Journal of Molecular Liquids 318 (2020) 114250

Contents lists available at ScienceDirect

Journal of Molecular Liquids

journal homepage: www.elsevier.com/locate/molliq

Review

Recent developments of nanoparticles additives to the consumables liquids in internal combustion engines: Part I: Nano-fuels

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ARTICLE INFO

Article history:
Received 21 June 2020
Received in revised form 14 August 2020
Accepted 5 September 2020
Available online 12 September 2020

Keywords:
Nano-fuel
Internal combustion engine
Bio-diesel
Exhaust emission
BSFC

ABSTRACT

The main objective of this review study is investigation of the nanofluids application in internal combustion engines. For this aim, three main sections about using consumable nanofluids in engines (i.e. fuel, lubricant and coolant) are considered to collect both numerical and experimental studies. In this part of review, nano-fuels are introduced which their base fuel can be diesel, bio-diesel, gasoline, alcoholic or blended fuels. By a complete review, effects of these nano-fuels on the engine performance, BSFC, exhaust emissions are discussed and finally the most efficient nano-fuels are introduced form the exhaust emission reduction, BSFC reduction or engines efficiency improvements viewpoints.

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https://doi.org/10.1016/j.molliq.2020.114250
0167-7322/

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1. Introduction

Nanotechnologies are one of the main and novel topics in internal combustion engines (ICEs). Nanotechnologies in ICEs have a wide range of applications such as nano-fluids, nano-composites, nano-rubbers, nano-materials, etc. Based on our experience in nanofluids application in heat transfer [1–6], they have excellent efficiency in the heat transfer and lubrication process which motivated the researchers to examine those applications in ICEs as nano-coolant and nano-lubricants which are reviewed at two other parts of this review study. Furthermore, combustion characteristics of some nanoparticles make them suitable for using as nano-fuel additives which is presented here in ICEs applications. ICEs can use different base fuels due to their advantages. For instance, Ghazikhani et al. [7–10] used ethanol additives to gasoline engines for reducing the exhaust emissions and exergy recovery improvements. Hatami et al. [11–15] used the diesel engines for the heat recovery applications [16,17] such as Combined Heating and Power (CHP) cycles by using different heat exchanger designs.

The most important usage of nanofluids is additives to fuels which is widely introduced by researchers. Gad and Jayaraj [18] blended Nano additives such as Carbon Nano Tubes (CNTs), TiO_2 and Al_2O_3 to the biodiesel fuel and found that biodiesel blend with nano Al_2O_3 as J20Al100 (i.e. 20% Jatropha biodiesel+100 ppm Al_2O_3) led to a maximum improvement of 6.5% in thermal efficiency compared with all other experimented fuels. Jatropha biodiesel blend with CNTs as J20C50 (20% Jatropha biodiesel+50 ppm CNT) produced higher decreases in CO and NOx emissions about 35 and 52%, respectively compared with all tested fuels. Also, Jatropha biodiesel blend with TiO_2 as J20T25 produced higher reductions in HC and smoke emissions about 22 and 50%, respectively compared to all other fuels. Fig. 1 shows the SEM images of CNTs, TiO_2 and Al_2O_3 used in their study which confirms the nano-scales of added nanoparticles.

Gharehghani and Pourrahmani [19] used CeO_2 for the diesel engine shown in Fig. 2 and investigated the engine performance such as Brake Specific Fuel Consumption (BSFC) and emissions in different part per millions (ppms). They reported that if the focus of analysis changes to higher Brake Thermal Efficiency (BTE) (like previous investigations), the values of biodiesel and nano-particles should be approximately about 48% and 112 ppm, respectively.

Hoseini et al. [20] used the graphene oxide (GO) nano-particles additives in biodiesel-diesel blends. Their results showed that by using GO, power and Exhaust Gas Temperature (EGT) significantly increase. Furthermore, by using GO nano-particles, significant reductions in CO (~5%–22%) and Unburned Hydro-Carbons (UHCs) (~17%–26%) were observed. Other nanoparticle additives such as Al_2O_3 and Fe_3O_4 were used in diesel engines by Aalam [21]. In this complete review study (in three different parts), all three nano-liquid applications are gathered and discussed on the effects on the engines performance (especially for the nano-fuel additives). So, the main achievement of this project is usable for the car industries to find how they can improve the engines efficiency using nanotechnology such as nanofluids application in fuels additives, cooling and lubrication processes. They can find best nanomaterial for the fuel, coolant and lubricant to have the greatest performance and minimum losses on the engine performance and emissions. Furthermore, this project considered both the experimental and numerical studies to report the industrial and educational achievements.

2. Nanofuels

Nano-fuels are defined as the common fuels which nanoparticles as additives were added to it to improve its combustion characteristics. In this study, common fuels which are considered as the base fuel are diesel, gasoline, bio-diesel, alcoholic and blended fuels. Elahi et al. [22] reviewed the studies related to nano-additives to the diesel-biodiesel fuels. Their review results generally confirmed an enhancement in the thermophysical properties, improvement in the heat transfer rate and stabilization of the fuel mixtures as well as an increase in the engine performance parameters and reduction in the harmful exhaust emissions depending on the nanofluid additives dosage [22]. As a main result, they concluded that alumina, $FeCl_3$, CeO_2, MnO, CuO (metallic nano additives) nanoparticles reduced the ignition delay significantly in diesel engines. They also introduced the secondary atomization (splitting larger fuel droplets into smaller and finer droplets as shown in Fig. 3) as one of the main mechanisms for nanoparticles combustion improvements. Also, they pointed out that oxygen in nanoparticles structure and water (as emulsion) produces micro-explosion due to rapid evaporation and very fine size fuel droplets which is formed and enhanced the combustion properties. Among their reviewed studies, Graphene Nano-Platelets (GNPs) had better micro-explosion process than Al_2O_3 and CeO_2 due to weaker van der Waals forces. Also, they reported that TiO_2 additive was more efficient than other applied nanoparticles for enhancing the engine's power [22]. Furthermore, they mentioned that

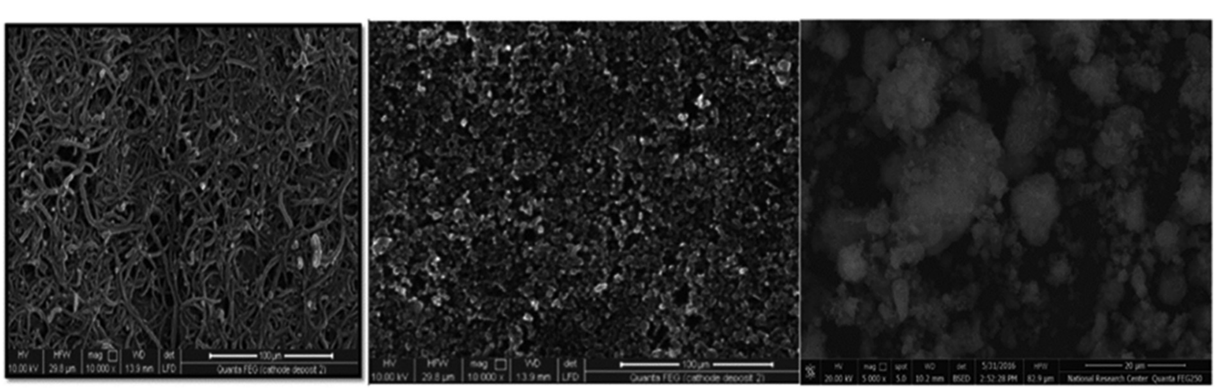


Fig. 1. SEM images of CNTs, TiO_2 and Al_2O_3 used for diesel engine [18].

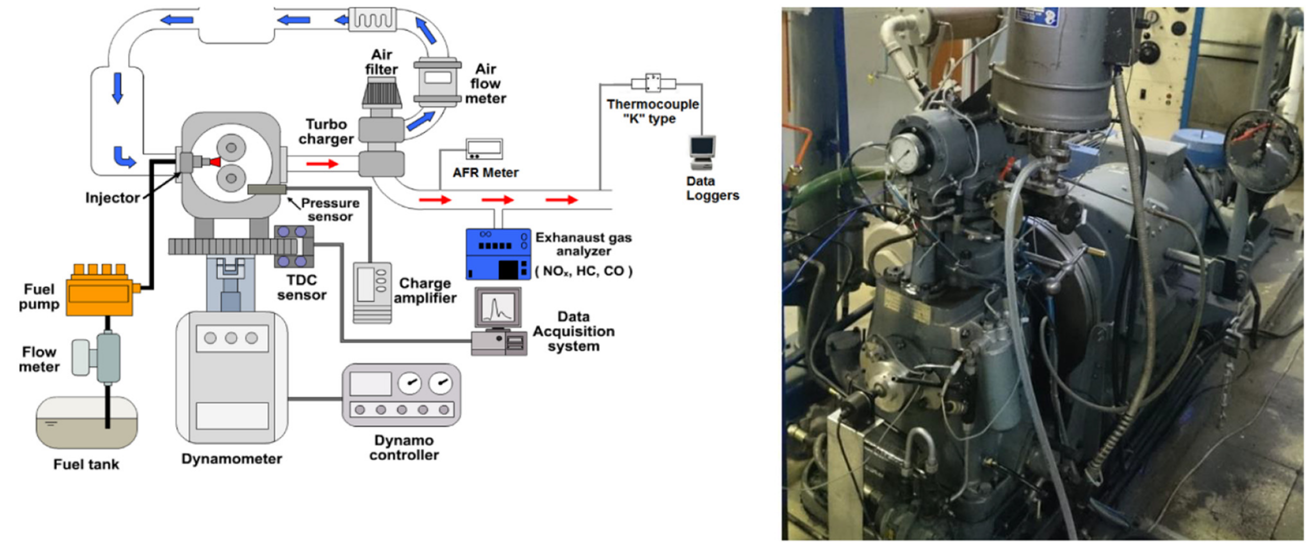


Fig. 2. Experimental setup for nano-additives in diesel engine [2].

higher oxygen content and presence of lower aromatic compounds, reduced the exhaust emissions such as unburned hydrocarbons (UBHC), carbon monoxide (CO) and particulate matters (PM), significantly due to enhanced ignition characteristics by adding the metallic and oxygenated additives. The effect of oxygenated additives on the reaction with fuel will be discussed in Section 4. But, these additives lead to the formation of NOx due to the excess amount of oxygen supplied to the fuel. Another main advantage of nano-fuel is BSFC reduction due to higher calorific value of nanofuel, catalytic oxidation improvement and complete combustion for these types of blended fuel [22]. These effects depends on nanoparticles type which are discussed in next sections in details.

Ce_2O_3, copper and Al_2O_3 were introduced as the more reasonable nanoparticles due to viscosity index increment and flash point and ignition delay reduction as well as the emissions reduction and combustion improvements [23].

Dewangan et al. [24] reviewed the effect of metal oxide nanoparticles additives (such as SeO_2) to diesel engines and reported that metal oxide nanoparticles and oxygenated additives (such as Diethyl Ether (DEE) derived from ethanol) had low auto-ignition temperature, high oxygen content and outstanding cetane number, so improve the combustion and emissions, significantly. Also, Nanthagopal et al. [25] reviewed the studies about nanoparticles and alcohol additives to diesel engines and reported that zinc oxide and carbon nanotubes are the most preferable nanoparticles compared to others due to their better anticorrosion effect and thermal conducting behaviors. Another study on the engine performance enhancement, fuel properties improvements and exhaust emissions reductions by nano-additives and alcoholic additives is performed by Fayyazbakhsh and Pirouzfar [26]. Khond and Kriplani [27] reviewed the studies which are approved until 2015 about the nanoparticle additives to diesel stationary engines to reduce the exhaust emissions. Based on their review, most of researchers stated that addition of nanoparticles in fuels improve cetane number and calorific value of fuel. Some of researchers such as Banković–Ilić et al. [28] focused on the bio-diesel synthesis by the nano-catalysts such as calcium oxide (CaO) as a cheap, highly active and easily available in different forms of nano CaO catalysts (neat, doped, loaded) which are not considered in this review study.

2.1. Additives to diesel fuels

In this section, as summarized in Table 1, the nanoparticles added to diesel fuel is reviewed and the main effect reported is mentioned to be compared. Based on this table, Al_2O_3, CuO, CNT and CeO_2 are the most used nanoparticles as diesel additives. In most cases, density, viscosity, cetane number and heating value of nanofuel were increased and consequently BTE is improved while the BSFC and harmful emissions were reduced.

Based on Dhahad et al. [29] short review, graphene oxide in Jatropha fuel had the maximum thermal efficiency (25%), maximum fuel consumption reduction (35%), HC (50%), CO (55%) and NOx (45%) reduced. After GO, cerium oxide (CeO_2) had more suitable results for diesel engine applications. The JIS#2 diesel fuel and waste cooking oil based biodiesel fuels were used by Caliskan and Mori [31]. They studied the nanoparticles emissions and reported that diesel fuel had more carbon and

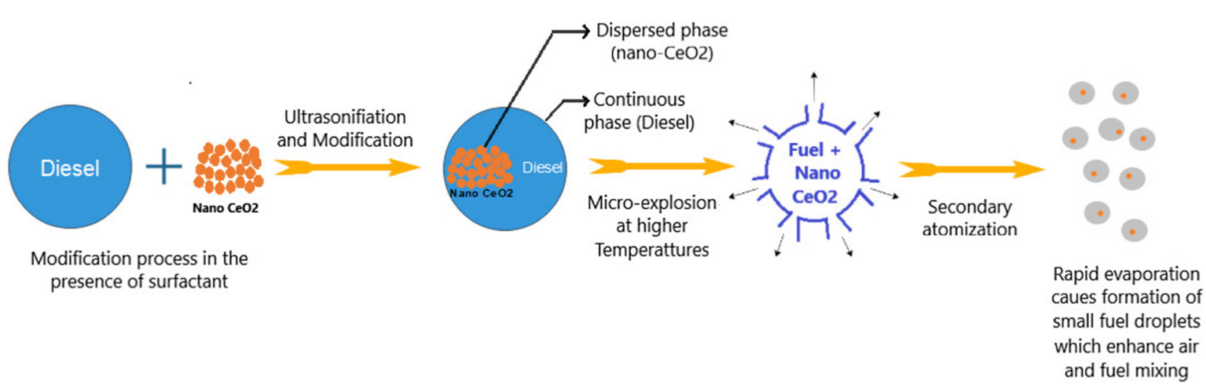


Fig. 3. Role of nano additives on the fuels combustion [25].

Table 1
Nanoparticles additives to diesel fuel and their main effects.

Base fuel	Nanoparticle	NPs dosage and size	Main effect	Ref.
Iraqi diesel fuel	Al_2O_3-ZnO	50 ppm and 100 ppm, 30–35 nm, 20–30 nm	Density, viscosity, and thermal conductivity increased. The specific fuel consumption decreased. Carbon monoxide, unburnt hydrocarbons, and all kinds of particulate matters, sulfur dioxide and hydrogen sulphate decreased. NOx increased due to higher generated temperature inside the combustion chamber.	[29]
JIS#2 diesel fuel	Waste cooking oil additives	20–100%	Maximum CO_2 and NOx emissions rates determined for the BDF100 biodiesel fuel; while the minimum ones are calculated for the JIS#2 diesel fuel. Maximum CO and HC emissions rates were computed for the JIS#2 diesel fuel; while the minimum ones were found for the BDF100 biodiesel fuel. Fuel consumptions from maximum to minimum were BDF100 > BDF50 > BDF20 > JIS#2 at all of the engine loads	[31]
Fossil diesel, karanja	Graphene oxide (GO) and graphene nanoplatelets (GNP)	20-60 ppm, 1-4 nm, $3-8$ nm	Maximum soot reduction was 29.2% for 40 ppm of GO and 60 ppm of GNP had 26.4% reduction in nitric oxide emission. GO had a lower soot tendency, whereas GNP had exhibited better emission reduction respect to NO, CO, and HC.	[32]
Diesel fuel	CNT-MoO_3	40, 80 nm	CNT-diesel was more favorable, due to more benefits in promoting combustion efficiency and emissions reduction than MoO_3	[33]
Standard diesel fuel	CeO_2-CNT	25,50 nm, 40-60 nm, 40 ppm	Cylinder pressure of DF-CNT was a little lower than that of DF due to more heat absorption during the evaporation process.	[35]
Diesel fuel	Graphite (G), Iron oxide (Fe_2O_3)	50-150 mg/L, 50 nm	Maximum decrease of 4.9% in viscosity and an increase of 3.26% in cetane index were detected for graphite blends. G-blends showed a higher increase in torque, power, BTE and greater decrease in BSFC than Fe_2O_3 blends. Also, its NOx was lower.	[36]
Diesel engine with common-rail fuel supply	Nano-sized water droplets	10–15% emulsion	BTE of the engine was improved by 14.2% compared to pure diesel, the NOx emissions was reduced by 30.6%	[37]
82.4% diesel, 5% water	Nano-organic additives	12.6%vol.	BTE improved. NOx emission reduced due to the presence of water, which makes the peak flame temperature come down.	[38]
Diesel emulsion fuel (W/D)	Aluminum oxide (Al_2O_3), copper(II) oxide (CuO), magnesium oxide (MgO), manganese(IV) oxide (MnO) and zinc oxide (ZnO)	50 ppm, 32-34 nm	Density, viscosity, water droplet size and oxidative thermo-kinetics increased, but the stability period decreased, E10Al_2O_3 yielding the highest reduction in BSFC was the best case of nano-additive	[39]
Diesel fuel	CuO	0.5% (wt./wt.)	CuO nanofuel with magnetic fuel conditioning had noticeable effect on enhancing the BTE and reducing the pollutants of the compression ignition engine.	[40]
Diesel fuel	Cu	<0.2 ppm	Soot reduction was 7–14%. Ignition probability was improved.	[41]
Diesel fuel	Titanium (IV) dioxide (TiO_2), copper (II) nitrate ($Cu(NO_3)_2$) and cerium (III) acetate hydrate ($Ce(CH_3CO_2)3 \cdot H_2O$)	25-50 ppm	Increase in heating value and cetane number Titanium dioxides and cerium acetate hydrate nanoparticles considerably reduced pollutants emissions regardless of NOx emissions.	[43]
Diesel fuel	CeO_2	10-40 ppm, 10-30 nm	significant reduction in NOx and HC and a slight increase in CO emissions Minor decrease observed for BSFC while the brake power presented no significant changes	[45]
Diesel fuel	Aluminum oxide, carbon nanotubes and silicon oxide	25-100 ppm	BSFC reduced by up to 19.8% and BTE enhanced by 18.8% for CNT Silicon oxide blends showed better results than aluminum oxide blends, CNT reduced the NOx more competently.	[46]
Diesel fuel	Aluminum oxide and copper oxide	25-100 ppm, 30–50 nm	Combustion characteristics were improved. Engine performance efficiency and environmentally friendly emissions were recognized.	[47]
Diesel fuel	Manganese oxide and copper oxide	200 mg/L	Performance improved and emissions reduced.	[48]
Diesel fuel	Aluminum (A1), iron (F1) and boron (B1)	5-150 nm	Reduced ignition delay, longer flame sustenance and agglomerate ignition. Elevated temperatures resulted marginal rise in NOx emission.	[50]
Diesel fuel	CeO_2	50-100 mg/L	The peak values of in-cylinder pressure and heat releasing rate increased. By decreasing the particle sizes, the oxidation of particles promoted, and the ignition combustion temperature reduced.	[51]
Diesel fuel	Al_2O_3	1–10%wt. 51 nm	Increased the BTE up to 5.5%, and reduced the BSFC up to 3.94%	[52]

less oxygen compared to biodiesel fuels. So, diesel fuel had greater CO and HC emissions and lesser CO_2 and NOx emissions than biodiesel fuels [31]. Approximately in all studies in nanoparticles additive to diesel fuels, micro-explosion phenomenon is introduced as the main reason of combustion improvements, this phenomena makes instantaneous and intense vaporization of the water droplets within the fuel when the fuel is exposed to high temperature gas, so large fuel droplets are broken into many smaller droplets and significantly improve the fuel vaporization and combustion process [37,38]. As an example of water diesel emulsion, Noor El-Din et al. [44] reported that BSFC reduced by 8% compared to pure diesel fuel at 7 wt% water content. In their study, the lowest HC, CO and NOx emissions values were 66, 48 and 32%, respectively which found for the case of using 7% water content.

Yildiz et al. [42] investigated the nanoparticles size emitted from diesel engines and concluded that maximum particle concentration from JIS K 2204 Diesel fuel No. 2 is determined around 10^6 1/cm^3 which is smaller than other fuels, also they measured the particle size between 5 nm and 15 nm. In another study on diesel additives, nano-aluminum (nAl) was used to enhance the combustion characteristic which maximum 26.5% increase in burning rates was observed [49].

Table 2
Nanoparticles additives to gasoline fuel and their main effects.

Base fuel	Nanoparticle	NPs dosage and size	Main effect	Ref.
Gasoline engine	Di-Methyl Carbonate (DMC) additives	–	Reduced unburnt hydrocarbon (UHC) approximately 30% and PM emissions by 60%.	[53]
Gasoline engine	Fe_2O_3 and TiO_2	–	An improvement of engine performance and a reduction in emission of pollutant gases were observed.	[55]
Gasoline	Mn_2O_3	10-20 ppm	Reduced CO and UHC and increased the NOx and CO_2 because of the abundant oxygen bonds. The best blend in terms of UHC and BSFC reduction was gasoline-10% ethanol 20 ppm Mn_2O_3.	[56]
Gasoline	Hydrogen nanobubble	149 nm and about $11.35*10^8$ particles/mL	Power was improved to 4.0%, BSFC was improved from 291.10 g/kWh (for the conventional gasoline) to 269.48 g/kWh.	[57]

2.2. Additives to gasoline fuels

Table 2 shows the studies on the nanoparticles additives to gasoline engines. Compared to diesel and bio-diesel fuels, there are a little studies focused on gasoline engines which Fe_2O_3, TiO_2 and Mn_2O_3 are used nanoparticles in this application where improved the engine performance and reduced the emissions except NOx due to oxygen contents in their structures.

As an example of additives to gasoline fuels, Chan et al. [53] studied the exhaust PM with Thermogravimetric Analysis (TGA) to know its oxidation behavior and composition, Transmission Electron Microscopy (TEM) to find the agglomerate morphological characteristics and Raman Spectroscopy (RAMAN) to analyze the particle nano-structure and reported a total unburnt hydrocarbon (UHC) reduction by approximately 30% and PM emissions reductions by 60%. Also, He et al. [54] reviewed the application potential of the micro-nano structure designs and manufacturing technologies in the petroleum industry [54]. Valihesari et al. [55] used TiO_2 and Fe_2O_3 nanoparticles as gasoline additives and found a 16.7% decrease in viscosity and 10.9% increase in the octane index in the Benz mix N-methanol-Fe_2O_3 and 9.9% increase in octane index for gasoline-TiO_2 [55]. Another main effect of nanoparticle additives to gasoline fuels was BSFC reduction which decreased to 34.69% and 38.89% by adding 10 ppm and 20 ppm Mn_2O_3 to gasoline-ethanol blended fuel [56].

2.3. Additives to bio-diesel fuels

CeO_2, TiO_2, CNT and Al_2O_3 are the most used nanoparticles as additives to bio-diesel fuels as presented in Table 3. Among these nanoparticles, Al_2O_3 had better results in BTE improvements, CNT for CO and NOx reduction, TiO_2 for HC and soot reduction and CeO_2 for BSFC reductions.

As an example of nano-additives to bio diesel, Kumar et al. [58] added the TiO_2 to waste orange peel oil biodiesel and found that BTE increased up to 1.4% and 3.0% with OOME OOME-T50 and OOME-T100 fuels. Some other researchers used the nanoparticles as catalyst for producing the bio-diesel. Zandi-Atashbar et al. [60] used the nano-CeO_2/SiO_2 particles, as a catalyst of waste engine oil to produce a rich liquid bio-diesel fuel product (60.7 wt%) with low sulfur (0.02 wt%) and inorganic pollutants (0.01 wt%). Patel et al. [62] also performed the same study for producing the bio-diesel from waste engine oil (WEO) through the blending of pyrolytic oil in diesel fuel and showed that the highest calorific value of the blended oil was obtained at 20% blending [62]. Some other studies produced biodiesel from waste oils can be found in [75,76,79,81], for instance, reusable nano-catalyst (Fe_3O_4/Cs_2O) [76] is applied to produce bio-diesel from fat extracted from tannery waste.

Gad and Jayaraj [61] added the CNTs, TiO_2 and Al_2O_3 to Jatropha biodiesel and found a power increase in all nanoparticles due to the surface to the volume ratio of nanoparticles. Furthermore, they reported a reduction in the ignition delay and combustion duration of the fuel due to higher peak cylinder pressure and faster heat release rate. Also, they mentioned some other benefits of nanoparticle addition to the fuel such as: better fuel droplet propagation and injected fuel dispersion, better reaction surfaces as a potential catalyst, fuel-air mixing improvements, improvements of fuel droplet propagation and injected fuel dispersion, smaller droplets, lower fuel viscosity and expose to higher effective fuel surface [61]. In another study which investigated the effect of base biodiesel, graphene oxide (GO) nanoparticles were added to three types of oilseeds, namely evening primrose (Oenothera lamarckiana), the fruit of tree of heaven (*Ailanthus altissima*) and Camelina (*Camelina sativa*) by Hoseini et al. [71] and found that the tree of heaven contains 38% oil which was higher than the evening primrose (26%) and Camelina (29%). Sadhik Basha [78] reported that CNT and DEE with the biodiesel emulsion fuels can shortened the ignition delay and exhibited higher brake thermal efficiency and reduced emissions (NO, smoke) than that of pure diesel and biodiesel.

2.4. Additive to diesel/biodiesel blended fuels

Based on Table 4 analysis, CeO_2, GO, Al_2O_3, CNT and TiO_2 are the most used nanoparticles additives to diesel/biodiesel blended fuels. These nanoparticles had benefits such as higher premixed combustion heat release rate, higher thermal conductivity, catalyst function, oxygen contents and more free radicals, faster burning and etc. which makes them more favorable for BSFC reduction, emissions reduction and efficiency improvements for ICEs. In Section 4, the most characteristics of these nanoparticles are presented for more information.

As an example of diesel/biodiesel blended fuel, Hoseini et al. [86] mixed the biodiesel obtained from Oenothera lamarckiana with diesel fuel in the ratio of 20% (B20) and nano-graphene oxide powder with dosage of 30, 60, and 90 ppm were added to blended fuel using the ultrasonic approach. They concluded that engine power increased due to prevent of deposition by nanoparticles and reduction in friction losses. Also, they showed that nano-particles increased the heat of evaporation and decreased the ignition delay and the combustion duration, so makes higher peak cylinder pressure and faster heat release rate [86]. Another study on the blended fuels is performed by addition of cerium oxide by following structures: tyre pyrolysis oil of 5%, diesel of 90% with cerium oxide nano additives 50 ppm (B5D90+ CeO_2 50 ppm), tyre pyrolysis oil of 5%, diesel of 85% with cerium oxide nano additives 100 ppm (B5D85+ CeO_2 100 ppm), tyre pyrolysis oil of 10%, diesel of 85% with cerium oxide nano additives 50 ppm (B10D85 + CeO_2 50 ppm) and tyre pyrolysis oil of 10%, diesel of 80% with cerium oxide nano additives 100 ppm (B10D80 + CeO_2 100 ppm). Results revealed that all the fuel properties were increased compared to without nano additives [89]. Janakiraman et al. [91] used three types of oxide nanoparticles (Cerium, Zirconium and Titanium oxide of 25 ppm concentration) in a blended fuel (20% GGME biodiesel+80% diesel) and concluded that TiO_2 was the most suitable nanoparticle additives to this type of blended fuel.

In a different study, Venu et al. [92] investigated the effect of EGR and Nanofuel (palm biodiesel nanofuel, PBN), simultaneously. They

Table 3
Nanoparticles additives to bio-diesel fuel and their main effects.

Base fuel	Nanoparticle	NPs dosage and size	Main effect	Ref.
Waste orange peel oil	TiO_2	50-100 ppm, 20 nm	BTE increased, emissions reduced, cylinder peak pressure and heat release rate were increased.	[58]
Waste fry oil methyl ester	MWCNT	25-50 ppm	BTE was significantly increased and harmful emissions and environmental pollution were reduced	[59]
Jatropha biodiesel	CNTs, TiO_2, and Al_2O_3	25-100 ppm, 10-50 nm	Al_2O_3 as J20Al100 managed a maximum improvement of 6.5% in BTE. CNTs as J20C50 created higher decreases in CO and NOx emissions by 35 and 52%. TiO_2 as J20T25 produced greater reductions in HC and smoke emissions about 22 and 50%	[61]
Pungamia pinnata non-edible oil biodiesel	Coconut shell (CS) nano particles	20 nm	18.56% decreased the NOx. CO and CO_2 emissions were reduced. Increased engine performance and increased the SFC.	[63]
Lemon and orange peel oil	CNT, CeO_2	50-100 ppm	Brake thermal efficiency was slightly lower than diesel fuel. 50 ppm cerium oxide with lemon peel oil blend had 16.4% reduction in BSEC and 53.8% reduction in CO emission.	[64]
Waste cooking oil (WCO)	Hydroxyapatite nanorods	0-30 ppm	30% decrease of NO emission, 60% decrease of CO emission, 44% decrease of HC emission and 38% decrease of smoke emission.	[65]
Cymbopogon flexuosus biofuel	Cerium oxide	20 ppm	Thermal efficiency was enhanced by 1.75%. Emissions such as hydrocarbon; carbon monoxide and smoke were reduced. An increase of oxides of nitrogen emission.	[66]
Nerium oleander biofuel (ENOB)	Cerium oxide	30 ppm, 15.01 nm	Reduction in CO, smoke opacity, HC, and NOx emissions	[67]
microalgae methyl ester	TiO_2 and SiO_2	50-100 ppm	Improvement in performance characteristic and reduction in exhaust emissions	[68]
neat mustard oil methyl ester	TiO_2	100-200 ppm, 50 nm	Reduced various emissions over neat mustard oil methyl ester	[69]
Cordiamyxa bio-oil	$BaMoO_4$ -Ce_2O_3	0.25–0.75 wt%	Better engine performance and emission reduced compared to fossil fuels	[70]
Three kinds oilseeds	graphene oxide (GO)	60 ppm, 1.2 nm	A reduction in UHCs, CO, and BSFC with a fine of increased NOx emissions was observed	[71]
Lemongrass Oil (LGO)	CeO_2	30 ppm, 16.27 nm	Reduction of (CO), (UHC), (NOx) and marginal decrease of smoke emission. Improvement in BTE was also observed due to improved atomization and rapid evaporation rate of fuel due to large surface area to volume ratio of CeO_2 nanoparticle.	[72]
Jatropha Methyl Ester (JME)	GO	25-100 mg/L	Enhanced the BTE by 17%. The peak cylinder pressure, the highest rate of pressure rise, and maximum heat release rate were increased by 8%, 6%, and 6%, respectively. The CO and UHC emissions were decreased significantly by 60% and 50%, respectively, NOx emission was reduced by 15%.	[73]
Waste cooking oil	CeO_2	80 ppm, 50 nm	Amount of hydrocarbon, oxides of nitrogen and smoke decreased with nanoparticle addition for higher injection pressures.	[74]
Water emulsified biodiesel blend (NWEB) with Mahua oil	Cerium oxide	50-100 ppm	Optimal emulsifying parameters were determined as 69.7 ppm nano-oxide concentration, 10% water, 1% surfactant and 2500 rpm of stirrer	[75]
Tannery waste	Cs_2O	10 nm to 3500 μm	Optimum conditions was 21:1 methanol-to-oil molar ratio, 7% wt catalyst at 65 °C for 300 min with a constant stirring rate of 500 rpm	[76]
Soybean Biodiesel	CNT	10 ppm	Water/biodiesel blends had a lower magnitude of NOx and smoke emissions, and 10WSB showed better HC and CO emissions compared to SB and 20WSB	[77]
Jatropha oil	Carbon Nanotubes and Di-Ethyl Ether	50 ppm CNT + 50 mL DEE	BTE, NO and smoke emission of CNT + DEE fuels was 28.8%, 895 ppm and 36%, while it was 25.2%, 1340 ppm and 71% for pure diesel, respectively.	[78]
Bombax ceiba oil	CaO	0.6 g/100 mL	96.2% of Bombax ceiba methyl ester (BCME) was reached to optimum conditions. The CaO-NPs were reused up to 5 cycles with noticeable loss of yield.	[79]
Jatropha oil biodiesel	Aluminum oxide hydroxide (AlO (OH))	25-100 ppm	BTE was lower, and NO level was higher for the biodiesel than that the neat diesel. Performance and emission characteristics were especially enhanced by the addition of water and nanoparticles.	[80]
Canola oil	$ZnO/BiFeO_3$	1–5 wt%	Optimum conditions reported for the molar ratio of methanol/canola oil of 15:1, a reaction temperature of 65 °C and a catalyst amount of 4 wt%, where the conversion of canola oil was 95.43%.	[81]
Neat neem oil methyl ester	Silver oxide	5-10 ppm	Enhancement of (BTE) with a reduction in (BSFC). CO, HC, NOx, and smoke were decreased by 12.22, 10.89, 4.24, and 6.61% for BD100+ Ag_2O (5 ppm) and 16.47, 14.21, 6.66, and 8.34% for BD100, respectively.	[82]
Neat palm stearin biodiesel (PSBD)	Silver oxide, AgO	5-10 ppm, 10-20 nm	Improvement in ignition characteristics due to enhanced surface area to volume ratio. AgO nano-additive enhanced the (BTE) with a reduction in (BSFC)	[83]

presented that PBN-10EGR and PBN-20EGR had BSFC of 0.458 kg/kWh and 0.392 kg/kWh which was 6.53% and 19.85% lower than PBN without EGR at 25% load. They mentioned the reason as improved oxidation rate, higher cylinder temperatures, better combustion efficiency, oxygen buffer and oxidation catalyst function of nanoparticles [92]. Khalife et al. [108] also focused on the simultaneously usage of water (3, 5, and 7 wt%) and cerium oxide nanoparticles (90 ppm) into biodiesel/diesel fuel blend (B5). Furthermore, hybrid nanoparticles [119], supramolecular complex (SC1) [Mn(EIN)4(NCS)2] [120] and iron oxide (Fe_3O_4) nanoparticles were used by researchers to blended biodiesel and found that not only improve the performance features but also aids to reduction of harmful emissions from ICEs [134].

2.5. Additive to alcoholic fuels

Alcoholic properties variations moving from Methanol to Decanol are presented in Fig. 4. As seen, by increasing the carbon content, cetane number, lower heating value and flash point will increase, while oxygen content and self-ignition temperature will decrease. Al_2O_3, GO and CNT

Table 4
Nanoparticles additives to diesel/biodiesel blended fuel and their main effects.

Diesel blended with	Blended percentage	Nanoparticle	NPs dosage and size	Main effect	Ref.
Fusel oil	5–20%	Sugarcane nano-biochar (SNB)	25-125 ppm, 100 nm	The optimal value of parameters for engine performance and exhaust emissions achieved using the Response Surface Method	[84]
Waste cooking oil	0–20%	CeO_2, $Ce_{0.5}Co_{0.5}$	25-100 mg/L	Reduction in CO, NOx and UBHC were 18.27%, 6.57% and 23.46%, respectively using CeO_2 (100 ppm), while 24.18%, 13.96% and 40.74%, respectively for $Ce_{0.5}Co_{0.5}$ nano-composite oxide (100 ppm)	[85]
Oenothera lamarckiana biodiesel	20%	Graphene oxide (GO)	30-90 ppm	Power and EGT significantly increase. Significant reductions in CO (~5%–22%) and UHCs (~17%–26%). A slight increase in CO_2 (~7%–11%) and NOx (~4%–9%) emissions	[86]
Botryococcus braunii algae oil methyl ester	20%	CuO_2	25-100 ppm	B20 was the most efficient fuel ratio Significant reduction in CO, HC and smoke emissions.	[87]
Neochloris oleoabundans algae oil	20%	CeO_2	25-100 ppm	BTE had been improved. The exhaust engine emission was decreased. BSFC had been decreased. NOx level elevated about 25 ppm CeO_2	[88]
Tyre pyrolysis oil	5–20%	Cerium oxide	50-100 ppm, 50-80 nm	B5D85 + $CeO_2$100 ppm had higher brake thermal efficiency, higher NOx beside the lower smoke emissions	[89]
Waste frying oil biodiesel	20%	Manganese oxide and cobalt oxide	25-50 ppm, 10-30 nm	BSFC and BTE were considerably enhanced while the NOx and CO emission were significantly decreased.	[90]
Garcinia gummi-gutta methyl ester	20%	Cerium oxide (CeO_2), zirconium oxide (ZrO_2) and titanium oxide (TiO_2)	25 ppm	B20 (Garcinia) + TiO_2(25 ppm) fuel had greater impact and faster performance, reduction in CO, UHC and smoke emissions, lower combustion temperature	[91]
Palm biodiesel	10–30%	TiO_2	25 ppm	Increase in EGR percentage in PBN, cylinder pressure was slightly lower and heat release rate was higher than PBN.	[92]
Hydrotreated vegetable oil (HVO)	10–30%	Cerium dioxide and ferrocene	–	A significant reduction of carbon monoxide (52%) and hydrocarbon (47%) emissions	[93]
Botryococcus braunii algae oil methyl ester	20%	CuO_2	25-100 ppm	A significant reduction in CO, HC and smoke emissions. Proposed nanofuel was best suited as an alternative diesel engine fuel	[94]
Pongamia biodiesel	20%	CuO	50-100 ppm	4.01% increase in BTE, a reduction of around 1.0% in BSFC and a reduction of around 12.8% in smoke emission and 9.8% reduction in NOx emission for the blend B20CuO100.	[95]
Waste cooking oil	5–10%	Alumina	30-90 ppm	Predicted different parameters of engine for various conditions using the training algorithm of back-propagation with 25–25 neurons in hidden layers (logsig-logsig)	[96]
Calophyllum inophyllum	20%	Graphene oxide (GeO)	25-75 ppm	BTE, cylinder pressure, heat release rate increased by 3.28%, 8.21%, and 11.85% with CB20 + GeO50 ppm. The ignition delay, combustion duration, BSFC, CO, UHC, smoke opacity were reduced by 10.52%, 7.4%, 3.2%, 7.8%, 6.4%, 6.6% with CB20 + GeO50 ppm.	[97]
Dairy scum oil methyl ester (DSOME)	20%	Graphene oxide	20-60 ppm, 23-27 nm	BTE improved by 11.56%, BSFC reduced by 8.34%, UHC by 21.68%, smoke by 24.88%, CO by 38.662% for the nanofuel blend DSOME2040 and oxides of nitrogen emission by 5.62% for fuel DSOME(B20)	[98]
Waste cooking oil	20%	Carbon nano tubes (CNT), Silver nanoparticles	40-120 ppm	Engine power and torque output increased up to 2% and BSFC was decreased 7.08%. CO_2 emission increased maximum 17.03% and CO emission was lower significantly (25.17%) than pure diesel fuel. UHC emission with silver nanoparticles decreased (28.56%) while with CNT nano particles increased maximum 14.21%. NOx increased up to 25.32% compared to the net diesel fuel.	[99]
Eucalyptus green fuel blend (EME20)	20%	Aluminum oxide nanoparticles (ANPs)	50-100 ppm	Significant improvement in the BTE and smaller hazardous pollutants (such as CO, HC and smoke)	[100]
Soybean methyl ester	50%	Aluminum Oxide (Al_2O_3)	100 mg	4% improvement in BTE for B55N additive compared to B55 without additive. Decrease in HC emission by using B55 biodiesel, due to its fuel bound oxygen content. Aluminum oxide B55N fuel showed 62% reduction in HC.	[101]
Neochloris oleoabundans algae oil	20%	CeO_2	25-100 ppm	Energy of cerium oxide increased the combustion properties, and decreased carbon deposits in the cylinder wall.	[102]
Pongamia oil	20%	CeO_2 and CeO_2: Gd	50 ppm	Emission decreased in the CeO_2:Gd dispersed biodiesel	[103]
Neochloris oleoabundans methyl ester	20%	CuO_2	25-100 ppm	Better combustion, greater BTE, EGT and lesser BSFC were observed	[104]
Neochloris oleoabundans algae oil	20%	CeO_2	25-100 ppm, 50 nm	BTE had been improved and the BSFC and exhaust engine emissions were decreased.	[105]
Cotton seed oil	20%	ZnO	40-120 ppm	The emissions were decreased without correcting the performance and combustion characteristics.	[106]
Waste cooking oil	5%	CeO2	0-90 ppm	The lowest cost per unit of exergy was reported to be 48.81 USD/MJ for neat diesel at full load condition. The most appropriate fuel blend according to the conventional exergy analysis was B5W3m.	[107]
WCO	5%	CeO2	90 ppm	BSFC of B5 containing 3% water and 90 ppm cerium oxide (B5W3m) was 5% and 16% less than those of neat B5 and neat B5 containing 3%	[108] [125]

(continued on next page)

Table 4 (*continued*)

Diesel blended with	Blended percentage	Nanoparticle	NPs dosage and size	Main effect	Ref.
				water (B5W3), respectively. B5W3m fuel blend increased BTE by over 23 and 11% compared with B5W3 and B5, respectively B5W3m also significantly reduced CO, HC, and NOx emissions by 51, 45, and 27% compared to B5W3.	
Vegetable methyl ester (Biodiesel) (WCO)	0–100%	CNT and Ag	40–120 ppm	Peak pressure increased up to 15.38% in BD + CNT120. Increased the peak pressure rise rate and heat release rate by up to 23.33% and 28%, respectively. Ignition delay was reduced by 8.98% in BD + CNT120.	[109]
Waste cooking oil methyl ester	10%	Aluminum oxide (Al_2O_3), titanium oxide (TiO_2) and silicon oxide (SiO_2)	100 ppm	CO, HC and NOx emissions were significantly decreased.	[110]
Waste cooking oil	15%	Carbon quantum dot	60 ppm	Increased the engine torque and power while decreased the brake specific fuel consumption. By employing the B15W5-CQD60 fuel diesel engine power at the rate of 2700 rpm was improved by 21% compared with the B15 pure fuel.	[111]
Mahua methyl ester (MEOM)	20%	Copper oxide	50 ppm	The BTE was 2.19% improved compared to 20MEOM blend without additive at full load condition. Emissions of HC, CO and smoke were noticeably reduced.	[112]
Mahua biodiesel	0–50%	Zinc oxide (ZnO)	50-100 ppm	Optimal combination of nanoparticles, biodiesel and diesel was found by a classical differential evolution algorithm (DEA). BTE is 2–3% more than the B20 added with 50 and 100 ppm ZnO. B20 with 50 ppm ZnO had lower NOx emission.	[113]
Waste cooking oil	0–10%	Alumina	30-90 ppm	Torque, power, BTE and EGT increased 5.36%, 5.36%, 10.63% and 5.80%, respectively, while the SFC reduced by 14.66%. The CO and UHC exhaust emissions decreased by 2.94% and 20.56%, respectively, while NO emission increased by 43.61%.	[114]
Waste frying oil	30%	Ferrocene	50-300 mg/L	Increased BTE by 3% and 8%. The ferrocene increased CO_2 and decreased NOx emissions for diesel fuel at medium and high loads.	[115]
Jatropha oil bio-diesel	20%	(n-Al_2O_3)	0.25–1.0 g/L	Enhancement in the BTE due to the additive improved degree of mixing with air and better combustion characteristics.	[116]
WCO	30–40%	CeO_2	80 ppm	BTE of B30 with additives was 29.57% and was 29.72% at par with neat B20 operation. Maximum reduction of HC and smoke emissions were 16% and 11.7% less than neat B20 fuel operation. B30 with diethyl ether and CeO_2 nanoparticles showed minimum NOx emission, 6% less than neat B20.	[117]
Ailanthus altissima	0–20%	Graphene oxide (GO)	30-90 ppm	Power, torque, and EGT significantly increased. CO and UHC emissions approximately 7–20% and 15–28% reduced, respectively. A slight increases in CO_2 and NOx emissions (approximately 6–10% and 5–8%, respectively) was observed.	[118]
Waste cooking oil	5–20%	Hybrid nanocatalyst containing cerium oxide on amide-functionalized multiwall carbon nanotubes (MWCNT)	30-90 ppm	NOx, CO, HC and soot were decreased up to 18.9%, 38.8%, 71.4% and 26.3%. Power and torque increased up to 7.81%, 4.91%, respectively, and fuel consumption decreased by 4.50%.	[119]
Soybean and sunflower oil	50%	Supramolecular complex (SC1) $[Mn(EIN)_4(NCS)_2]$	50-150 ppm	Improved the BTE by 14.8–20.52%. CO and HC emissions were significantly decreased by 48.19–62.05% and 15.34–60.94% compared to pure diesel fuel, respectively for SC1 nanofluid emulsions. NOx emissions for all SC1 nanofluids combustion increased by 30.41–67.62% while the smoke emissions reduced by 32–44.27%.	[120]
Calophyllum inophyllum biodiesel	30%	Zinc oxide and titanium dioxide	50-100 ppm, 20-35 nm	Improved BTE by 5–17%. CO and HC emissions were reduced. The smoke emission was reduced, but NOx increased.	[122]
Poultry litter oil	20%	Alumina	30 mg/L	Reduced the CO, UHC, while increased the NOx. Emissions were achieved using B20 biodiesel blend compared with neat diesel	[123]
Corn stalk pyrolysis bio-oil	25%	$Ce_{0.7}Zr_{0.3}O_2$	50 ppm	Calorific value was reduced by 18.5%. Fuel saving rate was near to 8.4%. Reduced CO, HC and smoke emissions.	[124]
Dairy waste biodiesel (DWB)	10–30%	MWCNT	125-500 ppm	BTE was higher than that of diesel. MWCNT up to 250 PPM improved the efficiency. CO and HC emissions of B20 blend was 20 and 6.17% smaller than Diesel By addition of 125 ppm of MWCNT to B20, the CO and HC emissions reduced by 5 and 3.94% respectively.	[126]
Jojoba biodiesel-diesel (JB20D)	20%	Al_2O_3	10-50 mg/L	NOx by 70%, CO by 80%, UHC by 60%, and Smoke opacity by 35% reduced. Reduction of BSFC was about 12%.	[127]
Calophyllum Inophyllum biodiesel	20%	TiO_2	40 ppm	The smoke emissions were increased by 16.23% and 12% for the B20 + 20%EGR and B2040TiO_2 + 20%EGR fuel samples	[128]
Waste cooking oil (WCO)	5%	Aqueous carbon nanoparticles	38-150 μM	Decreased the BSFC about 107.3 g/kWh. Increased BP and BTE by 1.07 kW and 11.58%.	[129]
Soybean biodiesel	10–40%	ZnO	25-100 ppm	The performance and emissions characteristics had powerfully enhanced at the optimal parametric setting.	[130]

Table 4 (*continued*)

Diesel blended with	Blended percentage	Nanoparticle	NPs dosage and size	Main effect	Ref.
Seed methyl ester	10–30%	Alumina oxide, MWCNT	30-60 ppm	1.6% greater BTE, 15–51%, 24–68% and 7–9% reduction in CO, UHC and NOx.	[131] [132]
Acacia Concinna biodiesel	40%	TiO_2	50-200 mg/L	BTE, BSFC, ignition delay (ID), HC, smoke emissions were improved by 3.25%, 18.42%, 7%, 38%, 20% respectively with marginally higher NOx emissions.	[133]
WCO	5–20%	CNTs	30-90 ppm	Enhancement in power (3.67%), BTE (8.12%), and EGT (5.57%). A significant reduction in SFC was observed. CO, UHC, and soot exhaust emissions decreased, and NOx emissions increased.	[135]
Jatropha methyl ester	20%	GNPs	25-100 mg/L	Increased 25% in the BTE and a reduction of 20% in the BSFC. Emissions of NOx, CO, and UHC were reduced by 40%, 60%, and 50%, respectively	[136]
Pongamia	20%	Ferrous based nanoparticles (Fe_3O_4)	0.5–1.5%vol.	Decreasing BSFC by 8% compared to non-additive fuel. CO and HC emission were decreased too.	[137]
Palm oil methyl ester	10%	Carbon coated aluminum (Al@C)	30-ppm	Reduced BSFC by 6% averagely; a drop of 6% in NOx emission. CO emission was reduced by 19% comparing with B10.	[138]
Pongamia methyl ester	25%	Al_2O_3	50-100 ppm	BTE increased slightly while BSFC decreased. CO, HC and smoke emission slightly decreased. NOx emissions were higher for aluminum oxide nanoparticles blended pongamia methyl ester.	[139]
Azadirachta indica biodiesel	25%	NiO	25-100 ppm	The average reduction in BSFC for timing of 27°bTDC compared to 23°bTDC for dosing levels of 25 ppm, 50 ppm, 75 ppm and 100 ppm were 5.29%, 6.91%, 7.13% and 7.86%, respectively.	[140]

were more used by researchers as additives to ethanol/butanol blended fuels based on Table 5 details and reasons.

Alcoholic additives (mainly Ethanol and Butanol) are used to can enhance the environment by pollution reduction. For instance, Somasundaram et al. [142] estimated the Global Warming Mitigation Potential (GMP) by producing carbon credit from the engine using diesel-ethanol-bio-diesel blends with alumina doped ceria-zirconia nano additives. Venu et al. [143] improved the combustion characteristics by ternary (diesel-biodiesel-ethanol) blends and nano additives. They used 10% ethanol, but proposed that additional studies can be extended with higher ethanol content with the final optimized engine condition. Also, Kumar Sonia et al. [144] revealed that 30% Methanol (D + M30) with nanoparticles blend produced lower emissions except NOx emission. So, it was selected as an optimum blend in their application. They mentioned the reason of this behavior for oxygen content in methanol, lower cetane number and consequently higher in-cylinder temperature makes reduction in HC and smoke. Addition of water nano-droplets, reduces the combustion temperature (and consequently reduces NOx) due to its heat sinking effect which takes the heat of combustion chamber to evaporate. Also, increasing the methanol ratio in the fuel blend makes an increase in the BSFC due to lower heating value of the blend fuel [144].

Mardi et al. [145] used blended Ethanol-Methanol-Butanol fuels with CNT, Al_2O_3 and TiO_2 nano additives and found significant improvement in every aspect of performance such as enhanced brake power (BP) and brake thermal efficiency (BTE) by 8.1% and 4.5%, respectively along with the BSFC reduction by 4%. Also, they presented excellent reduction in all emissions by 26%, 7.5%, 9.2% and 36% in CO, UHC, NOx and smoke, respectively using CNT additives. In another study, it is mentioned that the addition of n-butanol to the fuel blends significantly affected density, kinematic viscosity and cold flow properties, while it is reported that the addition of TiO_2 has not much effect on properties [146].

Heidari-Maleni et al. [147] investigated the effect of ethanol percentage and graphene quantum dot (GQD) nanoparticles additives to biodiesel as depicted in Fig. 5 and found that GQD nanoparticles

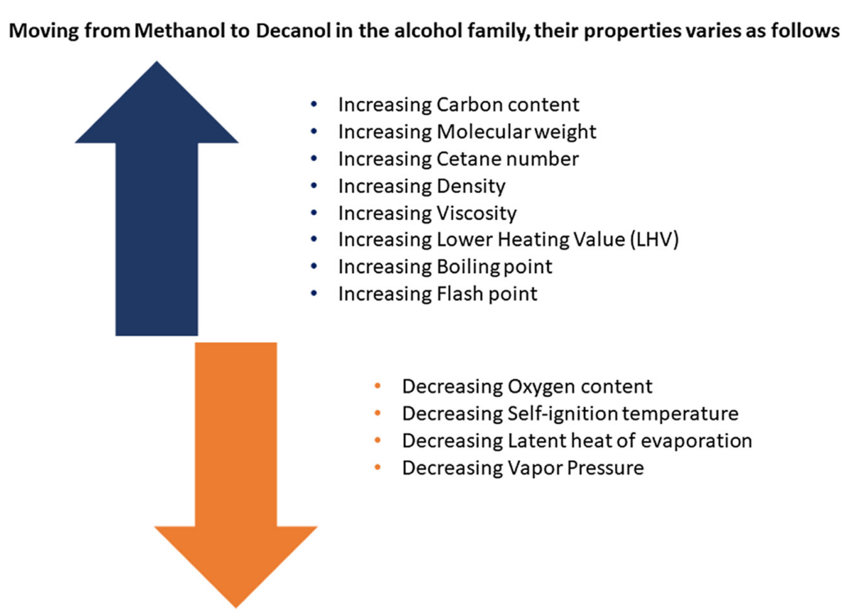


Fig. 4. Alcoholic properties changes moving from Methanol to Decanol [25].

Table 5
Nanoparticles additives to alcoholic fuel and their main effects.

Alcoholic Additive	Bio-diesel blended	Percentages of alcohol	Nanoparticle	NPs dosage and size	Main effect	Ref.
Methyl ester	Honge oil	20%	Aluminum oxide	20-60 ppm	BTE enhanced by 10.57%, a decline in BSFC by 11.65% and the engine exhaust emission: HC, CO, and smoke reduced by 26.72%, 48.43%, and 22.84%, while the NOx increased by 11.27%.	[141]
Ethanol	Biodiesel	45%	Alumina doped ceria-zirconia	50-100 ppm	The NOx emissions were lower for the diesel-biodiesel-ethanol blend than the nano blends. Reduction in emissions such as CO and CO_2 were converted into carbon credits for blends with nano additives.	[142]
Ethanol	Jatropha	10%	Alumina	10-30 ppm	HC and CO emissions reduced about 9.18% and 16.83% HPF-TRCC22 resulted highest BTE of about 32.8%, in comparison with DF100-HCC23 (32.7%), HPF-TRCC21 (31.4%), HPF TRCC24 (32.5%). HPF-TRCC21 caused in lowered NOx emissions by 22.53%.	[143]
Methanol	–	0–30%	Nano emulsion	–	NOx emission was reduced significantly by using 15% water nano emulsified blend, whereas other emission were increased, slightly.	[144]
Ethanol-methanol-butanol	Fatty Acid Methyl Ester	3%	CNT, Al_2O_3, TiO_2	50 ppm	Improved BP and BTE by 8.1% and 4.5%, respectively along with the most BSFC reduction by 4%. Reduction in all emissions by 26%, 7.5%, 9.2% and 36% in CO, UHC, NOx and smoke, respectively.	[145]
n-Butanol (C 4H 9 OH)	WCO	10%	TiO_2	0.01% by mass	BT (brake torque) and BP (brake power) improved 10.20% and 9.74% and decreased the BSFC 27.73% and 28.37%, respectively.	[146]
Bioethanol	Refined fish oil	2–8%	Graphene quantum dot (GQD)	30 ppm	Increased power and torque by 28.18% and 12.42% correspondingly, and reduced SFC, CO and UHC by 14.35%, 29.54% and 31.12%, respectively,	[147]
n-Heptanol	–	20–40%	graphene oxide (GO), graphene nanoplatelets (GNPs), and multiwalled carbon nanotubes (MWCNTs)	50 mg/L	H20D and H40D blends explained that the BSFC was increased by 10%, while soot and NOx emissions were reduced by 40% and 12%. By addition of CNT, H20D, and H40D a reduction in the SFC by about 15% was observed	[148]
Ethanol	Jojoba	20%	(Al_2O_3)	25-100 mg/L	Reduction BSFC was approximately 20%.	[149]
Jojoba methyl ester	–	20%	MWCNTs	10-50 mg/L	16% increase in the BTE and 15% decrease in the BSFC. NOx, CO and UHC were reduced by 35%, 50% and 60%, respectively.	[150]
n-Butanol	Jatropha methyl ester (JME)	40%	Graphene oxide (GO), graphene nanoplatelets (GNPs), and multiwalled carbon nanotubes (MWCNTs)	50 mg/L	Peak pressure and BSFC were increased up to 6%, and 22%, respectively. CNT make a significant reduction in the SFC by 35% and NOx, CO and UHC by 45%, 55% and 50%, respectively.	[151]
Calophyllum inophyllum methyl ester (CIME)	–	100%	Zinc oxide (ZnO), ethanox (anti-oxidant)	10-50 ppm, 200-500 ppm	ZnO improved the efficiency by 4.7% and 12.6% reduction of NOx. 500 ppm of Ethanox resulted in maximum decrease of 17.8% for NOx.	[152]
Benzaldehyde, anisole, n-butanol/n-heptane	–	40–60%	–	–	n-butanol/n-heptane blend offered a higher premixed burn fraction and a higher pressure rise rate.	[153]
Ethanol	–	–	Al	5.0 mg/mL	Nano-Al concentration of 5.0 mg/mL had ultrafine and uniformly distributive of the atomized droplets.	[156]

increased the power and torque of the engine by 12.42% and 28.18%, averagely. Also, they reported that SFC was reduced in mixed fuels (B10 + E2 + GQD30, B10 + E4 + GQD30, B10 + E6 + GQD30 and B10 + E8 + GQD30) by 14.35% compared to diesel fuel (D100) [147]. BTE improvement was also obvious with water and CNT additives to Jatropha Methyl Ester biodiesel. It was 24.80% for JME, while it was 26.34% and 28.45% for the JME2S5W and JME2S5W100CNT fuels, respectively [154]. Other studies also approved the soot reduction, cetane

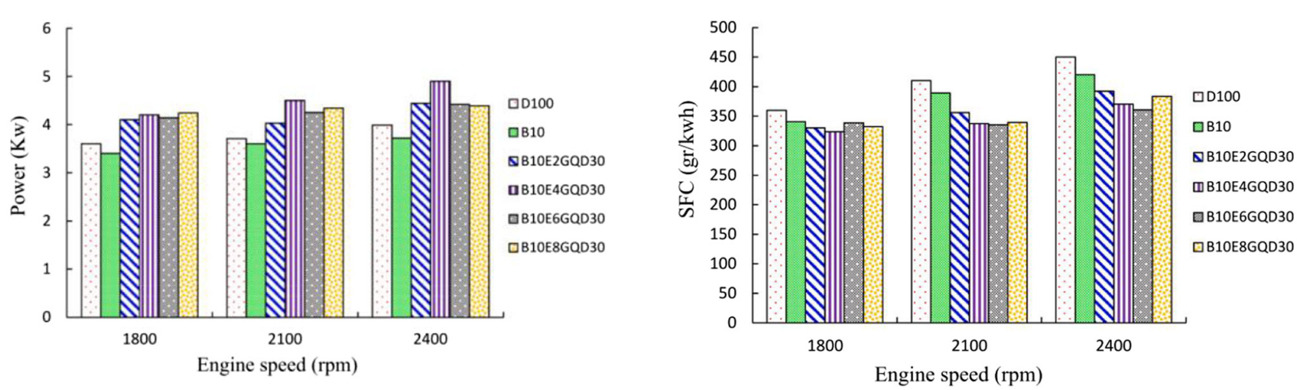


Fig. 5. Effect of ethanol and GDQ nanoparticles on power and SFC of engine [147].

Table 6
Nanoparticles additives to hydrogen fuel and their main effects.

Blended fuel	Hydrogen amount	Nanoparticle	NPs dosage and size	Main effect	Ref.
Hydrogen-corn-vegetable oil methyl ester	10%	Zinc oxide and Titanium dioxide	50-100 ppm	Improved the BP by 22% (Titanium dioxide) and 4% (Zinc oxide). Also, 18% and 15% reduction in BSFC. Reduction of emission values by 37% and 26% in HC, 26% and 36% for CO, 19% and 15% in NOx and followed by 13% and 8% of smoke opacity.	[157]
Hydrogen+diesel	20% (0.2 kg)	TiO_2, CNT, Al_2O_3, CuO and CeO_2	100 ppm (0.02 kg)	CeO_2 and Al_2O_3 improved the BTE by 4.3% and 2.5%. No significant change in BSFC was observed for CeO_2. CNT and TiO_2 reported 23% and 22% reduction in BSFC.	[158]
Hydrogen+jatropha methyl ester	0.5 and 1.5 L/min	Zinc oxide (ZnO)	100 ppm	By increasing H_2 flow rate, hydrocarbon (HC) emissions decreased for nanoparticles of size 20 nm, but increased for 40 nm. B20-ZnO20 nm had 2.9% greater BTE with a 1.5 L/min H_2 flow rate, but for the larger nanoparticles, B30-ZnO40 nm exhibit higher BTE.	[159]

improvements and engine performance increment using ethanol additives [155].

2.6. Additive to hydrogen fuels

ZnO, TiO_2 and Al_2O_3 was the most applicable nanoparticles to hydrogen blended fuels which is confirmed by Table 6 data. Versus previous studies on other base fluid, CeO_2 is not recommended for hydrogen fuels due to no significant effect on BSFC, but ZnO, TiO_2 and Al_2O_3 not only reduced the BSFC significantly, but also decreased the emissions, considerably due to their catalytic activity in presence of H_2.

Manigandan et al. [157] added hydrogen with 10% vol. and 50–100 ppm zinc oxide and titanium dioxide nanoparticles to base biodiesel and found an increase in cetane number but not quite sufficient to diesel performance and efficiency. They also reported emission of CO dropped massively due to increase the content of oxygen in biodiesel by mixture of hydrogen in fuel. Moreover, some sources confirmed that hydrogen in the diesel fuel increases the O and OH radicals [158]. Javed et al. [159] introduced H_2 and ZnO nanoparticles at high loads and increased the BTE of engine due to the complete burning of JME blends at high combustion temperatures (Fig. 6).

3. Nano-fuels effects on engines performance

After introducing the all studies categorized based on nanoparticle additives to diesel/biodiesel and bended fuels, in this section main effects of this addition on engine performance are summarized based on engine type. Based on Table 7, the most effects are combustion

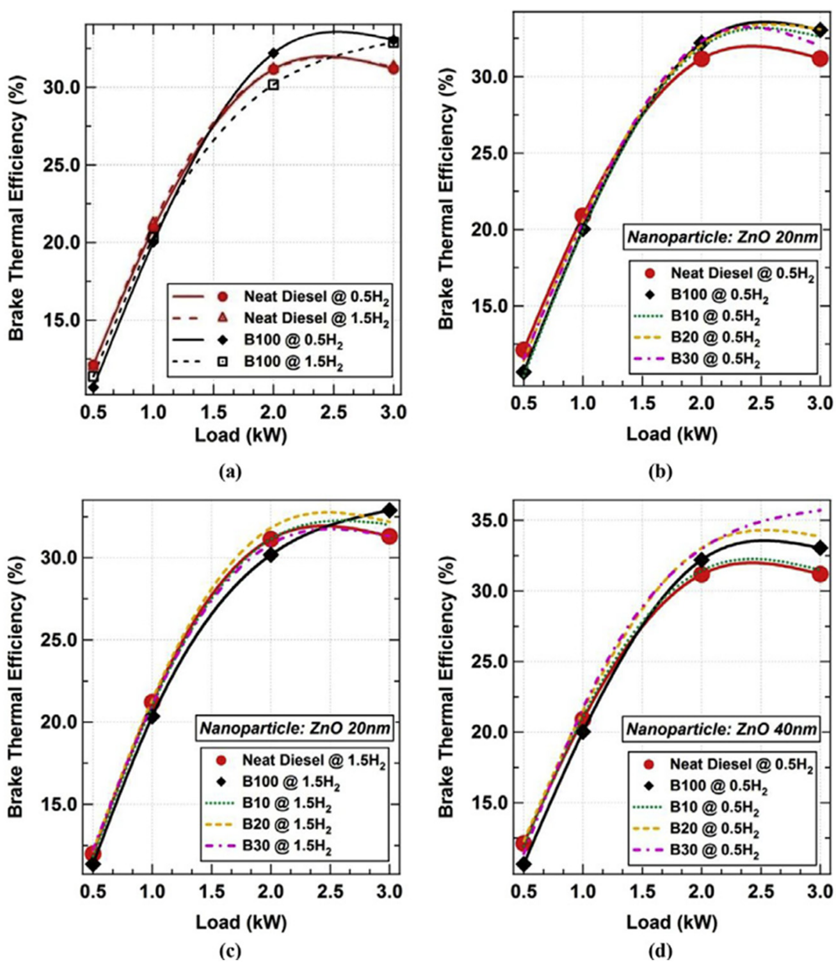


Fig. 6. Effect of hydrogen and ZnO nanoparticle additives on engine performance [159].

Table 7
Nanofuels effects on the ICEs performance.

Engine type	Base fuel	Nano-particles	NPs dosage and size	Main effect	Ref.
Fiat direct-injection diesel engine	Iraqi diesel fuel	Al_2O_3-ZnO	50 ppm and 100 ppm, 30–35 nm, 20–30 nm	The calorific value and cetane numbers increased as the amount of nanoparticles increased.	[29]
Single cylinder 4-stroke water-cooled direct injection diesel engine	Palm oil	Titanium (IV) oxide	50-100 mg	2–3% increase in torque was observed due to increase in backpressure. BTE increased since reduced heat losses from engine through heat transfer to ambient.	[30]
4-Cylinder, 3 L, turbocharged, intercooled Mitsubishi Fuso diesel engine	JIS#2 diesel fuel	Waste cooking oil additives	20–100%	Maximum CO and HC emissions rates were computed for the JIS#2 diesel fuel; while the minimum ones were found for the BDF100 biodiesel fuel, minimum BSFC occurred for diesel fuel.	[31]
Twin-cylinder, four-stroke turbocharged diesel engine	Fossil diesel, karanja	Graphene oxide (GO) and graphene nanoplatelets (GNP)	20-60 ppm, 1-4 nm, 3-8 nm	KBD20 with 60 ppm of GNP had better control over CO (30%), HC (23.2%) and NO (26.3%) emissions. Maximum smoke emission reduction (29.2%) was recorded for a blend of 40 ppm GO in WBD20.	[32]
186FA single-cylinder common rail diesel engine	Diesel fuel	CNT-MoO_3	40, 80 nm,	The peak pressure of CNT-diesel occurred prior to that of MoO_3-diesel. CNT and MoO_3 could efficiently advance the ignition timings of nano-fuels and simultaneously reduce the heat release peaks.	[33]
Cummins ISB4.5 heavy-duty four-stroke diesel	Diesel fuel	CeO_2-CNT	25,50 nm, 40-60 nm, 40 ppm	CO and HC were decreased due to more uniform fuel-air mixture and more sufficient combustion. Reduced NOx was recognized due to lower combustion temperature, improved spray and deoxidization of NOx. The PN reduction was because of two contradictory effects: the improved spray and lower combustion temperature, and its nucleation effect.	[35]
Diesel GWE-80/DWE-60/150-P provided by Tokyo Meter Co., Ltd. Tokyo, Japan	Neat diesel	Graphite (G), Iron oxide (Fe_2O_3)	50-150 mg/L, 50 nm	Cetane index and a decrease in kinematic viscosity were the important factors affecting the fuel economy and improving the engine performance. Graphite fuel additives were more suitable to be used in large scale turbocharged diesel engines.	[36]
One cylinder, air cooled, vertical engine	Diesel/water emulsion fuel	Aluminum oxide (Al2O3), copper(II) oxide (CuO), magnesium oxide (MgO), manganese(IV) oxide (MnO) and zinc oxide (ZnO)	50 ppm, 32-34 nm	The E10Al_2O_3, E10CuO, and E10MnO had greater torque and brake power compare to E10. The E10Al_2O_3 and E10CuO regularly showed less BSFC compared to E10 at all BMEP. The E10Al_2O_3 showed the largest BSFC reduction up to 5.5% compared to E10. The E10Al_2O_3, E10MgO, and E10ZnO showed a lower BSNOx and BSCO emissions compared to E10. E10ZnO had the highest reduction of $BSCO_2$ emission. The E10MgO and E10ZnO increased the BSHC emissions by up to 41.8 and 32.7%.	[39]
Kirloskar, 4-stroke, CI engine	Diesel fuel	CuO	0.5% (wt./wt.)	An average of 4% reduction in BSFC and 4% increase in BTE was observed. Maximum mechanical efficiency and BTE according to neat diesel results were 7% and 6.7%.	[40]
Direct Injection High Pressure Common Rail (DI HPCR) single cylinder Ricardo Hydra research engine	Diesel fuel	Cu	$<$0.2 ppm	Higher heat release rate was observed during premixed combustion phase. Combustion enhancement and the consequent soot reduction was due to catalytic effect of copper.	[41]
VCR engine	Diesel fuel	Titanium (IV) dioxide (TiO_2), copper (II) nitrate ($Cu(NO_3)_2$) and cerium (III) acetate hydrate ($Ce(CH_3CO_2)_3 \cdot H_2O$)	25-50 ppm	Cerium acetate hydrate was a dominant factor in the reduction of the harmful exhaust emissions. Also, sound pressure level of engine block decreased.	[43]
6 cylinder diesel engine MF-399	Diesel fuel	CeO_2	10-40 ppm, 10-30 nm	Reduction in fuel consumption, nitrogen oxide (NOx), and HC emissions. Increase in carbon monoxide (CO) was observed compared with pure diesel.	[45]
YANMAR TF120M four-stroke single-cylinder diesel engine	Diesel fuel	Aluminum oxide, carbon nanotubes and silicon oxide	25-100 ppm	CNT improved BSFC up to 19.85% due to its higher calorific value. CNT had highest improvement in BTE (compared to DF) of 18.8% for DC50 due to shorter ignition delay.	[46]
Lombardini/15LD 350 diesel engine	Diesel fuel	Aluminum oxide and copper oxide	25-100 ppm, 30–50 nm	Increase in the torque and brake power Reduction the BSFC and emissions	[47]
Kirloskar TV1, Four-stroke, CI, single-cylinder	Diesel fuel	Al, Fe, B	5-150 nm	Reduction of 7% in BSFC with Al as well as exhaust emissions reduction.	[50]
4-cylinder, in-line, turbocharged	Diesel fuel	CeO_2	50-100 mg/L	The combustion beginning point advanced, the heat release rate and pressure rise rate increased The activation energy of diesel fuel reduced, and the soot production was inhibited.	[51]
DI TD 313 Diesel engine	Iraqi diesel fuel	Al_2O_3	1–10%wt. 51 nm	Reduced the SFC, reduced the carbon monoxide, HC, NOx and PM levels	[52]
Gasoline Direct Injection (GDI)	Gasoline	DMC	–	BSFC of D8 blend was nearly 10% greater than gasoline fuel. Emissions reduced.	[53]

Table 7 (*continued*)

Engine type	Base fuel	Nano-particles	NPs dosage and size	Main effect	Ref.
XU7JP/L3 Gasoline Engine	Gasoline	Fe_2O_3 and TiO_2	–	16.7% decrease in viscosity, the octane index in the Benz mix N-methanol-Fe_2O_3 increased by 10.9% and in gasoline-TiO_2 compounds by 9.9%.	[55]
Gasoline-fueled SI EF7 engine	Gasoline	Mn_2O_3	10-20 ppm	The BP increased by 2.63% with gasoline-10%ethanol, 14.38% with gasoline-10%ethanol-10 ppmMn_2O_3, and 19.56% with gasoline-10%ethanol-20 ppmMn_2O_3 compared to gasoline. Emissions reduced.	[56]
Four cylinder SI engine	Gasoline	Hydrogen nano-bubble	149 nm and about $11.35*10^8$ particles/mL	BSFC had lower levels than single-fuel mode (gasoline)	[57]
Kirloskar AV-1, Single cylinder	Orange oil methyl ester (OOME)	TiO_2	50-100 ppm, 20 nm	The BTE was improved for OOME-T50 and OOME-T100 fuel by 1.6% and 3.0%, respectively compared to pure OOME at maximum load condition.	[58]
Vertical in-line diesel engine	waste fry oil methyl ester	MWCNT	25-50 ppm	The BTE of WFOME-MWCNTs blended fuels were improved. UHC emissions of WFOME-MWCNT blended fuels were reduced.	[59]
Four stroke DEUTZ F1L511	Jatropha biodiesel	CNTs, TiO_2 and Al_2O_3	25-100 ppm, 10-50 nm	CNT had a maximum decrease in smoke emission (up to 50%) Maximum decrease in HC emission occurred for (J20T25) about 22%. Maximum decrease in NOx emission was up to 52% at 75% of engine load for J20C50, also it produced maximum reduction in CO emission (up to 35%)	[61]
Kirloskar TV-1	Pungamia pinnata non-edible oil biodiesel	Coconut shell (CS) nano particles	20 nm	For all loads NO, CO and CO_2 emissions were reduced Increased engine performance and increased the SFC	[63]
Kirloskar TV1	Lemon and orange peel oil	CNT, CeO_2	50-100 ppm	Lemon oil with CeO_2 had better BTE and BSFC due to low density of lemon oil and higher thermal conductivity of CeO_2. CNT nanoparticles with both biofuels increased the NOx emission due to longer ignition delay.	[64]
Kirloskar Engine TV 1 diesel Engine	Waste cooking oil (WCO)	Hydroxyapatite nanorods	0-30 ppm	B20HW100: 30% reduction in NO, 60% decrease in CO, 44% decrease in HC and 38% reduction in the emission of smoke compared to B100.	[65]
Kirloskar TV1 Vertical diesel engine	Cymbopogon flexuosus biofuel	cerium oxide	20 ppm	Emissions such as HC, CO, and smoke were reduced by 3.63%, 4.75%, and 5.05%, respectively due to the entrapment of the heat inside the combustion zone. While oxides of nitrogen were increased.	[66]
Kirloskar	Nerium oleander biofuel (ENOB)	Cerium oxide	30 ppm, 15.01 nm	The BTE and the BSFC of cerium oxide nanoparticle mixed with the nerium oleander emulsion biofuel were enhanced.	[67]
Kirloskar	Neat mustard oil methyl ester	TiO_2	100-200 ppm, 50 nm	TiO_2 nanofluid in mustard oil methyl ester reduced HC, CO and smoke emissions.	[69]
Four-stroke ICEs	Cordiamyxa bio-oil	$BaMoO_4$ -Ce_2O_3	0.25–0.75 wt%	The best result of 87.50% of methyl ester yield had developed from Cordiamyxa oil under optimum conditions of 0.5 wt% of catalyst and 16:1 ratio of oil to methanol.	[70]
Lombardini DIESEL 3LD 510	Three kinds oilseeds	Graphene oxide (GO)	60 ppm, 1.2 nm	A slight increase of BP was observed. A reduction in UHCs, CO, and BSFC with a slight increase of NOx emissions with graphene oxide (GO).	[71]
Kirloskar water cooled diesel engine	Lemongrass Oil (LGO)	CeO_2	30 ppm, 16.27 nm	Reduction in cylinder peak pressure and HRR for LGO. Nano emulsion fuel reduced all emissions and improved engine performance due to the reduced ignition delay period and development of premixed combustion.	[72]
HATZ-1B30–2	Jatropha Methyl Ester (JME)	GO	25-100 mg/L	Concentration of 50 mg/L had the optimum enhancement in the overall characteristics of engine. The BTE was improved by 20% and the BSFC was reduced by 17% with the addition of GO.	[73]
Kirloskar TV1	Waste cooking oil	CeO_2	80 ppm, 50 nm	Ignition delay was reduced by 25% for the CeO_2. Mean gas temperature and mass of burned gas were both larger. An increase in BTE and a reduction in BSEC were obtained. A maximum increase of 2.5% in BTE and a 3.1% reduction in BSEC. Reduction of XHC by 20%, XNOx by 23% and smoke by 14%.	[74]
	Soybean Biodiesel	CNT	10 ppm	100CNT10WSB emulsion fuel revealed better emissions level. A drop of 46.1%, 21.6%, 20.8%, 12.1% and 19.3% was	[77]

(continued on next page)

Table 7 (*continued*)

Engine type	Base fuel	Nano-particles	NPs dosage and size	Main effect	Ref.
				approved for 100CNT10WSB emulsion fuel in terms of NOx, HC, CO, CO_2 and smoke emissions, respectively.	
Kirloskar/TAF1	Jatropha oil	Carbon Nanotubes and Di-Ethyl Ether	50 ppm CNT + 50 mL DEE, 16 nm	Maximum BTE at the full load was 28.8% for JME5W50CNT50DEE, whereas it was 25.2%, 25.8%, 26.1%, 26.8% and 27.5% for the pure diesel, JME, JME5W, JME5W50CNT and JME5W50DEE, respectively. The NO level and smoke opacity for the pure diesel was 1340 ppm & 71% at the full load, while it was 895 ppm & 36% for the JME5W50CNT50DEE fuel, respectively.	[78]
Kirloskar, TAF1	Jatropha oil biodiesel	Aluminum oxide hydroxide (AlO(OH))	25-100 ppm, 8–15 nm	The engine performance was approximately constant, but CO, UHC, NO and smoke opacity emissions were reduced by 50, 39, 37 and 25% for BD10W100 fuel compared to neat diesel. BTE was improved up to 6%.	[80]
Kirloskar AV1	Neat neem oil methyl ester	Silver oxide	5-10 ppm	BTE at peak conditions for diesel, BD100, BD100+ Ag_2O (5 ppm), and BD100+ Ag_2O (10 ppm) were 29.8, 26.6, 27.9, and 28.4%, respectively. In addition, the BSFC values of BD100 reduced.	[82]
CT159	Diesel+ Fusel oil	Sugarcane nano-biochar (SNB)	25-125 ppm, 100 nm	The optimal values of parameters were engine speed of 2300 rpm, fusel oil ratio of 10% and SNBs concentration of 100 ppm. The engine power, brake torque and BSFC at optimal conditions were 7.7 Nm, 1.8 kW, 227 g/kWhr, respectively. Optimal values of exhaust emissions were 217 ppm for NOx, 0.01 vol% for CO and 30 ppm for UHC.	[84]
KAM-SD-1100B	Diesel+WCO	CeO_2, $Ce_{0.5}Co_{0.5}$	25-100 mg/L	The $Ce_{0.5}Co_{0.5}$ nano-composite oxide was more useful than CeO_2.	[85]
Lombardini DIESEL 3LD 510	Diesel+OLB	GO	30-90 ppm	Power improved, the emission of CO and UHC decreased, CO_2 and NOx emissions increased.	[86]
Kirloskar	Diesel+ botryococcus braunii algae oil methyl ester	CuO_2	25-100 ppm	EGT growths with increasing CuO_2-nanoparticle concentration, combustion improved, BSFC reduced and BTE increased.	[87]
CI engine	Diesel+ tyre pyrolysis oil	Cerium oxide	50-100 ppm, 50-80 nm	B5D85+ CeO_2 100 ppm blend was the optimum blend due to the heating value of the blend nearer to diesel value. This blend increased the BTE by 2.94% and decreased smoke emission by 7.46% compare to diesel at full load condition.	[89]
4-Cylinder diesel engine	Diesel+waste frying oil	Manganese oxide and cobalt oxide	25-50 ppm, 10-30 nm	The engine used fewer fuel with B20 + Mn_2O_3 and B20 + Co_3O_4 blends than that of B20 for producing the same power output. Cobalt oxide showed better NOx and CO reduction.	[90]
Kirolskar TAF-1	Diesel+GGME	ZrO_2, TiO_2, CeO_2	25 ppm	BTE was found around 6.05% for 25 ppm of TiO_2 The CO of B20 + CeO_2 (25 ppm) and B20+ ZrO_2 (25 ppm) were lower than B20 by 2.70% and 1.33%, respectively. B20 + TiO_2 (25 ppm) had lowered NOx emission by 22.57% for B100 fuel blend. 25 ppm TiO_2 added to B20 had 16.25% lower smoke emission.	[91]
Fiat Panda	Diesel+HVO	Cerium dioxide and ferrocene	–	Confirmed the effect of fuel modification on the emission reduction from diesel engines. Practically, both ferrocene nano-particles and cerium dioxide additives to B7, improved the combustion process.	[93]
Kirloskar	Diesel+PB	CuO	50-100 ppm	With B20CuO100 blend BSFC decreased up to 1.0%, while the BTE increased about 4.01%. Considering greenhouse gases CO, HC, smoke and NOx emission reduced to about 29%, 7.9%, 12.8% and 9.8%, respectively compared with B20 blend.	[95]
Kirloskar TV1	Diesel+CB	GeO	25-75 ppm	Approximately BTE increased 3.28% with CB20 + GeO50 ppm The BSFC were reduced by 3.2% with CB20 + GeO50 ppm. Ignition delay and combustion duration were reduced by 10.5% and 7.4% with CB20 + GeO 75 ppm. All emissions reduced.	[97]
CI engine, 6 Cylinder	D + waste cooking oil	Carbon nano tubes (CNT), Silver nanoparticles	40-120 ppm	Increased the brake power and torque, decreased the BSFC. CO_2 and NOx concentrations were increased while the concentration of CO and HC were decreased.	[99]
CI engine, 6 Cylinder	D + WCO	CNT and Ag	40–120 ppm	CO and HC were reduced and CO_2 & NOx increased compared to neat diesel fuel. Increased engine performances, power and torque increased and specific fuel consumption decreased.	[109]

Table 7 (*continued*)

Engine type	Base fuel	Nano-particles	NPs dosage and size	Main effect	Ref.
Single cylinder, four stroke	D + MEOM	CuO	50 ppm	Improvement in the BTE up to 2.19% and lowered the BSFC. Reduced HC, CO and smoke emissions up to 5.33%, 33% and 12.5%. The NOx emission slightly increased up to 3.2%.	[112]
TecQuipment TD212)	D + WFO	Ferrocene	50-300 mg/L	Maximum 8% increase in BTE compared to base fuels. The optimal amount of ferrocene nanoparticles in diesel and B30 were reported to be 250 and 300 mg/L, respectively.	[115]
Kirloskar TV1	WCO + D	CeO_2	80 ppm	BTE calculated for B30DEE5C and B40DEE5C were greater than their neat forms, while B30DEE5C had the highest value around 29.57% at par with neat B20 operation (29.72%).	[117]
Lombardini Diesel 3LD510	AAB + D	Graphene oxide (GO)	30-90 ppm	Power, torque and EGT significantly increased. CO and UHC emissions reduced approximately 7–20% and 15–28%, respectively. Slight increase in CO_2 and NOx emissions were observed (approximately 6–10% and 5–8%, respectively)	[118]
Lombardini Model 3LD510	WCO + D	CNTs	30-90 ppm	Power, BTE, SFC, and EGT of the B5C90 fuel blend changed by +3.67%, +8.12%, −7.12%, and + 5.57%, respectively, compared with those of pure diesel fuel. CO, HC, and soot emissions decreased by 65.70%, 44.98%, and 29.41%, respectively. However, the NOx emission raised by 27.49%.	[135]

characteristics (such as temperature, pressure, cetane number, heat release, etc.), engine performance (Brake power (BP), brake thermal efficiency (BTE), brake specific fuel combustion (BSFC), etc.) and exhaust temperature and emissions (such as CO, UHC, NOx, Soot and Smoke). In next sub-sections these effects are discussed more in details.

Wang et al. [34] revealed that metal nanoparticles (NPs) and metal oxide NPs had important effects on the fuel combustion. NPs can decrease the oxidation temperature and improve the cetane number of the fuel. By improving the cetane number, the ignition features were enhanced and the evaporation of fuel droplets increased, significantly. So, the evaporation process makes enhancement of combustion process and consequently makes significant reduction of engine emissions and heat release rates [34]. Based on their review, carbon nanotubes and nano-aluminum particles reduced the emissions of these three kinds of exhaust gases, importantly [34]. A complete review on the nanoparticles effect on engine performance is presented in Table 7. For instance, SiO_2 with the lowest thermal conductivity recorded highest cylinder pressure and shortest ignition delay especially at DS100 [46]. Abdul Sheriff et al. [64] revealed that 50 ppm CNT added to diesel/biodiesel blend increased the brake thermal efficiency up to 34.29%. This fact was observed because of its lower viscosity, causing in improved atomization and evaporation and consequently improving combustion efficiency [64]. In next sub-sections the effect of nanoparticles to engines performances will be discussed in more details, statistically.

3.1. BSFC and fuel consumptions

BSFC is defined as the fuel mass flow rate per unit brake power obtained. Table 8 compare the BSFC, EGT, BTE and power changes using different nanoparticles and base fuels. Based on this table, in all nanoparticle additives BSFC is reduced and BTE is increased which are the most reasonable issues for using nanoparticles. But percentages of these effects depend on nanoparticle type and concentration. So, it can be found that for the BSFC reduction purposes the best nanoparticles are: CeO_2 (−30%), TiO_2 (−23.42%), GO (−20%), CNT (−19.85%), Al_2O_3 (−14.66%) for diesel engines and Mn_2O_3 (−38.89%) for SI engines. Maximum exhaust temperature decrease reported for Al_2O_3 (−27%), while maximum BTE improvements occurred for MWCNT (+36.81%), Al_2O_3 (+24.7%), CeO_2 (+23%), CNT (+18.8%), GO (+17%).

As an example of Table 8's data, Fig. 7 is obtained from the literature which shows the BSFC and BTE improvements using ZNO and AL_2O_3 additives to diesel fuels in 50 and 100 ppm dosages. Chen et al. [46] reported high EGT for CNT blends due to the highest calorific value and produce more heat per unit mass compared to Al_2O_3 and SiO_2 blends. Also, long ignition delay of CNT blends caused slower fuel burning process and the combustion gases had higher temperature.

Although most researchers revealed that nanoparticles decreased the BSFC due to increase in the calorific value and higher surface area of metallic additives [43], but some researchers such as Zhang et al. [35] believed that lower heating value (LHV) of nanofuel, which defines power output, cannot be improved by such small amount of additives, so brings negligible difference to fuel consumption.

As seen in Fig. 8, Chacko et al. [32] showed that higher BSFC occurred for GO and GNP due to the limited calorific value of biodiesel. These additives improved the oxidation of carbon and thus ensured efficient combustion. To have minimum BSFC, GO nanoparticles were applied with a concentration of 40 ppm and GNPs with 60 ppm. For instance, the optimum concentrations of GO and GNP reduced the BSFC by 5.4% and 4% for D100, respectively [32]. Another advantages of nanoparticle additives is presented by Mei et al. [33] which used CNT and nano-MoO_3 in fuel blends and confirmed that they can act as enhancers of the cetane number and consequently increase the heat and mass transfer during the low-temperature chemical reaction. The similar reason of higher cetane index is mentioned by Ahmed et al. [36] to confirm the higher fuel conversion efficiency for graphite blends as compared to FO-blends as shown in Fig. 9. Also, ability of nanoparticles to accelerate the combustion is another reason of BSFC reduction for CNT blends mentioned by researchers [46].

Based on Table 8, maximum BSFC reduction occurred for MN_2O_3 additives to gasoline fuel as depicted in Fig. 10. Amirabedi et al. [56] reported that BSFC of engine can be reduced by 22.81% with ethanol addition, while it can be further decreased to 34.69% and 38.89% by adding 10 ppm and 20 ppm nano-oxides to blend of gasoline-ethanol, respectively. Kumar et al. [58] also showed that diesel BSFC value is lower than biodiesel, while OOME-T50 and OOME-T100 (by TiO_2 additives) produced lower BSFC compared with pure OOME and caused a decrease in smoke emission due to the rapid evaporation and the incidence of the enhanced air-fuel mixture. Furthermore, NOx reduction was due to the higher cetane number and decreasing the combustion temperature. In a comparison study performed by Sheriff et al. [64], CNT showed higher fuel consumption for orange oil compared to CeO_2 due to rapid oxidation which was the result of higher carbon and

Table 8
BSFC, EGT, BTE and power changes using nanofuels.

Base fuel - nano-particles	BSFC	EGT	BTE	Power	Ref.
Diesel-Al_2O_3-100 ppm	-8%	–	+6%	–	[29]
Palm oil- titanium (IV) oxide	–	–	–	+3%	[30]
GO-diesel fuel	-9%	–	+2.3%	–	[32]
CNT-diesel	−5.1%	–	+5.2%	–	[33]
G-diesel	−2.6%		+4.1%	+9.6%	[36]
Al_2O_3-diesel	−5.5%	−10.3%	–	+3.69%	[39]
CuO-diesel	−6%	–	+7%	–	[40]
DTiCeA100	−12.12%	–	–	–	[43]
Diesel emulsion	Decrease	Decrease	Increase	–	[44]
CeO_2-diesel	−9.5%	–	–	–	[45]
CNT-diesel	−19.85%	Increase	+18.8%	–	[46]
Al_2O_3-diesel	−1.2%	–	–	+3.28%	[47]
Metal-oxide	–	–	+4%	–	[48]
Al-diesel	−7%	+9%	+9%	–	[50]
Al_2O_3-diesel	−3.94%	−20%	+5.5%	–	[52]
Mn_2O_3-gasoline	−38.89%	–	–	+ 19.56%	[56]
TiO_2- orange peel oil	–	–	+ 3.0%	–	[58]
WFOME-MWCNT	–	–	+36.81%	–	[59]
J20C50	−4%	−2%	+4%	–	[61]
J20T25	−3%	−5%	+3%	–	[61]
J20Al100	−6.5%	−27%	+6.5%	–	[61]
BD-DF-CS	Increase	Decrease	Increase	+0.65%	[63]
B-CeO_2	Decrease	–	+1.75%	–	[66]
NENOB (CeO_2 added)	−30%	–	+2.4%	–	[67]
B20-TiO_2 SiO_2	Decrease	–	Increase	–	[68]
Camelina-GO	Decrease	–	–	Increase	[71]
LGO-CeO_2	−5.87%	–	+3.55%	–	[72]
JME-GO	−20%	Decrease	+17%	–	[73]
WCO-CeO_2	−3.1%	Increase	+2.5%	–	[74]
100CNT10WSB	−14.4%	−13.6%	–	–	[77]
JME5W50CNT	+1.6%	–	–	–	[78]
BD10W100	Decrease	Decrease	+6%	–	[80]
BD100+ Ag_2O (10 ppm)	−9.9%	–	+1.8%	–	[82]
PSBD* 20 nm AgO (10 ppm)	−2.7%	–	+2.4%	–	[83]
Diesel+ Fusel oil+SNB	+1%	Decrease	–	–	[84]
Diesel+OLB + GO	–	Increase	Increase	–	[86]
Diesel+BBAOME+CuO_2	Decrease	Increase	Increase	–	[87]
B5D85 + CeO_2 100 ppm	–	–	+2.94%	–	[89]
Diesel+WFOB+Mn_2O_3	−2%	–	+1.2%	–	[90]
Diesel+WFOB+Co_3O_4	−4%	–	+2.7%	–	[90]
B20+ TiO_2 (25 ppm)	−23.42%	–	+6.05%	–	[91]
PBN (TiO_2)-EGR	−19.85%	+11%	–	–	[92]
B20CuO100	−1%	Decrease	+4.01%	–	[95]
CB20 + GeO50	−3.2%	–	+3.28%	–	[97]
DSOME20GeO	−8.34%	–	+11.56%	–	[98]
D + WCO + CNT-S	−7.08%	–	–	+2%	[99]
EME20-ANP100	−7.66%	–	+7.28%	–	[100]
BD-CuO_2	Decrease	Increase	Increase	–	[104]
B20-CeO_2	Decrease	Increase	Increase	–	[105]
B5W3_m-CeO_2	−16%	–	+23%	–	[108]
DB-CNT-Ag	Decrease	Increase	Increase	Increase	[109]
B15W5-CQD60	- 3%	–	–	+21%	[111]
20MEOM + CuO	Decrease	–	+2.19%	–	[112]
WCO + D + Al_2O_3	−14.66%	+5.80%	+10.63%	+5.36%	[114]
WFO + D + F	Decrease	–	+8%	–	[115]
JOB+D + Al_2O_3	Decrease	–	+24.7%	+3.85%	[116]
B40DEE5C	–	Decreased	+ 29.72%	–	[117]
B20G90	−14.48%	+4.22%	–	+14.3%	[118]
WCO + D + CeO_2 + MWCNT	−4.5%	–	–	+7.81%	[119]
B50SC1	−17.19%	−15.5%	+20.52%	–	[120]
D + DWB + MWCNT	- 2.71%	Increased	+ 0.96%	–	[126]
JB20D-Al_2O_3	−12%	Decreased	+15%	–	[127]
B2040TiO_2	Decreased	–	+3.1%	–	[128]
B + D + CNP	Decreased	–	+11.58%	–	[129]
TSME+Al_2O_3	Decreased	–	+ 4.5%	–	[131]
ASB + TiO_2	−18.42%	–	+3.25%	–	[133]
WCO + D + CNTs	−7.12%	+5.57%	+8.12%	+3.67%	[135]
JB20 + GNPs	−20%	–	+25%	–	[136]
Pongamia+D + Fe_3O_4	−8%	Decrease	+16.6%	–	[137]
B10E4N30	−6%	–	–	–	[138]
NBE25 + NiO	−7.86%	–	+6.3%	–	[140]
HOME20Al_2O_3	- 11.65%	–	+ 10.57%	–	[141]

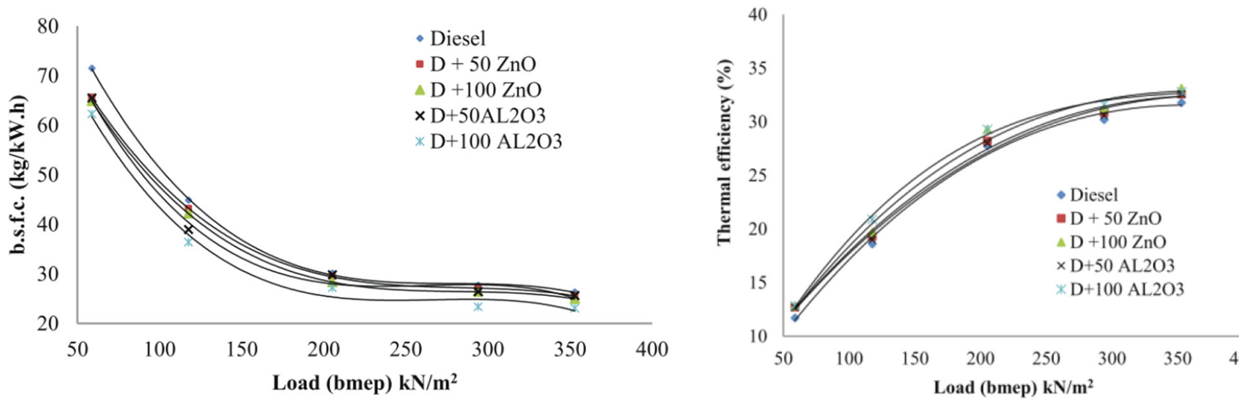


Fig. 7. The BSFC and BTE improvements using ZNO and AL_2O_3 additives [29].

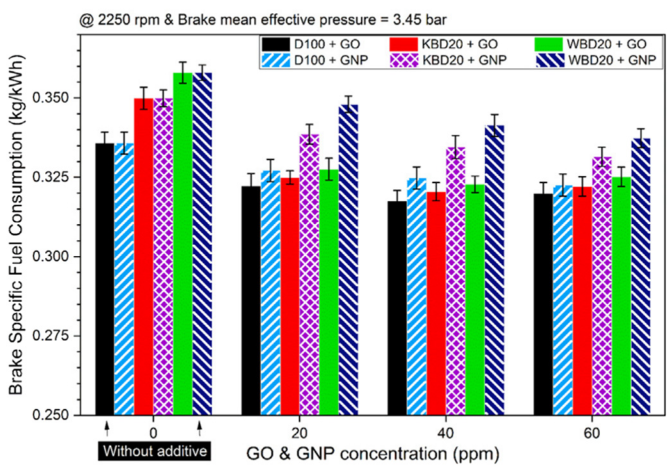


Fig. 8. Effect of GO and GNP on BSFC [32].

oxygen content as well as Devarajan et al. [82] mentioned the reason of lower BSFC for silver oxide nano-particles as excess oxygen molecule present in structure and endorses the combustion reaction. CeO_2 is also used by Annamalai et al. [72] as additive to LGO and showed lower Brake specific energy consumption (BSEC) compared with LGO emulsion as depicted in Fig. 11. This reason is mentioned due to faster evaporation rate caused by cerium oxide nanoparticle. Also, it oxides the UHC deposited in the engine cylinder wall leading to reduced energy consumption [72].

Approximately in all studies, BSFC for water-biodiesel emulsions was higher than of neat biodiesel and neat diesel due to lowered

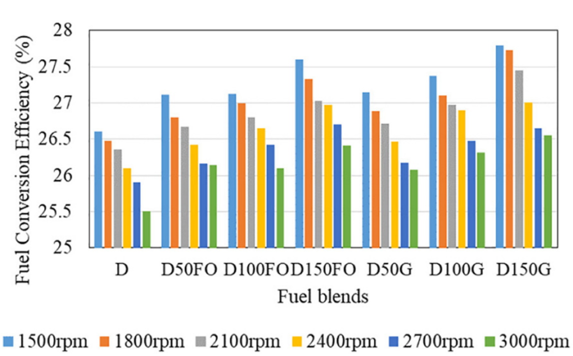


Fig. 9. Fuel conversion efficiency comparison for GO and FO [36].

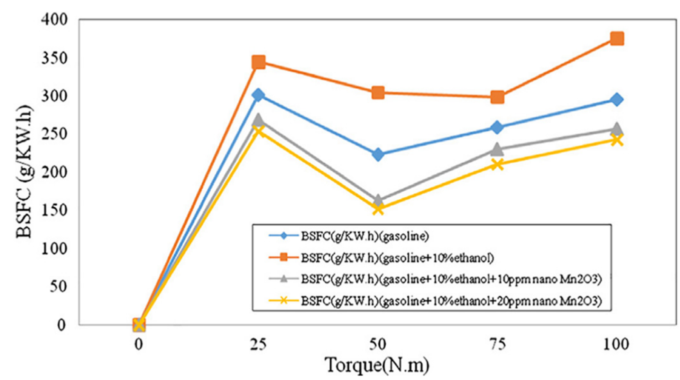


Fig. 10. BSFC reduction in gasoline engine [56].

calorific value [80] and nanoparticle additives leads to increase the surface to volume ratio which enhances the heat transfer between the particles and the fuel droplets. Moreover, the higher CV, oxygenate reaction, density, viscosity helps to better atomization and better mixing process in combustion and produce lower emission than diesel fuel [97,106].

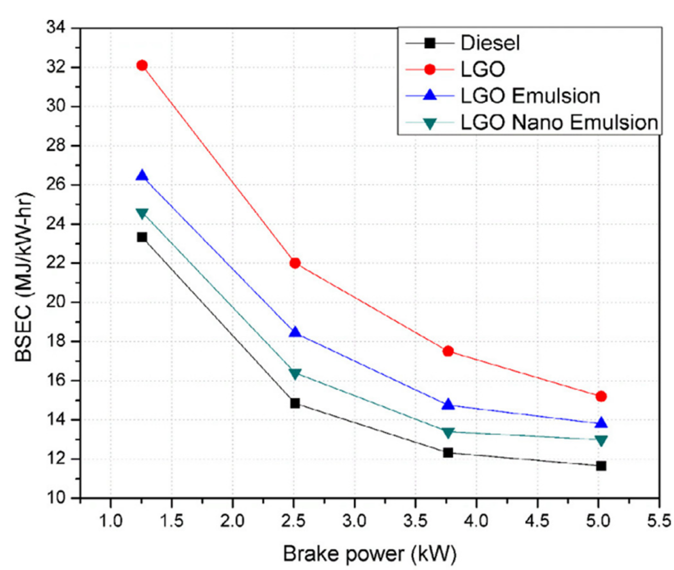


Fig. 11. BSEC reduction by LGO nano emulsion [72].

3.2. BTE and combustion characteristics

In this section, BTE and other combustion characteristics are presented which have significant effects on engines performance. Based on Table 8 and as mentioned, maximum BTE improvements occurred for MWCNT (+36.81%), Al_2O_3 (+24.7%), CeO_2 (+23%), CNT (+18.8%), GO (+17%). Ignition delay (ID) is one of the most important parameter which affects the combustion quality. Chacko et al. [32] investigated the effect of Graphene oxide (GO) and Graphene nano platelet (GNP) on the ID and presented that GNP addition reduced the ID up to 1.6 CAD as depicted in Fig. 12, and the maximum change of ID reduction was noted for WBD20 with 60 ppm of GNP. They considered that GO had limited thermal conductivity when compared to GNP; and it had oxygen-carrying functional groups to promote the early combustion of fuel. On the other hand, higher thermal conductivity of the GNP improved the evaporation rate of fuel droplets and improved the BTE [32].

Mei et al. [33] used CNT and found that it prompts the fuel and air to mix more rapidly and sufficiently for later complete combustion. In addition, since the flame is disposed to circulate in small gaps, such as holes, layers and tubes, the specific tubular structure of CNT plays a practical role in accelerating the fuel burning rate and minimizing the ID, which has significance results in the beneficial increase in BTEs [33].

Furthermore, increase in carbon content of CNT blends makes in higher calorific value affecting confidently on the BTE improvements [46]. Also, when CNT and surfactant is mixed with fuel, a quick evaporation will occur and results improved combustion and less ignition delay period compared to CeO_2 [64]. Micro-explosion events because of large surface-volume ratio and intensified thermal transmissibility of nanoparticles is another reason of combustion improvements presented by Sahoo and Jain [40] for CuO nanoparticles. Karthikeyan and Prathima [68], Kumaravel et al. [89] and Gowtham et al. [97] also mentioned the surface to volume ratio of fuel droplets and nano-additives improves the evaporation rate and leads to shorter ignition delay and combustion improvements for TiO_2/SiO_2, CeO_2 and GO nanoparticles, respectively.

In-cylinder pressure is another main parameter which affects the combustion process and widely is investigated by researchers, separately. Liu et al. [51], as seen in Fig. 13, found that maximum in-cylinder pressures of 50CeO_2 and 100CeO_2 increased by 1.25% and 2.98% due to higher catalytic activity at high temperature and reduced the activation energy of diesel fuel, also they indicated that the ignition delay period shortens while the peak heat release rate increases [51].

Kumaran et al. [65] also confirmed that the fuel with higher calorific value and smaller viscosity leads to higher BTE for entire load range during complete combustion due to the improved combustion, atomization and rapid evaporation of the nanoparticles. Dhinesh et al. [66] also improved the BTE and reduced BSEC by nanoadditive-based blends due

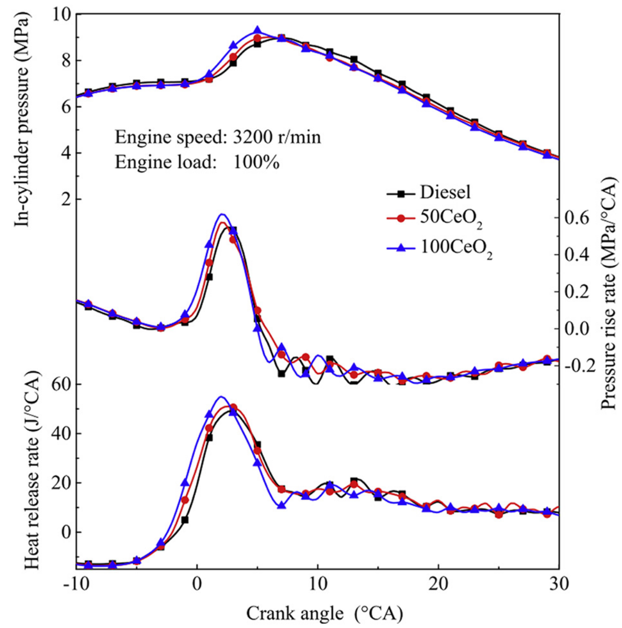


Fig. 13. In-cylinder pressure and heat release for CeO_2 nanoparticle additives [51].

to the oxygen vacancy capability of the additive which enhanced the combustion efficiency (Fig. 14).

Hoseini et al. [71] increased the engine power by GO nanoparticles additives which increased the heat of fuel evaporation, so the density of the fuel-air mixture increased and consequently power improved. Devarajan et al. [83] revealed that catalytic activity of AgO nano-additives enhanced the heat transfer which outcomes was improved combustion and great BTE [83] Mehregan and Moghiman [90] proposed Co_3O_4 nanoparticles had better enhancement in BTE than Mn_2O_3 nano-additives because of higher calorific value of the blended fuel with Co_3O_4 compared to Mn_2O_3 [90] (Fig. 15).

3.3. Exhaust emissions

In this section, all the studies are compared based on the pollutant emissions which are harmful for the human. Among the existence emissions, NOx, CO, UHC and soot (smoke, PM) are considered and analyzed by all researchers to can minimize them by nano-additives, while unregulated emissions such as formaldehyde, acetaldehyde,

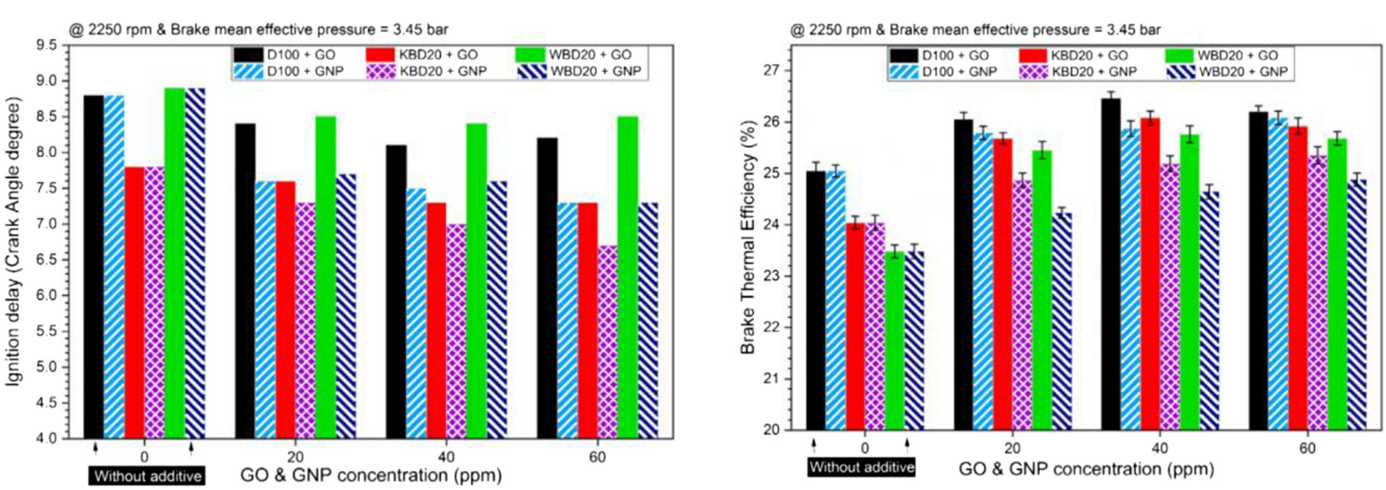


Fig. 12. ID and BTE for GO and GNP additives [32].

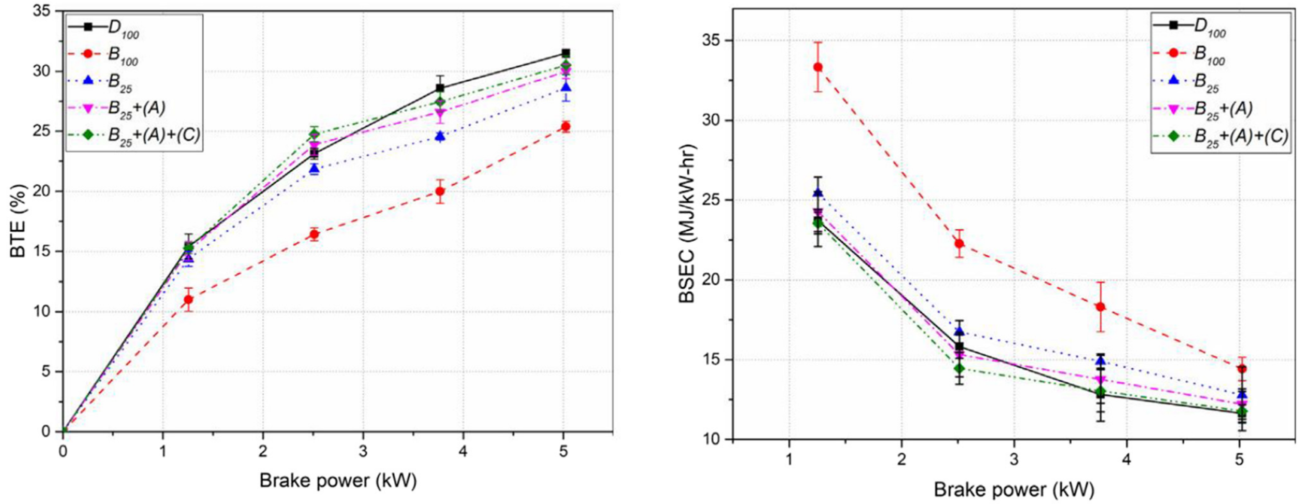


Fig. 14. BTE and BSEC improvements by oxygenated nano-additives [66].

benzaldehyde, toluene, crotonaldehyde are considered by Gowtham and Prakash [97] which were reduced by 13.09%, 12.05%, 15.24%, and 23.55% with CB20 + GeO 75 ppm at peak load condition.

Based on Table 9 review data, approximately for all nanoparticle additives, UHC, CO and soot decreased, significantly, while for the NOx emissions it has different treatment and in some cases NOx is increased. So, it is very important parameter to find suitable nanoparticle additives. For the NOx reduction: Al_2O_3 (−70%), GNP (−55%), CNT (−52%), and CeO_2 (−42.7%); for the CO reduction: Al_2O_3 (−80%), CNT (−65.70%), GNP (−65%), GO (−60%), CeO_2 (−52%); for UHC reduction: CeO_2 (−45%,-71.4%), Al_2O_3 (−68%), GNP (−65%), Mn_2O_3 (−51.83%), GO (−50%), CNT (−44.98%); for soot (smoke, PM) reduction: Al_2O_3 (−65%, −87.4%), Fe_3O_4 (−37%), CNT (−35%), CeO_2 (−30%) are the most suitable nano-additives. Following some of the reasons mentioned by the researchers are discussed.

Chaichan et al. [52] reported −41.3% NOx reduction by aqueous alumina additives and its reason was referred to several factors: water high evaporation temperature which was absorbed from the combustion temperature, the high thermal capacity of water and the existence of nanoparticles. Fig. 16 shows the emissions of diesel engine when using CNT and CeO_2 nano-additives. CNT has the minimum values of CO, NOx and HC emissions [35]. Dhinesh et al. [66] also studied the emissions of CeO_2 nanofuel in different dosage as depicted in Fig. 17. They found that enhanced calorific value, reduced viscosity and increased surface area capability of the Nano additive had key roles in emissions reduction where smoke emission dropped down to 13–59 ppm. Also, oxygen vacancy capability and oxidizing agent of cerium oxide were mentioned as other reasons for NOx and HC emission reductions.

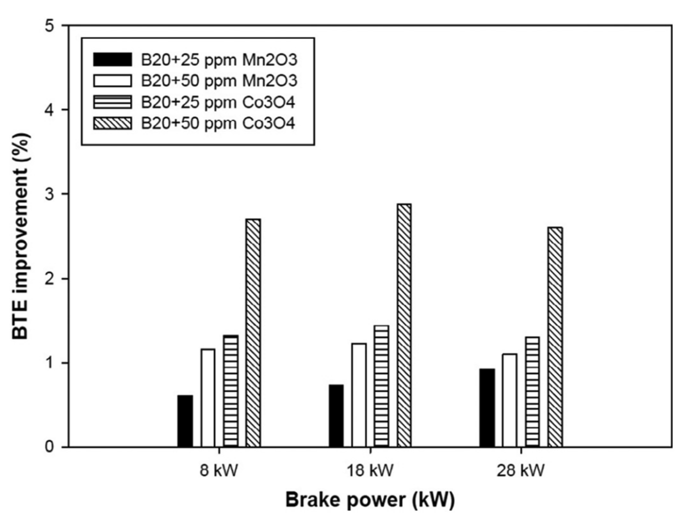


Fig. 15. BTE improvements by Co3O4 nanoparticles [90]

Dobrzynska et al. [93] mentioned that NOx emissions depend strongly on the temperature. When HC and CO emissions are reduced by an increase in combustion temperature, NOx generally increases, due to the increased reaction rate of chemical reactions involving oxygen and nitrogen. They concluded that ferrocene had better results than CeO_2 because it acts as a preventive agent against soot build-up in the exhaust system [93].

3.3.1. NOx

Nitrogen oxides are mainly composed of nitric oxide (NO) and nitrogen dioxide (NO_2). By adding further oxygenated materials to the diesel fuel, the amount of NOx concentration will increase. Velmurugan et al. [30] reported that NOx emissions with nanoparticles additives was 24.6% where for the pure diesel it was 30.6%. Chacko et al. [32] described that less NOx was formed for the GNP (compared to GO) due to lower combustion temperature caused by shorter ID which allows less fuel to be burned in the premixed combustion phase [32]. Mei et al. [33] found the same treatment which low temperature in the cylinder decreased the NOx for the CNT nanoparticles which advanced the ignition timing and reduced the amount of mixture in the premixed combustion and caused a slight decrease in the cylinder temperature. Zhang et al. [35] also mentioned lower temperature as the main reason of NOx reduction for CNT, also they added a secondary reason as DF-CNT generates more uniform spray field due to its lower viscosity and thermal diffusivity, and third reason of NOx reduction was due to a form of elemental carbon, which can probably act as a deoxidizer during combustion [35]. Based on their study, CeO_2 nanoparticles had a catalyst function which were converted between $CeO_2(Ce^{+4})$ and Ce_2O_3 (Ce^{+3}), CeO_2 helps to oxidize unburnt fuel compositions, while the Ce_2O_3 deoxidizes products and reduces NOx [35].

Sahoo et al. [40] presented another reason for NOx reduction when using CuO additives. These nanoparticles acted as heat sink which absorb the generated heat and hence maximum temperature inside the combustion chamber reduces and caused to less NOx emissions. Gumus et al. [47] observed that Al_2O_3 and CuO nano-additives increased the NOx because of oxygenated additives enhanced the combustion and make higher combustion temperature and consequently higher NOx

Table 9
Different emissions changes when using nanofuels.

Base fuel - nano-particles	NOx	CO	UHC	Soot/smoke/PM	SOx	H2S	Ref.
Diesel-Al_2O_3-100 ppm	+10%	−17%	−17%	−26%	−19%	−19%	[29]
Palm oil-titanium (IV) oxide	Decreased	Decreased	Decreased	–	–	–	[30]
GNP-diesel	−26.3%	−30%	−23.2%	−29.2%	–	–	[32]
CNT-diesel	−8.9%	−9.6%	−11.4%	−15.2%	–	–	[33]
CNT-diesel	−21%	−20%	−22.6%	−5.5%	–	–	[35]
G-diesel	+29.9%	+14.2%	–	–	–	–	[36]
Al_2O_3-diesel	−17%	−6.92%	−32.7%	−65%	–	–	[39]
CuO-diesel	−19%	−13%	–	–	–	–	[40]
Cu-diesel	–	–	–	−14%	–	–	[41]
DTiCeA100	−27.77%	−43.24%	−23.25%	–	–	–	[43]
Diesel emulsion	−32%	−48%	−66%	–	–	–	[44]
CeO_2-diesel	−42.7%	Increased	−28.5%	–	–	–	[45]
CNT-diesel	−4.48%	+ 0.038%	−6.4 ppm	–	–	–	[46]
Al_2O_3-diesel	−6%	−11%	−13%	–	–	–	[47]
Metal-oxide	−4%	−37%	−1%	–	–	–	[48]
Al-diesel	+5%	−40%	−8%	+8%	–	–	[50]
CeO_2-diesel	–	–	–	−11%	–	–	[51]
Al_2O_3-diesel	−41.3%	+26% (CO_2), −14.49% (CO)	−27.94%	−52.18%	–	–	[52]
Mn_2O_3-ethanol-gasoline	−32.34%	− 24.09%	−51.83%	–	–	–	[56]
TiO_2- orange peel oil	−9.7%	−18.4%	−16.0%	−24.2%	–	–	[58]
WFOME-MWCNTs	Decreased	Decreased	Decreased	Decreased	–	–	[59]
J20C50	−52%	−35%	−12%	–	–	–	[61]
J20T25	−35%	−16%	−22%	–	–	–	[61]
J20Al100	−36%	−19%	−18%	–	–	–	[61]
BD-DF-CS	−18.56%	Decreased	Decreased	–	–	–	[63]
B20HW100	−30%	−60%	−44%	−38%	–	–	[65]
B-CeO_2	Increase	−4.75%	−3.63%	−5.05%	–	–	[66]
NENOB (CeO_2 added)	−30%	−20.5%	−30%	−30%	–	–	[67]
B20-TiO_2 SiO_2	Increase	Decrease, CO_2:increase	Decrease	–	–	–	[68]
TiO_2-MOME	Decrease	Decrease	Decrease	–	–	–	[69]
Camelina-GO	Increase	Decrease	Decrease	Decrease	–	–	[71]
LGO-CeO_2	−24.8%	−26%	−35.5%	−19.8%	–	–	[72]
JME-GO	−15%	−60%	−50%	–	–	–	[73]
WCO-CeO_2	−23%	–	−20%	−14%	–	–	[74]
100CNT10WSB	−46.1%	−20.8	−21.6%	−19.3%	–	–	[77]
JME5W50CNT	−33.2%	–	–	−35%	–	–	[78]
BD10W100AlO(OH)	−37%	−50%	−39%	−25%	–	–	[80]
BD100+ Ag_2O(10 ppm)	−4.24%	−12.22%	−10.89%	−6.61%	–	–	[82]
PSBD* 20 nm AgO (10 ppm)	−14.4%	−11.9%	−8.8%	–	–	–	[83]
Diesel+ Fusel oil+SNB	−20.51%	+33%	−25%	–	–	–	[84]
Diesel+WCO + CeO_2	−6.57%	−34.32%	−23.46%	–	–	–	[85]
Diesel+WCO + $Ce_{0.5}Co_{0.5}$	−13.96%	−39.08%	−40.74%	–	–	–	[85]
Diesel+OLB + GO	+9%	−22%	−26%	–	–	–	[86]
D + NOAO+CeO_2	Increase	Decrease	Decrease	Decrease	–	–	[88]
B5D85 + CeO_2 100 ppm	+1.4%	−13.33%	−4.5%	−7.46%	–	–	[89]
Diesel+WFOB+Mn_2O_3	−14%	Decrease	–	–	–	–	[90]
Diesel+WFOB+Co_3O_4	−40%	Decrease	–	–	–	–	[90]
B20+ TiO_2 (25 ppm)	−25%	- 35.89%	−6.39%	−16.25%	–	–	
B20+ CeO_2 (25 ppm)	−23%	- 8.16%	−3.99%	−14%	–	–	[91]
B20+ ZrO_2 (25 ppm)	−22%	−3.92%	−5.64%	−12%	–	–	
PBN (TiO_2)-EGR	Decrease	Decrease	Decrease	Decrease	–	–	[92]
B7 + 30%HVO + nano ferrocene	+4%	−20%	−40%	−7%	–	–	[93]
B7 + 30%HVO + CeO_2	+2%	−5%	−8%	−1%	–	–	[93]
B20 + 100 (CuO_2)ppm	Increase	Decrease	Decrease	Decrease	–	–	[94]
B20CuO100	−9.8%	−29%	−7.9%	−12.8%	–	–	[95]
CB20 + GeO 50 ppm	+8.8%	−7.8%	−6.4%	−6.6%	–	–	[97]
DSOME20GeO	Increase	−38.662%	−21.68%	−24.88%	–	–	[98]
WCO + D + CNT (Ag)	+25.32%	−25.17%	−28.56% (Ag) + 14.21%(CNT)	–	–	–	[99]
EME20-ANP100	+7.83%	−49%	−26.04%	Decreased	–	–	[100]
B55N(Al_2O_3)	−15%	−12%	−62%	–	–	–	[101]
B5W3$_m$-CeO_2	−27%	−51%	−45%	–	–	–	[108]
B15W5-CQD60	Decrease	Not regular	Decrease	–	–	–	[111]
20MEOM + CuO	+3.2%	−33%	−5.33%	−12.5%	–	–	[112]
WCO + D + Al_2O_3	+43.61%	−2.94%	−20.56%	–	–	–	[114]
B + DEE5C	−6%	−52%	−16%	−11.7%	–	–	[117]
B20G90	+7.93%	−8.26%	−27.47%	–	–	–	[118]
WCO + D + CeO_2 + MWCNT	−18.9%	−38.8%	−71.4%	−26.3%	–	–	[119]
B50SC1	+ 67.62%	−62.05%	−60.94%	–	–	–	[120]
DWB-D-MWCNT	−2.33%	−5%	−3.94%	–	–	–	[126]
JB20D-Al_2O_3	−70%	−80%	−60%	−35%	–		[127]
B2040TiO_2	Increased	−23%	−12%	Decreased	–	–	[128]
SB + D + ZnO	+1.9%	−25%	−11.5%	−3.9%	–	–	[130]
TSME ANP60	−9%	−56.6%	−68%	−87.4%	–	–	[131]
ASB + TiO_2	Increase	–	−38%	−20%	–	–	[133]
WCO + D + CNTs	+27.49%	−65.70%	−44.98%	−29.41%	–	–	[135]

Table 9 (*continued*)

Base fuel - nano-particles	NOx	CO	UHC	Soot/smoke/PM	SOx	H2S	Ref.
JB20 + GNPs	−55%	−65%	−65%	–	–		[136]
Pongamia+D + Fe_3O_4	Decrease	−35.8%	−22.9%	−37%	–	–	[137]
B10E4N30	−6%	−19%	–	–	–	–	[138]
NBE25 + NiO	+6.1%	−25.4%	−10.8%	–	–	–	[140]
HOME20Al_2O_3	+11.27%.	−47.43%	−37.72%	−27.84%	–	–	[141]

emissions. NOx emissions of gasoline engine also were reduced when nano particles were introduced to fuel. 23.43% and 32.34% reduction of NOx were obtained with gasoline-10%ethanol-10 ppmMn_2O_3 and gasoline- 10%ethanol-20 ppmMn_2O_3, respectively [56].

Water contents in the fuels such as emulsion fuels or water injection can reduce the combustion temperature and consequently NOx will decrease. Safieddin Ardebili et al. [84] observed that NOx emission reduced by 20.51% when increasing the fusel oil content from 5% to 20% due to higher water content of fusel oil and lower heat release rates and in-cylinder pressure [84]. Higher oxygen content in the fuels with CeO_2 [87,91], TiO_2, ZrO_2 [91], ZnO [106] additives caused higher temperature within the combustion chamber and increased the NOx [87]. Janakiraman et al. [91] found that TiO_2 had more NOx reduction than CeO_2 and ZrO_2 due to the presence of nanometal oxides that can provide more oxygen vacancies followed by more reactive oxygen which promotes soot oxidation. Kumar et al. [106] stated that zinc oxide increased the combustion average temperature due to improved calorific value which leads to greater oxygen in the blend to react leading to lower NOx emissions. Actually, ZnO absorbs the oxygen for the NOx reduction.

3.3.2. CO

Carbon monoxide appears due to the incomplete combustion of fossil fuels (especially diesel fuel). Most studies shows increasing of the oxygen content by combining the oxygenated fuels causes further distribution of the CO [27], while with the presence of oxygen in blended fuels, higher cetane value tends to reduce CO emissions [32]. Mei et al. [33] revealed that the multilayer tubular structure of CNT can store the extra oxygen, so reduce the CO [33]. DF-Ce50 was better

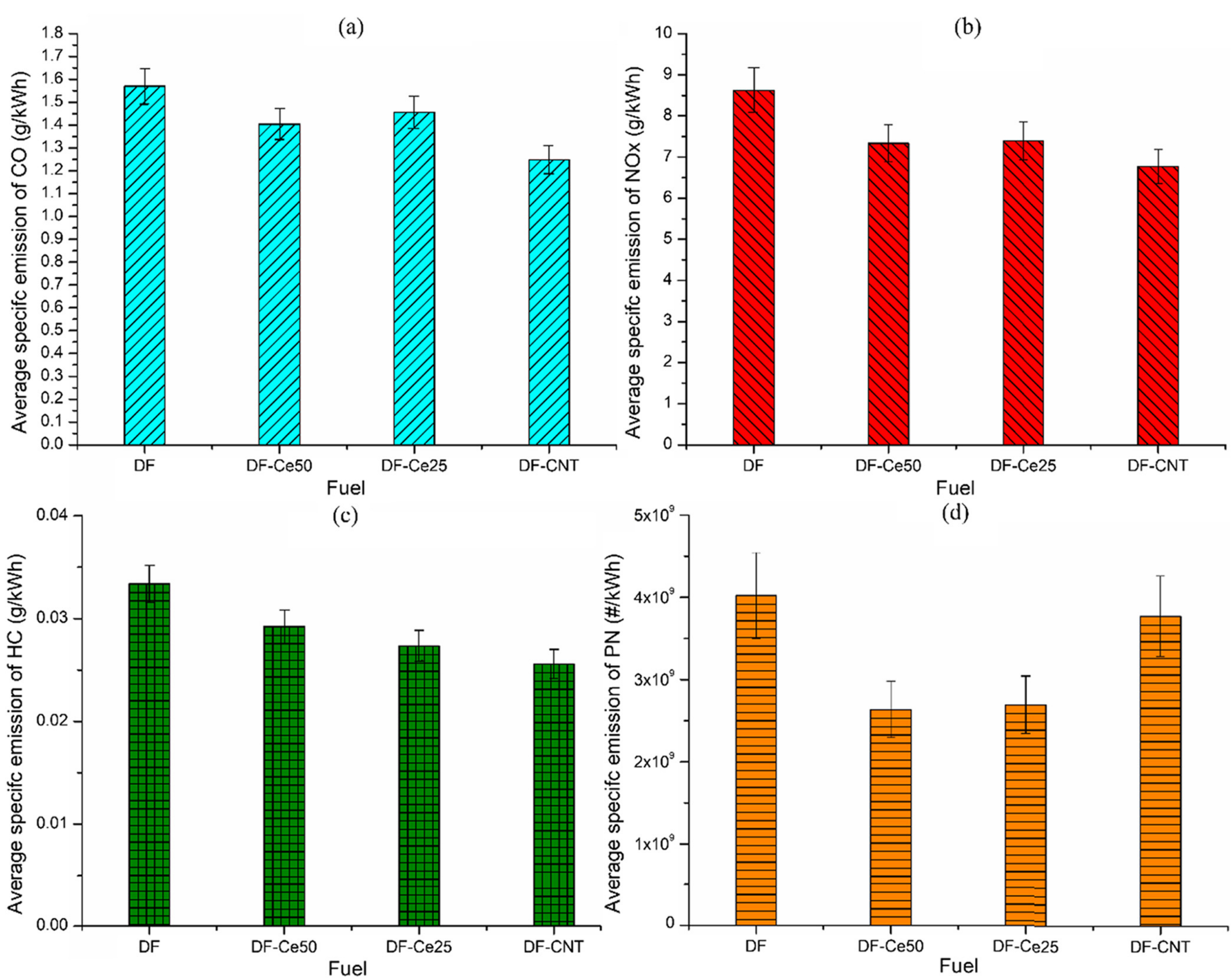


Fig. 16. Emissions comparison for CeO_2 and CNT [35].

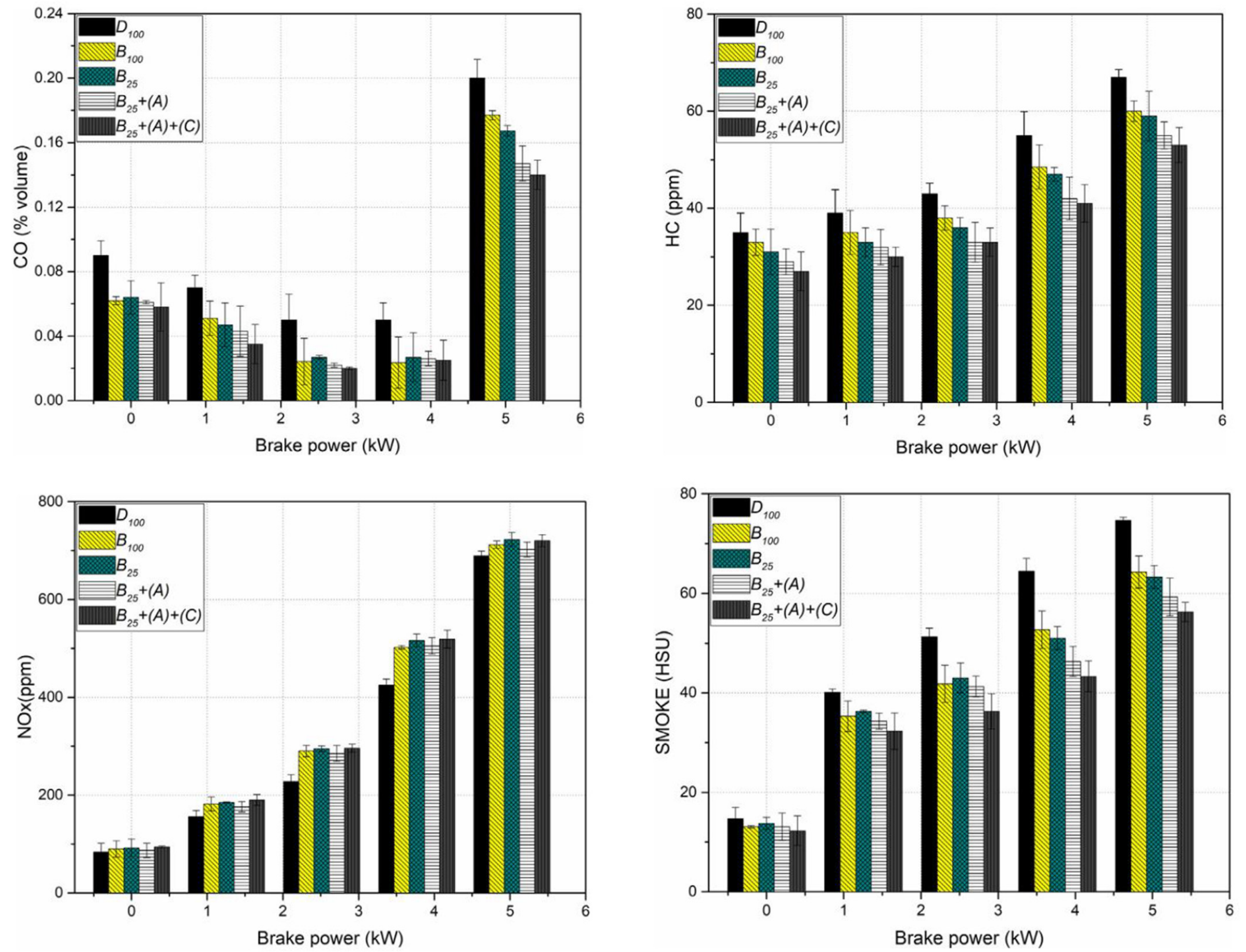


Fig. 17. Emission from engine exhaust using CeO_2 additives [66].

for the reduction of CO emissions than that of DF-Ce25 due to larger space between the two limits [35]. Iron oxide also decreased the CO due to its decomposition in the combustion process to discharge iron and oxygen atoms into the reaction zone [36]. Graphite particles increased the CO because it was a form of carbon having no oxygen molecules in it [36]. CuO reduced the CO emissions due to more reduction of the ignition delays time, which leads to more complete combustion [40]. By increasing in carbon content of CNT blends, CO increased due to increasing in the oxygen during combustion [46]. Higher surface to volume ratio of CNT that improves ignition characteristics was mentioned as the main reason of lower CO compared with CeO_2 [64].

Dhinesh et al. [67] presented that CO emission was reduced due to the addition of the cerium oxide nanoparticle which acts as an oxidation catalyst and increased the evaporation and mixing rates. Akram et al. [85] showed that $Ce_{0.5}Co_{0.5}$ nano-composite oxide reduced more effectively CO emissions compared with CeO_2 due to shorter ignition delay period, better carbon combustion and optimum air-fuel mixing effect [85]. Also, the same reasons were mentioned for the lower CO emissions of graphene oxide nanoparticles [118]. Among metal-oxide nanoparticles considered by Ağbulut et al. [110], the presence of Al_2O_3 mostly increased the oxygen content of the blends which ensured the most reduction in CO emission for $B10Al_2O_3$ test fuel in all engine loads. Then $B10TiO_2$ and $B10SiO_2$ followed to $B10Al_2O_3$, respectively [110].

3.3.3. UHC

Unburned hydrocarbon or UHC is one of the main pollutants produced from incomplete combustion. Like the CO, adding the oxygenated materials to the diesel fuel increases the HC amount. When the engine temperature comes down, all air pollutant amount, especially HC, decreases, significantly [27]. But, lower local temperature and oxygen concentration in the cylinder makes incomplete combustion and consequently higher emissions of PM, HC and CO [27]. Mei et al. [33] pointed out that great thermal conductivity of CNT is favorable to make complete combustion of the fuel and reduce the HC emissions. Zhang et al. [35] introduced the catalytic reaction of CeO_2 as the main reason of HC reduction, while Soukht Saraee et al. [45] and Sheriff et al. [64] mentioned that CeO_2 provides more oxygen for the oxidation of the hydrocarbon and transformed it into cerous oxide (Ce_2O_3) and reduce the UHC. Other researchers also mentioned reasonable effects of nano-additives for the HC reduction. For instance, CuO nanoparticle enhanced the surface-area-to-volume ratio and allows more fuel to react with the oxidizer and reduced the HC [40]. Mn_2O_3 acted as a nano-catalyst for gasoline complete combustion and decreased UHC by 40.64% and 51.83% using gasoline-10%ethanol-10 ppmMn_2O_3 and gasoline-10%ethanol-20 ppmMn_2O_3 blends [56]. CNT reduced the HC amount due to significant shortened ignition delay and improved combustion characteristics [78]. But, in some studies such as [109], CNT

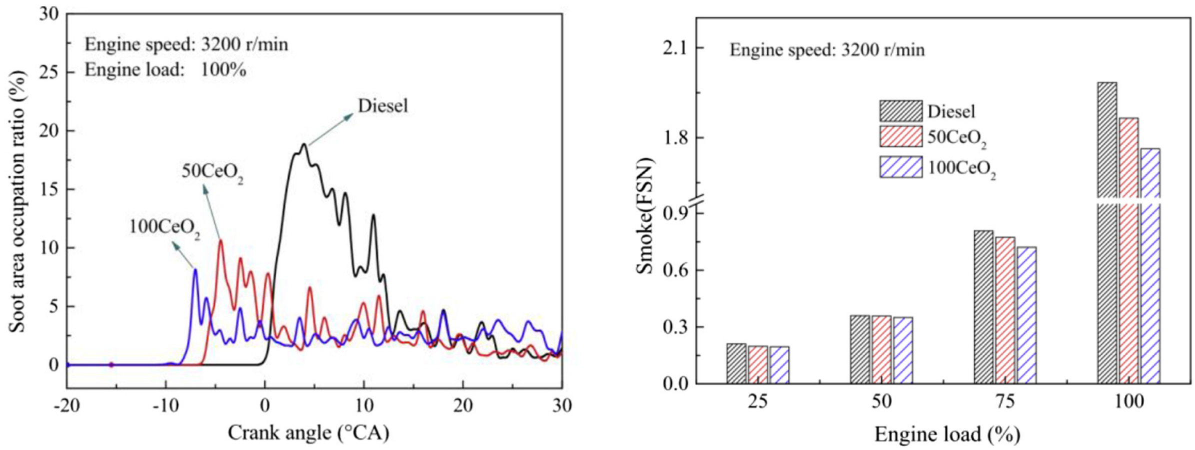


Fig. 18. Soot area occupation ratio and smoke amount emitted by diesel-CeO_2 nanofuel [51].

caused increase in HC due to existence of carbon in its structure. SiO_2 also decreased the HC amount by 82.14%, 70.94%, 80.44%, and 80.98% for the B10, $B10TiO_2$, $B10AL_2O_3$, and $B10SiO_2$, respectively [110]. Kumar et al. [106] found that presence of nano additives acts as a binder and avoids the undesirable fuel collection and crevice area penetration thus decreases the HC emissions.

3.3.4. Soot, PM, smoke

Soot, PM and smoke form due to incomplete combustion, so improving the quality of combustion and the high heating value of fuel resulted in high combustion temperatures inside the combustion chamber and significantly reduced the emitted particles [29]. Dhahad et al. [29] and Chacko et al. [32] mentioned the smoke reduction reason as the availability of oxygen molecules for improved oxidation of soot particles in the combustion zone for Al_2O_3 and GO as fuel additives, respectively. Mei et al. [33] observed that addition of nanoparticles (especially CNT) increases the heat transfer coefficient between the fuel and air, which promotes fuel evaporation and makes the formed mixture more uniform. They revealed that soot was generated by the thermal cracking of fuel under high temperature and anoxic conditions [33]. Zhang et al. [35] found that CeO_2 can oxidize particulate matters by consuming some HCs before convert to PMs through dehydrogenation and carbonization mention. They declared that PM will be formed by the dehydrogenation and carbonization of unburnt fuels at high temperature and low oxygen conditions. Furthermore, their study showed that CNT improved spray and lower combustion temperature and acts as the nucleus for the formation of particulate matters [35].

As seen in Fig. 18, soot area occupation ratio of CeO_2-diesel is meaningfully lower than diesel fuel. Also, smoke emissions of $50CeO_2$ and $100CeO_2$ were reduced by 6.0% and 11.1%. Liu et al. [51] stated that this was due to replacement effects of oxygen in CeO_2 crystal which can accelerate the diffusion and oxidation of fuel molecules, effectively promoting fuel chain reaction. Other reasons presented by researchers for the smoke and soot reduction by nano-additives are: high catalytic activity owing to its high surface-area-to-volume ratio [83], oxygen enrichment reduces the ignition delay, leads to higher burning rate and shorter combustion duration [103] and increased evaporation rate and improved fuel-air mixing resulting in shortened ignition delay and enhanced oxidation rate [127].

3.4. Exhaust Gas Temperature (EGT)

Because the exhaust gas temperature has significant effect on the exhaust emissions, it is investigated by many researchers during their studies. EL-Seesy et al. [73] noticed that the addition of GO to biodiesel reduced the EGT by improved the combustion process. Kumar et al. [74] reported that addition of nano sized CeO_2 particles to fuel, makes a reduction in the delay period, so more energy will release during the premixed combustion phase and cylinder temperature will increase as well as the in-cylinder pressure [74]. GO nano-additives increased the EGT because of increasing the heat release rate due to the improvement in the combustion process by increasing the oxygen of the fuel blends [86]. Also, CuO_2 increased the EGT due to combustion improved [87]. Perumal et al. [95] showed that EGT of diesel was low as compared to B20CuO50 and B20CuO100 because of CuO addition in PME increases the heat release rate due to the complete combustion by oxygenating behavior of the fuel blends [95]. As presented in Fig. 19 from [105], CeO_2 raised the EGT related to the enhanced fuel injection, higher utilization of oxygen by the CeO_2, promoted the burning process, enhanced the peak temperature, so improved the EGT. El-Seesy et al. [127] found that reduction in the EGT with increase of Al_2O_3 concentration level proceeds until certain dose; then EGT begins to rise again. Finally, Kumar et al. [137] revealed that adding the nanoparticles, will reduce the ignition delay and increase the cetane number of the fuel, so a significant part of the combustion completes before Top Dead Centre (TDC). This better combustion will reduce the exhaust temperature of nano-fuel.

3.5. Vibration and noise

There are some studies focused on the vibration and noise effects of blended fuels such as nano-additives fuels. Velmurugan et al. [30]

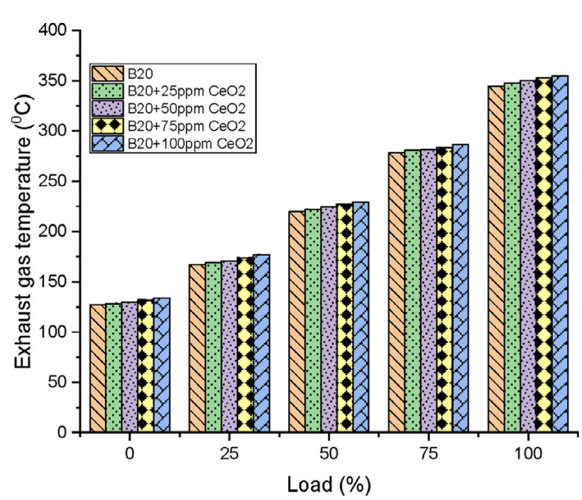


Fig. 19. Exhaust gas temperature for biodiesel-CeO_2 nanofuel [105].

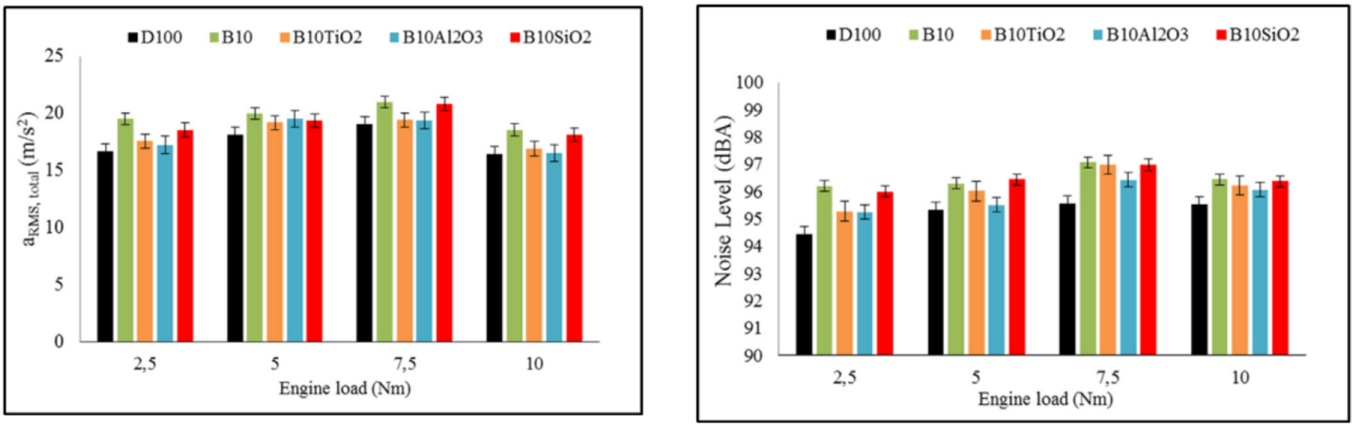


Fig. 20. Vibration level and Noise level with TiO_2, Al_2O_3 and SiO_2 nanoparticles [110].

introduced the biodiesel as one of the current trends in the development of reducing the environmental pollution and annoying noise and vibration which affects the health of the engines and operators [30]. Yaşar et al. [43] reported that nanoparticles addition into diesel fuel decreased both vibration and sound pressure level and observed that DTiCuN100 and DTiCeA100 had better results in terms of vibration and sound pressure level [43]. In another study, low n-Alumina concentration had limited (max. 4%) noise values [52]. Generally, as depicted in Fig. 20, when the engine load increased, vibration and noise values also increased up to the engine load of 7.5 Nm and then decreased for all nanoparticle additives [110].

3.6. Corrosion in engine

Although no direct study was found which focused on the corrosion effect of nano-fuel on engines, but some researches confirmed that nano-particles prevent the deposition of carbon and iron in cylinder, thus the friction of different parts of the engine reduces and consequently decreases the corrosion and increases the engine power [86].

4. Nanoparticles type as fuel additives

As described in previous sections, nanoparticles are widely used by researchers as fuel additives due to their amazing characteristics which are categorized here. Kumar et al. [25] and Khond et al. [27], as shown in Fig. 21, categorized these functions to: oxygen buffer, higher surface/volume ratio, micro-explosion property, anti-wear and corrosion, high thermal conductivity and catalytic activity. Furthermore, more lubrication and more swirl and turbulence in the fuel are also mentioned for nanoparticles duty in the literature [25,27].

Table 10 shows the effect of nanoparticles on the thermal properties of nanofuels. In some cases, significant effect on the properties were observed, while in several samples no changes were reported. For example, CeO_2 and CNT [35] couldn't change the lower heating value (LHV) [35], also these nanoparticles additives caused no significant variation

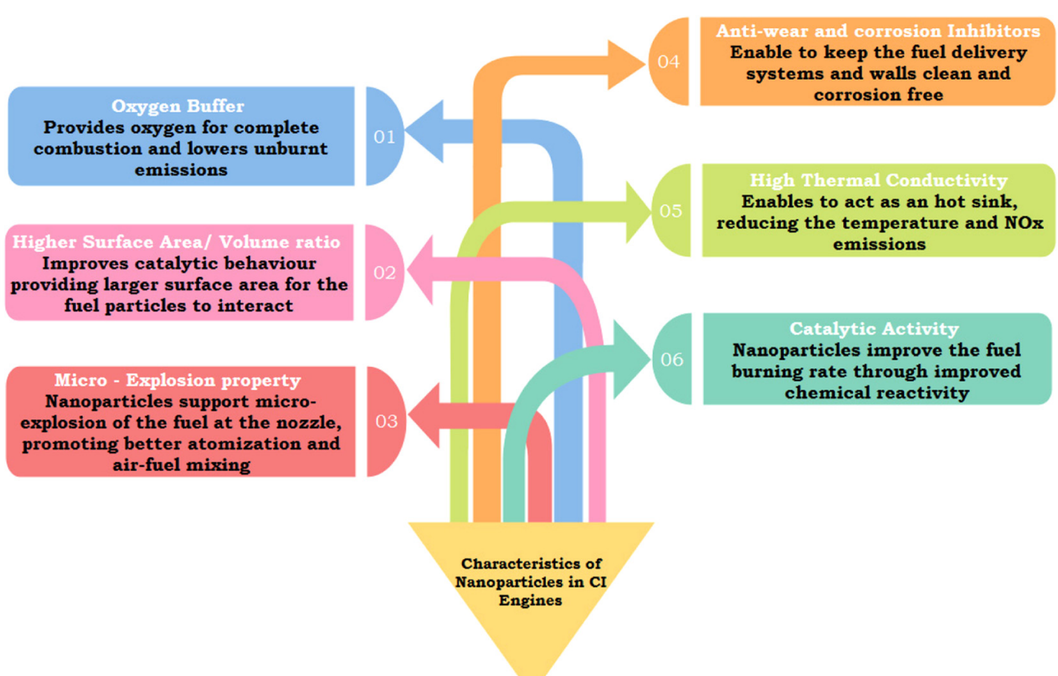


Fig. 21. Nanoparticles function in fuel as well as more swirl and more lubrication [27] [25].

Table 10
Nanofuels properties with different nanoparticles additives.

Nano-fuel	Density (kg/m^3)	Viscosity (mm^2/s)	Thermal conductivity (W/m K)	Heating value (kJ/kg)	Flash point (C)	Cetane number	Ref.
Diesel	840.2	5.4	0.125	43,430	55	49	
D + 50 nano-ZnO	841.5	5.6	0.133	43,800	57	51	[29]
D + 100 nano-ZnO	842.4	5.7	0.137	44,123	60	52	
D + 50 nano-Al_2O_3	842.0	5.5	0.132	43,790	56	50	
D + 100 nano- Al_2O_3	842.9	5.7	0.14	44,500	61	53	
D100 + GO	829	3.32	–	42,710	67	–	[32]
D100 + GNP	827	3.32	–	42,700	68	–	
DF	840.4	2.82	0.0879	42,853	–	–	
DF-Ce50	840.4	2.82	0.0897	42,853	–	–	[35]
DF-Ce25	840.4	2.81	0.0940	42,853	–	–	
DF-CNT	840.4	2.77	0.1020	42,853	–	–	
D	849.2	3.775	–	–	76	46	
D150FO	851.02	3.64	–	–	75	47.2	[36]
D150G	851.8	3.59	–	–	78	47.5	
D	833	3.6	–	42,000	60	–	[40]
D-CuO	834.1	3.5	–	42,430	66	–	
D	835.3	2.699	–	44,630	–	56.864	
DTiCuN100	837.4	2.799	–	45,220	–	57.512	[43]
DTiCeA100	837.2	2.739	–	45,230	–	57.529	
DCuO50	834.1	3.5	–	–	66	54.5	[47]
DAl50	834.3	3.5	–	–	68	54.4	
OOME	850.7	4.83	–	38,100	94	47	
OOME-T50	856.5	5.17	–	35,976	96	50	[58]
OOME-T100	861.3	5.42	–	36,103	99	53	
WFOME	898	4.21	–	43,850	160	–	
WFOME+25 ppm MWCNTs	830	4.75	–	43,730	57	–	[59]
WFOME+25 ppm MWCNTs	831.1	4.45	–	43,930	65	–	
Diesel oil	829	3	–	42,000	75	47	[61]
Jatropha biodiesel (J100)	876	4.5	–	38,789	121	55	
LPO20-50CeO_2	856	2.43	–	41,996	44	–	
LPO20-100CeO_2	856	2.56	–	42,443	40	–	[64]
LPO20-50CNT	856	2.38	–	42,112	42	–	
LPO20-100CNT	856	2.64	–	41,875	44	–	
OPO20-50CeO_2	858	2.54	–	42,484	46	–	
OPO20-100CeO_2	858	2.8	–	42,322	42	–	
OPO20-50CNT	858	2.72	–	42,414	44	–	
OPO20-100CNT	858	3.01	–	42,179	43	–	
B100	912	5.83	–	38,085	176	51.48	
B100PM30	875	4.51	–	38,487	110	63.61	[65]
D100	820	2.9	–	44,120	66	47	[66]
Cymbopogon flexuosus biofuel (B100)	905	4.6	–	37,000	55	52	
B25	848.5	3.375	–	42,053	50	47.9	
ENOB	906	4.67	–	35,800	74	–	[67]
NENOB (CeO_2 added)	916.4	4.99	–	36,200	67	–	
B20	817	3.12	–	40,422	60.49	47	[68]
B20TiO_2 SiO_2 100	817	3.01	–	44,000	63.61	48	
MOME	864	4.30	–	38,108	–	52	[69]
MOMET200	891	4.38	–	37,652	–	57	
D	820	2.9	–	44,120	75	50	
LGO emulsion	906	4.67	–	35,800	74	46.3	[72]
LGO emulsion+CeO_2	916.4	4.99	–	36,200	67	48.8	
JME100	883	5.25	–	40,630	–	52	
JME50GO	884	5.13	–	40,638	–	54.5	[73]
JME100GO	846	5.064	–	40,655	–	57.3	
10WSB	884.4	4.88	–	34,800	140	53.4	[74]
100CNT10WSB	885.1	4.91	–	35,000	142	55.2	
Diesel	830	2.1	–	42,300	50	46	
JME5W	919.2	5.92	–	36,750	162	47	[78]
JME5W50CNT	920.1	5.95	–	37,550	160	49	
BD	870	5.20	–	39,900	162	55	[80]
BD10W (Biodiesel+10%water)	883	5.55	–	35,300	185	52	
Diesel	820	2.4	–	42,957	50	48	
BD100	844	4.28	–	37,510	140	55	[82]
BD100+ Ag_2O(10 ppm)	862	4.35	–	38,112	136	56	
PSBD	844	4.28	–	37,510	140	–	
PSBD* 10 nm AgO (10 ppm)	819	3.98	–	38,012	136	–	[83]
PSBD* 20 nm AgO (10 ppm)	797	3.71	–	38,542	132	–	
B20	841	5.721	–	43,870	–	–	
B20G30	838	5.611	–	44,012	–	–	[86]
B20G90	836	5.554	–	44,293	–	–	

(continued on next page)

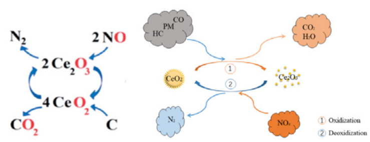
Table 10 (*continued*)

Nano-fuel	Density (kg/m^3)	Viscosity (mm^2/s)	Thermal conductivity (W/m K)	Heating value (kJ/kg)	Flash point (C)	Cetane number	Ref.
B20	830	4.73	–	43,540	176	58	
B20 + 25 (CuO_2)ppm	831	5.187	–	44,512.5	176.5	54.5	[87]
B20 + 100 (CuO_2)ppm	8329	5.689	–	45,519	178	52	
B20	832	4.71	–	43,590	175	58	
B20 + 25 (CeO_2)ppm	831.9	5.177	–	44,606	175.5	54.75	[88]
B20 + 100 (CeO_2)ppm	831.6	5.688	–	46,219	177	52	
B5	815	6.25	–	43,200	50	–	
B5D90 + CeO_2 50 ppm	817	6.35	–	43,240	51	–	[89]
B5D85 + CeO_2,100 ppm	819	6.4	–	43,280	52	–	
B20	863	4.51	–	40,810	90.7	50.7	
B20+ TiO_2 (25 ppm)	864	4.39	–	41,064	96.8	51.62	[91]
B20+ CeO_2 (25 ppm)	863	4.54	–	40,677	90.2	50.85	
B20+ ZrO_2 (25 ppm)	866	4.51	–	41,307	93.1	50.91	
DIESEL	845	2.64	–	42,400	67	–	
PB (30% palm biodiesel +70% diesel)	862	3.14	–	40,200	122	–	[92]
PBN (30% palm biodiesel +70% diesel+25 ppm TiO_2)	854	2.76	–	41,300	117	–	
B7 + 30%HVO	814.3	2.765	–	–	59	64.6	
B7 + 30% HVO+ nano CeO_2	817.7	2.717	–	–	60	62.3	[93]
B7 + 30%HVO+ nano ferrocene	817.8	2.754	–	–	59	62.4	
B20	830	4.73	–	43,540	176	58	
B20 + 50 (CuO_2)ppm	831.7	5.64	–	45,483	177	51.5	[94]
B20 + 100 (CuO_2)ppm	831.9	5.68	–	45,519	178	52	
B20	824	3.02	–	43,680	69	–	
B20CuO50	835	4.79	–	43,780	67	–	[95]
B20CuO100	846	4.85	–	43,820	66	–	
CB20	754	3.98	–	39,400	107	51	[97]
CB20 + GeO 50 ppm	748	3.4	–	41,200	96	53	
DSOME (B20)	835.4	3.9	–	40,658	133	52.25	[98]
DSOME2060	834.9	3.34	–	40,950	132.5	53.95	
B20	832	4.71	–	43,590	175	58	[102]
B20 + 100 (CeO_2)ppm	831	5.68	–	46,219	177	52	
B20CSME	914	4.3	–	29,000	307	53	[106]
B20CSME + 120ZNO	852.6	2.58	–	42,025	67.56	54.96	
Diesel	835	4.24	–	45,720	–	46	[109]
BD + Ag120	858.8	4.49	–	46,920	–	50	
BD + CNT120	891.6	4.91	–	48,680	–	61	
B10TiO_2	844.7	3.19	–	42,730	>100	52.134	
B10Al_2O_3	844.7	3.19	–	43.05	>100	51.983	[110]
B10SiO_2	844.7	3.19	–	42.89	>100	51.676	
MEOM	880	5.9	–	39,000	136	–	
20MEOM	849	4.7	–	42,500	67	–	[112]
20MEOM + CuO	840	4.3	–	43,100	60	–	
CIME	868.6	4.72	–	38,000	122	52	
CIME-Z50	871.1	4.76	–	37,020	123	54	[122]
CIME-Z100	872.4	4.78	–	37,320	126	56	
CIME-T50	869.2	4.73	–	37,120	123	53	
CIME-T100	870.4	4.75	–	37,540	124	55	
B20	850	2.59	–	41,690	69	–	
B20 125 PPM	851	2.72	–	41,570	74	–	[126]
B20 250 PPM	852	2.81	–	41,510	77	–	
TSME20	843	3.86	–	41,700	74	48	
TSME20 ANP 30	845.5	3.88	–	41,750	75	51	[131]
TSME20 ANP 60	846.4	3.89	–	41,760	77	53	
B25	843	4.4	–	41,458	68	50	
B25A50	845	4.35	–	41,482	63	51	[139]
B25A100	848	4.31	–	41,505	58	52	
B20	842.1	2.79	–	40,786.3	71.25	–	
B20But10	840.1	2.62	–	39,957.9	46.75	–	[146]
B20But10 + TiO_2	840.2	2.63	–	39,842.4	45	–	

in the physicochemical properties of the fuel blends compared to the base fuel [36]. But, CuO and Al_2O_3 [47] slightly increased in the flash point temperature and cetane index. Also, in [55] nanoparticles increased the octane index of gasoline fuel. GO nanoparticles [73] reduced the viscosity and decreased the ignition delay with an increase in cetane number, its oxygen content improved the combustion quality of fuel, but it reduced the fuel heating value. CNT's [78] presence in the JME5W fuel improved the cetane number and the calorific value of base fuel increased with increase in AgO nanoparticle size [83].

Based on Kumaravel et al. [89] study, the improvement in fuel properties are noticed if the CeO_2 nano additives are doped with the fuel blends. Dobrzynska et al. [93] found a relation between higher cetane

Table 11
Important chemical reactions for nanoparticles and emissions formations.

Chemical reaction	Details
Alumina:	
$Al_2O_3 \rightarrow Al_2O + 2O$ $Al_2O \rightarrow 2Al + O$	Aluminum oxide nanoparticles dissociate at high temperatures.
Ceria:	
$(2x+y)CeO_2 + C_xH_y \rightarrow \left[\frac{1}{2}(2x+y)\right]Ce_2O_3 + \frac{x}{2}CO_2 + \frac{y}{2}H_2O$ $2CeO_2 + CO \rightarrow Ce_2O_3 + CO_2$ $4CeO_2 + C_{soot} \rightarrow 2Ce_2O_3 + CO_2$ $4CeO_2 \rightleftarrows 2Ce_2O_3 + O_2$ $Ce_2O_3 + NO \rightarrow 2CeO_2 + N_2$ 	The mechanism of oxygen supply by cerium oxide which leads to reduced emissions of UHC, soot and CO. Oxidize CO by utilizing cerium oxide. Oxidation of the soot particles using CeO_2. CeO_2 acts as a catalyst which provides more oxygen to accelerate the combustion reaction [35]. Cerium oxide (Ce_2O_3) adsorb oxygen which breaks NOx into simple nitrogen [22, 35].
CNT:	
$C + 2NO \rightarrow N_2 + CO_2$	CNT act as a deoxidizer during combustion, thus prohibit the formation of NOx.
$N_2 + O \rightarrow NO + N$ $N + O_2 \rightarrow NO + O$ $N + OH \rightarrow NO + H$	Three main reactions producing thermal NOx
Heat release rate in combustion:	
$\frac{dQ_{gross}}{d\theta} = \left(\frac{1}{\gamma-1}\gamma p \frac{dV}{d\theta}\right) + \left(\frac{1}{\gamma-1}V\frac{dp}{d\theta}\right) + \frac{dQ_{wall}}{d\theta}$ $\frac{dQ_{wall}}{d\theta} = h_c A_\theta (T - T_{wall})\left(\frac{1}{6N}\right)$ $\gamma = 1.35 - 6\times10^{-5}T + 10^{-8}T^2$ $V_\theta = V_c + \frac{V_c \times (r_c - 1)}{2} \times \left(R + 1 - \cos(\theta) - (R^2 - \sin(\theta)^2)^{0.5}\right)$ $A_\theta = \frac{\pi B^2}{4} + \frac{\pi BL}{2} \times \left(R + 1 - \cos(\theta) - (R^2 - \sin(\theta)^2)^{0.5}\right)$ $h_c = C_1 \times V^{-0.06} \times p^{0.8} \times T^{0.4} \times (C_2 + V_m)^{0.8}$	Heat release rate from the intake valve closure to the exhaust valve opening [40], where γ is the ratio of the speci c heats, p is the in-cylinder pressure, V is the cylinder volume. Other parameters can be found in [150].

number, lower density and lower emission of carbon oxides and hydrocarbons. In their study, HVO addition reduced the density of the fuel mixture and consequently decreased the engine power and increased BSFC. Najafi [109] revealed that adding nano articles to the biodiesel-diesel blends will increase the cetane number and decrease the ignition delay. Ağbulut et al. [110] indicated that metal-oxide based nanoparticles increased the viscosity, cetane number and heating value of biodiesel. Literatures confirms that nanoparticles are not the only additives which changed the fuel property, alcoholic additives also modify fuels characteristics, powerfully. For example, Örs et al. [146] revealed that Butanol strongly affected some of the important properties of fuel blends such as density, kinematic viscosity and flash point. Table 11 summarize the chemical reaction mechanism of most used nanoparticles.

In next section and based on above sections, the most used nanoparticles (CNT, CeO/CeO_2, Al_2O_3, GO/GNP and TiO_2) in nanofuel application are shortly reviewed for their properties and behaviors.

4.1. CNTs

CNTs improved the cetane number and burning rate of the fuel by acting as a catalyst. Actually, CNT has been introduced as an environmentally kind additives due to its free-metal and enhancement the thermal conductivity [33]. CNT had an advantage of improved spray and lower combustion temperature which reduced all emissions (except PN) compared with CeO_2 [35]. Also, combustion characteristics of CNT nanofuel had a radical reduction of combustion pressure thus lowering the formation of NOx [46]. Another reason of CNT NOx reduction is its higher premixed combustion heat release rate and complete combustion [59]. Also, CNT caused shorter ignition delays and better combustion characteristics in the combustion engine [64]. Finally, higher thermal conductivity of CNT nanoparticle improves the evaporation rate of water particles in the emulsion fuel during the pre-mixed combustion period and reduces the IDP which result is improved engine performance [77].

4.2. CeO-CeO_2 (Ceria)

Natural oxygen content promotes cerium oxide as a catalyst to burn completely and rapidly, which produce higher BTE and lower BSFC [25]. Cerium oxide (CeO_2) [+4 state] becomes constructively transformed to cerous oxide (Ce_2O_3) [+3state] via low-energy reaction during the oxidation of the hydrocarbons. CeO_2 has lower emissions, because it has higher reaction rate due to its larger surface area [35]. Ceria reduced

CO and HC emission due to improved ignition characteristics. But it increased NOx due to increase in combustion temperature [43]. Also, CeO_2 makes more active free radicals such as O, H and OH which promotes the chain reaction and improves the fuel burning rate and complete combustion [51]. CeO_2 reduces the flame temperature compared to CNT, which consequently reduces the NOx emissions [64]. The cerium oxide (CeO_2) reacts with hydrocarbon and reduced it to form cerous oxide (Ce_2O_3), water vapor (H_2O) and carbon dioxide (CO_2), acting as an oxidation catalyst and thus providing oxygen to the fuel which CO gets converted to carbon dioxide [72]. Furthermore, cerium oxide supplies oxygen for the reduction of hydrocarbons as well as soot oxidation to form cerious oxide [74,117].

4.3. Al_2O_3

Generally, Al_2O_3 acts as a perfect combustion catalyst to reduce the pollutant emissions while improving the combustion behavior. Alumina increases the in-cylinder pressure and decreases the ignition delay [25]. The addition of aluminum oxide yielded better results in engine power because of promote an increase in oxidation rate and a decrease in ignition temperature [47]. Aluminum oxide reduced the HC and CO emissions due to more shorten ignition delay and improved ignition characteristics of nanoparticles. Also, CO_2 concentrations increased with adding aqueous N-Alumina to diesel due to reductions in CO and HC concentrations [52]. Alumina has the ability to interact with water at high temperatures producing hydrogen, which in turn promotes fuel combustion [52]. Furthermore, alumina nanoparticle exhibits lower BSFC value as compared to CNT due to the presence of higher oxygen content in its structure [131]. Many of researches revealed aluminum oxide is efficient nano-additives for emissions reduction [100,101,114,132].

4.4. GO/GNP

A compacted multilayer of 2D sheets (usually up to 10 layers) is called GNP, while GO is used for a multilayer of graphene with oxygen functional group in its structure [32]. Inert nature of graphene avoids it from chemical reactions with other materials. The graphite can be suspended and dispersed in inter molecular gaps of the fuel droplets, might cause a bit easier slip of the adjacent layers by reducing the kinematic viscosity [36]. GO/GNP improves the combustion process and rises the cylinder pressure, which improves the combustion temperature and consequently increases the NOx emissions [49]. Additionally, high thermal conductivity and high surface area of GO improves combustion and increases the cylinder pressure [71]. GO nanoparticles develops the combustion where a balance between CO and CO_2 forms, i.e. when CO emission decreased, CO_2 formation increased [71]. Actually, larger surface area of GO increases the chemical reactivity, so decrease the ignition delay and improve the combustion for CO reductions. GO nanoparticles increase in the cetane number and reduce the kinematic viscosity of the fuels [73]. Also these additives reduced the combustion duration and increased the average mean temperature, significantly, so leading to an increase in NOx emission, but reduced the CO and UHC emissions [73]. More studies such as [97,98] used GO for the emissions reduction. GO nanoparticles increased the cetane number of biodiesel fuel and decreased the specific fuel consumption (SFC) of the blend, consequently. Physically, oxygen existence in the GO-nanoparticle structure enhances combustion and makes higher brake power and lower SFC [118]. GNP additives enhanced the carbon oxidation rate due to efficient combustion process and reduction in BSFC. Also, these additives reduced the burnout time and minimized the late combustion duration in the exhaust stroke, so it decreased the incomplete combustion that caused fuel-rich combustion products [136].

4.5. TiO_2

TiO_2 in the nanofuel acts as an oxidation catalyst which offers more oxygen to the burning fuel inside the cylinder resulted in excellent combustion and reduced the CO emissions formation [58,69,121]. Activation energy generated by the TiO_2 nanoparticles burned the deposited carbon particles and reduced the HC emissions [68]. BTE of the doping of TiO_2-SiO_2 blended fuels was greater than that of the diesel due to the high heat release rate. But, NOx amount was increased because of higher cylinder peak pressure, early injection timing and shortened ignition delay [68].TiO_2 nanofuel also provides high surface energy due to its large surface to volume ratio which accelerates the combustion process [69]. TiO_2 reduced the HC emission due to the complete combustion because of surplus oxygen molecules present in its structure [69]. TiO_2 had higher BTE as compared with pure fuel due to the event of oxygen buffer and very energetic TiO_2 nanocatalyst. It assists to have faster burning rate during the combustion procedure by thermal energy obtained from novel nanocatalyst and produce economic fuel atomization [91].

5. Conclusion

In this review study, recent and novel nano-fuels in engines were analyzed and discussed. Different nanoparticles added to diesel, bio-diesel, gasoline, alcoholic and blended fuels were investigated in the results of emissions and BSFC reduction as well as the engines efficiency improvements. Following main points can be concluded:

- Nanoparticles have different functions such as: oxygen buffer, higher surface/volume ratio, micro-explosion property, anti-wear and corrosion, high thermal conductivity and catalytic activity. Furthermore, more lubrication and more swirl/turbulence in the fuel also were mentioned for nanoparticles duty in the literature.
- Al_2O_3, CuO, CNT and CeO_2 are the mostly used nanoparticles for diesel additives. Fe_2O_3, TiO_2 and Mn_2O_3 are the frequently used nanoparticles in SI engines application. CeO_2, TiO_2, CNT and Al_2O_3 are the commonly applied nanoparticles as additives to bio-diesel fuels. CeO_2, GO, Al_2O_3, CNT and TiO_2 are the most used nanoparticles additives to diesel/biodiesel blended fuels. Al_2O_3, GO and CNT were used as additives to ethanol/butanol blended fuels and ZnO, TiO_2 and Al_2O_3 were the applicable nanoparticles for hydrogen blended fuels.
- For the BSFC reduction purposes the best nanoparticles are: CeO_2 (−30%), TiO_2 (−23.42%), GO (−20%), CNT (−19.85%), Al_2O_3 (−14.66%) for diesel engines, and Mn_2O_3 (−38.89%) for SI engines. Maximum exhaust temperature decrease reported for Al_2O_3 (−27%), while maximum BTE improvements occurred for MWCNT (+36.81%), Al_2O_3 (+24.7%), CeO_2 (+23%), CNT (+18.8%), GO (+17%).
- For the NOx reduction: Al_2O_3 (−70%), GNP (−55%), CNT (−52%), and CeO_2 (−42.7%); for the CO reduction: Al_2O_3 (−80%), CNT (−65.70%), GNP (−65%), GO (−60%), CeO_2 (−52%); for UHC reduction: CeO_2 (−45%,-71.4%), Al_2O_3 (−68%), GNP (−65%), Mn_2O_3 (−51.83%), GO (−50%), CNT (−44.98%); for soot (smoke, PM) reduction: Al_2O_3 (−65%, −87.4%), Fe_3O_4 (−37%), CNT (−35%), CeO_2 (−30%) are the most suitable nano-additives.

6. Future studies

Based on this review study and concluded main points, following suggestions can be presented for future studies:

- Because a single type nanoparticle cannot present all the benefits, for instance Al_2O_3 was very efficient for emissions reduction, while CeO_2 had the better BSFC reduction, so using hybrid nanoparticles (such as Al_2O_3-CeO_2) can fill this gap which is ignored.
- Based on this review, additives to gasoline engines are not widely

considered by researchers, while these engines are more available and applicable than CI engines, so it can be considered more by researchers.
- Finding an optimum percentage for the nanoparticle concentration is also necessary which are not considered by researchers, while this factor has very significant effect on the results.
- Nanofuels, due to its lubrication and friction functions in cylinder, have significant effect on the cylinder corrosion, while it was not discussed by the researchers.
- Exergy-economic studies are also necessary to have a suitable decision for using these types of fuel additives.

Declaration of competing interest

We declare that we have no financial and personal relationships with other people or organizations that can inappropriately influence our work, there is no professional or other personal interest of any nature or kind in any product, service and/or company that could be construed as influencing the position presented in, or the review of, the manuscript entitled.

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