Review Article

A Comprehensive Review on Effects of Nanoparticles-antioxidant Additives-biodiesel Blends on Performance and Emissions of Diesel Engine

S. Naresh Kumar Reddy* and M. Marouf Wani
Department of Mechanical Engineering, National Institute of Technology, Srinagar, India

* Corresponding author. E-mail: nareshkumar_2017@nitsri.net DOI: 10.14416/j.asep.2020.06.002
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Abstract
The present review investigates the effects of different nanoparticles and antioxidants blended with biodiesel on the diesel engine's performance and emission characteristics. Biodiesel usage in diesel engine decreases the dependence on imported petroleum and yields benefits like reduction in global warming and engine exhaust emissions. However, inherent drawbacks like lower calorific value (CV), higher density, and viscosity while increased fuel consumption and nitrogen oxides (NO_x) emissions limit the biodiesel application in engines. In this way, the additives in the form of nanoparticles of different materials and antioxidants play a prominent role in mitigating the drawbacks of biodiesel. This review paper focuses on the effect of various additives in the form of nanoparticles and antioxidants blended with biodiesel on engine performance and emission characteristics. Biodiesel blended with additives reveals that the reduction of carbon monoxide (CO), unburnt hydrocarbons, and NO_x emissions and also improvement in brake thermal efficiency (BTHE) and brake specific fuel consumption (BSFC) as compared to diesel and neat biodiesel. The comprehensive review suggests that nanoparticles of different materials and antioxidants blending with biodiesel improved its characteristics and also establish an optimum improvement in engine performance and emission characteristics.

Keywords: Additives, Antioxidants, Biodiesel, Diesel, Emissions, Nanoparticles, Performance

1 Introduction

Most of the research focused to replace conventional fossil fuels, as they are not sufficient to meet the ever growing energy demand. Alternative fuels are renewable and decreasing the concentrations of emission levels in the environment. Diesel was a fuel used in transportation, and the agriculture sector compels for the alternative of diesel fuel. The primary alternative fuels are vegetable oils and alcohols since they are renewable, eco-friendly, and the characteristics are close to diesel fuel. Biodiesel yields many advantages due to its decreased CO_2 emissions and highly degradable nature. Biodiesel production using non-edible oils (microalgal oils, plant oils, and animal oils) has many socioeconomic benefits because these feedstocks are considered as waste and are highly abundant.

Furthermore, they do not pose a threat to food security, unlike edible-oils (sunflower oil, soybean oil, rapeseed oil, coconut oil, palm oil, groundnut oil, etc.). So this also makes the process of biodiesel to be commercially competitive due to reduced process costs. Though the drawbacks of vegetable oils are high viscosity, low volatility, and it causes combustion problems. Biodiesel produced through the process of transesterification reduces the viscosity of vegetable oils almost equal to conventional diesel. So most of the studies focused on biodiesel as an alternative fuel in diesel engines [1]–[10].

Buyukkaya [11] conducted experiments on a

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diesel engine by use of rapeseed biodiesel as a fuel. The results revealed higher BSFC and increased NO_x emissions. However, it decreases HC, CO, and smoke emissions. Rao *et al*. [12] investigated the effects of performance and emissions on diesel engines by using rice bran oil methyl ester. The results showed that reduced the BSFC, soot, hydrocarbons (HC), and CO emissions and increased NO_x emissions as compared to diesel. Lin *et al*. [13] used vegetable oil methyl ester by evaluating the diesel engine's performance and emissions. It found that no change in brake power and reduction in all emissions except NO_x emissions. Previous research studies reported that biodiesel's problems as a fuel in diesel engines require improvement in properties, decrease NO_x emissions, and stability of the fuel. However, the available information to overcome the drawbacks of biodiesel blends was adding additives like nanoparticles and antioxidants.

Guru *et al*. [14] examined the use of magnesium additives blended in waste chicken fat biodiesel as fuel on the compression ignition (CI) engine. The results showed that reduced BTHE and increased BSFC of magnesium additives blended with biodiesel fuel as correlated to other fuels. The CO and smoke emissions decreased but increase NO_x emissions as compared to other fuels. Kao *et al*. [15] explored the effects of alumina (Al_2O_3) nanoparticles blended in diesel fuel on the CI engine. The results revealed that BSFC lowered with the additives blended fuels as correlated to other fuels. Still, diesel as fuel at higher speeds showed better results as related to fuel added additives. The smoke and NO_x emissions reduced with the use of additives in diesel as correlated to conventional diesel. Velmurugan *et al*. [16], studied the influence of Pyridoxine Hydro-Chloride (PHC), Di-Ethyl Amine (DEA), and Tert Butyl Hydro Quinone (TBHQ) antioxidant additives blended with mango seed biodiesel as fuel on a diesel engine. The performance results reported that the same BTHE obtained with and without antioxidants in biodiesel. The emission results showed that reduced NO_x emissions by added additives in biodiesel and CO, HC and smoke emissions increased as correlated to conventional biodiesel.

Section 2 discusses the effects of performance and emission parameters by the use of biodiesel on CI engines. The primary aim of biodiesel as fuel is decreasing dependence on imported petroleum, reducing global warming, increasing lubricity and reducing the exhaust emissions of diesel engines. The major advantages of biodiesel are non-toxic, renewable fuel and release fewer emissions to the atmosphere as compared to diesel. From the previous studies reported that the use of biodiesel on diesel engines increase BSFC and lower brake power (BP). The emissions of HC, CO, PM reduced, and NO_x and CO_2 emissions raised by the use of biodiesel as fuel in diesel engines. To overcome drawbacks of biodiesel blends used as fuels on a diesel engine was added additives of nanoparticles and antioxidants in biodiesel blends. Section 3 discusses the effect of additives on the fuel properties of biodiesel. The major advantage of additives added in biodiesel is to enhance the properties of biodiesel fuel. Nano additives improved CV, flash point, and viscosity of biodiesel fuel. Antioxidant additives are effective in increasing flashpoint, CN as well as oxidation stability of biodiesel. But the CV of biodiesel was reduced with the addition of antioxidants.

Section 4 discusses the effects of engine performance and emissions with different nano additives. The major advantage of nano additives added in biodiesel is to improve engine performance while resulting in a notable reduction in engine exhaust emissions expect CO_2. From the previous studies reported the higher CV, thermal conductivity, and surface to volume ratio properties of nanoparticles enhanced the engine performance, combustion, and emissions. But, a slight increase in CO_2 emissions was observed with nanoparticle-added biodiesel compared to neat biodiesel and biodiesel-diesel blends. Section 5 discusses the effects of engine performance and emissions with different antioxidant additives. The major advantage of antioxidant additives added in biodiesel is to improve engine performance while resulting in a high percentage of decrease in NO_x emissions but a slight increase in other emissions. Previous research studies showed that adding antioxidants with biodiesel would improve engine performance slightly, resulting in a decrease in NO_x emissions but a slight increase in other emissions.

The objective of the review is to identify the suitable non-fossil renewable fuels that perform better than conventional diesel in terms of performance, emission, and combustion characteristics without any hardware modification. The present investigation, therefore, seeks to use the impact of both nanoparticle and antioxidant additives blend with biodiesel as fuels in the CI engine.

2 Effects of Performance and Emission Parameters by Use of Biodiesel

From the previous studies noted that a lot of experimental and theoretical investigations had been carried out in a diesel engine to study the alternate fuel for diesel. Palvannan *et al*. [17] investigated the effect of cashew nut biodiesel on a diesel engine. The performance results showed that BTHE of B20 fuel was equal to diesel as fuel, but further increase blend percentage shows the low BTHE value as correlated to conventional diesel. The smoke and HC emissions reduced, but it increases NO_x and carbon dioxide (CO_2) emissions because of the complete combustion of biodiesel and high exhaust gas temperature (EGT). Rampure *et al*. [18] examined the performance and emission analysis with rice brain biodiesel as fuel on the CI engine. The BTHE value decreases with a higher percentage of blends because of the high viscosity of biodiesel. The BSFC, CO_2, and NO_x emissions increased by the use of biodiesel blend as compared with conventional diesel because of the oxygen content of biodiesel, poor atomization of fuel, and higher combustion temperatures.

Mahesh *et al*. [19] conducted the experiments by the use of honge oil methyl ester (HOME) as fuel on a diesel engine. The performance results showed that BTHE and BSFC values increased because of low calorific value as correlated to diesel. The NO_x emissions and EGT value increased because of the complete combustion of biodiesel. Sahoo *et al*. [20] examined the influence of Karanja, polanga, and jatropha biodiesel as fuels on a tractor engine. The emission results showed that reduced HC and Particulate Matter (PM) emissions because of the complete combustion of fuel. Still, it increased BSFC, CO, NO_x emissions because of low CV values, oxygen percentage of biodiesel, and high viscosity of fuels. Abed *et al*. [21] investigated the effect of waste cooking-oil biodiesel on performance and exhaust emissions of a diesel engine. It reported low BTHE and higher BSFC and EGT obtained by biodiesel blends as correlated to convention diesel. The biodiesel blends produced less CO, HC, and other emissions except for NO_x and CO_2 emissions as correlated to convention diesel.

Uyumaz [22] studied the effects of combustion, performance, and emission characteristics of a DI diesel engine fueled with mustard oil biodiesel blends at different engine loads. It reported low BTHE and higher BSFC obtained by mustard biodiesel blends as correlated to convention diesel. The biodiesel blends produced less CO and smoke emissions except for NO_x emissions as correlated to convention diesel. Shrivastava *et al*. [23] investigated the effects of engine performance and emission characteristics of CI engine operated with roselle and karanja biodiesel. The results revealed that the reduced NO_x and smoke emissions and increased BSFC and CO_2 emissions obtained by roselle biodiesel blends as correlated to convention diesel. The results showed reduced BTHE, EGT, NO_x and smoke emissions and increased BSFC obtained by karanja biodiesel blends as correlated to convention diesel. Anantha Raman *et al*. [24] investigated the performance, combustion, and emission analysis of a direct injection diesel engine fuelled with rapeseed oil biodiesel. It reported low BTHE, heat release rate (HRR), maximum cylinder pressure, and higher BSFC and EGT obtained by biodiesel blends as correlated to convention diesel. The biodiesel blends produced less CO and HC emissions except for NO_x and smoke emissions as correlated to convention diesel.

Simsek [25] studied the effects of canola, sefflower oils, and waste oils biodiesels on engine performance and exhaust emissions. The results revealed that the BSFC and BTHE increased as the ratio of BD75 and decreased by 1.95% for BD100 as correlated to convention diesel. The biodiesel blends produced less CO, HC, and smoke and increased NO_x and CO_2 emissions as correlated to convention diesel. Table 1 summarizes the literature findings on the performance, combustion, and emission analysis of the CI engine by adding biodiesel as a fuel. Previous studies reported that biodiesel's use in diesel engines increases BSFC and lower BP. The emissions of HC, CO, PM reduced, and NO_x and CO_2 emissions raised by the use of biodiesel as fuel in diesel engines. To overcome drawbacks of biodiesel blends used as fuels on a diesel engine was added additives of nanoparticles and antioxidants in biodiesel blends.

3 Effect of Additives on Fuel Properties

Density, viscosity, flash point, CV, and CN are important properties of fuels. Density is a significant factor that affects engine power indicators such as CN and CV. Higher fuel viscosity influences both spray and combustion characteristics of the diesel engine. A

Table 1: Impact of different biodiesel on performance, combustion, and emissions

Investigators	Year	Fuel	Remarks
Raheman and Phadatare [26]	2004	Karanja biodiesel	It reported low BTHE and higher BSFC obtained by biodiesel blends as correlated to convention diesel. The biodiesel blends produced less CO, NO_x, and smoke emissions as correlated to convention diesel.
Ramadhas *et al*. [27]	2005	Methyl esters of rubber seed oil	It reported that higher BSFC and NO_x emissions obtained by the use of biodiesel blends as correlated to convention diesel.
Puhan *et al*. [28]	2005	Mahua oil methyl ester	The results reported that biodiesel fuel has low CV value, so it increased the engine's BSFC value.
Labeckas and Slavinskas [29]	2005	Rapeseed methyl ester and it blends with diesel	The NO_x emissions because of the complete combustion of biodiesel.
Yoshimoto [30]	2006	Rapeseed oil	It reported that slight performance values enhanced but higher CO and NO_x emissions because of the complete combustion of fuel.
Pereira *et al*. [31]	2007	Soybean biodiesel	The biodiesel blends produced less CO, HC, and SO_x, but higher NO_x emissions as correlated to convention diesel.
Roskilly *et al*. [32]	2008	Biodiesel from recycled cooking oil	It reported that higher BSFC and lower CO and NO_x emissions obtained by the use of biodiesel blends as correlated to convention diesel.
Altun *et al*. [33]	2008	Sesame oil blended with diesel	The biodiesel blends produced less CO and NO_x emissions as correlated to convention diesel.
Correa and Arbilla [34]	2008	Commercial biodiesel	It reported that at low speeds produced higher total carbonyls as compare to higher speeds.
Zheng *et al*. [35]	2008	Soy, Canola and yellow grease derived biodiesel fuels	The biodiesel blends produced higher NO_x emissions because of the high cetane number (CN) as correlated to convention diesel.

higher flash point is an important property to handle, storage, and safe operation of fuels. CN is an important property for the ignition quality of fuel. Fuels have a low CN, and it has given high particulate matter emissions because of incomplete combustion. The CV of the fuel significantly affects the performance parameters of a diesel engine. Biodiesel has a high viscosity, high density, high flash point, high CN, low oxidation stability, and lower CV, but it does not contain aromatic compounds and sulfur content. The use of biodiesel on diesel engines increases BSFC and lower BP because of biodiesel properties that have lower heating value, high viscosity, and density. The HC, CO, PM emissions are reduced, and NO_x and CO_2 emissions are raised by biodiesel as fuel in diesel engines because it contains oxygen molecules, lower carbon to hydrogen ratio, and advanced injection and high CN.

The previous literature reported that enhance the fuel properties by use of different additives blended with biodiesel fuel. From the previous studies, nanoparticles and antioxidants additives are used to improve biodiesel fuel properties like viscosity, density, flash point, calorific value, and oxidation stability. Guru *et al*. [14] conducted experiments using Mg-based nanoparticles as additives in chicken fat methyl ester biodiesel as fuel on the CI engine. The results reported that reduce the viscosity and flash point of fuel by using magnesium (Mg) nanoparticles blended fuel as correlated to conventional biodiesel. Caynak *et al*. [36] examined the effects of physical properties by using the Mg additive in pomace oil biodiesel. The results reported that reduced viscosity and a flashpoint of fuel with nano additives as correlated to conventional biodiesel. Uyumaz [22] studied the effects of combustion, performance, and emission characteristics of a DI diesel engine fueled with mustard oil biodiesel blends at different engine loads. The results reported that increased density, viscosity, and flash point and reduces the CV of fuel by using biodiesel blends as compared to diesel.

Anantha Raman *et al*. [24] investigated performance, combustion, and emission analysis of a direct injection diesel engine fuelled with rapeseed oil biodiesel. The results reported increased density, viscosity, CN, and flash point, reducing the CV of fuel by using biodiesel blends compared to diesel. Rajak *et al*. [37] investigated the effects of spirulina microalgae biodiesel enriched with diesel fuel on performance and emission characteristics of the CI engine. The results reported increased density, viscosity, CN, and flash point, reducing the CV of fuel by using biodiesel blends compared to diesel. Vellaiyan [38] carried out experiments to evaluate the improvement in combustion, performance, and emission characteristics of a diesel engine fueled with neat petro-diesel (PD), soybean biodiesel (SB), and 50% SB blended PD (PD50SB) by using carbon nanotube (CNT) as an additive. The results reveal that the density of SB is 4.9% higher than PD. The viscosity of SB and PD50SB is 62.7 and 30.3% higher than PD, respectively. The nanoparticle inclusion further marginally increases the fuel density and viscosity.

Prabu [39] studied the effects of nanoparticles-dispersed aloe vera biodiesel blends on the performance, combustion, and emission characteristics of a DI diesel engine. The results reported that increased density and CV of fuel and reduces flashpoint by using biodiesel with nano additives as compared to biodiesel. Katam *et al*. [40] studied the effects of the CI engine's performance and emissions using algal biomass as an antioxidant additive in coconut and karanja methyl esters. The results revealed that biodiesel blend with antioxidant showed increased density, viscosity, and flashpoint, but it reduced the CV of fuel as compared to biodiesel. Kannan *et al*. [41] conducted experiments on a diesel engine using iron chloride ($FeCl_3$) nanoparticles blended with biodiesel. The results reported that reduced flash point and small improvement of CV value of fuel with nano additives as correlated to conventional biodiesel but no change in viscosity with and without additives in biodiesel blends.

Fattah *et al*. [42] conducted experiments on a diesel engine using antioxidant additives blended with biodiesel as fuels. The results reported that flashpoint, viscosity, oxidation stability, and density values increased but reduced CV value of fuel as compared to conventional biodiesel. Ileri *et al*. [43] examined the effect of fuel properties by adding antioxidants in biodiesel. The results reported that high oxidation stability and cetane number of fuel with antioxidants as correlated to conventional biodiesel. Table 2 depicts the effect of additives on biodiesel properties, such as density, viscosity, flash point, pour point, cetane number, calorific value, etc. From the previous studies reported that nano additives main properties are higher CV, thermal conductivity, and surface to volume ratio properties of nanoparticles enhanced the engine performance, combustion, and emissions. Still, the slight increase of other emissions was observed with nanoparticle-added biodiesel compared to neat biodiesel and biodiesel-diesel blends. Antioxidant additives are effective in increasing flashpoint, CN as well as oxidation stability of biodiesel. But the CV of biodiesel is reduced with antioxidant addition. Antioxidants additives could effectively control NO_x emissions by preventing the formation of free radicals during both fuel storage and the combustion process. Antioxidants addition to biodiesel would improve engine performance slightly while resulting in a decrease in NO_x emissions but somewhat increase other emissions.

4 Effects of Engine Performance and Emissions with Different Nano-additives

A few research works did by blending nanoparticles with diesel-biodiesel blends. So, exploring the fullest potential is an invention for researchers. The principle of nano additives action consists of a catalytic effect on the combustion of hydrocarbons. These additives reduce exhaust emissions because of the metals reacting with water vapor to make hydroxyl and react with carbon atoms, therefore discharging the oxidation temperature. Metal-based additives are promoting complete combustion, reduce BSFC, and hydrocarbon emissions of biodiesel blends in diesel engines. Diesel engines release low emissions of carbon monoxide and hydrocarbon but reject more emissions of nitric oxide and particulate matter. In this work, the literature is studying the effects on engine performance and emissions of various nano-additives.

Sajeevan and Sajith [51] examined the performance and emission parameters using cerium oxide (CeO_2) nanoparticles, which blended with diesel as fuel on a diesel engine. All experiments conducted at 1500 rpm constant speed on the engine. The experimental results showed that 6% BTHE increased, and 40–45% HC emissions also reduced NO_x emissions reduced up to 30% at high load with blended CeO_2 nanoparticles in diesel as a fuel. Sajith *et al*. [52] investigated the use of CeO_2 nanoparticles with biodiesel as a CI engine. The results showed that 1.5% increased BTHE, reduced HC emissions of 25–40%, and reduced up to 30% NO_x emissions by use of nanoparticles in biodiesel. Still,

Table 2: Properties of biodiesel fuel blends with different additives

Feed Stoke of Biodiesel	Additives (%)	Density at 20°C (g/cm^3)	Viscosity at 40°C (mm/S^2)	Flash Point °C	Cetane Number	Calorific Value (MJ/kg)	Sulfur Content (mg/kg)	Carbon Content (% mass)	Oxidation Stability	Ref.
Diesel		0.82	3.4	71	45	43.2	<10	290	110	[42], [44], [45]
Palm oil (B100)		0.88	3.94	160	50–52	38.69	-	-	7.2	[42], [44], [46]
Palm oil (B35)	1% NPAA	0.845	4.02	-	51	45.1	-	-	-	[44]
Jatropha oil(B100)		0.865	4.72	182.5	53	39.83	-	-	3.7	[45]
Jatropha oil (B20)	0.15% DPPD	0.833	3.276	88.5	-	44.466	-	-	-	[45]
Canola oil (B100)		0.875	3.32	107	61.5	-	0.001	-	7	[47]
Palm oil (B20)	1000 ppm BHA	0.84	4.06	79.5	-	43.79	-	-	30.9	[42]
Palm oil (B20)	1000 ppm BHT	0.84	4.06	79.5	-	43.82	-	-	29.6	[42]
Canola oil (B20)	1000 ppm BHA	0.849	4.23	-	53.459	-	-	-	24.8	[43]
Canola oil (B20)	1000 ppm BHT	0.849	4.57	-	50.004	-	-	-	11	[43]
Canola oil (B20)	1000 ppm TBHQ	0.85	3.85	-	50.328	-	-	-	38.7	[43]
Canola oil (B20)	1000 ppm EHN	0.849	4.61	-	58.784	-	-	-	9.8	[43]
Palm oil (B100)	2% FBC	0.865	4.51	167	6868	38.3	-	-	-	[42]
Jatropha oil (B15)	5% cerium oxide	0.875	-	56	-	39.887	-	-	-	[48]
Palm oil (B5)	0.15% PXAP	-	3.34	85	-	-	-	-	-	[49]
Palm oil (B5)	0.2 g Natural organic	-	3.1	82	-	-	-	-	-	[49]
Palm oil (B5)	0.2% TiO_2	-	3.19	73	-	-	-	-	-	[49]
Tall oil (B60)		0.867	5.3	88	50	41.511	10.29	-	-	[50]
Tall oil (B60)	4% cobalt	-	4.9	84	-	-	-	-	-	[50]

there was no change in CO_2 emissions as correlated to diesel. Selvan *et al*. [53] studied the effects on CI engine with the use of CeO_2 nanoparticles blended with biodiesel blends as fuels. The results reported that high BTHE by combined with CeO_2 nanoparticles in fuels because these nanoparticles increase the calorific value of fuel and reduced ignition delay of combustion. The emissions of smoke and CO reduced, but NO_x emissions increased with the blended of nanoparticles in diesel blends.

Manikandan and Sethuraman [54] examined the effects of performance and emission parameters on CI engine with the use of CeO_2 nanoparticles blended in ethanol-blended fuels. The results reported that increased BTHE and reduced BSFC of E10Ce10 fuel as correlated to other fuel blends. EGT value increased with all combinations an increase of load on engine expect CeO_2 nanoparticles added fuel blends. NO_x and HC emissions reduced with the addition of CeO_2 nanoparticles added fuel blends on the CI engine. Karthikeyan *et al*. [55] investigated the effects of performance and emission parameters on CI engine at 1500 rpm with the use of zinc oxide (ZnO) nanoparticle in canola oil biodiesel. The results showed that increased BTHE and reduced BSFC values with the addition of ZnO nanoparticle additives in biodiesel because these additives reduce the ignition delay of combustion. CO and HC emissions reduced by the use of additives in biodiesel. Tewari *et al*. [56] conducted experiments on CI engine with the influence of performance and emission parameters by adding multi-walled carbon nanotubes (MWCNT) nanoparticles in Honge oil biodiesel. The results gave high BTHE and reduced all emissions except CO emissions by using MWCNT nanoparticles in HOME as correlated to other fuels.

Fangsuwannarak and Triratanasirichai [49] studied the effects of performance and emission parameters on CI engine at maximum load conditions with Titanium oxide (TiO_2) nanoparticles in palm biodiesel. The results showed that increased BTHE and reduced BSFC of TiO_2 nanoparticles blended biodiesel fuel as correlated to other fuel blends. The emission results showed that lowered CO, CO_2, and NO_x emissions with the addition of TiO_2 nanoparticles added fuel blend on the CI engine. Yuvarajan *et al*. [57] examined the effects of emission parameters on CI engine with the addition of titanium oxide (TiO_2) nanoparticles in mustard oil methyl ester (MOME) biodiesel. The emission results showed that reduced HC and CO emissions but increased NO_x emissions at all loads by use of TiO_2 nanoparticles in biodiesel as correlated to conventional diesel. Sabet Sarvestany *et al*. [58] investigated the effects of emission parameters on CI engine with the addition of magnetic nanofluid particles (Fe_3O_4) in diesel. The results showed reduced SO_2 and NO_x emissions but increased CO emissions and smoke opacity by using Fe_3O_4 nanoparticles blended with diesel fuel compared to conventional diesel.

Soudagar *et al*. [59] investigated the effects of graphene oxide nanoparticles on performance and emissions of a CI engine fueled with dairy scum oil biodiesel. The results revealed that the blend of DSOME2040 improved BTHE by 11.56%, reduced BSFC by 8.34%, HC by 21.68%, smoke by 24.88%, CO by 38.662% and oxides of NO_x emissions by 5.62% as compared to DSOME(B20). Tamilvanan *et al*. [60] studied the Effects of nano-copper additive on performance, combustion, and emission characteristics of Calophyllum inophyllum biodiesel in CI engine. The results showed that the addition of nano-additives increased BTHE and reduced BSFC as compared to biodiesel blends but slightly lower than diesel. Combustion characteristics also are enhanced by improved oxidation reactions inside the combustion chamber, which resulted in a higher heat release rate. The emissions of HC, NO_x, and O_2 are significantly reduced for nano-additive blends but increased CO_2 emissions as compared to diesel.

Vellaiyan [38] carried out experiments to evaluate the improvement in combustion, performance, and emission characteristics of a diesel engine fueled with neat petro-diesel (PD), soybean biodiesel (SB), and 50% SB blended PD (PD50SB) by using carbon nanotube (CNT) as an additive. The results reveal that the SB and its blend promote shorter ignition delay period (IDP) that is resulting in lower in-cylinder pressure (ICP) and net heat release rate (NHR) compared to PD. The SB and its blend increased the BSFC, and reduced the brake specific energy consumption (BSEC) and EGT, due to lower heating value, and efficient combustion. Compared to PD, the emissions of SB and its blend promote reduced HC, CO, CO_2, and smoke emissions, except for NO_x emissions. Vinukumar *et al*. [61] investigated the effects of emissions on a CI engine by using Pungamia pinnata biodiesel with coconut shell nano additives. The results reported that the addition of nano-additives increased BTHE and BSFC as compared to biodiesel. The emissions of CO, CO_2 reduced at all loads, and NO_x emissions reduced at maximum load as compared to biodiesel. From the previous studies reported that enhanced the engine performance, combustion, and emissions but a slight increase in CO_2 emissions was observed with nanoparticles added biodiesel compared to neat biodiesel and biodiesel-diesel blends.

5 Effects of Engine Performance and Emissions with Different Antioxidant Additives

A few research work did by blending antioxidant additives with diesel-biodiesel blends. Therefore, exploring the fullest potential is a new concept for researchers. Unstable species in diesel fuel produce free radicals which combine with O_2 to produce further free radicals in a chain reaction and react with olefinic compounds to form gums. These can also result in polymerization to form nitrogen, sulfur compounds, and organic acids to form sediments. Antioxidants inhibit chain branching reactions free radicals to form stable hindered radicals which do not propagate further. It leads to fuel darkening and the production of gums and sediments consequently to reduce fuel instability of biodiesel through the application of antioxidants. A large number of research studies argue that biodiesel as a fuel in diesel engines resulted that it increased NO_x emissions because of oxygen content in biodiesel. The vital feature of antioxidants is reduced NO_x emission by absorbing excess oxygen while using biodiesel in fuel blends [16], [45]. In this work, the literature studies the impacts on engine performance and emissions of various antioxidant additives with diesel-biodiesel blends.

Ileri *et al*. [43] studied the effects of a turbocharged direct injection (TDI) diesel engine by using biodiesel with antioxidants. The results reported that low BSFC obtained by use of Tert-butyl hydroquinone (TBHQ) antioxidant wit biodiesel among all other fuel blends. The lower NO_x emissions obtained by the use of 2-Ethylhexyl nitrate (EHN) antioxidants with biodiesel among all different fuel blends, but CO emissions were increases with all fuel blends. Varatharajan *et al*. [16] examined the use of different antioxidant additives blended with jatropha biodiesel as fuel on a CI engine. The results reported that low BSFC obtained by use of ethylenediamine and p-phenylenediamine, but slightly increases with L-ascorbic acid, BHT and a-tocopherol as correlated to conventional biodiesel. The lower NO_x emissions obtained by the use of all antioxidant additives, but p-phenylenediamine gave optimum reduction as related to other fuel blends. The emission of CO and HC emissions increased with all antioxidant fuel blends. Palash *et al*. [45] conducted experiments on CI engine with the influence of performance and emission parameters by adding N, N'-diphenyl-1,4-phenylenediamine (DPPD) antioxidant in jatropha biodiesel. The obtained results showed that this additive gave the same power and BSFC with and without adding the additive. The obtained results revealed that the reduction of NO_x emissions increases with increased blends of biodiesel. However, it slightly increases the emissions of HC and CO. Still, it should be low as compared to conventional diesel.

Rashed *et al*. [62] investigated the effects on a diesel engine by using Calophyllum biodiesel with antioxidants additives NPPD, EHN, and DPPD. The results showed high BSFC, and low brake power (BP) and BTHE obtained using biodiesel without additives. The BP and BTHE of biodiesel with antioxidants were increased and reduced BSFC as compared to conventional biodiesel. These all antioxidants reduced NO_x emissions but increased CO and HC emissions as compared to traditional biodiesel. Prabu *et al*. [63] conducted experiments using waste cooking oil biodiesel with BHT and n-butanol antioxidant additives on the CI engine. The performance results reported that BTHE reduced and BSFC value increased by biodiesel with antioxidants as compared to conventional diesel because of the lower CV value of a fuel. The emission results reported that reduced CO and increased NO_x emissions as correlated to diesel. Ashok *et al*. [64] examined the performance and emission analysis on the CI engine with Ethanox and BHT antioxidant additives blended with different proportions in Calophyllum inophyllum biodiesel. The performance results showed that BTHE value enhanced by added additives in biodiesel as correlated to conventional biodiesel. The emission results showed that reduced NO_x emissions by added additives in biodiesel and CO, HC and smoke emissions increased as related to conventional biodiesel.

Karthickeyan *et al*. [65] investigated the effects of performance and emission characteristics on a diesel engine by using Pistacia khinjuk methyl ester (PB) with Geraniol (GE) and Pyrogallol (PY) antioxidants. The results reported that PB20 + PY blend noticed better performance characteristics than PB20 + GE. The lower CO, HC, and smoke opacity and NO_x emissions of PB20 + PY blend as compared to PB20 + GE blend. Katam *et al*. [40] studied the effects of the CI engine's performance and emissions using algal biomass as an antioxidant additive in coconut and karanja methyl esters. The results revealed that biodiesel blend with antioxidant showed high BTHE and low NO_x emissions as compared to biodiesel blends. Cristina Dueso *et al*. [66] investigated the effects of a diesel engine's performance and emissions using sunflower biodiesel

Table 3: Impact of different additives on performance and emissions of various biodiesel blends

Ref. fuel	Type of Additive	Name of Additives	BP (KW)	η_{th} (%)	SFC (kg/kw-h)	CO (% volume)	CO_2 (% volume)	NO_X (PPM)	HC (PPM)	PM (mg/m^3)	Ref.
WCOME	Antioxidant	BHT				↑38.8		↑4.9	↑4	↓6.06	[63]
WCPOME	Nano-additive	$FeCl_3$				↓52.6	↓6.7	↓4.1	↓26.6	↓6.9	[41]
POME	Nano-additive	ZnO_2						↑33.3	↓22.2	↓56.4	[68]
HOME	Nano-additive	Ferrofluid				↓32.1			↓16.7	↓14.3	[69]
JOME	Nano-additive	CeO_2		↑1.5		↓37		↓ 30		↓ 40	[52]
POME	Nano-additive	TiO_2	↑1.6		↓11.1	↓29	↑7.8	↓27			[49]
POME	Antioxidant	BHA BHT	↓0.6 ↓0.3		↓0.6 ↓0.18	↑12.3 ↑8.6		↓12.6 ↓9.8	↑13.6 ↑22		[70]
CIOME	Antioxidant	DPPD NPPD EHN			↓2.68 ↓4.44 ↓3.76	↑18.9 ↑4.89 ↑8.56		↓4.74 ↓1.46 ↓3.1	↑10.5 ↑5.26 ↑7.9	↓10.8 ↓12.8 ↓25.1	[62]
JOME	Nano-additive	Cobalt oxide		↑1	↓2	↓50		↓45			[71]
CIOME	Antioxidant	BHT TBHQ						↓12.6 ↓15.2			[64]
JOME	Antioxidant	DPPD				↓ 13.4		↓16.5	↑7.69		[45]
HOME	Nano-additive	MWCNT		↑8.6		↓53		↓22			[56]
GSME	Nano-additive	ZnO_2		↑5.8	↓12	↓27.2		↑6.84	↓ 8.3		[72]
COME	Nano-additive	ZnO_2		↑14.2	↑18.2	↓14.2		↓18.7			[55]
MSOME	Antioxidant	PHC TBHQ DEA						↓18.2 ↓14.4 ↓16.3			[73]
TSME	Nano-additive	Al_2O_3		↑1.6		↓15		↓7	↓24		[74]
SOME	Antioxidant	Bio-Oil				↑0.7		↓3	↑14.3		[69]
JJME	Nano-additive	Al_2O_3			↓12	↓80		↓70	↓60		[75]
POME	Antioxidant	DTBP		↑2	↓10	↓6		↓9	↑5		[76]
GSME	Nano-additive	ZnO_2		↑29.34		↓4.6		↓10.8	↓13		[77]

BP, brake power; PPM, parts per million

with a renewable antioxidant additive from bio-oil. The results reported that a slight difference in performance parameters found with and without antioxidants of biodiesel. The antioxidant additive combined with the sunflower biodiesel reduced NO_x emissions and smoke opacity and increased CO and HC emissions of the diesel engine compared to diesel. Rajendran [67] studied the effects of nitrogen (NO_x) emissions of CI engine by using the Annona biodiesel blend (A20) with p-phenylenediamine (PPDA), A-tocopherol acetate (AT) and L-ascorbic acid (LA). The results revealed that 250 mg concentration of PPDA additive with A20 blend was optimum for NO_x mitigation up to 25.4% when compared to that of diesel without any major modification. Table 3 summarizes the literature findings on the performance and emission characteristics of a diesel engine by adding antioxidants and nanoparticles as additives in biodiesel. Previous research studies referred that adding antioxidants with biodiesel would improve engine performance slightly while resulting in a decrease in NO_x emissions but somewhat increase other emissions.

6 Conclusions

The conclusions of several studies in the literature reported that biodiesel as fuel in engine shows lower unburned hydrocarbon, carbon monoxide, smoke, and higher NO_x compared to diesel due to its higher oxygen content, low aromatic compounds and lower compressibility. The use of biodiesel as fuel on diesel engines also increases BSFC and lower BP because of lower CV, high viscosity, and density. The present review highlights the use of various antioxidants and nanoparticles blended with different biodiesels as well as an overview of the current status of biodiesel research progress and their effects on the performance and emissions of a diesel engine.

This review study found that the higher CV, thermal conductivity, and surface-to-volume ratio properties of nanoparticles enhanced engine performance, combustion, and emissions. But the slight increase in CO_2 emission was observed with nanoparticles added biodiesel compared to neat biodiesel and biodiesel-diesel blends. The antioxidants blended with biodiesel found to be more effective in suppressing the NO_x emission by disrupting the chain propagating reactions, trapping free radicals, and decomposing peroxides. Adding antioxidants with biodiesel would improve engine performance slightly while resulting in a decrease of NO_x emissions but a slight increase in other emissions. The further investigation seeks to use the impact of both nanoparticle, and antioxidant additives blend with biodiesel at different blends used as fuels in the CI engine.

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