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Strategies in the application of nanoadditives to achieve high-performance diesel, biodiesels, and their blends

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ABSTRACT

Nanoparticles are being used as additives for solid and liquid fuels owing to their high specific surface area (high reactivity) and potential ability to store energy in surfaces. The use of nanoparticles in diesels, biodiesels, and their blends is a novel area with unrealised potential owing to the higher catalytic activity of nanoparticles compared with that of micro-sized materials Nanoparticles have been shown to disperse more evenly in fuels and exhibit high stability. In addition, nanoparticles in similar media burn faster than micro-sized particles. The addition of nanoparticles into diesel, biodiesels, and their blends affect the physicochemical properties of the fuels such as kinematic viscosity, density, flash point, and cetane number. Studies have shown that nanoparticles affect the brake specific fuel consumption, brake specific energy consumption, and brake thermal efficiency, depending on the dosage and type of nanoparticles. Studies have also shown that the addition of nanoparticles affect carbon monoxide, carbon dioxide, nitrogen oxide, and unburned hydrocarbon emissions, along with smoke opacity. This review presents the application of various types of nanoparticles in diesel, biodiesels, and their blends to enhance the physicochemical properties of the fuels, combustion efficiency, and engine performance, and reduce harmful exhaust emissions. It is believed that this review will be beneficial to scholars, researchers, and industrial practitioners looking forward to improve diesel engine performance and reduce exhaust emissions by exploiting nanotechnology.

Introduction

Nanoparticles have received considerable attention from the scientific community because of their capability to be routinely synthesiaed and characterised. The physicochemical and electrical properties of materials at the nanoscale are remarkably different from those of materials at the macroscale. In most cases, the size of nanoparticles falls somewhere between 1 and 100 nm [1]. Research on nanomaterials is an essential part of the puzzle, which involves deciphering the energy behaviour of materials at extremely small length scales [2]. Nanoparticles possess exceptional characteristics that render hem invaluable for various applications such as biomedicine, energy storage and utilisation, environmental remediation, electronics and optoelectronics, food science, and agriculture.

Nanoparticles have emerged as a promising solution for various energy applications, revolutionising the way energy is produced and utilised. The infinitesimal size and unique properties of nanoparticles render them highly efficient in enhancing energy conversion and storage. In the biodiesel field, nanoparticles have shown great potential in improving the efficiency of the biodiesel conversion process. Nanocatalysts, such as metal and metal oxide nanoparticles, have been shown to significantly increase the rate and yield of biodiesel production. In addition, the use of nanoparticles can reduce the need for harsh

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Nomenclature

Ag	silver
Al_2O_3	aluminium oxides
APTES	2-amino-propyltriethoxysilane
B100	pure biodiesel
Bn	blending of n% of biodiesel with diesel
BP	black phosphorus
BSFC	brake specific fuel consumption
BTE	brake thermal efficiency
CeF_3	cerium (III) fluoride
CeO_2	cerium oxide
CNTs	carbon nanotubes
CO	carbon monoxide
CO_2	carbon dioxide
D2S15WAl	alumina nanoparticles in blended water–diesel emulsion
D2S5WCNT	CNTs in the water-diesel emulsion
D70C10E20	diesel (70 %)-Caster oil (10 %)-Ethanol (20 %)
Fe_2O_3	ferric oxide
$FECL_3$	ferric chloride
GSOME	grape seed oil methyl ester
HC	hydrocarbon
JME	Jatropha Methyl Esters
MnO	magnesium oxide
MNO_2	magnesium dioxide
MoS_2	molybdenum disulphide
MoS_2QDs	molybdenum disulphide quantum dots
MWCNTs	multiwalled carbon nanotubes
NOx	nitrogen oxide
SFC	specific fuel consumption
SiO_2	silicone oxide
TiO_2	titanium dioxide
UHC	unburned hydrocarbon
ZnO	zinc oxide

chemical reactants, which will minimise environmental impact. Apart from biodiesel production, nanoparticles can be blended with biodiesels and their blends to improve the combustion characteristics of diesel engines. Nanoparticles can be incorporated into biodiesel formulations to improve the physicochemical properties of the fuels, which in turn, will promote combustion efficiency and reduce harmful exhaust emissions of diesel engines. The addition of metal oxide nanoparticles into biodiesels and their blends have been shown to enhance combustion efficiency and reduce particulate emissions by promoting the oxidation of hydrocarbons, resulting in a more complete combustion.

Nanoparticles have shown improved catalytic activity [3], superparamagnetic behaviour [4], and superplasticity [5], as well as lower melting temperatures [6] and sintering temperatures [7]. In addition, the theoretical densities of nanoparticles are significantly higher compared with those of materials at the microscale or greater dimensions [8]. Materials with a lower melting point can ignite more easily. Nanopowders will boost combustion rates compared with micropowders. To illustrate these points, the ratio of the number of surface atoms to the total number of bulk atoms in a spherical iron crystal is shown in Fig. 1, which is organised according to the particle size. The surface atoms have poorer coordination and therefore, their electrical and thermophysical properties are different. Bulk materials might take on the surface atom characteristics when the surface-to-bulk atom ratio is high. Inert materials such as gold with a particle size of 1–5 nm have outstanding catalytic properties [9].

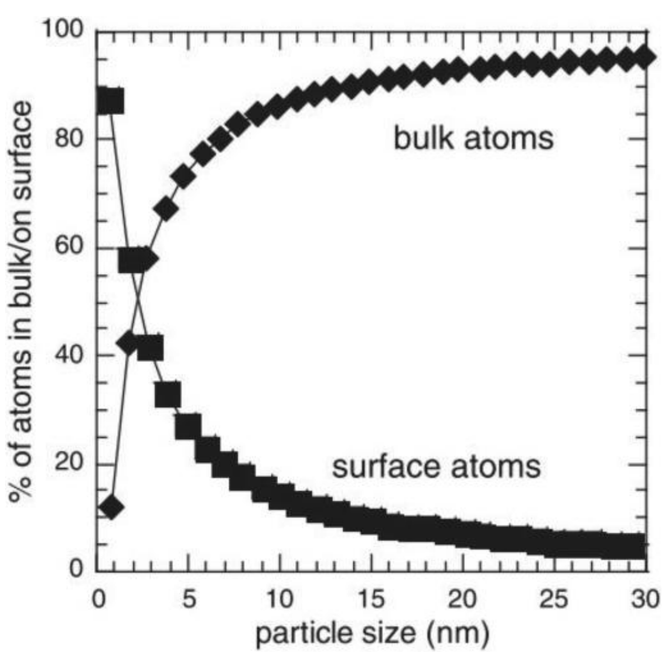

Fig. 1. Ratio of the number of surface atoms to the total number of bulk atoms in a spherical iron crystal [28].

Hollomon and Turnbull [10] explored the size-dependent freezing points of small droplets, while Takagi [11] developed a function to predict the melting temperatures based on the crystal size using electron diffraction in 1954. Lai et al. [12] examined the effects of particle size (5–50 nm) on the melting properties of tin (Sn) using a scanning nanocalorimeter. Delogu [13] demonstrated the size dependency of the melting point and latent heat of fusion of nanoparticles with a radius within a range of 5–50 nm using classical thermodynamic principles. Likewise, Vanfleet and Mochel [14] employed classical thermodynamic principles and showed that reducing the diameter of nanoparticles to below 10 nm led to significant alterations in the physicochemical properties of nanoparticles such as melting point, freezing point, and heat of fusion. Experimental and theoretical studies have consistently shown that there is an inverse relationship between the nanoparticle radius and changes in the melting point [15–17]. Furthermore, the size of nanoparticles influences the melting point and heat of fusion. Although the application of nanotechnology in the combustion of energetic materials is relatively limited, it is evident that numerous facets of fuel combustion (including diesel, biodiesels, and their blends) will soon be significantly influenced by nanotechnology [18]. Nonetheless, despite the recent studies on the use of nanoparticles for fuel combustion [19], this particular aspect of nanotechnology requires further development.

Even though diesel engines are known for their robustness, reliability, and fuel efficiency, they inherently produce toxic emissions such as smoke, nitrogen oxide (NOx), carbon monoxide (CO), and unburned hydrocarbons (UHC) [20]. Consequently, much effort has been made to mitigate these harmful exhaust emissions by optimising the engine design, altering the fuel formulation, and implementing exhaust gas treatment methods. To date, most of these efforts are focused on altering fuel formulations since this approach can reduce harmful exhaust emissions without the need for significant engine design modifications. Fuel modification entails the addition of specific fuel additives into diesel in order to reduce exhaust emissions, enhance fuel stability (e.g., viscosity index), and reduce the ignition delay time (time between the start of fuel injection and the start of combustion) as a result of the lower flash point [21–24]. The primary aim of incorporating nanoadditives into diesel is to enhance engine performance and mitigate the emission of harmful pollutants from diesel engines.

It has also been shown that the addition of nanoparticles improves the lubricity of diesel, biodiesels, and their blends. Superior lubricity is crucial to enhance mobility, durability, and efficiency. Fuel lubricity is also essential to reduce emissions [25]. From an energy perspective, approximately 23 % of the global total energy consumption in 2017 was due to tribological contacts [26]. From this, one fifth was for overcoming friction and 3 % was for re-producing worn parts and spare tools as well as wear-related failures. From an environmental perspective, the majority of existing base oils used in the industrial and automotive sectors today are crude oil derivatives [27]. At present, nanoadditives are used to improve the physicochemical properties of diesel, biodiesels, and their blends, which in turn, will boost engine performance and reduce exhaust emissions. The use of nanoadditives in diesel, biodiesels, and their blends is greatly expanding, with many studies published in the literature over the years. Hence, this review highlights the key findings of these studies and provide a summary on the application of nanoadditives in enhancing the performance and reducing the exhaust emissions of diesel engines fuelled with diesel, biodiesels, or their blends. It is believed that this review will be beneficial to scholars, researchers, and industrial practitioners looking forward to improve diesel engine performance and reduce exhaust emissions with the use of nanoadditives.

Effects of nanoadditives on the physicochemical properties of fuels

The physicochemical properties of diesel, biodiesels, and their blends are strongly dependent on the production process. The characteristics of the fatty acid esters have a significant effect on the overall characteristics of the fuel [29,30]. Both the fatty acid and alcohol molecules can have a significant effect on the fuel quality [31–36]. In general, the cetane number, heat of combustion, melting temperature, and viscosity of fatty acid compounds increase with an increase in the chain length of fatty acids. In addition to the changes required for transesterification reaction, the long alcohol chain makes isopropanol cost-ineffective compared with methanol. For this reason, methanol is primarily used to form fatty acid methyl ester (biodiesel) [37]. To overcome the disadvantages of methanol, numerous researchers use nanoparticles, which work as a catalyst for biodiesel production. In addition, nanoparticles are used as additives, where the nanoparticles are blended with diesel, biodiesels, and their blends to improve their overall properties. The effects of nanoparticles on the physicochemical properties of diesel, biodiesels, and their blends are discussed in the following sub-sections.

Effects of nanoadditives on the kinematic viscosity of fuels

The kinematic viscosity of fuels plays a vital role in lubrication, particularly in systems that incorporate rotary distributor injection pumps and are completely dependent on the fuel for lubrication [38,39]. Kinematic viscosity is one of the most important properties of diesel, biodiesels, and their blends, and is related to different factors [40,41]. It is generally understood that biodiesels and biodiesel–diesel blends have higher kinematic viscosity than diesel at different temperatures. Engine manufacturers have expressed concern regarding the higher kinematic viscosity of biodiesels as the use of biodiesels becomes more extensive [42]. At present, nanoadditives are used to enhance the physicochemical properties of diesel, biodiesels, and their blends. The nanoparticles disperse in the fuel, which improves air–fuel mixing and combustion efficiency. The addition of nanoparticles enhances the physicochemical properties of the fuel, which in turn, improves engine performance and reduces exhaust emissions [43,44]. The lowest kinematic viscosity has been observed for pure diesel (2 cSt) whereas the highest kinematic viscosity (11.4 cSt) has been observed for biodiesel–diesel blend with nanoorganic additives [45]. By blending ferric chloride ($FeCl_3$) nanoparticles with palm waste cooking oil-based biodiesel, Kannan et al. [46] reported an average kinematic viscosity of 4.55 cSt. They showed that the kinematic viscosity gradually increased with an increase in the dosage of $FeCl_3$ nanoparticles. Selvan et al. [47] reported a kinematic viscosity of 2.00 and 2.35 cSt for diesel and D70C10E20 (diesel–castor oil–ethanol blend), respectively. By using a water content of 15 % and blending alumina nanoparticles with water–diesel emulsion fuel, Basha and Anand [48] reported an average kinematic viscosity of 4.95 cSt. They also showed that the water content was a key factor that increased the kinematic viscosity of diesel. In another study, Basha and Anand [49] showed that when the water content was reduced from 15 % to 5 %, the kinematic viscosity decreased dramatically from 4.95 cSt to 3.33 cSt. Fangsuwannarak and Triratanasirichai [50] conducted an experimental study where they improved palm biodiesel with different palm oil fractions (2, 10, 20, 30, 40, 50, and 100 %) by adding titanium dioxide (TiO_2) nanoparticles. The kinematic viscosity increased with an increase in the percentage of biodiesel in the fuel blend. They also showed that the TiO_2 nanoparticles did not significantly affect the kinematic viscosity. Lenin et al. [51] employed copper oxide (CuO) and manganese oxide (MnO) nanoparticles to improve the physicochemical properties of diesel. The results revealed that the physicochemical properties of diesel can be enhanced by the proper selection of nanoadditives. By developing water–diesel emulsion fuel with nanoorganic additives, Yang et al. [52] showed that the water content was a key factor that increased the kinematic viscosity of the fuel. Furthermore, they showed that the kinematic viscosity was strongly influenced by the water content of the water–diesel emulsion fuel and nanoorganic additives. Carbon nanotubes (CNTs) with exceptional chemical [53], physical [54], thermal [55], and mechanical [56–59] properties have been used as fuel additives. By using CNTs in water–diesel emulsion fuel, Basha and Anand studied the effects of CNT dosage. They showed that the addition of CNTs increased the kinematic viscosity of the water–diesel emulsion fuel. In another study, Basha and Anand [60] reported the effects of CNTs in Jatropha methyl ester (JME) emulsion fuel. Again, they showed that the kinematic viscosity of the fuel increased with an increase in the CNT dosage. Tewari et al. [61] blended multi-walled carbon nanotubes (MWCNTs) with biodiesel. The MWCNTs (mass fraction: 25 and 50 ppm) were blended with biodiesel using a mechanical homogeniser and an ultrasonicator. They showed that the kinematic viscosity of the biodiesel increased with an increase in the dosage of MWCNTs. The significant effects of nanoadditive on the kinematic viscosity of biodiesel have been demonstrated by their research. Vairamuthu et al. [62] reported an increase in the kinematic viscosity of B50 fuel blend by increasing the dosage of cerium oxide (CeO_2) nanoparticles from 40 ppm to 60 ppm.

Effects of nanoadditives on the density of fuels

Density can be defined as the mass of an object divided by its volume. The density of diesel is generally lower than those of biodiesels. The density of biodiesel–diesel blend increases with an increase of the percentage of biodiesel in the fuel blend [63]. The addition of nanoadditives can alter the density of biodiesels and biodiesel–diesel blends, depending on the type of nanoparticles. The lowest and highest densities of Waste cooking biodiesel-diesel blends were reported to be 820 and 900 kg/m^3, respectively. Metal-based nanoadditives can influence the density of diesel, biodiesels, and their blends. The effects of metal-based nanoadditives on density have been reported by Kannan et al. [46]. They found that the use of $FeCl_3$ as a fuel-borne catalyst resulted in a decrease in the density of biodiesel. By using CeO_2 nanoparticles in diesel and diesel–biodiesel–ethanol blends, Selvan et al. [47] observed a decrease in the density of the diesel–biodiesel–ethanol blends compared with that of pure diesel. Basha and Anand [49]observed an increase in the density of water–diesel emulsion fuel (D2S15WAl) added with alumina (Al_2O_3) nanoparticles. However, the increase in density by the addition of nanoadditives was negligible compared with that by the addition of biofuels. Basha and Anand [64] showed that the water content of the water–diesel emulsion fuel affected the density of the fuel even for the same dosage of alumina nanoparticles. Yang et al. [52,65]

reported an increase in density of the water–diesel emulsion fuel added with nanoorganic additives compared with that of pure diesel. Likewise, Basha and Anand [66] reported an increase in the density of water–diesel emulsion fuel (D2S5WCNT) by the addition of CNTs.

Effects of nanoadditives on the flash point of fuels

The experimental findings presented in the literature indicate that there is a direct connection between the percentage of biodiesel in the fuel blend and its flash point. It is possible to determine the flash point of a biodiesel–diesel blend if the percentage of biodiesel in the fuel blend is known. This can be done if the flash points of B0 (pure diesel) and B100 (pure biodiesel) are also known. According to Mattos et al. [67] and Gülüm and Bilgin [68], at lower biodiesel concentrations in the biodiesel–diesel blends, the flash point is mostly influenced by the flash point of diesel. Studies have shown that the addition of nanoparticles has a significant effect on the flash point of biodiesels and their blends. The addition of water into fuels is another significant factor that affects the flash point. In this section, the effects of nanoadditives and water content on the flash point of fuels reported in current studies are reviewed. Kannan et al. [46] showed that the flash point of palm waste cooking oil-based biodiesel decreased with an increase in the dosage of $FeCl_3$ nanoparticles. The effects of nanoadditives on the flash point of water–diesel emulsion fuel were studied by Selvan et al. [69]. They showed that the water content was a key factor that influenced the flash point of the fuel. Mirzajanzadeh et al. [70] used a combination of MWCNTs and CeO_2 nanoparticles with a dosage of 30, 60, and 90 ppm in two types of biodiesel–diesel blends (B5 and B20). They reported a significant reduction in the flash point from 171.1 °C to 68.3 °C with the use of nanoadditives. By using CeO_2 nanoparticles in *Calophyllum inophyllum* biodiesel–diesel blends, Vairamuthu et al. [62] showed that the flash point decreased from 120 °C to 118 °C with an increase in the dosage of nanoparticles in the B50 blend.

Effects of nanoadditives on the cetane number of fuels

Cetane number is one of the most significant properties of diesel, biodiesels, and their blends [41,71]. The cetane number is a measurement of how easily a fuel ignites. A high cetane number results in a low ignition delay. Normal alkanes with higher molecular weight have higher cetane numbers, which affect gas and particulate matter emissions [72]. Cetane improvers have been developed by different researchers [73,74]. Ethylhexyl nitrate is a substance that is used most frequently and is capable of enhancing the combustion characteristics along with reducing the flash point and the length of time it takes for ignition to occur [75]. The addition of nanoparticles has been shown to influence the cetane number of fuels.

Based on different reports, the cetane number is influenced by different factors such as the type of nanoparticles, the type of biofuels, and water content. By using TiO_2 nanoparticles in the palm biodiesel–diesel blends (B2, B10, B20, B30, B40, B50 and B100) with a nanoparticle dosage of 1–2 %, Fangsuwannarak and Triratanasirichai [50] reported an increase in the cetane number for the B2, B10, B20, and B30 blends. In contrast, the cetane number of the B40, B50, and B100 blends decreased with an increase in the dosage of TiO_2 nanoparticles. Some studies have shown that an increase in the water content decreases the cetane number of water–diesel emulsion fuels. The cetane number varies depending on the dosage and type of nanoparticles. Basha and Anand [49] showed that there were changes in the cetane number of the water–diesel emulsion fuel, depending on the water content and dosage of alumina nanoparticles. For a water content of 15 %, Basha and Anand [49]reported an increase in the cetane number upon the addition of 25 and 50 ppm of alumina nanoparticles. They also reported that the cetane number of the water–diesel emulsion fuel no longer changed upon the addition of 100 ppm of alumina nanoparticles compared with that upon the addition of 50 ppm of alumina nanoparticles. The water content (15 %) also increased the cetane number of the water–diesel emulsion fuel. In another study, Basha and Anand [66] showed that the cetane number decreased by adding 5 % of water into diesel. They also showed the cetane number of the fuel gradually increased upon the addition of CNTs. However, Basha and Anand [60] observed that the water content decreased the cetane number of Jatropha methyl ester–water emulsion fuel blended with CNTs. The physicochemical properties of different types of fuels added with nanoadditives are summarised in Table 1.

Effects of nanoadditives on engine performance and exhaust emissions

Studies have shown that nanoadditives have significant effects on engine output. Kao et al. [79] used aluminium nanofluid with a nanoparticle size of 40–60 nm and showed that the NOx emissions varied within the range of engine speeds investigated in their study while the smoke emissions reduced upon the addition of aluminium nanofluid. The results showed that the brake specific fuel consumption (BSFC) was lower for the fuel added with aluminium nanofluid compared with that for diesel at engine speeds below 1800 rpm. The addition of aluminium nanopowder into diesel led to a discernible decrease in smoke and NOx emissions at engine speeds below 1800 rpm. The fuel consumption and exhaust emissions were reduced upon the addition of a specific amount of aluminium nanofluid. The BSFC decreased with an increase in engine speed up to 1800 rpm whereas the BSFC increased within an engine speed range of 1800–2400 rpm. By using $FeCl_3$ as a fuel-borne catalyst for palm waste cooking oil-based biodiesel at a constant engine speed of 1500 rpm, Kannan et al. [46] obtained a substantial reduction in carbon monoxide (CO), unburned hydrocarbon (UHC), and smoke emissions. In addition, they observed a slight increase in nitric oxide (NO) and carbon dioxide (CO_2) emissions, as well as engine efficiency. Furthermore, the biodiesel produced from palm waste cooking oil showed lower emissions at higher cylinder gas pressures compared with pure diesel. They concluded that the $FeCl_3$ nanoparticles were effective to enhance the quality of biodiesel produced from palm waste cooking oil. This biodiesel can serve as a viable replacement for diesel.

Mehta et al. [80] conducted an experimental study and the results showed that the combustion characteristics and emissions of the engine changed upon the addition of aluminium (Al), iron (Fe), and boron (B) nanoparticles into diesel. Compared with diesel, they observed significantly higher evaporation rates with early ignition occurring at 0.2 s. The BSFC also decreased upon the addition of aluminium nanoparticles compared with those upon the addition of other nanoparticles. In addition, they observed reduced ignition delay, longer flame sustenance, and agglomerate ignition for the fuels considered in their study. Their results also showed that there was an increase in NOx emissions whereas there was a decrease in CO and UHC emissions. At maximum load, the combustion rate and brake thermal efficiency (BTE) improved for the fuels added with nanoparticles compared with those for pure diesel. Selvan et al. [47] reported that the BTE increased to 7.5 % for the E20 biodiesel blend upon the addition of CeO_2 nanoparticles and CNTs. The addition of 50 ppm of CeO_2 nanoparticles and 50 ppm of CNTs into the E20 biodiesel blend increased the CO emissions to 22.2 %. In contrast, the addition of CeO_2 nanoparticles and CNTs at the aforementioned concentrations improved combustion and reduced UHC and smoke emissions by 7.2 and 47.6 %, respectively, compared with pure E20 biodiesel blend. The presence of CeO_2 nanoparticles and CNTs boosted the cylinder gas pressure and peak heat release rate by reducing ignition delay and accelerating combustion. However, the addition of CeO_2 nanoparticles and CNTs into the E20 biodiesel blend did not reduce NOx emissions.

By adding alumina nanoparticles in the water–diesel emulsion fuel, Basha and Anand [76] obtained a substantial reduction in NOx and smoke emissions. The addition of alumina nanoparticles into the water–diesel emulsion fuel improved the BTE of the engine at different load settings. The water–diesel emulsion fuel added with alumina

Table 1
Effects of nanoadditives on the physicochemical properties of fuels.

Researchers	Fuel(s)	Nanoadditive(s)	Water content	Dosage of nanoadditives	Kinematic viscosity (cSt)	Density (kg/ m^3)	Flash point (°C)	Fire point (°C)	Cetane number
Kannan et al. [46]	Biodiesel produced from palm waste cooking oil	$FeCl_3$	—	5–50 μmol	4.51–4.57	864.6–866.0	165.0–170.0	183.0–190.0	66.00–69.60
Selvan et al. [47]	Diesel–biodiesel–ethanol blends, where the biodiesel was produced from castor oil	CeO_2	—	—	2.00–2.35	820.0–830.0	11.0–50.0	14.0–56.0	39.00–42.30
Basha and Anand [76]	Water–diesel emulsion fuel	Al_2O_3	15 %	25–100 ppm	2.10–5.01	830.0–859.6	50.0–66.0	—	—
Fangsuwannarak and Triratanasirichai [50]	Palm biodiesel	TiO_2	—	1–2 %	3.64–5.25	—	66.0–141.0	—	49.21–57.36
Lenin et al. [51]	Diesel	MnO and CuO	—	—	2.24–2.70	—	40.0–48.0	46.0–54.0	—
Yang et al. [65]	Water–diesel emulsion fuel	Nanoorganic additives	10–15 %	10.0– and 11.5 %	2.80–11.40	850.0–890.0	—	—	—
Basha and Anand [66]	Water–diesel emulsion fuel	CNTs	5 %	25 and 50 ppm	2.10–3.42	830.0–848.9	50.0–54.0	—	44.00–47.00
Tewari et al. [61]	Biodiesel	CNTs	—	25 and 50 ppm	5.60–5.80	880.0–900.0	164.0–170.0	—	—
Basha and Anand [60]	Jatropha methyl ester–water emulsion fuel	CNTs	25 %	25, 50, and 100 ppm	5.05–5.91	895.0–899.4	85.0–122.0	—	51.00–56.00
Özgür et al. [77]	Rapeseed biodiesel	MgO and SiO_2	—	25 and 50 ppm		895.0–896.0	>180.0	—	—
Mirzajanzadeh et al. [70]	Biodiesel–diesel blends	CeO_2 on amide-functionalised MWCNTs	—	30, 60, and 90 ppm	3.36–5.54	827.0–869.0	68.3–171.1	—	—
Shaafi and Velraj [78]	Diesel–soybean biodiesel and diesel–soybean biodiesel–ethanol blends	Al_2O_3	—	100 mg/L	2.61–4.78	—	85.0–110.0	—	42.00–57.00
Vairamuthu et al. [62]	*Calophyllum inophyllum* biodiesel–ultra-low-sulphur diesel blends	CeO_2	—	20, 40, and 60 ppm	2.83–5.30	—	56.0–179.0	58.0–181.0	46.00–52.80

nanoparticles emitted more UHC and lower CO emissions than neat water–diesel emulsion fuel. Fangsuwannarak and Triratanasirichai [50] observed that the CO, CO_2, and NOx emissions reduced appreciably upon the addition of TiO_2 nanoparticles into palm biodiesel. Their empirical study showed that the indirect injection diesel engine can be adapted to run more efficiently. They found that 0.1 % of TiO_2 nanoparticles was useful to reduce exhaust emissions and it was most effective for the B30–0.1 % fuel. Sajith et al. [81] employed CeO_2 nanoparticles (20–80 ppm) to improve the performance of Jatropha biodiesel. Engine tests were carried out and the results showed that the engine efficiency improved with the addition of CeO_2 nanoparticles into the fuel. The incorporation of CeO_2 nanoparticles resulted in a sizeable cutback in the amount of UHC and NOx emissions. In addition, it is well-known that the thermal stability of CeO_2 promotes the oxidation of hydrocarbons (HCs) while simultaneously reducing the production of NOx.

Ranaware and Satpute [82] found that the addition of ferrofluid into diesel had a noticeable effect on engine performance. The BSFC and BTE increased by up to 11 and 12 %, respectively, compared with those for pure diesel. Furthermore, they discovered that the addition of ferrofluid into diesel resulted in lower NOx emissions and a minor increase in CO emissions compared with diesel. Selvaganapthy et al. [83] found that biodiesel added with zinc oxide (ZnO) nanoparticles resulted in higher NOx emissions at loads of more than 50 % and lower NOx emissions at loads of 30–40 % compared with diesel.

Based on the findings of Sajeevan and Sajith [84], the incorporation of CeO_2 nanoparticles into diesel increased the engine efficiency by up to 5 %, and decreased of UHC and NOx emissions by 45 and 30 %, respectively. Moreover, the lowest UHC emissions and highest BTE were obtained for a nanoparticle dosage of 35 ppm. Basha and Anand [85] employed alumina nanoparticles in biodiesel emulsions (83 % of Jatropha biodiesel, 15 % of water, and 2 % of surfactants) and studied the effects of these nanoparticles on the engine performance and exhaust emissions. The engine performance improved whereas the exhaust emissions reduced by the addition of alumina nanoparticles into the biodiesel emulsion fuel compared with those for neat biodiesel emulsion fuel and Jatropha biodiesel. Xin et al. [86] studied the effects of $Ce_{0.9}Cu_{0.1}O_2$ and $Ce_{0.9}Zr_{0.1}O_2$ nanoadditives on the combustion characteristics and exhaust emissions of a diesel engine. Their results showed that the addition of nanoadditives increased the temperature and peak pressure of the cylinder in a high-speed diesel engine, which improved combustion performance. Shafii et al. [87] found that the addition of ferrofluid into diesel increased the BTE and decreased the BSFC. In addition, the NOx emissions significantly decreased whereas the CO emissions increased with an increase in the dosage of ferrofluid. Sabet Sarvestany et al. [88] used 0.4 and 0.8 vol% of iron(II,III) oxide (Fe_3O_4) nanoparticles dispersed in diesel. The results confirmed that the nanofluid fuel with 0.4 vol% of nanoparticles had better combustion characteristics than the nanofluid fuel with 0.8 vol% of nanoparticles. Their results clearly showed that the selection of a proper nanoparticle dosage had a strong effect on engine performance and emissions. They found that the NOx and silicon dioxide (SO_2) emissions decreased dramatically whereas the smoke opacity and CO emissions increased significantly with an increase in the dosage of nanoparticles. Furthermore, the magnetic capability (where the nanoparticles can be collected at the end of the exhaust pipe using a magnetic bar) and low toxicity of the Fe_3O_4 nanoparticles render them a suitable additive for fuels.

Yang et al. [65] introduced an emulsion fuel added with nanoorganic additives (dosage: 10.0 and 11.5 %) with superior stability. The results showed that the BTE improved by 14.2 % whereas the NOx emissions reduced by 30.6 % for the emulsion fuel with nanoorganic additives compared with those for pure diesel. The BTE increased significantly when a water content of 10 % was used for the emulsion fuel. The results indicated that selecting a suitable nanoparticle dosage had a significant effect on engine performance. In another study, Yang et al. [52] used 12.6 vol% of nanoorganic additives and the results showed that the NOx emissions decreased because of the presence of water. The results also showed that a higher BTE was obtained as a result of the micro-explosion of water droplets within the fuel droplets when the fuel was exposed to high-temperature gas. Moreover, the emulsion fuel had a longer ignition delay than pure diesel and a shorter combustion period, which boosted engine efficiency. Basha and Anand [66] reported that the use of CNTs (dosage: 25 and 50 ppm) in water–diesel emulsion fuel resulted in considerable improvement in the BTE and a substantial reduction in harmful pollutants. Tewari et al. [61] reported a noticeable increase in the BTE and a substantial decrease in pollutant emissions by incorporating MWCNTs into HOME. The BTE and NOx emissions of the HOME–MWCNT fuel blends were fairly better compared with those of HOME. Basha and Anand [60] reported that the addition of CNTs into JME emulsion fuel significantly improved the BTE compared with neat JME and JME emulsion fuels. The BTE improved by 3.8 % using 100 ppm of CNTs in the JME emulsion fuel compared with that for pure JME. Selvan et al. [69] investigated the effects of CNTs and CeO_2 nanoparticles in diesel–biodiesel–ethanol (diesterol) blends. The results showed that the BTE increased to 7.5 % when CNTs and CeO_2 nanoparticles were added into the E20 diesterol blend. The addition of CNTs and CeO_2 nanoparticles accelerated the initiation of combustion owing to the reduced ignition delay. Furthermore, the results showed that the engine performance and exhaust emissions of the engine fuelled with diesterol was strongly dependent on the percentage of biodiesel and dosage of nanoparticles in the fuel blend. A novel soluble nanocatalyst (CeO_2–MWCNT) for biodiesel–diesel blends was developed by Mirzajanzadeh et al. [70]. They observed a decrease in UHC, CO, soot, and NOx emissions by 71.4, 38.8, 26.3, and 18.9 %, respectively, for the B20 blend added with 90 ppm of nanocatalyst compared with those for neat B20 blend. In addition, the engine power and torque increased by 7.81 and 4.91 %, respectively, whereas the fuel consumption decreased by 4.50 %. George et al. [89] examined the performance and emissions of a diesel engine fuelled by diesel blended with aluminium oxide (Al_2O_3) and cobalt oxide (Co_3O_4) nanoparticles. They observed a discernible increase in BTE for the diesel blended with nanoparticles. The best results were obtained when an equal amount of Al_2O_3 and Co_3O_4 nanoparticles were incorporated into diesel.

Babu and Raja [90] reported an increase in the thermal efficiency of diesel–alumina fuel compared with that of pure diesel for all engine loads (0–150 %) investigated in their study. The NO_x emissions of the engine fuelled with diesel–alumina fuel were lower than those of the engine fuelled with pure diesel. The smoke opacity decreased by using alumina nanoparticles as an additive. However, they reported an increase in CO emissions for the diesel–alumina fuel compared with that for pure diesel. They also conducted computational fluid dynamics (CFD) analysis and the simulation results showed good agreement with those obtained from experiments. To gain insight into the combustion process, they proposed that the flame temperature should be estimated precisely and the reaction chemistry of the diesel–alumina fuel should be investigated in future studies. Özgür et al. [77] observed a slight increase in engine performance using magnesium oxide (MgO) and silicon dioxide (SiO_2) nanoadditives and reported that the CO and NOx emissions reduced by 10.4 and 7.2 %, respectively. They also reported an increase in CO_2 emissions by 7 % for a nanoadditive dosage of 25 ppm. In addition, a dosage of 25 ppm was found to be most effective for the biodiesel.

Shaafi and Velraj [78] studied the influence of alumina nanoparticles on the exhaust emissions of a diesel engine fuelled with diesel–soybean-biodiesel–ethanol blends and reported a significant reduction in CO, CO_2, and UHC emissions for the D80SBD15E4S1 blend. Arockiasamy and Anand [91] used Al_2O_3 and CeO_2 nanoparticles to investigate the performance and emission characteristics of a direct injection diesel engine fuelled with Jatropha biodiesel. The NOx, UHC, and CO emissions, and smoke opacity decreased by 9, 33, 20, and 17 % respectively, for the Jatropha biodiesel blended with Al_2O_3 nanoparticles. In contrast, the decrease in NOx, UHC, and CO emissions, and smoke opacity was more pronounced for the Jatropha biodiesel blended with CeO_2 nanoparticles, with a value of 7, 28, 20, and 20 %, respectively. In addition, owing to the high surface area-to-volume ratio of the nanoparticles, the BTE improved by 5 % for both of the test fuels. Banapurmath et al. [92] experimented with the addition of graphene and silver (Ag) nanoparticles as well as MWCNTs into honge oil methyl ester (biodiesel) and found that the addition of nanoparticles improved the BTE and reduced harmful engine emissions.

Karthikeyan et al. [93] blended CeO_2 nanoparticles with grape seed oil methyl ester (GSOME), and the results showed that the engine performance was enhanced (lower BSFC and higher BTE) while the CO, UHC, and NOx emissions were reduced when the air-cooled direct injection diesel engine was fuelled with the B20$CeO_2$50 and B20$CeO_2$100 blends. Zhang et al. [94] studied the effects of using ceria additive on the emission characteristics of ultra-low-sulphur diesel fuel. They reported a decrease in CO_2 and CO emissions and an increase in NOx emissions (9.3 %). Santhanamuthu et al. [95] blended 10, 20, and 30 % of iron oxide nanoparticles with neat diesel. The engine performance of the B25 blend composed of 25 % of polanga oil and 150 ppm of iron oxide nanoparticles was similar to that of neat diesel. Moreover, they observed that the CO_2, CO, NOx, and UHC emissions along with smoke density were strongly dependent on the dosage of nanoparticles and percentage of polanga oil in the fuel blend. They reported a decrease in exhaust emissions in most of the cases investigated in their study. Basha [76] observed a reduction in CO and UHC emissions when alumina nanoparticles were blended with diesel. The experimental results also showed an improvement in the BTE for all dosages of alumina nanoparticles (25, 50 and 100 ppm).

In another study, Basha [48] blended alumina nanoparticles and CNTs with water–diesel emulsion fuel and the results showed that the BTE increased for this fuel. The experimental results also revealed a reduction in CO, NOx, and smoke emissions. Attia et al. [96] added alumina nanoparticles into jojoba biodiesel–diesel blend at different dosages (10 –50 mg/L). Based on the engine performance, they concluded that the most suitable dosage of alumina nanoparticles that yielded favourable results was 30 mg/L. Furthermore, they reported a reduction in the BSFC by ~6 % for this dosage. The BTE increased by up to 7 % and the engine emissions decreased for the jojoba biodiesel–diesel blended with alumina nanoparticles compared with those for the B20 blend containing 20 % of biodiesel. Sathiyagnanam and Gopal [97] used CeO_2 and MnO_2 nanoparticles as additives in pure diesel and biodiesel. The ideal dosage was determined to be 25 ppm for both CeO_2 and MnO_2 nanoparticles. Moreover, the NOx and CO emissions marginally decreased while the engine performance parameters slightly enhanced with the addition of nanoparticles. Mandal and Kanagaraj [98] used CeO_2 nanoparticles (dosage: 0.02, 0.04, 0.06, 0.08, and 0.10 wt%) to investigate the engine performance and emissions of diesel blended with these nanoparticles. The best engine performance was achieved when 0.06 wt% of CeO_2 nanoparticles were dispersed in diesel at an engine load of 75 %. At this optimum engine load, the NOx and CO emissions and specific fuel consumption (SFC) decreased by 50, 40, and 10 %, respectively. Furthermore, the mechanical efficiency and BTE improved by 7 and 28 %, respectively. Karthikeyan et al. [99] studied the effects of ZnO nanoparticles on the performance and exhaust emissions of a direct injection diesel engine fuelled with pomolion stearin wax biodiesel. The results revealed that the addition of ZnO nanoparticles resulted in a decrease in BSFC and an increase in BTE for all engine loads investigated in their study. Furthermore, the results revealed that the CO and UHC emissions along with smoke opacity decreased significantly with the addition of ZnO nanoparticles in the biodiesel–diesel fuel blend. The effects of nanoadditives on engine performance and exhaust emissions of diesel engines fuelled with diesel, biodiesels, and their blends are summarised in Table 2.

Table 2
Effects of nanoadditives on engine performance and exhaust emissions.

Researchers	Fuel(s)	Nanoadditive(s)	Nanoad ditive osage	Efficiency			Emissions			
				BSFC	BSEC	BTE	NOx	CO	CO_2	UHC
Kao et al. [79]	Diesel	Al	30–50 cm^3	↑	—	—	↓	—	—	—
Kannan et al. [46]	Biodiesel produced from palm waste cooking oil	$FeCl_3$	5–50 μmol	8.6% ↓	—	6.3% ↑	↑	52.6% ↓	↑	26.6% ↓
Mehta et al. [80]	Diesel	Al, Fe, and B	—	↑	↑	2–-9% ↑	↑	25–40% ↓	—	4-8% ↓
Selvan et al. [47]	Diesel–biodiesel–ethanol blends, where the biodiesel	CeO_2 and CNTs	25–100 ppm	↑	—	7.5% ↑	No change	↑	—	↓

(continued on next page)

Table 2 (*continued*)

	was produced from castor oil									
Basha and Anand [49]	Water–diesel emulsion fuel	Al	25–100 ppm	—	—	3.7% ↑	↓	↓	—	↑
Fangsuwannarak and Triratanasirichai [50]	Palm biodiesel	TiO_2	0.1–0.2 vol%	↓	—	↑	↓	↓	↓	↓
Sajith et al. [81]	Jatropha biodiesel	CeO_2	2080 ppm	—	↑	—	↓	—	—	↓
Ranaware and Satpute [82]	Diesel	CeO_2 and ferrofluid	Up to 0.8%	11% ↓	—	12% ↑	↓	↑	—	—
Selvaganapthy et al. [83]	Diesel	ZnO	250–500 ppm	—	—	1.35% ↑	↑	—	—	—
Lenin et al. [51]	Diesel	MnO and CuO	100 mg/L	—	—	4% ↑	—	37% ↓	—	1% ↓
Sajeevan and Sajith [84]	Diesel	CeO_2	5–35 ppm	—	—	5% ↑	30% ↓	—	—	45% ↓
Basha and Anand [85]	Jatropha biodiesel–water emulsion	Al_2O_3	25, 50, and 100 ppm	↓	—	—	↓	—	—	↓

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Table 2 (*continued*)

	fuel									
Xin et al. [86]	Heavy oil	$Ce_{0.9}Cu_{0.1}O_2$ and $Ce_{0.9}Zr_{0.1}O_2$	—	—	—	—	↓	↓	—	—
Shafii et al. [87]	Diesel	Ferrofluid	0.0, 0.4, and 0.8 ferrofluid/diesel ratios by volume	11% ↓	—	12% ↑	↓	↑	—	—
Sabet Sarvestany et al. [88]	Diesel	Fe_3O_4	0.4 and 0.8 vol%	↑	—	—	↓	↑	—	↑
Yang et al. [65]	Water–diesel emulsion fuel	Nanoorganic additives	10 and 11.5%	—	—	14.2% ↑	30.6% ↓	↓	—	↑
Yang et al. [52]	Water–diesel emulsion fuel	Nanoorganic additives	12.6 vol%	↑	—	↑	↓	—	—	↓
Basha and Anand [66]	Water–diesel emulsion fuel	CNTs	25 and 50 ppm	—	—	↑	↓	↓	↓	↓
Tewari et al. [61]	Honge Biodiesel	MWCNTs	25 and 50 ppm	—	—	↑	↓	↑	—	↑

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Table 2 (*continued*)

Basha and Anand [60]	Jatropha methyl ester–water emulsion fuel	CNTs	25, 50, and 100 ppm	↓	—	3.8% ↑	↓	—	—	↓
Selvan et al. [69]	Diesterol blends	CeO_2 and CNTs	25, 50, and 100 ppm	—	—	7.5% ↑	—	22.2% ↑	—	7.2% ↓
Mirzajanzadeh et al. [70]	Biodiesel –diesel blends	CeO_2 on amide-functionalised MWCNTs	30, 60, and 90 ppm	4.5% ↓	—	—	18.9% ↓	38.8% ↓	—	71.4% ↓
George et al. [89]	Diesel	Al_2O_3 and CO_3O_4	5–150 ppm	↓	—	↑	↓	—	↓	↓
Babu and Raja [90]	Diesel	Al_2O_3	25–75 ppm	↑	—	↑	↓	—	↑	↑
Özgür et al. [77]	Rapeseed Biodiesel	MgO and SiO_2	25 and 50 ppm	—	—	2.4% ↑	2.2% ↓	10.4% ↓	7% ↑	—
Shaafi and Velraj [78]	Diesel–soybean biodiesel and diesel–soybean biodiesel–ethanol blends	Al	100 mg/L	↑	—	↑	↓	↓	↓	↓

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Table 2 (*continued*)

Arockiasamy and Anand [91]	Jatropha biodiesel	Al_2O_3 and CeO_2	30 ppm	—	—	5% ↑	9% ↓	20% ↓	—	33% ↓
Banapurmath et al. [92]	Honge oil methyl ester (HOME)	Graphene, Ag, and MWCNTs	25 and 50 ppm	—	—	↑	↓	↓	—	↓
Karthikeyan et al. [93]	Grape seed oil methyl ester (GSOME)	CeO_2	50 and 100 ppm	↓	—	↑	↓	↓	—	↓
Zhang et al. [94]	Ultra-low-sulphur diesel	CeO_2 (Envirox)	0.1×, 1×, and 10× of 0.5 mL of Envirox/ L of fuel	4–10% ↓	—	—	9.3% ↑	10.6% ↓	↓	—
Santhanamuthu et al. [95]	Diesel–polanga oil blends	Iron oxide	100, 200, and 300 ppm	—	—	↑	↓	↓	↓	↓
Basha [76]	Diesel	Al_2O_3	25, 50, 100 ppm	—	—	↑	↓	↓	—	↓
Basha [48]	Water–Jatropha	CNTs and Al_2O_3	50 ppm	—	—	↑	↓	↓	—	—

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Table 2 (*continued*)

	biodiesel emulsion fuel									
Attia et al. [96]	Jojoba methyl ester–diesel blends	Al_2O_3	10–50 mg/L	6% ↓	—	7% ↑	70% ↓	75% ↓	—	55% ↓
Sathiyagnanam and Gopal [97]	Diesel and biodiesel	CeO_2 and MnO_2	25 and 50 ppm	—	—	↑	↓	↓	—	↓
Mandal and Kanagaraj [98]	Diesel	CeO_2	0.02–0.10 wt%	10% ↓	—	28% ↑	50% ↓	40% ↓	—	—
Karthikeyan et al. [99]	Pomolion stearin wax biodiesel	CeO_2	50 and 100 ppm	—	—	↑	↓	↓	—	↓

Effects of nanoadditives on the tribological properties and characteristics of fuels

The addition of nanoparticles can assist in the creation of transfer layers, leading to three-body abrasive wear, which in turn, decreases the friction coefficient or the incidence of wear [100,101]. The tribochemical deposition as a result of the addition of nanoparticles can lead to the formation of an anti-wear boundary coating and a reduction in shear stress. The nanoparticles also function as a spacer, preventing metal-to-metal contact. However, not all tribological reaction products can be used to enhance wear resistance. For instance, even though cerium(III) fluoride (CeF_3) nanoparticles have outstanding extreme pressure and friction-reducing properties, they lack anti-wear properties. This is due to the fact that the CeF_3 surface atoms are more reactive, resulting in higher corrosiveness as well as inferior anti-wear capabilities [102]. Therefore, it is important to understand the tribological properties and characteristics of fuels upon the addition of nanoparticles.

The addition of nanoparticles into fuel can lead to the formation of an effective tribolayer. Upon the addition of nanoparticles, tribolayers can form on the worn surfaces. Chen et al. [103], for instance, found that the addition of pure ferric oxide (Fe_2O_3) nanoparticles resulted in the formation of insert-type tribolayers for AISI1045 steel sliding against 52, 100 steel. It shall be highlighted that the insert-type tribolayers were less protective and lubricative compared with cover-type tribolayers. They also showed that the addition of $MoS_2 + Fe_2O_3$ nanoparticles resulted in the formation of cover-type tribolayers. Fig. 2 shows the morphologies of the worn surfaces without and with the addition of nanoadditives. It can be observed that cover-type tribolayers were also formed by the addition of pure MoS_2 nanoparticles.

It is important to understand the role of nanoparticles in altering the sliding wear characteristics. Chang and Friedrich [104] investigated the effects of nanoparticles on the contact mechanics and wear characteristics of the transfer film. The results showed that the addition of nanoparticles did not play a significant role in the creation of a superior transfer film. However, the presence of nanoparticles may decrease the transfer film–polymeric specimen adhesion, thus decreasing the friction coefficient. Such is the case for high sliding circumstances, where the rolling behaviour of the nanoparticles can greatly enhance the tribological properties and performance. Fig. 3 illustrates the function of

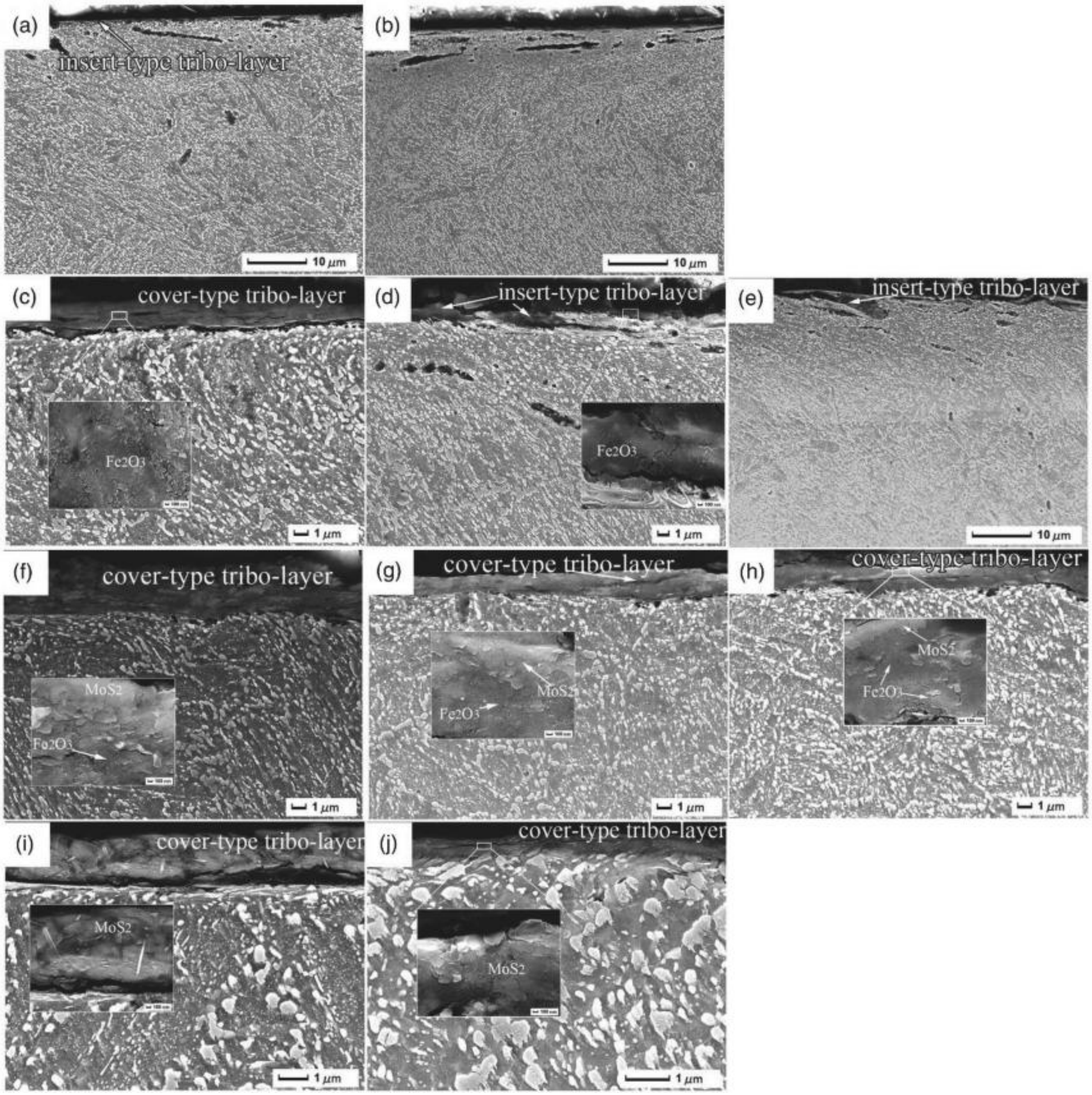

Fig. 2. Cross-sectional morphologies of the tribolayers for AISI1045 steel without nanoadditives at a load of 10 N (a) and 50 N (b). Cross-sectional morphologies of the tribolayers with the addition of Fe_2O_3 nanoparticles at a load of 10 N (c), 20 N (d), and 30 N (e). Cross-sectional morphologies of the tribolayers with the addition of Fe_2O_3 + 20 wt% of MoS_2 nanoparticles at a load of 40 N (f), Fe_2O_3 + 50 wt% of MoS_2 nanoparticles at a load of 40 N (g), Fe_2O_3 + 80 wt% of MoS_2 nanoparticles at a load of 40 N (h), and MoS_2 nanoparticles at a load of 10 N (i) and 50 N (j) (reused with permission from SAGE [103]).

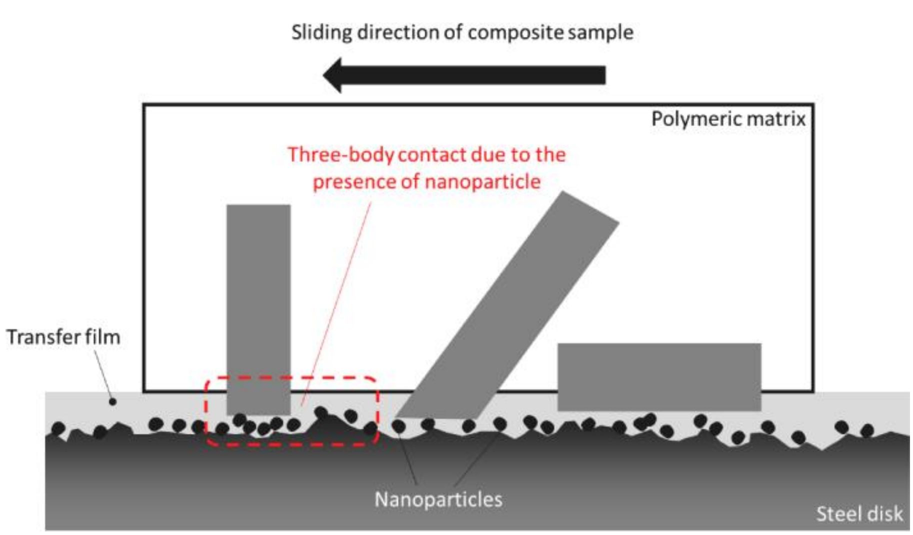

Fig. 3. Nanoparticles as a third body between two metals (reproduced from Chang and Friedrich [104]).

nanoparticles as a third body between two metals.

Black phosphorus (BP) is a novel two-dimensional material with promising physicochemical properties at the nanoscale. Tang et al. [105] examined BP dotted with silver nanoparticles (Ag/BP) and found that the Ag/BP yielded exceptional lubrication performance. The friction coefficient and wear rate of the oil dispersed with 0.075 wt% of BP dotted with silver nanoparticles decreased by ~70 and 90 %, respectively. By dispersing hexagonal boron nitride (hBN) into SAE 20 W50 military grade diesel engine oil, Thachnatharen et al. [106] reported an improvement in the wear diameter and friction coefficient by 9.47 and 20.5 % compared with those for the base oil.

Guo et al. [107] used molybdenum disulphide quantum dots (MoS_2 QDs) as a lubricant additive to improve engine efficiency. They found that the friction coefficient of the paroline oil added with 0.3 wt% of MoS_2 QDs was 0.061, which was significantly lower compared with that of pure paroline oil (0.169). This can be attributed to the formation of a stable tribofilm by the MoS_2, molybdenum trioxide (MoO_3), ferrous sulphide (FeS), and ferrous sulphate ($FeSO_4$) composite in the wear track. The synergistic lubrication mechanism of the tribofilm along with the ball bearing significantly reduced wear and friction. Alqahtani et al. [108] investigated the tribological and rheological properties of SAE 5W-30 engine oil added with graphene nanoplates and found that the wear scar and friction coefficient reduced by 15 and 33 % with the addition of graphene nanoplates.

The selection of nanoparticles is a crucial step to enhance tribological performance. The lower elastic modulus and higher strength of nanoparticles can yield superior lubricating properties [109]. It shall be noted that at high speeds, the re-creation of solid-like tribofilms is highly unlikely. This is because the thickness of lubricant film is larger than the diameter of nanomaterials [110]. The addition of nanoparticles can increase lubricity and improve load-bearing capability, and play a pivotal role in reducing friction and wear [111].

The impact of nanoparticles on the environment

The impact of nanoparticles on the environment is multi-faceted, encompassing both positive and negative impacts, especially when the nanoparticles are added into diesel, biodiesels, and their blends. From the discussion in preceding sections of this paper, it is evident that the addition of nanoparticles into fuels improve combustion efficiency and reduce harmful exhaust emissions, which in turn, reduces air pollution. The nanoparticles enter the environment through fuel combustion. The presence of nanoparticles can be detected in the exhaust of a vehicle along with other exhaust emissions. The nanoparticles are not directly released to the environment before combustion. In addition, incomplete combustion will result in residual nanoparticles in the waste stream [112]. However, this is not a cause for concern since the combustion of diesel, biodiesels, or their blends added with nanoparticles produces lower exhaust emissions owing to the improved physicochemical properties of the fuels. The addition of the nanoparticles into fuels does not pose major threats to the environment [45]. However, little is known on the negative impact of nanoparticles on the environment as there is no information on the long-term effects of nanoparticles on ecosystems and wildlife as result of the increase in the concentration of nanoparticles in the environment [112]. It is possible that nanoparticles released into the environment may interact with other contaminants, particularly in water bodies, which may affect marine life. More detailed studies are required to assess the environmental impact of nanoparticles when they are added into fuels to ensure their safe and responsible use. At present, researchers are exploring ways to optimise the combination of nanoparticles with diesel, biodiesels, and their blends to maximise their benefits while simultaneously minimise potential adverse impacts on nature.

Conclusions

Nanoparticles were originally used to improve the thermal properties of fluids. However, the use of nanoparticles has been shown to improve the physicochemical properties of diesel, biodiesels, and their blends. The addition of nanoparticles in fuels affect the physicochemical properties of fuels. Nanoparticles work as stabilisers and antioxidants in fuels, where they effectively minimise harmful exhaust emissions and improve combustion efficiency. In addition, metal nanoparticles work as a catalyst for the combustion process, resulting in a more complete combustion, which in turn, reduces exhaust emissions. However, to date, there is a lack of studies on the optimum dosage of nanoparticles for diesel, biodiesels, and their blends. Further research is needed to explore various combinations of metal and metal oxide nanoparticles with diesel, biodiesels, and their blends, to optimise the dosage the nanoparticles in fuels, and to explore hybrid nanoparticles composed of at least two different nanoparticles on the physicochemical properties of fuels, combustion efficiency, engine performance, and exhaust emissions.

CRediT authorship contribution statement

Jassinnee Milano: Writing – review & editing, Conceptualization. **Hwai Chyuan Ong:** Writing – review & editing, Writing – original draft, Supervision. **Zhi Chao Ong:** Validation, Formal analysis. **Ghasem Ghadyani:** Writing – original draft, Conceptualization. **Zubaidah Binti Ismail:** Supervision, Formal analysis. **Ibham Veza:** Validation. **A. Masudi:** Methodology. **Sieh Kiong Tiong:** Visualization. **A.S. Silitonga:** Writing – review & editing, Supervision, Methodology.

Declaration of competing interest

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

Data availability

The data that has been used is confidential.

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