 80 ppm |
| Engine performance: Lower BSFC | | | |
| Harmful emission: Lower CO, CO ₂ , HC, and NO _x emission | | | |
| 12 Pandey et al. [73] | Karanja oil biodiesel | CeO ₂ | 30, 40, 45, 50, and 80 ppm |
| Engine performance: Lower BSFC | | | |
| Harmful emission: Lower CO, CO ₂ , HC, and NO _x emission | | | |
| 13 Babu and Praneeth [74] | Karanja biodiesel | CeO ₂ | — |
| Engine performance: Improvement in BTE | | | |
| Harmful emission: Lower emissions | | | |
| 14 Ananda et al. [75] | Ethanol–gasoline blend | CeO ₂ | 100, 150, and 200 mg |
| Engine performance: Improvement in BTE | | | |
| Harmful emission: Lower emissions | | | |
| 15 Janakiraman et al. [76] | Garcinia gummi-gutta biodiesel | CeO ₂ , ZrO ₂ , TiO ₂ | 25 ppm |
| Engine performance: Higher BTE and lower BSEF | | | |
| Harmful emission: Lower CO, lower NO _x , and smoke emissions | | | |
| 16 Senthil and Ramesh [80] | Ginger grass oil | CeO ₂ | 30 ppm |
| Engine performance: Higher BTE and lower BSFC | | | |
| Harmful emission: Lower CO ₂ , HC, and NO _x emission. All samples have lower CO emission except for B10, which was higher at lower load and then decreased at maximum load | | | |
| 17 Thangavelu et al. [81] | Waste tyre oil | CeO ₂ | 100 ppm |
| Engine performance: Improvement in BTE | | | |

Table 2: Continued

| Authors | Base fuel | Nanoparticles | Mass fraction of nanoparticles | |
|---------|--|-----------------------------|--|---------------------|
| 18 | Hawi et al. [82] | Waste cooking oil biodiesel | CeO ₂ | 90 ppm |
| | Harmful emission: Reduced emissions for HC, CO, and smoke by 3, 1.33, and 7.7%, respectively | | | |
| | Engine performance: Improved BSFC and BTE under low to medium loads | | | |
| 19 | Akram et al. [83] | Waste cooking oil biodiesel | CeO ₂ and Ce _{0.5} Co _{0.5} | 100 ppm |
| | Harmful emission: NO _x emission reduced up to 15.4%. No significant effect on HC emissions | | | |
| | Engine performance: Not mentioned | | | |
| | Harmful emission: CO, NO _x , and UBHC emissions reduced by 18.27, 6.57, and 23.46%, respectively, for CeO ₂ and 24.18, 13.96, and 40.74%, respectively, for Ce _{0.5} Co _{0.5} | | | |
| 20 | Selvan et al. [86] | Diesterol fuel | CeO ₂ and CNT | 25, 50, and 100 ppm |
| | Engine performance: Lower BSFC and higher BTE | | | |
| | Harmful emission: The addition of E20 + CERIA 50 + CNT 50 increased CO emission to 22.2% and reduced the hydrocarbon and smoke emission to 7.2% and 47.6%, respectively, as compared to diesterol fuel | | | |

fuel particles. Due to the high surface activity of the water molecules, hydrogen atom decomposes from the water during combustion which promotes complete combustion.

Gumus et al. [50] carried out a study to investigate the influence of Al₂O₃ and CuO nanoparticles in diesel fuel. The nanoparticle fuel blends were prepared from a concentration level of 50 ppm before comparing the performance, combustion, and emission characteristics of the blends with standard diesel fuel. The testing was conducted between 1,200 and 3,600 rpm with an interval of 250 rpm. Based on their findings, the BSFC of nanoparticle fuel blend was lower than that of diesel fuel. The BSFC of CuO and Al₂O₃ additives decreased by up to 0.5 and 1.2%, respectively. With the addition of Al₂O₃ to pure diesel, CO, HC, and NO_x emissions reduced up to 11, 13, and 6%, respectively. On the contrary, the CO, HC, and NO_x emissions of CuO additive reduced up to 5, 8, and 2%, respectively. The presence of excess oxygen and nanoparticles in diesel fuels improved the fuel properties and combustion efficiency, which led to lower BSFC and harmful emissions [92,93].

In another study, Ang et al. [49] demonstrated a significant reduction in BSFC and higher BTE in the diesel fuel blends with Al₂O₃, CNT, and SiO₂ nanoparticles. As compared to Al₂O₃, and SiO₂ blend, the CNT blend exhibited the highest emission reduction of 19.8% with a 100 ppm of CNT blends with pure diesel (DC100) under 25% engine load. Similarly, the CNT blend also had the highest reduction in BTE. From the findings of Selvan et al. [88], CNT blends also demonstrated an improvement in BSFC. These results can be ascribed to the higher calorific value of CNT which led to a substantial reduction in BSFC and BTE. However, the findings are in contrast with the results obtained by Raju et al. [94] who

investigated the effect of different dosing levels of Al₂O₃ and CNT nanoparticles in novel tamarind seed methyl ester (TSME) biodiesel for diesel engine applications. As compared to other samples, the TSME biodiesel with a dosing level of 60 ppm Al₂O₃ nanoparticles exhibited better diesel engine characteristics with a lower BSFC value. This can be explained by the oxygen content of Al₂O₃ in TSME biodiesel. Besides, the addition of nanoparticles showed a remarkable improvement in exhaust emissions except for NO_x. The NO_x emission was found to be higher in the fuel blend of Al₂O₃ nanoparticles with a dosing level of 60 ppm and lower than the B20 fuel blends. The most significant observation from this study was the engine combustion characteristics of TSME biodiesel with nano-additive demonstrated a remarkable improvement in exhaust emission as compared with B20 fuel blends.

Balasubramanian et al. [95] investigated the influence of Al₂O₃ nanoparticles in lemongrass oil biodiesel in a single-cylinder diesel engine. Different concentrations of nanoparticle additive (10, 20, and 30 ppm) were prepared and blended in the lemongrass oil biodiesel using an ultrasonicator. The best engine combustion performance and exhaust emissions were obtained under the dosing level of 20 ppm. For the same concentration level of Al₂O₃ nanoparticles, BTE was significantly improved by 11.5% as compared to the neat biodiesel. All emissions like HC, CO, NO_x, and smoke emission decreased by 40, 6, 31, and 39%, respectively, as compared to the neat biodiesel. It is worth noting that the addition of Al₂O₃ nanoparticle in the lemongrass oil biodiesel improved engine combustion performance and reduced the harmful emission owing to the lower NO_x emission and better combustion characteristics.

Recently, Soudagar *et al.* [96] studied the potential use of Al₂O₃ nanoparticles as a fuel additive in Honge oil methyl ester (HOME20) biodiesel using different dosing levels of 20, 40, and 60 ppm. Based on their experiments, HOME20 fuel blend with a nanoparticle concentration level of 40 ppm demonstrated a better engine combustion performance as compared to that of 20 and 60 ppm. For the dosing level of 40 ppm, BTE was found to be increased by 10.57% with a reduction in BSFC by 11.65%. Furthermore, HC, CO, and smoke emission reduced by 26.72, 48.43, and 22.84%, respectively. Conversely, the NO_x emission increased by 11.27%.

Table 3 summarized all of the above-mentioned experimental studies with some other undiscussed research works.

4.3 TiO₂

Recently, Kumar *et al.* [103] investigated the influence of TiO₂ nanoparticles on the performance, emission, and combustion characteristics of waste orange peel oil biodiesel with the dosing levels between 50 and 100 ppm. From the findings, the addition of nanoparticles with the dosing levels of 50 and 100 ppm promoted the BTE for about 1.4% and 3.0%, respectively, under maximum break power. However, pure diesel fuel showed maximum efficiency as compared with other testing samples. Also, they observed a significant reduction in smoke (24.2%), NO_x (9.7%), CO (18.4%), and HC (16.0%) for the sample with a dosing level of 100 ppm. Overall, orange oil biodiesel nano-emulsions (OOMEs) with TiO₂ additive had better engine combustion performance as compared to neat biodiesel due to the improvement in the cylinder peak pressure, heat release rate, and combustion emissions. Furthermore, TiO₂ nano-additives produce hydrogen from water, which can be attributed to its catalytic photoelectric effect [104,105] and its ability to activate molecular bonds in the water–diesel emulsion [106].

In another recent study, Senthil *et al.* [107] evaluated the influence of two different dosing levels of TiO₂ nanoparticles on the emission behaviour of diesel fuel in four-stroke, single-cylinder, CI engine. Under the dosing levels of 50 and 100 ppm, the addition of TiO₂ nanoparticles improved the calorific values by 0.4 and 0.68%, respectively. Likewise, the flashpoint of the biodiesel was also enhanced by 4.4 and 6.67% under the dosing level of 50 and 100 ppm, respectively. The addition of TiO₂ to diesel fuel also caused a significant reduction

in CO, HC, NO_x, and smoke emissions. These findings are consistent with the conclusions of previous studies [52,62,108].

Karthikeyan and Viswanath [109] studied the effect of TiO₂ nanoparticle on the combustion performance and emission characteristics of tamanu biodiesel in a two-cylinder diesel engine under a constant speed of 2,000 rpm. All emissions such as HC, CO, NO_x, and smoke were found to be lower. The concentration level of 100 ppm produced the best combustion performance among other concentrations.

The influence of TiO₂ nanoparticles in *Calophyllum inophyllum* biodiesel on the properties of fuel combustion features, engine performance, and emissions was studied by Praveen *et al.* [110]. They found that the kinematic viscosity, calorific value, and cetane number of the biodiesel increased with the addition of TiO₂ nanoparticles as compared to the biodiesel. Higher cetane numbers improved the BTE owing to the higher oxygen quantity. The NO_x and HC emissions reduced with the addition of nanoparticles as compared to the neat biodiesel. Similar findings were also reported by the previous researcher who studied the influence of TiO₂ nanoparticles in *Calophyllum inophyllum* biodiesel [62].

Nanthagopal *et al.* [62] carried out the experiment using two different types of nanoparticles, namely, TiO₂ and ZnO; 50 and 100 ppm of each nanoparticle were blended into the biodiesel using an ultrasonicator. It was reported that a higher BTE was observed in the biodiesel with the addition of TiO₂ and ZnO nanoparticles as compared to pure biodiesel. For biodiesel fuel doped with 100 ppm of TiO₂ nanoparticles, BTE increased by 17% as compared to that of pure biodiesel. Balasubramanian *et al.* [111] also observed a similar result when *Mimusops elengi* methyl ester (MEME) biodiesel was doped with TiO₂ nanoparticle. This effect was due to the function of TiO₂ nanoparticles as oxygen buffers and fuel boosters, which resulted in complete combustion and higher thermal efficiency.

El-Seesy *et al.* [112] carried out the experimental investigations to evaluate the combustion performance and emission characteristics of different fuel mixtures with varying percentages of *n*-hexane (5, 10, and 15% by volume) and dosing levels of TiO₂ nanoparticles (25 and 50 ppm). All of the mixtures were tested in a diesel engine under different engine loads and at a constant speed of 2,000 rpm. It was found out that by adding TiO₂ nanoparticles in jojoba biodiesel–diesel–*n*-hexane mixture J30D5H (30% JME + 65% D100 + 5% *n*-hexane), the BTE increased up to 15% as compared to the J30D5H fuel blend. A significant reduction in BSFC up to 12% was

Table 3: Summary of Al₂O₃ nanoparticles studies as an additive in diesel/biodiesel fuel

| Authors | Base fuel | Nanoparticles | Mass fraction of nanoparticles |
|--|---|---|--------------------------------|
| 1 Sathiamurthi et al. [88] Engine performance: Higher BTE Harmful emission: Reduction in NO _x and UBHC contents of all loads | Diesel fuel | Al ₂ O ₃ | 0.5 and 1 g/L |
| 2 Venkatesan and Kadiresh [89] Engine performance: Higher BTE Harmful emission: Reduction in NO _x and UBHC contents of all loads | Diesel fuel | Al ₂ O ₃ | 1 and 1.5 g/L |
| 3 Basha [90] Engine performance: Higher BTE Harmful emission: Reduction in NO _x , CO, and smoke emissions | Diesel fuel | Al ₂ O ₃ | 25, 50, and 100 ppm |
| 4 Gumus et al. [50] Engine performance: Lower BSFC. Al ₂ O ₃ and CuO reduced by 0.5 and 1.2%, respectively Harmful emission: CO, UHC, and NO _x reduced by 11, 13, and 6% for Al ₂ O ₃ and 5, 8, and 2%, respectively, for CuO | Diesel fuel | Al ₂ O ₃ and CuO | 50 ppm |
| 5 Ang et al. [49] Engine performance: Lower BSFC. Higher BTE for all cases (CNT blends improved the BSFC by 19.85%) Harmful emission: HC emissions of Al ₂ O ₃ and SiO ₂ blends were 1.76 times lower and no change in NO _x . NO _x emissions of CNT improved by 4.48% with an increase in CO, CO ₂ , and HC emissions | Diesel fuel | Al ₂ O ₃ , CNT, SiO ₂ | 25, 50, and 100 ppm |
| 6 Raju et al. [94] Engine performance: Lower BSFC and higher BTE Harmful emission: A significant reduction in smoke, HC, and CO emissions. A higher NO _x for Al ₂ O ₃ with 60 ppm | Tamarind seed methyl ester | Al ₂ O ₃ and CNT | 30 and 60 ppm |
| 7 Balasubramanian et al. [95] Engine performance: Higher BTE and lower BSFC Harmful emission: HC and CO emissions reduced by 40% and 6%. NO _x and smoke emissions decreased by 31% and 39% as compared to pure biodiesel | Lemongrass oil biodiesel | Al ₂ O ₃ | 10, 20, and 30 ppm |
| 8 Soudagar et al. [96] Engine performance: BTE improved by 10.57%, while BSFC decreased by 11.65% Harmful emission: CO emission reduced by 42 and 3% as compared to B5W7 and B5, respectively | Honge oil methyl ester | Al ₂ O ₃ | 90 ppm |
| 9 Anchupogu et al. [63] Engine performance: Higher BTE and lower BSFC with an increase in brake power for all the fuel samples Harmful emission: CO, HC, NO _x , and smoke emissions reduced by 6.09, 12.24%, 7.76, and 6.2%, respectively | <i>Calophyllum inophyllum</i> biodiesel | Al ₂ O ₃ | 40 ppm |
| 10 Mahalingam and Ganesan [97] Engine performance: Maximum BTE (10 ppm) was achieved under full load. For the case of 15 and 20 ppm, BTE decreased. BSFC decreased with a higher engine load Harmful emission: 20 ppm had a higher CO emission (0.35%). NO _x emission for 10 ppm was higher when compared to the other samples | Rubber seed oil | Al ₂ O ₃ | 10, 15, and 20 ppm |
| 11 Shaafi and Velraj [98] Engine performance: Higher BTE and lower BSFC under a higher engine load Harmful emission: Remarkable reduction in harmful emissions. Observed a small increase in NO _x emission with nano-additive | Soybean biodiesel | Al ₂ O ₃ | 100 ppm |
| 12 Prabu and Anand [85] Engine performance: BTE and BSFC were almost similar to neat diesel Harmful emission: Lower NO _x , CO, UHC, and smoke opacity | Jatropha biodiesel | Al ₂ O ₃ and CeO ₂ | 10, 30, and 60 ppm |
| 13 Ramesh et al. [99] Engine performance: Higher BTE Harmful emission: Lower CO, UBHC, and NO _x emissions | Poultry litter oil methyl ester | Al ₂ O ₃ | 30 ppm |
| 14 Sivakumar [100] Engine performance: 100 ppm exhibited a better BTE and BSFC under maximum load Harmful emission: Lower HC, CO, and smoke emissions for both ppm | Pongamia methylester | Al ₂ O ₃ | 50 and 100 ppm |
| 15 Syed Aalam et al. [101] Engine performance: BSFC values of 25 ppm were nearly the same as pure diesel fuel. BSFC value decreased by about 6% for 50 ppm. BTE increased; 50 ppm showed a maximum increase (2.5%) when compared to 25 ppm Harmful emission: Lower HC, CO, and smoke emissions with a slight increase in NO _x emission | <i>Zizipus jujube</i> methyl ester blended fuel | Al ₂ O ₃ | 25 and 50 ppm |
| 16 Mehta et al. [102] Engine performance: Reduced by 7% in BSFC with Al ₂ O ₃ . Increase in BTE by 9, 4, and 2% for Al ₂ O ₃ , FeO ₂ , and B ₂ O ₃ , respectively, as compared to diesel under higher loads Harmful emission: CO emission reduced by 25–40% in CO (vol%), HC emission reduced by 8 and 4% for Al ₂ O ₃ and FeO ₂ , respectively. NO _x emission increased by 5 and 3% for Al ₂ O ₃ and FeO ₂ , respectively | Petrodiesel | Al ₂ O ₃ , FeO ₂ , and B ₂ O ₃ | — |

also observed in the J30D5H nanoparticle's fuel blend. This can be credited to the beneficial presence of the nanoparticles which enhanced the combustion and mixing process. Furthermore, the NO_x emission was observed to be higher when the nanoparticles were blended with J30D5H

biodiesel. Surprisingly, the addition of *n*-hexane and *n*-pentane enhanced the BTE and reduced the harmful emissions [113].

Table 4 summarizes the effect of TiO₂ nanoparticles on the performance, combustion, and emission characteristics

Table 4: Summary of TiO₂ nanoparticles as an additive in diesel/biodiesel fuel

| Authors | Base fuel | Nanoparticles | Mass fraction of nanoparticles |
|---|---|--------------------------|--------------------------------|
| 1 Kumar et al. [103] | OOME biodiesel | TiO ₂ | 50 and 100 ppm |
| Engine performance: For 50 and 100 ppm, BTE increased by 1.6 and 3.0%, respectively, under maximum load condition. Lower BSFC | | | |
| Harmful emission: A reduction in Co, HC, and smoke emission. NO _x showed an increasing trend with the addition of nanoparticle | | | |
| 2 Senthil et al. [107] | Diesel fuel | TiO ₂ | 50 and 100 ppm |
| Engine performance: — | | | |
| Harmful emission: For 50 and 100 ppm, HC emissions reduced by 1.7 and 2.3%, respectively. Likewise, for 50 and 100 ppm, NO _x emissions decreased by 3.7 and 4.1%, respectively. CO and smoke opacity also decreased | | | |
| 3 Yuvarajan et al. [108] | Mustard oil methyl ester | TiO ₂ | 100 and 200 ppm |
| Engine performance: — | | | |
| Harmful emission: Lower HC, CO, and smoke emissions. NO _x emissions were higher than diesel under all load conditions | | | |
| 4 Karthikeyan and Viswanath [109] | Tamanu biodiesel | TiO ₂ | 25, 50, 75, and 100 ppm |
| Engine performance: — | | | |
| Harmful emission: CO, NO _x , and smoke emissions reduced | | | |
| 5 Anchupogu et al. [110] | <i>Calophyllum inophyllum</i> biodiesel | TiO ₂ | 40 ppm |
| Engine performance: Higher BTE and heat release | | | |
| Harmful emission: CO and HC decreased by 23 and 12%, respectively. Smoke emission also decreased | | | |
| 6 Nanthagopal et al. [62] | <i>Calophyllum inophyllum</i> biodiesel | TiO ₂ and ZnO | 50 and 100 ppm |
| Engine performance: Higher BTE with increasing engine load. Lower BSFC | | | |
| Harmful emission: Lower HC, CO, CO ₂ , NO _x , and smoke emissions | | | |
| 7 Balasubramanian et al. [111] | MEME biodiesel | TiO ₂ | 25, 50, 75, and 100 ppm |
| Engine performance: Higher BTE in 25 ppm | | | |
| Harmful emission: Lower HC and smoke emissions. NO _x emission rose marginally | | | |
| 8 Manigandan et al. [114] | Corn methyl ester biodiesel | TiO ₂ | 100, 200, and 300 ppm |
| Engine performance: Higher BP and BTE. Lower BSFC | | | |
| Harmful emission: Lower CO, HC, and smoke emissions. Lower NO _x and particulate emission | | | |
| 9 Sundararajan and Anand [115] | Plastic diesel oil | TiO ₂ | 20 ppm |
| Engine performance: Higher BTE and lower BSFC. Improved combustion efficiency | | | |
| Harmful emission: Lower NO _x emissions | | | |
| 10 El-Seesy et al. [112] | J30D5H blended biodiesel | TiO ₂ | 25 and 50 ppm |
| Engine performance: BSFC reduced by 12%, while BTE increased by 15% | | | |
| Harmful emission: CO and UHC emissions decreased by 20 and 50%, respectively. However, there was an increase in NO _x by 15% | | | |
| 11 Örs et al. [116] | Waste cooking oil biodiesel | TiO ₂ | — |
| Engine performance: Increased the maximum cylinder pressure and heat release rate values. Higher BTE. Lower BSFC | | | |
| Harmful emission: Lower CO, HC, and smoke opacity emission. Higher CO ₂ and NO emissions | | | |
| 12 Kandasamy and Jabaraj [117] | Cottonseed oil methyl ester | TiO ₂ | 20 and 40 ppm |
| Engine performance: Improved combustion efficiency | | | |
| Harmful emission: Lower exhaust gas emissions | | | |
| 13 Nithya et al. [64] | Canola biodiesel | TiO ₂ | 300 ppm |
| Engine performance: — | | | |
| Harmful emission: NO _x reduced by 5%. CO, HC, and smoke opacity emissions reduced to 32, 30, and 52%, respectively | | | |
| 14 Pandian et al. [118] | Mustard oil biodiesel | TiO ₂ | 100, 200, and 300 ppm |
| Engine performance: — | | | |
| Harmful emission: Significant reduction in HC, CO, NO _x , and smoke emission. The dosing level of 300 ppm produced the best performance | | | |
| 15 Prabhu et al. [119] | Neem oil biodiesel | TiO ₂ | 250 and 500 ppm |
| Engine performance: BTE increased, and BSFC decreased | | | |
| Harmful emission: Lower CO, HC, and smoke emissions. However, a slight increase was observed in NO _x for the dosing level of 250 ppm as compared with B20 and 500 ppm. Overall, 250 ppm produced the best performance | | | |

of diesel/biodiesel fuel with some other undiscussed research works.

4.4 Other metal oxides nanoparticles

The effects of other metal oxide nanoparticles as an additive on the performance, combustion, and emission characteristics in the ICE are presented in this section and listed in Table 5. Recently, Mehregan and Moghiman [120] added 25 and 50 ppm Mn_2O_3 and Co_3O_4 , respectively, into the waste frying oil biodiesel which contained 20% wastes frying oil biodiesel and 80% ultralow sulphur diesel and urea-selective catalytic reduction (SCR) system. A reduction in NO_x emissions was reported from the nanoparticle fuel blend. Co_3O_4 with the dosing level of 50 ppm demonstrated remarkable thermal properties.

Recently Vedagiri et al. [121] investigated the influence of different open burning chamber geometries on the performance, combustion, and emission of CI engines by adding ZnO nanoparticles into grapeseed oil methyl ester (GOME) biodiesel as a fuel additive. With the addition of ZnO nanoparticles, the BTE was found to be increased from 28.17 to 29.3%, and BSFC decreased slightly from 0.3258 to 0.3128 kg/kWh. A significant reduction in NO_x , HC, and CO emissions was also observed. Overall, the toroidal combustion chamber produced a better combustion performance as compared to the other combustion chambers.

Amirabedia et al. [122] and Amirabedi et al. [123] blended two different types of nanoparticles into the spark-ignition (SI) gasoline along with ethanol. An ultrasonicator was used to blend 10 ppm Mn_2O_3 and 20 ppm Co_3O_4 nanoparticles into the gasoline-ethanol fuel. From the results, it was observed that higher BP values were obtained with increasing dosing levels of nanoparticles. For the dosing levels of 10 and 20 ppm Mn_2O_3 , the BP values increased by 14.38 and 19.56%, respectively. Meanwhile, the BP values of 10 and 20 ppm Co_3O_4 increased by 7.96 and 11.5%, respectively. Furthermore, a reduction in CO and UHC emissions was observed with an increase in CO_2 when ethanol was mixed with the nanoparticles. From the results, the gasoline-ethanol fuel blend with 20 ppm Mn_2O_3 nanoparticles produced the best combustion and emission performances. These findings are consistent with the previous study by Ananda et al. [75], where the addition of ethanol and nanoparticle additives in gasoline fuel improved engine performance and exhaust emissions.

Devarajan et al. [53] investigated the effect of different mass fractions of AgO nano-additive (5 and 10 ppm) and

particle sizes (10 and 20 nm) on the performance, emission, and combustion behaviour of palm stearin biodiesel. At peak load conditions, a higher BTE value and a low BSFC emission were obtained from the biodiesel fuel blend with nanoparticles with a particle size of 20 nm and a concentration level of 10 ppm. The addition of AgO nanoparticles to the biodiesel reduced the harmful emission. It was observed that the biodiesel fuel with 10 ppm of 20 nm AgO nanoparticles exhibited the best engine performance. As compared to biodiesel, the in-cylinder pressure reduced by 2.2% and the net heat release rate value improved by 4.7%.

Tamilvanan et al. [124] investigated the performance, combustion, and emission behaviours of *Calophyllum inophyllum* seed oil (CISO) biodiesel with 30 ppm Cu additives in a single-cylinder diesel engine under varying loads. At all loads, a higher BTE value was obtained from the biodiesel blend with Cu as compared to that without additive. However, the BTE value was slightly lower than diesel. The reduction in BTE value in biodiesel can be ascribed to the lower heat of combustion. The addition of Cu nanoparticles in biodiesel fuel blends increased the combustion properties of the engine and reduced the emissions significantly.

Venu and Appavu [125] added Zr nanoparticles into the jatropha biodiesel for the CI engine. It was pointed out that the BSFC value of jatropha biodiesel with Zr nanoparticles was the lowest, and the BTE value was the highest as compared to diesel and biodiesel without Zr nanoparticles. A significant reduction in HC, CO, and smoke emissions was observed with a slight increase in NO_x and CO_2 emissions. Some similarities can be found between this work and the work of Yogaraj et al. [126] who used Ag-TiO₂ nanoparticle as the fuel additive. By adding the additives, incomplete combustion led to lower BSFC, CO_2 , and HC emissions. However, a higher NO_x emission was observed in all cases.

The effect of adding CuO nano-additives to the *Neochloris oleoabundans* methyl ester diesel (NOMED) blend was investigated by Kalaimurugan et al. [127]. A month later, the same authors published the work using RuO₂ nanoparticles, whose fuel properties were very similar to that of CuO nanoparticles [128] except for the difference in the cetane index value. The cetane index of RuO₂ and CuO was 52 and 55, respectively. The fuel test was performed using different concentration levels between 25 and 100 ppm under varying load conditions. From the results, both 100 ppm nanoparticles promoted a lower BTE, BSFC, and exhaust emissions.

Srinidhi et al. [129] studied the CI performance of NiO nanoparticles in *Azadirachta indica* biodiesel at different injection timings and dosing levels from 25 to 100 ppm.

Table 5: Summary of other metal oxides nanoparticles as an additive in diesel/biodiesel fuel

| Authors | Base fuel | Nanoparticles | Mass fraction of nanoparticles |
|--|-------------------------------------|---|--------------------------------|
| 1 Mehregan and Moghiman [120] | Waste frying oil biodiesel | Mn ₂ O ₃ and Co ₃ O ₄ | 25 and 50 ppm |
| Engine performance: — | | | |
| Harmful emission: Reduced NO _x emissions. Co ₃ O ₄ with 50 ppm produced better results | | | |
| 2 Vedagiri <i>et al.</i> [121] | GOME biodiesel | ZnO | 100 ppm |
| Engine performance: Higher BTE and lower BSFC | | | |
| Harmful emission: Lower smoke emissions, HC, CO, and NO _x | | | |
| 3 Amirabedia <i>et al.</i> [122] | gasoline fuelled | Mn ₂ O ₃ and Co ₃ O ₄ | 10 and 20 ppm |
| Engine performance: Higher BTE and BP. Lower BSFC | | | |
| Harmful emission: Lower CO, UHC, and NO _x emission. Higher CO ₂ emission. Gasoline – 10% of ethanol – 20 ppm Mn ₂ O ₃ produced better results | | | |
| 4 Amirabedi <i>et al.</i> [123] | Gasoline fuelled | Mn ₂ O ₃ | 10 and 20 ppm |
| Engine performance: Higher BTE and BP. Lower BSFC reduced | | | |
| Harmful emission: Lower CO, UHC, and NO _x emission. Higher CO ₂ emission | | | |
| 5 Devarajan <i>et al.</i> [53] | Palm stearin biodiesel | AgO | 5 and 10 ppm |
| Engine performance: Higher BTE and lower BSFC | | | |
| Harmful emission: HC and CO emissions were reduced by up to 8.8 and 11.9%, respectively. NO _x and smoke emissions were also reduced | | | |
| 6 Tamilvanan <i>et al.</i> [124] | CISO biodiesel | Cu | 30 ppm |
| Engine performance: Higher BTE and lower BSFC | | | |
| Harmful emission: HC, NO _x , and O ₂ emissions reduced. However, CO ₂ emission increased | | | |
| 7 Venu and Appavu [125] | Jatropha seed oil biodiesel | Zr | 25 ppm |
| Engine performance: Lower BSFC and higher BTE | | | |
| Harmful emission: Reduction in HC, CO emissions, and smoke opacity. But a slight increase in NO _x and CO ₂ emissions | | | |
| 8 Yogaraj <i>et al.</i> [126] | Jatropha biodiesel | Ag–TiO ₂ | 30 ppm |
| Engine performance: A marginal increase of 3.3% at maximum load in BTE. Higher BP and lower BSFC | | | |
| Harmful emission: Decreased UBHC by 12%, CO by 14% at a maximum load | | | |
| 9 Kalaimurugan <i>et al.</i> [127] | NOMAD blended | CuO ₂ | 25, 50, 75, and 100 ppm |
| Engine performance: Higher BTE and EGT. Lower BSFC | | | |
| Harmful emission: Lower CO, HC, and smoke emissions. Higher NO _x emission. The concentration level of 100 ppm produced better results | | | |
| 10 Kalaimurugan <i>et al.</i> [128] | NOMAD blended | RuO ₂ | 25, 50, 75, and 100 ppm |
| Engine performance: Lower BSFC. Higher BTE | | | |
| Harmful emission: Emits less CO and HC emissions. Unfortunately, a higher amount of NO _x emissions was observed compared to B20 | | | |
| 11 Srinidhi <i>et al.</i> [129] | <i>Azadirachta indica</i> biodiesel | NiO | 25, 50, 75, and 100 ppm |
| Engine performance: Higher BTE. Lower BSFC | | | |
| Harmful emission: Lower HC and CO emissions. Higher NO _x emission | | | |
| 12 Perumal and Ilangkumaran [54] | Pongamia methyl ester biodiesel | CuO ₂ | 50 and 100 ppm |
| Engine performance: Higher BTE. Lower BSFC | | | |
| Harmful emission: Lower CO, HC, NO _x , and smoke emissions | | | |
| 13 Prabakaran and Vijayabalan [130] | Diesohol blends | ZnO | 100, 200, and 300 ppm |
| Engine performance: Higher BTE | | | |
| Harmful emission: Lower CO, HC, and NO _x emissions | | | |
| 14 Prabakaran and Udhoji [131] | Diesel–biodiesel–ethanol blends | ZnO | 250 ppm |
| Engine performance: Higher BTE. Lower BSFC | | | |
| Harmful emission: Lower CO, NO _x , and smoke emissions. A slight reduction in HC emission | | | |
| 15 Gangwar <i>et al.</i> [132] | Diesel fuel | Cu–Zn alloy | 100 and 200 ppm |
| Engine performance: Higher BTE. Lower BSFC | | | |
| Harmful emission: Lower CO, UBHC, CO ₂ , and NO _x emissions under full load. 200 ppm of nanoparticles produced better results | | | |

Three types of injection timing were prepared including 23, 19, and 27°bTDC (before top dead centre). As a result, the increase in fuel injection timing and the presence of nanoparticles improved the overall engine performance

and reduced the release of harmful emissions from the engine.

The blending of CuO nanoparticles in pongamia biodiesel fuel has undergone different engine operation

characteristics in a single-stroke four-cylinder engine. By using a 10-mL Span80 surfactant and an ultrasonicator, 50 and 100 ppm CuO nanoparticles were mixed with the pongamia biodiesel to obtain different biodiesel blends. For the dosing level of 100 ppm, the engine performance and maximum emission reduction enhanced [54]. Higher cetane number and oxygen content improved the BTE value with a reduction in HC, CO, and smoke emissions [130–133].

4.5 Non-metal oxide nanoparticles

Aside from metal oxide nanoparticles, non-metal oxide nanoparticles also demonstrated excellent properties [133–148] in enhancing the performance, combustion, and emission characteristics of an ICE. Table 6 summarized all of the recent findings from previous studies.

In one of the most recent works, Soudagar et al. [134] investigated the influences of GO nanoparticles on the performance and emissions of a CI engine fuelled with dairy scum oil (DSOME) biodiesel using dosing levels of 20, 40, and 60 ppm under constant speed and varying BP and load conditions. GO is known as a nanoparticle with ultrahigh strength, good hydrophilicity, and dispersibility [147]. From the results, it was revealed that the net heat release and BTE values improved with an increasing amount of GO nano-additives in the fuel blends. Furthermore, the addition of GO nanoparticles in the biodiesel enhanced engine performance and emission characteristics. El-Seesy et al. [139,143] showed similar results on the performance and emissions of CI engine fuelled by Jatropa methyl ester biodiesel nanoparticle blend with GO nanoparticles. The addition of GO nanoparticles in the base fuel enhanced the combustion characteristics and reduced the exhaust emissions including CO, NO_x, SO₂, CO₂, and smoke. It also improved the overall engine performance parameters such as BTE and BP with a reduction in the BSFC values (as shown in Figure 4). Such superior performance can be attributed to the high surface area to volume ratio of the mixture, which promoted a better fuel–air mixing pattern during the combustion process.

Mei et al. [135] compared the combustion and emission of a standard rail diesel blended with non-metallic and metallic oxide nanoparticles. CNT and MoO₃ nanoparticles were used as the fuel additives in the study. All CNT diesel blend and MoO₃ diesel blend were found to achieve high efficiencies in fuel economy, combustion, and emissions as compared to pure diesel. This is because CNT nanoparticles possessed excellent thermal

conductivity and surface deficits [148], while MoO₃ owned superior catalytic oxidation performance. Based on the findings, it was observed that CNT offered superior combustion efficiency and better ability to reduce exhaust emissions as compared to MoO₃ diesel blend.

Sivathanu and Anantham [137] studied the capability of MWCNT as a fuel additive in improving the performance, emission, and combustion behaviour of diesel engine fuelled with waste fishing oil. As compared with neat biodiesel fuel, the addition of MWCNT in biodiesel promoted a lower exhaust emission and a shorter ignition delay. Under 100% load, BTE increased by 3.83%. On the contrary, the BSFC value by 3.87% with the presence of MWCNT. The findings also showed a substantial decrease in engine exhaust emissions including CO, UHC, NO, and smoke by 25, 9.09, 5.25, and 14.81%, respectively. At the same time, a slight increase by 17.39% in CO₂ emission was also observed. These results are in good agreement with the findings of Sulochana and Bhatti [138] and El-Seesy et al. [146].

Sandeep et al. [140] studied the ability of CNT as a fuel additive in improving diesel engine performance using HOME. As compared to pure biodiesel at full load, the addition of CNT enhanced the BTE value by 2.24% and reduced the BSFC by 20.68%. Besides, a remarkable reduction in harmful emissions was also observed.

Basha [141] investigated the combustion performance of pristine biodiesel and biodiesel emulsions blended with CNT and DEE in IC engines. The experimental results showed that the biodiesel emulsion fuel with CNT and DEE showed better efficiency, emission, and combustion characteristics in contrast to pure diesel and biodiesel. The BTE value of CNT + DEE fuel increased by 3.5%. Besides, NO_x and smoke emissions were reduced by 445 ppm and 35%, respectively, when compared with the pure diesel. The study also found out that the addition of 50 ppm of CNT and 50 mL of DEE to emulsified biodiesel fuel could reduce the delay in ignition. This is owing to higher cetane number of DEE.

Hosseini et al. [142] investigated the performance and emission characteristics of mixed diesel B5 and B10 with the addition of CNT. Different concentrations of 30, 60, and 90 ppm CNT nanoparticles were added into diesel. The findings revealed that the power, BTE, and EGT of all CNT fuel blends improved by 3.67, 8.12, and 5.57%, respectively. At the same time, biodiesel blends with CNT nanoparticle additive exhibited a significant reduction in BSFC. In terms of emission characteristics, it was found out that the CO, UHC, and soot emission of the diesel biodiesel mixture reduced with an increase in NO_x emission.

Table 6: Summary of non-metal oxides nanoparticles as an additive in diesel/biodiesel fuel

| Authors | Base fuel | Nanoparticles | Mass fraction of nanoparticles |
|---|----------------------------|--------------------------|--------------------------------|
| 1 Soudagar et al. [134] | DSOME biodiesel | GO | 20, 40, and 60 ppm |
| Engine performance: BTE improved by 11.56%. BSFC reduced by 8.34% | | | |
| Harmful emission: UBHC, smoke, CO ₂ , NO _x reduced by 21.68, 24.88, 38.662, and 5.62%, respectively | | | |
| 2 Mei et al. [135] | Neat diesel | CNT and MoO ₃ | 50 and 100 ppm |
| Engine performance: Higher BTE. Lower BSFC | | | |
| Harmful emission: All the emissions were decreased. CNT produced better results as compared to MoO ₃ | | | |
| 3 Hosseinzadeh et al. [136] | Waste cooking oil | Carbon | 38, 75, and 150 µM |
| Engine performance: Higher BP and BTE. Lower BSFC | | | |
| Harmful emission: HC, CO, and NO _x emission reduced under full load | | | |
| 4 Sivathanu and Anantham [137] | Waste fishing net oil | MWCNT | — |
| Engine performance: BTE increased by 3.83% and BSFC decreased by 3.87% | | | |
| Harmful emission: Reduction in CO, UHC, NO, and smoke by 25, 9.09, 5.25, and 14.81%. A slight increase in CO ₂ emission by 17.39% | | | |
| 5 Sulochana and Bhatti [138] | Waste fry oil methyl ester | MWCNT | 25 and 50 ppm |
| Engine performance: Higher BTE | | | |
| Harmful emission: Lower CO, HC, and NO _x emissions | | | |
| 6 El-Seesy et al. [139] | Jatropha methyl ester | GO, GNP and MWCNT | 50 ppm |
| Engine performance: BTE increased by 25% and BSFC decreased by 35% | | | |
| Harmful emission: Reduction in CO, UHC, NO, and smoke emissions by 55, 50, 45, and 14.81%, respectively | | | |
| 7 Sandeep et al. [140] | Honge oil methyl ester | CNT | 50 ppm |
| Engine performance: Higher BTE and lower BSFC | | | |
| Harmful emission: Lower HC emission. Higher NO _x emission | | | |
| 8 Basha [141] | Jatropha methyl ester | CNT | 50 ppm |
| Engine performance: Higher BTE | | | |
| Harmful emission: Harmful pollutants decreased | | | |
| 9 Hosseini et al. [142] | Waste cooking oil | CNT | 30,60, and 90 ppm |
| Engine performance: Increase in power (3.67%), BTE (8.12%), and EGT (5.57%) | | | |
| Harmful emission: CO, UHC, and soot exhaust emission reduced with an increase in NO _x emission | | | |
| 10 El-Seesy et al. [143] | Jatropha methyl ester | GO | 25, 50, 75, and 100 ppm |
| Engine performance: BTE, peak cylinder pressure, rate of pressure, and heat release rate enhanced by 17, 8, 6, and 6%, respectively | | | |
| Harmful emission: CO, UHC, and NO _x emissions decreases by 60, 50, and 15%, respectively; 50 ppm dosing level produced better results | | | |
| 11 El-Seesy et al. [144] | Jatropha methyl ester | GNPS | 25, 50, 75, and 100 ppm |
| Engine performance: Increased in BTE (25%) and reduced in BSFC (20%). Peak cylinder pressure, rate of pressure, and heat release rate increased by 6, 5, and 5%, respectively. | | | |
| Harmful emission: A remarkable decrease in CO, UHC, and NO _x emissions by 60, 50, and 40%, respectively. The dosing level of 50 ppm produced better results. | | | |
| 12 Hariram et al. [145] | Jajoba biodiesel | MWCNT | 50, 100, 1 and 150 ppm |
| Engine performance: Higher BTE and lower BSFC | | | |
| Harmful emission: Lower CO ₂ and smoke emission. Higher NO _x emission. The dosing level of 100 ppm produced better results | | | |
| 13 El-Seesy et al. [146] | Jajoba methyl ester | MWCNT | 10, 20, 30, 40, and 50 ppm. |
| Engine performance: Higher peak pressure | | | |
| Harmful emission: Lower NO _x , UHC, and CO emissions. The dosing level of 40 ppm produced better results | | | |

Hariram et al. [145] added MWCNT nanoparticles into the Jajoba biodiesel and the addition of 50, 100, and 150 ppm MWCNT nanoparticles reduced the ignition delay period. The BTE values of all concentration levels were found to be increased, while the BSFC reduced. The concentration level of 100 ppm MWCNT nanoparticles produced better combustion characteristics and engine performance as well as low harmful emissions.

El-Seesy et al. [146] studied the effect of different concentrations of MWCNT (1–50 ppm) into the jajoba

methyl ester diesel under different load conditions and engine speeds. The experimental analysis revealed that the addition of MWCNT nanoparticles improved the performance and emission characteristics. The BTE value increased upon the addition of MWCNT nanoparticle up to 16% in the biodiesel blend. At the same time, the BSFC performance decreased by 15%. By adding the MWCNTs into the biodiesel blend, the emissions of NO_x, UHC, and CO significantly reduced. With the nanoparticle's concentration of 20 ppm, the NO_x, CO, and UHC emissions

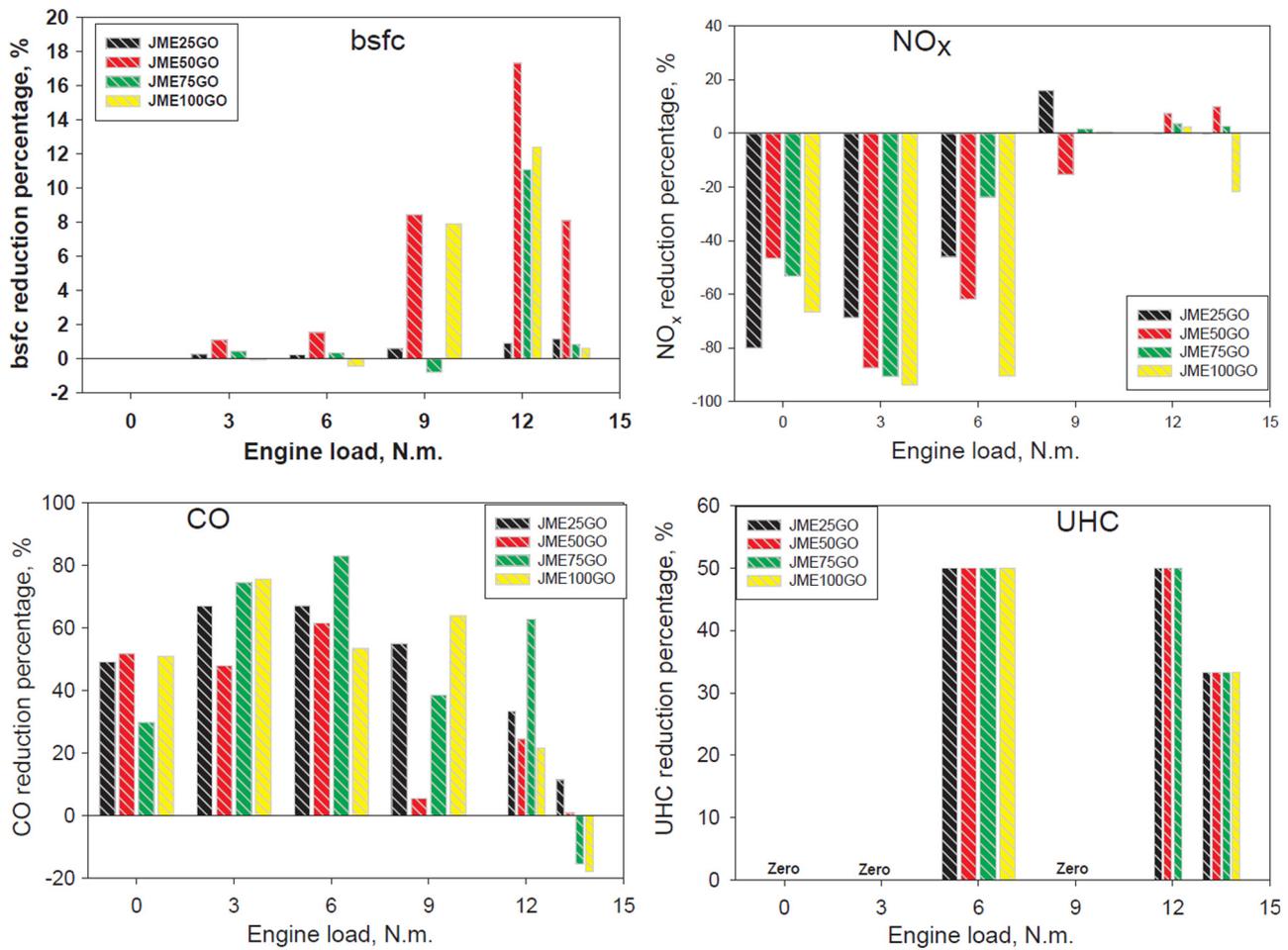


Figure 4: The reduction percentage of the BSFC, NO_x, CO, and UHC emissions under different engine loads [143].

decreased by 35%, 50%, and 60%, respectively Overall, the concentration level of 50 ppm produced better combustion characteristics and engine performance as well as low harmful emissions.

5 Conclusion

In this article, a recent review of the effects of nanofluid as a fuel additive in diesel/biodiesel is presented. The application of nanofluid biodiesel blend in the ICE can serve as a potential approach in reducing GHG emissions and improving engine efficiency. Many previous studies demonstrated that nanoparticles can be used to enhance the fuel properties, engine performance, fuel combustion, and exhaust emission. Fuel properties are one of the most significant factors that determine the engine performance and combustion quality. The summary of this review article is listed as follows.

- The addition of nanoparticles plays a vital role in promoting better combustion quality. With the addition of nanoparticles to the diesel/biodiesel, it can improve the fuel properties such as kinematic viscosity, caloric value, flash point, density, and cetane number, leading to complete combustion. The increase in BTE is due to the catalytic activity and improvement in fuel properties. In contrast, a low calorific value will increase BSFC. In short, a higher calorific value will promote a lower BSFC and higher BTE.
- Fuel properties such as kinematic viscosity, caloric value, flash point, density, and cetane number also depend on the type of biodiesel, type of nanoparticle and its size, and the amount of dosing level. This may have a varied effect on the combustion and emission characteristics.
- Increasing the dosing level of nanoparticles can greatly enhance the engine performance and emission characteristics, excessive number of nanoparticles will lead

to unburned fuel–air mixture during the combustion process.

- The addition of ethanol and nanoparticles in gasoline fuel can also improve engine performance and exhaust emissions.
- Among the above nanoparticles, aluminium is the best metal candidate, while CNT is used for non-metal nanoparticles. This is owing to their presence of excess oxygen quantity, and the positive effects of nanoparticles on the fuel properties (i.e. highest calorific value) of diesel/biodiesel blended could reportedly increase in combustion efficiency, leading to reduced BSFC and harmful emissions.

As a whole, the addition of nanoparticles in diesel/biodiesel plays a significant role in improving the fuel properties and enhancing the performance of the CI engine as well as reducing the exhaust emissions.

6 Current challenges and recommendations

From authors' review, most of the results are favourable, because the addition of nanoparticles in the diesel/biodiesel can enhance the performance of CI engine and reduce the harmful emissions (HC, CO, smoke, and NO_x emissions) causing the global air pollution. This literature review reveals that most of the experiments conducted showed a remarkable improvement in producing a lower exhaust emission.

Moreover, there are contradictory observations by researchers regarding the engine performance such as BTE, BSFC, peak pressure, and emissions characteristics such as HC, CO, smoke, and NO_x emissions as noted in the literature. Among them, few researchers reported that NO_x emission release was higher with the addition of additives. The discrepancy occurred due to the different types of biodiesel, types of nanoparticles and its size, and also its volume concentration. The particle size is one of the important key factors that affect the combustion quality. Further study is therefore needed to overcome this discrepancy by considering the source of vegetable oils and different types of nanoparticles and its size by varying the dosing level of nanoparticles.

Acknowledgements: The authors would like to express their appreciation to Universiti Teknologi Malaysia and the Ministry of Education for providing the financial

support for this work through FRGS-MSRA research grant (Vote No: 5F273) and LRGS (Vote No: 4L891).

Conflict of interest: The authors declare no conflict of interest regarding the publication of this paper.

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