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REVIEW ARTICLE

A review on the engine performance and exhaust emission characteristics of diesel engines fueled with biodiesel blends

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Abstract

Biodiesels have gained much popularity because they are cleaner alternative fuels and they can be used directly in diesel engines without modifications. In this paper, a brief review of the key studies pertaining to the engine performance and exhaust emission characteristics of diesel engines fueled with biodiesel blends, exhaust aftertreatment systems, and low-temperature combustion technology is presented. In general, most biodiesel blends result in a significant decrease in carbon monoxide and total unburned hydrocarbon emissions. There is also a decrease in carbon monoxide, nitrogen oxide, and total unburned hydrocarbon emissions while the engine performance increases for diesel engines fueled with biodiesels blended with nano-additives. The development of automotive technologies, such as exhaust gas recirculation systems and low-temperature combustion technology, also improves the thermal efficiency of diesel engines and reduces nitrogen oxide and particulate matter emissions.

Keywords Alternative fuel · Biodiesel blends · Engine performance · Exhaust emissions

Introduction

The depletion of fossil fuels is one of the issues that pose a major threat to the future generation due to the escalating energy demands over the years and the limited availability of fossil fuel reserves (Day and Day 2017). The burning of fossil fuels is also detrimental to the environment, being a major contributor of the greenhouse effect, global warming, air pollution, smog, and acid rain (Modak et al. 2018). The increasing amounts of air pollutants from vehicle exhaust emissions are hazardous to human health, increasing the number of asthmatic patients and aggravating the conditions of patients suffering from chronic respiratory diseases, such as emphysema (Drakaki et al. 2014). Hence, much effort has been made to develop cleaner alternative fuels in order to fulfill the escalating energy demands while simultaneously reduce harmful exhaust emissions to the environment.

Biodiesels are one of the alternative fuels to fulfill this need, and these fuels have been in use since the 1930s. Biodiesels are appealing substitutes for diesel because these fuels can be produced from a variety of renewable and sustainable feedstocks, ranging from edible oils, such as soybean, sunflower, and corn oils, to non-edible ones, such as *Jatropa curcas*, *Moringa oleifera*, and *Calophyllum inophyllum* oils. Biodiesels can also be produced from animal fats, algae (macroalgae and microalgae), and waste cooking oils (Ahmad et al. 2011). Biodiesels can be used directly in diesel engines without modifications. More importantly, biodiesels can be blended with other fuels in order to improve the physicochemical properties of the fuel, enhance engine performance, and reduce exhaust emissions of diesel engines (Alptekin et al. 2015; Najafi 2018). It is no

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wonder that biodiesels remain one of the significant alternative fuels to this day.

At present, there are six key areas of biodiesel research as follows: (1) exploration of various types of feedstocks for biodiesel production (edible plant-based oils, non-edible plant-based oils, animal fats, waste cooking oils, and algae) and particular attention has been given to reduce the usage of edible oils for biodiesel production because these oils are more suited for food production (Đurišić-Mladenović et al. 2018; Mazivila 2018); (2) development of techniques to reduce the free fatty acid content and acidity of the feedstocks, such as degumming, purification, acid-catalyzed esterification, and optimization methanol molar ratio (Eze et al. 2018; Wang et al. 2017); (3) development of biodiesel production processes, such as microwave irradiation-assisted transesterification and infrared radiation-assisted transesterification in order to boost biodiesel yields (Milano et al. 2018); (4) optimization of the biodiesel production process parameters (alcohol-to-oil molar ratio, reaction temperature, reaction time, and stirring speed) by modeling techniques, such as artificial neural networks (ANN), ant colony optimization (ACO), kernel extreme learning machine (K-ELM), and response surface methodology (RSM), in order to maximize biodiesel yields (Kusumo et al. 2017; Moradi et al. 2013); (5) improvement of the physicochemical properties (e.g., kinematic viscosity, density, flash point, acid value, oxidation stability, and calorific value) and cold flow properties (cloud point, pour point, and cold filter plugging point) by blending biodiesel with other types of biodiesels, bioethanols, biooils, waste-to-liquids (WTLs), gas-to-liquids (GTLs), and nano-additives; and (6) improving the engine performance (brake-specific fuel consumption (BSFC), brake power (BP), brake thermal efficiency (BTE), engine torque (ET), and exhaust gas temperature (EGT)) and exhaust emission characteristics (carbon monoxide (CO), carbon dioxide (CO_2), nitrogen oxide (NO_x), total unburned hydrocarbons (THC), soot, and particulate matter (PM)) of diesel engines—this can be done by formulating different biodiesel blends, modifying the geometry of the combustion chamber, modifying the injection timing (IT) and compression ratio (CR), installing exhaust aftertreatment systems, such as exhaust gas recirculation (EGR) systems, selective catalytic reduction (SCR) systems, catalytic converters, and diesel particulate filters (DPFs), as well as installing low-temperature combustion technologies.

Many studies have been carried out on biodiesels and their blends over the years, with a large number of papers published each year. A large number of review papers have also been published in the scientific literature, focusing on various aspects of biodiesel research. The recent review papers include biodiesel production from waste chicken fats and used cooking oils, recent developments of enzymatic hydroesterification (Pourzolfaghar et al. 2016; Zenevicz et al. 2017), in situ transesterification, and biomass-derived heterogeneous catalysts for biodiesel production, comparative analysis of various types of antioxidants in order to enhance the oxidation stability of biodiesels, and the use of ionic liquids as catalysts and solvents for biodiesel production and purification.

Nowadays, the automotive industry is geared toward reducing harmful vehicle exhaust emissions due to stringent environmental regulations and policies while at the same time, improving engine performance. One of the ways is to reduce the combustion temperature (Agarwal et al. 2017), which will reduce NO_x emissions—pollutants that are known to be the contributors of PM, smog, acid rain, and tropospheric ozone. There are recent reviews regarding the engine performance and exhaust emission characteristics of diesel engines; however, these reviews pertain to diesel engines fueled with biodiesels produced from a single feedstock or a specific group of biodiesel blends (e.g., biodiesel–alcohol blends) and the effect of biodiesels and their blends on a single exhaust emission characteristic, such as PM. To the best of the authors' knowledge, there are no recent reviews concerning the engine performance and exhaust emission characteristics of diesel engines fueled with various types of biodiesel blends and the latest developments in emission-reduction technologies. With the ever-increasing number of papers related to biodiesels and their blends published each year, it can be daunting to sift through the abundant literature to identify the papers relevant to this topic. With this in mind, in this paper, a brief review is presented on the key studies pertaining to the engine performance and exhaust emission characteristics of diesel engines fueled with various types of biodiesel blends (biodiesel blends produced from single and multiple feedstocks, blends in which biodiesels are mixed with biooils, WTLs, GTLs, and nano-additives, and biodiesel–alcohol blends). The recent developments of the methods used to reduce vehicle exhaust emissions, such as modifying the IT and CR and installing exhaust aftertreatment systems (specifically, EGR systems and DPFs), and low-temperature combustion technologies are also presented.

The rest of this paper is organized as follows. The "Diesel engines fueled with biodiesel blends" section is focused on a comparative analysis of the engine performance and exhaust emission characteristics of diesel engines fueled with various biodiesel blends. The discussion is centered on the following engine performance parameters (i.e., BSFC, BP, BTE, and ET) and exhaust emission parameters (i.e., CO, NO_x, and THC). A brief discussion on the effects of CR and IT on the engine performance and exhaust emissions of diesel engines fueled with biodiesels and biodiesel blends is also given in the "Optimization of injection timing, ignition delay, and compression ratio" section. The "Exhaust aftertreatment systems of diesel engines" section is focused on the key studies related to the use of exhaust aftertreatment systems in order to reduce the exhaust emissions of diesel engines. The

"Low-temperature combustion technology" section is focused on a brief description on the low-temperature combustion technology. The findings of the key studies reviewed in this paper are presented in tabular form, which will greatly facilitate scientists involved in biodiesel research as well as engine manufacturers to obtain quick information on the engine performance and exhaust emission characteristics for various biodiesel blends.

Diesel engines fueled with biodiesel blends

Biodiesel–diesel blends

Scientists and researchers have explored a variety of feedstocks for biodiesel production including waste cooking oils. The significant discoveries made through years of experimentation have led to the establishment of waste-to-wealth biodiesel production. Nowadays, biodiesels can be produced from inexpensive, readily available feedstocks, such as waste cooking oils, vegetable oils, yellow grease, and algae (Kusumo et al. 2017; Silitonga et al. 2017). Biodiesel production from waste cooking oils is indeed one of the strategies that can help reduce environmental impact since the waste cooking oils are reused to create a useful product. This strategy helps minimize the disposal of waste cooking oils into the landfill and reduce costs associated with waste disposal.

The changes in the engine performance and exhaust emission parameters of diesel engines fueled with a variety of biodiesel blends relative to those for diesel are summarized in Table 1. It shall be noted that the findings presented in this table pertain to biodiesels produced from a single feedstock. The changes in the physicochemical properties of the first-generation and second-generation biodiesels relative to those for diesel are also presented, and it can be seen that biodiesels have lower calorific values and higher kinematic viscosities, densities, flash points, and cetane numbers compared with diesel.

Indeed, the changes in the physicochemical properties of the biodiesels influence the performance parameters of diesel engines. According to Rahman et al. (2014b), the brake power is slightly higher when the diesel engine is fueled with *M. oleifera* biodiesel compared with *J. curcas* biodiesel with a difference of 1% because of its higher calorific value. Calorific value is not the only property that affects the engine fuel consumption, but also kinematic viscosity. For example, palm oil biodiesel has a lower calorific value by 14.4% compared with diesel, and therefore, the fuel consumption is higher for the diesel engine fueled with palm oil biodiesel by 10% (Sharon et al. 2012). This is indeed expected because palm oil is four times more viscous than crude palm oil, and the biodiesels produced from these oils result in similar fuel consumption even though there are differences in the calorific value. In addition, biodiesels result in higher BP compared with diesel, but this comes at the expense of higher BSFC (Malvade and Satpute 2013; Özener et al. 2014; Yusaf et al. 2011). There is a close relationship between the fuel consumption and kinematic viscosity, where a lower kinematic viscosity increases fuel atomization which will enhance fuel mixing and promotes complete combustion (Tan et al. 2013). A high kinematic viscosity increases heat losses due to friction, which deteriorates the combustion process (Ong et al. 2011; Wirawan et al. 2008).

The flash point is significantly higher for the palm methyl ester compared with that for diesel, with a remarkable difference of 130.7%. The higher flash point indicates that it is generally safer to handle, transport, and store the palm methyl ester because the higher flash point reduces the risk of fire hazards (Carareto et al. 2012). The BSFC of the palm methyl ester is higher than that for diesel by 2.6–14.5%, depending on the percentage volume of palm methyl ester in the blend. This is indeed undesirable because a higher BSFC indicates that more fuel is consumed to produce a unit of BP. The BTE of the palm methyl ester is also slightly lower than that for diesel by 0.3–2.2% (Sharon et al. 2012). In general, a higher BTE is desirable because this indicates that most of the energy in the fuel burned is converted into mechanical energy which drives the crankshaft in the diesel engine.

One of the advantages of biodiesels is the high oxygen content of these fuels, which will reduce CO emissions (Nabi et al. 2017; Rahman et al. 2014b). For instance, mixing 10% of *J. curcas* biodiesel with 90% of diesel and mixing 10% of *M. oleifera* biodiesel with 80% of diesel reduces CO emissions by 14% and 11%, respectively, compared with pure diesel, which can be attributed to the higher oxygen content of biodiesels (Rahman et al. 2014a; Sharon et al. 2012). In addition, the engine load and percentage volume of biodiesel in the fuel blend influence the CO emissions. In general, a lower engine load and higher percentage volume of biodiesel in the blend reduces CO emissions (An et al. 2012; Sharon et al. 2012). According to Omidvarborna et al. (2016), the degree of unsaturation in the biodiesel and a higher degree of long fatty acid chains in the methyl ester affect the CO emissions. In general, methyl esters with shorter fatty acid chains tend to have a lower degree of unsaturation and higher oxygen-to-carbon ratios (Omidvarborna et al. 2016).

THC result from incomplete fuel combustion due to the formation of carbon deposits and clogging of fuel injectors resulting from the high kinematic viscosity of the fuel (Liaquat et al. 2013). It can be seen from Table 1 that biodiesel blends generally produce lower THC compared with diesel, depending on the type of biodiesel and the percentage volume of biodiesel in the blend. This is probably due to the higher oxygen content of biodiesels, which improves the combustion quality. It is found in one study that pure rubber seed biodiesel with higher kinematic viscosity produces higher THC

Table 1 Changes in the engine performance and exhaust emission parameters of diesel engines fueled with various biodiesel blends relative to those for diesel. The biodiesels are produced from a single feedstock. Note that the changes in the physicochemical properties of the biodiesels relative to those for diesel are also included for comparison

Feedstock	Crude palm oil	Used palm oil	Rapeseed oil	Soybean oil	Crude rubber seed oil	*Jatropha curcas* oil	*Moringa oleifera* oil	*Calophyllum inophyllum* oil
Biodiesel	Palm methyl ester	Palm methyl ester	Rapeseed methyl ester	Soybean methyl ester	Rubber methyl ester	*Jatropa curcas* methyl ester	*Moringa oleifera* methyl ester	*Calophyllum inophyllum* methyl ester
• Calorific value	− 14.4%	− 5.9%	− 8.3%	− 13.2%	− 11.2%	− 12.1%	− 11.5%	− 9.6%
• Kinematic viscosity	+ 25.0%	+ 109.4%	+ 155.8%	+ 818.6%	+ 918.7%	+ 46.4%	+ 56.4%	+ 16.9%
• Density	+ 2.3%	–	+ 374.1%	–	–	–	–	–
• Flash point	+ 96.0%	+ 130.7%	–	–	+ 296.0%	+ 169.3%	+ 119.7%	+ 134.7%
• Cetane number	+ 6.0%	+ 30.4%	+ 20.0%	+ 21.3%	–	–	+ 17.3%	+ 19.7%
Type of biodiesel	First-generation biodiesel	First-generation biodiesel	First-generation biodiesel	First-generation biodiesel	Second-generation biodiesel	Second-generation biodiesel	Second-generation biodiesel	Second-generation biodiesel
Percentage volume of biodiesel blended with diesel (sample)	25% (PO25) 50% (PO50) 75% (PO75)	25% (PO25) 50% (PO50) 75% (PO75) 100% (PO100)	100% (R100)	100%(S100)	20% (RSB20) 40% (RSB40) 60% (RSB60) 80% (RSB80) 100% (RSB100)	10% (JB10)	10% (MB10)	10% (CIB10) 20% (CIB20) 30% (CIB30) 50% (CIB50)
Engine	Perkins 4–108 V diesel engine	Kirloskar TV1 diesel engine	–	–	Canon four-stroke diesel engine	Mitsubishi Pajero diesel engine	Mitsubishi Pajero diesel engine	Yanmar TF120M diesel engine
No. of cylinders	4	–	4	4	–	4	4	1
Engine performance								
• BP	PO25: − 7.5% PO50: − 2.5% PO75: + 2.5%	–	R100: − 2.5%	S100: − 5.3%	–	JB10: − 4.9%	MB10: − 4.2%	–
• ET	PO25: − 8.5% PO50: − 4.3% PO75: + 2.1%	–	R100: − 3.14%	S100: − 6.30%	–	–	–	–
• BSFC	PO25: + 8.0% PO50: + 9.0% PO75: + 10.0%	PO25: + 2.6% PO50: + 8.9% PO75: + 9.3% PO100: + 14.5%	R100: + 13.2%	S100: + 21.5%	RSB20: − 1.9% RSB40: − 1.2% RSB60: + 0.8% RSB80: + 16.3% RSB100: + 16.3%	JB10: + 3.4%	MB10: + 5.2%	CIB10: − 3.5% CIB20: + 14.7% CIB30: + 30.7% CIB50: + 43.4%
• BTE	–	PO25: − 0.3% PO50: − 1.7% PO75: − 1.3% PO100: − 2.2%	–	–	RSB20: + 2.9% RSB40: 0.0% RSB60: + 8.6% RSB80: + 2.9% RSB100: + 8.6%	–	–	CIB10: + 0.8% CIB20: − 0.1% CIB30: − 1.3% CIB50: − 1.9%
Exhaust emissions								
• CO	B25: + 82.6% B50: − 1.7%	PO100: − 52.9%	R100: − 22.2%	S100: − 44.4%	–	JB10: − 14.0%	MB10: − 11.0%	CIB10: − 5.0% CIB20: + 5.7%

Table 1 (continued)

Feedstock	Crude palm oil	Used palm oil	Rapeseed oil	Soybean oil	Crude rubber seed oil	*Jatropha curcas* oil	*Moringa oleifera* oil	*Calophyllum inophyllum* oil
	B75: − 17.4%	PO75: − 35.2% PO50: − 35.2% PO25: − 21.4%						CIB30: + 9.2% CIB50: + 12.2%
• THC	–	PO25: + 9.3% PO50: − 9.5% PO75: − 19.1% PO100: − 38.1%	–	–	–	JB10: − 16.0%	MB10: − 12.0%	–
• NO_x	B25: − 1.8% B50: − 5.4% B75: − 7.3%	PO25: + 10.0% PO50: + 8.0% PO75: + 4.0% PO100: + 6.7%	R100: + 12.0%	S100: + 28.0%	–	JB10: + 7.0%	MB10: + 7.0%	CIB10: + 7.2% CIB20: + 14.2% CIB30: + 19.2% CIB50: + 25.2%
References	Yusaf et al. (2011)		Çelikten et al. (2010)	Çelikten et al. (2010)	Ramadhas et al. (2005)	Rahman et al. (2014b)	Rahman et al. (2014b)	Ong et al. (2014)

(+) Increase in parameter relative to that for diesel

(−) Decrease in parameter relative to that for diesel

compared with diesel, with a difference of 27.78% (Ramadhas et al. 2005). In contrast, the JB10 blend (10% *J. curcas* biodiesel + 90% diesel) and MB10 blend (10% *M. oleifera* + 90% diesel) reduce the THC by 16% and 12%, respectively, relative to diesel (Rahman et al. 2014b). According to Mofijur et al. (2013), the higher oxygen content of biodiesels as well as higher combustion temperature result in higher NO_x emissions. However, the poor oxygen content during biodiesel combustion leads to the generation of soot because the oxygen atoms present in the biodiesel contribute to the oxidation of soot (Jiaqiang et al. 2016b).

Mixed biodiesel–diesel blends

Blending biodiesels produced from edible and non-edible feedstocks has gained much interest in recent years as scientists and researchers strive to enhance the physicochemical properties of biodiesel blends as well as produce biodiesel blends that are more cost-effective. These biodiesels are known as mixed biodiesels. Indeed, blending different types of biodiesels is one of the ways to enhance the engine performance and exhaust emission characteristics of diesel engines and reduce the dependency on fossil fuels and edible oils for fuel production (Atabani et al. 2013, Damanik et al. 2017).

The changes in the engine performance and exhaust emission parameters of diesel engines fueled with various mixed biodiesel–diesel blends are summarized in Table 2. The changes in the physicochemical properties of these blends are also presented for comparison. In general, the total percentage volume of biodiesels used in these blends is not more than 30%. It is apparent from Table 2 that the calorific value, kinematic viscosity, density, flash point, and cetane number are influenced by the type of biodiesels used in the blend. Increasing the percentage volume of mixed biodiesel results in higher kinematic viscosity, density, flash point, and cetane number of the fuel blend. For example, the kinematic viscosity of the coconut–palm biodiesel–diesel blend increases by 12.4% relative to that for diesel whereas this increase is slightly lower for the palm–*J. curcas* biodiesel blend (10% palm biodiesel + 10% *J. curcas* biodiesel + 80% diesel), with a value of 10.2%. This offers insight on how the fuel composition affects its physicochemical properties, as well as combustion and exhaust emission characteristics of the diesel engine. For example, the kinematic viscosity of biodiesels is influenced by the proportion of the saturated and unsaturated fatty acid methyl esters in the biodiesel. On one hand, high amounts of saturated fatty acid methyl esters, such as C16:0, C18:0, and C18:1 (fatty acid methyl esters with single double bonds), will increase the kinematic viscosity of the biodiesel (Jiaqiang et al. 2016c). On the other hand, high amounts of unsaturated fatty acid methyl esters, such as C18:2 and C18:3, will reduce the kinematic viscosity of the biodiesel, which improves fuel–air mixing and combustion characteristics of diesel engines

Table 2 Changes in the engine performance and exhaust emission parameters of diesel engines fueled with various mixed biodiesel–diesel blends. Note that the changes in the physicochemical properties of the biodiesels relative to those for diesel are also included for comparison

Fuel blend	Hazelnut–canola biodiesel–diesel blend	Hazelnut–canola biodiesel–diesel blend	Coconut–palm biodiesel–diesel blend	Palm–*Jatropha curcas* biodiesel–diesel blend	Palm–*Jatropha curcas* biodiesel–diesel blend
Blending composition	1% hazelnut biodiesel + 4% canola biodiesel + 95% diesel	2% hazelnut biodiesel + 8% canola biodiesel + 90% diesel	15% coconut biodiesel + 15% palm biodiesel + 70% diesel	5% palm biodiesel + 5% *Jatropha curcas* biodiesel + 90% diesel	10% palm biodiesel + 10% *Jatropha curcas* biodiesel + 80% diesel
• Calorific value	− 0.4%	− 0.9%	− 4.1%	− 1.3%	− 2.8%
• Kinematic viscosity	+ 3.3%	+ 6.6%	+ 12.4%	+ 3.3%	+ 10.2%
• Density	+ 0.4%	+ 0.7%	+ 1.3%	+ 0.5%	+ 0.8%
• Flash point	–	–	+ 5.9%	+ 3.5%	+ 27.5%
• Cetane number	+ 0.5%	+ 0.9%	–	0.0%	+ 2.1%
Engine	Antor 6LD400	Antor 6LD400	Yanmar TF120M	Yanmar TF120M	Yanmar TF120M
No. of cylinders	1	1	1	1	1
CR	18:1	18:1	–	17.7:1	17.7:1
IT	–	–	–	17°BTDC	17°BTDC
Engine performance	–	–			
• BP	–	–	− 4.2%	− 7.3%	− 10.9%
• ET	–	–	− 4.1%	–	–
• BSFC	*	+ 3.3%	+ 8.6%	+ 7.6%	+ 19.8%
• BTE	+ 0.3%	− 2.9%	− 3.9%	–	–
Emission					
• CO	*	0.0%	− 15.8%	− 9.5%	− 20.5%
• THC	*	10.0%	− 25.9%	− 3.7%	− 7.8%
• NO_x	*	− 1.7%	+ 4.5%	+ 2.8%	+ 6.8%
References	Öztürk (2015)	Öztürk (2015)	Habibullah et al. (2014)	Sanjid et al. (2014)	Sanjid et al. (2014)

(+) Increase in parameter relative to that for diesel

(−) Decrease in parameter relative to that for diesel

(*) Similar in value relative to that for diesel

(Jiaqiang et al. 2016c; Knothe and Steidley 2005). According to Liu et al. (2016), the increase in double-bond species in the biodiesel improves the combustion characteristics, shortens ignition delay, and reduces NO_x emissions. Hellier et al. (2013) found that the order of ignition delay (from shortest to longest) of the isomers is as follows: (1) 1-octene, (2) cis-3-octene, (3) trans-3-octene, and (4) trans-2-octene. The order of ignition delay is influenced by the double bonds and alkene position of the isomers. The longer ignition delay of trans-2-octene compared with trans-3-octene indicates that there is greater net reactivity of the saturated alkyl portions of the latter molecule (Hellier et al. 2013). The NO_x emissions are reduced when the ignition timing is slightly retarded (Sivasubramanian 2017).

It has been proven that blending biodiesels produced from different feedstocks improves the fatty acid methyl ester composition of the fuel blend. For example, biodiesel produced from a mixture of *C. inophyllum* and palm oils increases the percentage of saturated fatty acid methyl esters in the biodiesel (Damanik et al. 2017). It is shown that a higher percentage of saturated fatty acid methyl esters improves the oxidation stability of biodiesels (Botella et al. 2014; Neff and List 1999).

Flash point is the lowest temperature at which the vapors of a material will ignite in the presence of an ignition source (Gülüm and Bilgin 2015). Flash point is associated with the vapor pressure of a flammable liquid to form a combustible mixture with air (Carareto et al. 2012). Hence, blends with high capability to form combustible mixtures with air (i.e., high flash points) will significantly enhance engine performance. It can be seen from Table 2 that for the same type of diesel engine, the BSFC is different for the palm–*J. curcas* biodiesel–diesel blend and coconut–palm biodiesel–diesel blend. For example, the BSFC of the palm–*J. curcas* biodiesel–diesel blend (10% palm biodiesel + 10% *J. curcas* biodiesel + 80% diesel) is higher by 9.8% relative to the BSFC for diesel. The BSFC of the coconut–palm biodiesel–diesel blend (15% palm biodiesel + 15% *J. curcas* biodiesel + 70% diesel) is higher by 8.6% compared with that for diesel (Habibullah et al. 2014; Sanjid et al. 2014). This indicates that the coconut–palm biodiesel–diesel blend improves the engine performance because of the lower BSFC. In addition, the coconut–palm biodiesel–diesel blend results in lower CO and THC with a significant reduction of 15.8% and 25.9% relative to those for diesel. This indicates that this fuel blend reduces harmful exhaust emissions, though the NO_x emissions are slightly higher compared with those for diesel, with a difference of 4.5%.

Öztürk (2015) found that increasing the percentage volume of hazelnut–canola biodiesel increases the kinematic viscosity and density of the fuel blend. This is evident from Table 2 since the kinematic viscosity and density increase by 6.6% and 0.7% for the hazelnut–canola biodiesel–diesel blend (2% hazelnut biodiesel + 8% canola biodiesel + 90% diesel) relative to those for diesel. In contrast, the kinematic viscosity and density increase by 3.3% and 0.4% for the blend containing 1% of hazelnut biodiesel and 4% of canola biodiesel, respectively. However, based on the values, it can be deduced that the differences are minor, indicating that the kinematic viscosities and densities of the hazelnut–canola biodiesel–diesel blends are comparable to those for diesel. In addition, Öztürk (2015) also found that increasing the percentage volume of hazelnut–canola biodiesel increases the BSFC by 3.3% and decreases the BTE by 2.9% compared with those for diesel. The differences in the engine performance parameters between the hazelnut–canola biodiesel–diesel blend and diesel are small, indicating that this blend may be a suitable substitute for diesel. However, the hazelnut–canola biodiesel–diesel blend produces significantly higher THC compared with diesel, which is undesirable.

Sanjid et al. (2014) conducted experiments using a single cylinder engine fueled with palm oil–*J. curcas* biodiesel–diesel (PBJB) blend and they found that there is a significant reduction in the CO emissions by 20.5% compared with those when the diesel engine is fueled with diesel. The CO emissions are due to incomplete combustion of the fuel. This can be compensated by using fuels with high oxygen content (oxygenated fuels) in order to promote complete combustion (Baskar and Senthilkumar 2016; Sanjid et al. 2014).

Biodiesel–diesel–biooil blends

The engine performance and exhaust emissions of internal combustion engines fueled with biooils have also been investigated over the years. It has been shown that the poor combustion characteristics of internal combustion engines fueled with biooils are due to the longer ignition delays (Shihadeh and Hochgreb 2000). However, increasing the percentage of biooil in the blend effectively reduces NO_x emissions (Yang et al. 2014). Laesecke et al. (2017) conducted engine tests on a diesel engine fueled with biodiesel-fast pyrolysis oil (FPO)–diesel blends. Blending biodiesels with biooils is indeed beneficial considering that the fuel blend can be fully produced from renewable sources, which maximizes the benefits of renewable chains (Alcala and Bridgwater 2013). However, the solubility of FPOs in biodiesel is relatively low. According to Garcia-Perez et al. (2010), the addition of volatile and polar compounds can enhance the solubility of FPOs in biodiesels. Blending biodiesels with biooils have been proven to reduce the viscosity, acid number, and water content of biooils. The results obtained from the engine performance tests revealed that the fuel blends result in efficiencies within a range of 75–95% (which are slightly lower than that for diesel) as well as lower particulate matter emissions (41–62%) (Laesecke et al. 2017). The oxygen present in biooils derived from cellulose and hemicellulose improves fuel-mixing rate and results in fuel oxidation (Patel et al. 2018).

Biodiesel–WTL blends

WTL is a product made from non-biodegradable materials using municipal solid waste (MSW) recycling technology. Most non-biodegradable materials are petroleum-based products, such as low-density polyethylene (LDPE), high-density polyethylene (HDPE), polypropylene (PP), polystyrene (PS), polyvinyl chloride (PVC), and polyethylene-terephthalate (PET). PS is widely used because of its low cost, ease of manufacture, and favorable mechanical properties, rendering this material suitable for toys, medical consumables, electronics, food packaging, and construction consumables (Miandad et al. 2017a). Due to its high chemical stability, PS is known to be one of the major landfill pollutants which contribute to the accumulation of plastics in Earth (Savoldelli et al. 2017). Hence, development of WTLs is one of the solutions to handle these non-biodegradable wastes.

At present, there are various technologies used to convert MSWs to WTLs, such as gasification, pyrolysis, refuse-derived fuel (RDF), and plasma arc gasification. Miandad et al. (2017b) used pyrolysis technology to produce WTL products, and they found that the WTL products have high dynamic viscosities (1.77–1.90 mPa s), kinematic viscosities (1.92–2.09 cSt), densities (0.91–0.92 g/cm^3), pour points (− 11 to − 60 °C), freezing points (− 15 to − 65 °C), flash points (28.1–30.2 °C), and higher heating values (41.4–41.8 MJ/kg). The properties of the WTLs are similar to those for diesel (Miandad et al. 2017a). Mixtures of biomass and PS wastes were pyrolyzed at 550–600 °C, and the results showed that the WTLs have low viscosities, high calorific values, and higher aromatic content (Abnisa et al. 2013; Shadangi and Mohanty 2015). The quality of the WTLs is determined by the temperature during the pyrolysis process. The main products obtained from pyrolysis of PS are shown in Table 3. Liu et al. (2000) categorized the pyrolysis products according to the boiling temperature. Advanced products can be developed from the pyrolysis products, as shown in Table 3.

According to Kalargaris et al. (2017), the performance of the engine fueled with WTLs is similar to that for engine fueled with diesel at high engine loads. The BTE is slightly lower for the diesel engine fueled with plastic pyrolysis oil at full load compared with that for diesel-fueled engine. Even though plastic pyrolysis oil is petroleum-based, the use of WTL blends in diesel engine results in higher NO$_x$ emissions compared with diesel (Ayodhya et al. in press; Kalargaris et al. 2017). This is due to the longer ignition delay, and therefore, more fuel is accumulated in the combustion chamber, which increases premixed combustion. This, in turn, increases the heat release rate and in-cylinder temperature (Ayodhya et al. in press; Venkatesan et al. 2017). However, Damodharan et al. (2018) reported that the NO$_x$ emissions decrease up to 52.4% under an EGR rate of 30% when the injection timing of WTL is retarded from 25 to 21°CA BTDC. In advanced fuel injection cases, the combusted fuel stays at high temperature over a longer period until slightly after the gas mixture attains the peak in-cylinder pressure (i.e., before the combusted fuel is cooled by the expansion of gases in the expansion stroke). In advanced fuel injections, premixed combustion of fuel occurs much earlier before the piston reaches the TDC, which increases the resident time of the high-temperature gases. This creates favorable conditions (oxygen availability and high temperature) for the formation of NO$_x$. However, if the injection timing is retarded, this increases the fraction of diffusion combustion, which improves the combustion quality and reduces NO$_x$ emissions. The EGR system also preheats the fresh air, which shortens ignition delay. The NO$_x$ emissions significantly reduce with an increase in the percentage of EGR (Sindhu et al. 2017).

Another reason that may promote NO$_x$ emissions is the higher nitrogen content of the fuel. The fast pyrolysis process was carried out at a high temperature (900 °C), resulting in WTLs with high nitrogen content. The fast pyrolysis process produces an energy output of 30–35% in the gaseous phase and 60–65% in the liquid phase. The gas produced from the fast pyrolysis process is typically composed of methane, hydrogen, nitrogen, CO, and CO$_2$ (Kalargaris et al. 2017).

Studies on WTLs and biodiesels are now underway. Sharma et al. (2014) blended 10% and 50% of pyrolyzed polyethylene hydrocarbons (PPEH) with diesel, labeled as P10 and P50, respectively. They also blended the P10 and P50 samples with 2% and 5% of soybean methyl ester, respectively. The physicochemical properties of the fuel blends prepared in their study are summarized in Table 4. The PPEH (particularly PPEH-L) seems to maintain the higher heating value of the blends, which is likely due to the larger hydrocarbons with higher energy content. The PPEH-L also seems to maintain the cloud point, cold filter plugging point, cetane number, sulfur content, and specific gravity. However, these blends appear to be lacking in terms of oxidation stability, kinematic viscosity, density, and wear scar at 60 °C (Sharma et al. 2014). Overall, it is possible to improve the quality of biodiesels by blending them with WTLs.

Biodiesel–diesel–GTL blends

GTL is a synthetic liquid fuel produced from natural gas through the Fischer-Tropsch process. These synthetic liquids are primarily composed of long-chain paraffin molecules and contain negligible amounts of polyaromatics and sulfur. It is shown in one study that GTLs have high cetane number, zero sulfur content, high lower heating value, and low kinematic viscosity (Moon et al. 2010). GTL–biodiesel blends have also been used in diesel engines in order to determine the potential of these fuels in reducing exhaust emissions. It is found that direct injection engine fueled with GTL–biodiesel blends have lower NO$_x$, THC, and CO emissions compared with

Table 3 Main products obtained from pyrolysis of polystyrene

No	Process temperature	Pyrolysis products	Advanced products
1	Low fraction boiling point (boiling point ≤ 200 °C)	Benzene (C_6H_6)	Gasoline component (Aranda et al. 2010)
		Toluene (C_7H_8)	Gasoline component, solvent (Aranda et al. 2010)
		Ethyl benzene ($C_6H_5CH_2CH_3$)	Gasoline, solvent (Aranda et al. 2010)
		Xylene (C_8H_{10})	Coke fuel, solvent (Aranda et al. 2010)
		Styrene (monomer) ($C_6H_5CH{=}CH_2$)	Plastic and resins
		α-Methylstyrene	Plastic and resins
		Others	
2	Medium fraction boiling point (200 °C < boiling point ≤ 350 °C)	1,2-Diphenylethane	
		1,3-Diphenylpropane	
		2,4-Diphenyl-1-butene (dimer)	
		2,4- Diphenyl-1-pentene	
		Others	
3	High fraction boiling point (boiling point > 350 °C)	2,4,6-Triphenyl-1-hexene (trimer)	
		Others	

diesel-fueled engine (Moon et al. 2010; Rounce 2011; Sajjad et al. 2014). However, it is worth noting that GTLs are derived from natural gas, which is a form of fossil fuel.

Biodiesel–alcohol blends

Biodiesels have higher kinematic viscosities compared with diesel, which is proven from the results shown in Table 1 and Table 2. Higher fuel kinematic viscosity is highly undesirable since this will reduce combustion quality and result in clogging of the fuel injectors in the long term. The higher kinematic viscosities of biodiesels can be compensated by blending biodiesels with alcohols such as methanol, ethanol, and n-butanol (Ali et al. 2014; Lapuerta et al. 2017). Blending with ethanol will significantly reduce the kinematic viscosity of the fuel blend compared with n-butanol, which is due to the short-reactive carbon chains of ethanol. According to Dharma et al. (2016), the kinematic viscosities decrease to less than 2 cSt in 40% of ethanol–diesel and biodiesel–ethanol blends. Moreover, alcohol-containing fuels increase the heat capacity of combustion products, which reduces the combustion temperature and slows down the oxidation process, resulting in lower CO emissions. Datta and Mandal (2017) found that the palm biodiesel–surfactant–ethanol blends and palm biodiesel–methanol blends result in higher BTE and lower NO_x emissions compared with neat biodiesel. The surfactant reduces the surface tension between the water and oil, maximizing their superficial contact area and activating their surface (DeFries et al. 2004). The combustion efficiency is also improved while the emissions decrease due to micro-explosions when emulsified fuel is used (Lin and Lin 2007). Tests conducted on a spark ignition engine fueled with alcohol–gasoline mixtures also revealed that there was a reduction in CO, NO_x, and THC. The addition of water–alcohol mixtures to liquid hydrocarbon fuels has been proven to reduce NO_x emissions (Rajan 1984).

Biodiesels with nano-additives

In recent years, nano-additives are used in various applications, such as catalysts, sensors, semiconductors, capacitors, batteries, and nanomedicine (Piriyawong et al. 2012). According to Moy et al. (2001), nano-additives enhance the burning rate, reduce knocking, increase fuel viscosity, and make the fuels conductive. Conductivity is an important property because it indicates the ability of the fuel to dissipate static electrical charges. A fuel with low conductivity is highly undesirable because static electrical charges can accumulate in the fuel, which may lead to unexpected sparks. Hence, the presence of nano-additives enhances the conductivity of the fuels, which helps reduce fire hazards. In essence, nano-additives are materials with a particle size less than 100 nm. The significant differences between the properties of nano-additives and those of bulk materials are primarily due to the high relative surface area as well as quantum effects. The high surface-to-volume ratios of nano-additives make these materials favorable for chemical reactions. The properties of nano-additives, such as reactivity, strength, and electrical properties, can be tailored to fulfill a particular application by varying the surface-to-volume ratios of nano-additives (Chaturvedi et al. 2012).

For these reasons, scientists and researchers are now working on improving the thermo-physical properties of fuels, such as thermal conductivity, mass diffusivity, and

Table 4 Physicochemical properties of PPEH blends (Sharma et al. 2014)

	Units	ASTM D975	EN 590	Diesel	Low temperature		High temperature		SME	PPEH-L		PPEH-H		ULSD	
					P10	P50	P10	P50	(B100)	B2	B5	B2	B5	B2	B5
Low temperature															
Cloud point	°C	–	–	− 17.5	− 15.9	− 20.7	− 12.4	− 3.7	0.3	− 28.5	− 26.8	4.6	4.0	− 16.0	− 14.1
Pour point	°C	–	–	− 20.3	− 25.3	− 31.3	− 17.0	− 5.3	− 1.7	− 36.7	− 35.7	4.4	3.3	− 23.0	− 24.3
Cold filter plugging point	°C	–	–	− 16.0	− 17.7	− 26.0	–	–	–	–	–	–	–	–	–
Oxidation stability															
Induction period at 110 °C	h	–	≥ 20	≥ 24	16.5	6.3	21.1	10.3	4.6	3.9	3.9	4.6	6.4	19.7	18.1
Oxidation onset temperature	°C	–	–	196.2	194.9	183.0	194.7	192.0	175.4	174.8	176.5	189.9	186.5	195.6	193.7
Kinematic viscosity at 40 °C	mm^2/s	1.9–4.1	2.0–4.5	2.3	2.1	1.6	2.3	2.6	4.1	1.2	1.3	2.9	2.9	2.3	2.3
Cetane number		≥ 40	≥ 51	47.4	48.4	51.4	48.9	59.3	–	–	–	–	–	–	–
Flash point	°C	≥ 52	≥ 55	65.0	54.0	32.0	65.5	69.0	–	–	–	–	–	–	–
Wear scar at 60 °C	μm	≤ 520	≤ 460	581	538	422	503	256	152	267	201	177	173	247	231
Sulfur content	ppm	≤ 15	≤ 10	8	8	5	8	5	–	–	–	–	–	–	–
Specific gravity at 15 °C		–	–	0.841	0.834	0.809	0.838	0.823	–	–	–	–	–	–	–
Density at 15 °C	kg/m^3	–	820–845	840	834	809	837	822	–	–	–	–	–	–	–
Moisture content	ppm	–	≤ 200	49	55	79	40	60	–	–	–	–	–	–	–
Higher heating value	MJ/kg	–	–	45.15	45.22	45.56	45.19	46.03	–	–	–	–	–	–	–

surface-to-volume ratio of fuels by adding nano-additives (Hosseini et al. 2017). The findings of some studies pertaining to the effects of adding nano-additives, such as aluminum oxide (Al_2O_3), carbon nanotubes (CNTs), and hybridized nano-cerium oxide-multi-walled carbon nanotubes (CeO_2-MWCNTs), into biodiesels on the engine performance and exhaust emission characteristics of diesel engines are summarized in Table 5.

It is evident from Table 5 that the addition of nano-additives alters the engine performance and exhaust emission characteristics of diesel engines. For example, the addition of MWCNTs into the jojoba oil methyl ester results in lower BSFC and higher BTE compared with diesel. In addition, the presence of MWCNTs in the jojoba oil methyl ester results in lower NO_x, CO, and HC. It can also be seen that the addition of CNTs into the *J. curcas* methyl ester emulsion fuel results in higher BTE as well as lower NO_x emissions and smoke opacity. This is likely due to the enhancement of the cetane number of the fuel upon the addition of CNTs, which reduces ignition delay. When the *J. curcas* methyl ester emulsion fuel blended with CNTs is exposed to high pressure and temperature in the combustion chamber, the water droplets dispersed within the fuel absorb heat quickly due to the low boiling point of water. This increases the spray jet momentum of the fuel, which induces intense secondary atomization, as shown in Fig. 1 (Basha and Anand 2011b; Sadhik Basha and Anand 2014).

Optimization of injection timing, ignition delay, and compression ratio

As mentioned previously, one of the key areas in biodiesel research is to enhance engine performance and reduce exhaust emissions of diesel engines, and this can be achieved by formulating biodiesel blends with favorable physico-chemical properties. However, the performance of diesel engines and the exhaust emissions can also be reduced by optimizing IT and CR of diesel engines. It has been proven that these parameters have a significant effect on the BSFC, BTE, and EGT of diesel engines (Raheman and Ghadge 2008; Saleh 2009).

According to Debnath et al. (2013), CR and IT are important parameters that influence the thermal efficiency of internal combustion engines. The effects of CR and IT on the BSFC, BTE, and EGT of diesel engines fueled with various types of fuel are shown in Table 6. Based on the data, it can be deduced that the BTE is highest when the diesel engines are operating at full load. The BTE increases whereas the BSFC and EGT decrease with an increase in IT and CR for the MB-diesel blend (Al-Shemmeri and Oberweis 2011; Hirkude and Padalkar 2014). It can be seen that the BSFC, BTE, and EGT are 280 g/kWh, 33% and 280 °C, respectively, for the diesel engine fueled with WIP at full load. However, the BSFC increases drastically to 710 g/kWh whereas the BTE and EGT decrease significantly to 1% and 80 °C, respectively, when the diesel engine runs at low loads despite the fact that the IT and CR are maintained at 20°BTDC and 18:1. The results obtained for the WIP are comparable to those for diesel (except for the EGT) even though the diesel engine is run at a slightly lower CR (17.5:1) and the IT is slightly higher (23°BTDC). The retardation of IT from 23 to 20°BTDC and the slight increase in CR from 17.5:1 to 18:1 which reduce the clearance volume of the piston and cylinder showed a short compression stroke (Debnath et al. 2013). However, the IT and CR are also dependent on the block cylinder volume and fuel characteristics. It has been shown that the ignition delay is shortened when the diesel engine is fueled with biodiesel with high kinematic viscosity, low volatility, and high cetane number (El_Kassaby and Nemit_allah 2013; Raheman and Ghadge 2008). In some cases, even though the efficiency increases after resetting the CR and IT, the EGT also increases, which may initiate the formation of NO_x (Al-Shemmeri and Oberweis 2011; Hirkude and Padalkar 2014).

In cold climate regions, there is a significant increase in the fuel consumption and CO and THC emissions of diesel engines (Weilenmann et al. 2009). This is indeed common because it is difficult reach the ignition temperature due to the cold weather, making engine starts difficult. A number of studies have been carried out in recent years to investigate the performance of diesel engines under cold start conditions at low ambient temperatures. This includes optimizing the nozzle geometry, formulating fuel blends with improved cold flow properties, and developing cold flow improvers and preheat systems. Deng et al. (2018) observed that the longest preheat time is 10 s longer than the shortest warm-up time, which can directly increase the intake temperature. The cold start-voltage decreases by 15% as the temperature decreases by 9.5 °C, indicating that the cold-start voltage tends to decrease with a decrease in the ambient temperature. The cold-start duration is increased by 1.67 s when the temperature decreases from − 16 to − 25.5 °C (Deng et al. 2018).

Exhaust aftertreatment systems of diesel engines

Exhaust gas recirculation

It is known that biodiesels have higher oxygen content, which improves combustion quality. However, this comes at the expense of higher NO_x emissions. For this reason, some diesel engines are designed with EGR systems which recirculate a certain proportion of the exhaust gas into the intake manifold. Since exhaust gas is used instead of fresh air, this reduces the

Table 5 Effects of adding nano-additives in biodiesels on the engine performance and exhaust emissions of diesel engines

Nanoparticles	Al_2O_3	CNTs	Hybridized CeO_2-MWCNTs	MWCNTs	Al_2O_3
Manufacturer	Alfa Aesar, USA	NIT Trichy, India[a]	RIPI, Iran[b]	Arkema, France	US Research Nanomaterial, Inc., USA
Year	2011	2014	2014	2017	2017
Mean particle size	51 nm	16 nm	Diameter: 7–20 nm Length: 5–15 µm	Diameter:10–15 nm Length: 1–10 µm	50 nm
Surface area	32 m^2/g	672 m^2/g	–	~ 350 m^2/g	–
Purity	–	–	–	> 90%	99%
Appearance	White powder	Black powder	–	Black powder	White powder
Density	–	–	–	~ 0.05–0.17 g/cm^3	–
Thermal conductivity	–	–	–	~ 3000 W/m K	–
Mechanical conductivity	–	–	–	~ 1000 GPa	–
Base fluid	*Jatropha curcas* methyl ester	*Jatropha curcas* methyl ester	Waste cooking oil methyl ester	Jojoba oil methyl ester	Waste cooking oil methyl ester
Process	Emulsification	Emulsification	–	–	–
Results	• Higher cylinder peak pressure at full load • Higher BTE • Lower NO_x and smoke opacity	• Higher BTE • Lower NO_x and smoke opacity	• Higher BP and ET • Lower BSFC • Lower hazardous pollutants (NO_x, CO, HC, and soot)	• Lower BSFC • Higher BTE • Higher cylinder pressure, maximum pressure rise, and heat release rate • Lower NO_x, CO, and HC	• Higher BP and ET • Lower BSFC • Lower CO and HC • Higher NO_x and EGT
References	Basha and Anand (2011a)	Sadhik Basha and Anand (2014)	Mirzajanzadeh et al. (2015)	El-Seesy et al. (2017)	Hosseini et al. (2017)

[a] National Institute of Technology, Tiruchirappalli, India

[b] Research Institute of Petroleum Industry, Iran

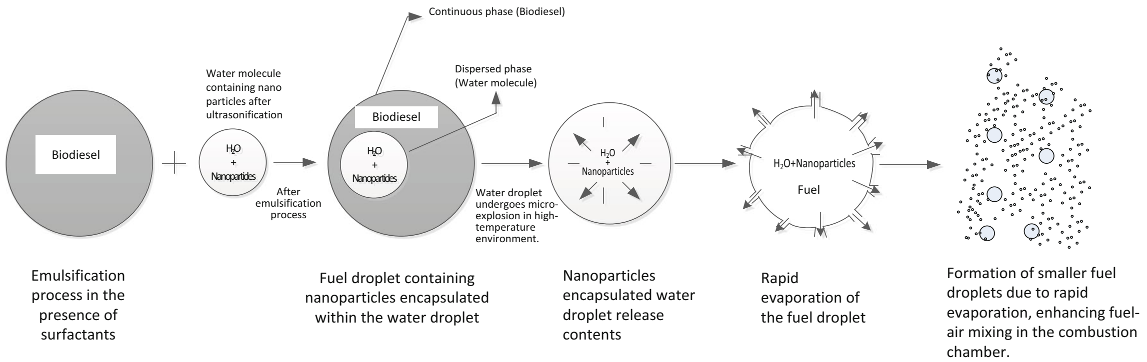

Fig. 1 Micro-explosion of water droplets containing nano-additives in the emulsion fuel, which enhances fuel–air mixing in the combustion chamber. Adapted from Sadhik Basha and Anand (2014)

amount oxygen available for combustion, which reduces the cylinder temperature and heat release during the combustion process and leads to lower NO_x emissions (Apireland 2012; Tsolakis et al. 2007). However, recirculating the exhaust gas into the intake manifold transports unburned inert gases back into the diesel engine, which reduces engine efficiency.

For this reason, several researchers have investigated the effects of EGR rate on the BSFC and NO_x emissions of diesel engines fueled with various types of biodiesels at different engine operating conditions and the results are summarized in Table 7. It can be observed that that the BSFC increases whereas the NO_x emissions decrease when the EGR rate is increased for the soybean biodiesel (Qi et al. 2011). Saleh (2009) obtained a good trade-off between the HC, CO, and NO_x emissions within an EGR rate of 5–15% for the diesel engine fueled with jojoba biodiesel. In addition, they found that the BSFC increases with an increase in EGR rate regardless whether the diesel engine is operated at full load or low load, as shown in Table 7. Solaimuthu et al. (2015) discovered that SCR results in lower NO_x emissions compared with the hot and cold EGR methods for the diesel engine fueled with mahua biodiesel.

Table 6 Effects of CR and IT on the BSFC, BTE, and EGT of diesel engines fueled with various types of fuel

Fuel	Load	IT (°BTDC[a])	CR	BSFC (g/kWh)	BTE (%)	EGT (°C)	References
MB[b]–diesel blend (20% MB + 80% diesel)	Full load	35	18:1	380	23	295	Raheman and Ghadge (2008)
	Full load	45	18:1	280	30	250	
	Full load	35	20:1	260	33	235	
	Full load	45	20:1	240	35	210	
	Low load	35	18:1	900	11	205	
	Low load	45	18:1	680	13	170	
	Low load	35	20:1	780	12	165	
	Low load	45	20:1	610	14	140	
Diesel	Full load	23	17.5:1	295	29	500	Debnath et al. (2013)
	Low load	23	17.5:1	745	1	115	
POME[c]	Full load	20	18:1	295	29	315	
	Low load	20	18:1	820	1	115	
WIP[d]	Full load	20	18:1	280	33	280	
	Low load	20	18:1	710	1	80	
WFOME[e]–diesel blend (70% WFOME + 30% diesel)	Full load	27	14.5:1	395	25	270	Hirkude and Padalkar (2014)

[a] °BTDC, degrees before top dead center

[b] MB, mahua biodiesel

[c] POME, palm oil methyl ester

[d] WIP, two-phase water-in-palm oil methyl ester emulsion

[e] WFOME, waste fried oil methyl ester

Table 7 Effects of EGR rate on the BSFC and NO_x emissions of diesel engines fueled with various types of biodiesel at different engine operating conditions

Biodiesel	Engine load	Engine speed (rpm)	EGR (%)	NO_x (ppm)	BSFC (g/kWh)	References
Soybean biodiesel	Full load	1500	43	155	287	Qi et al. (2011)
	Full load	1500	38	270	281	
	Low load	1500	54	15	355	
	Low load	1500	49	45	348	
Jojoba biodiesel	Full load	1600	0	525	240	Saleh (2009)
	Full load	1600	20	200	360	
	Low load	1600	0	380	350	
	Low load	1600	20	220	360	
Rice bran biodiesel	Full load	1500	0	807	–	Saravanan et al. (2013)
	Full load	1500	15	547	–	
	Low load	1500	0	1113	–	
	Low load	1500	15	945	–	
Rapeseed biodiesel	Full load	2500	0	1250	278	Tsolakis et al. (2007)
	Full load	2500	20	600	282	
	Low load	2500	0	810	308	
	Low load	2500	20	500	312	
Mahua biodiesel	Full load	1500	0	780	420	Solaimuthu et al. (2015)
	Full load	1500	SCR	630	440	
	Full load	1500	Hot EGR	710	440	
	Full load	1500	Cold EGR	710	430	

Diesel particulate filters

DPF technology was invented in order to reduce PM emissions of diesel engines. This technology is designed to trap PM from the exhaust gas within the walls of the DPF (Benaqqa et al. 2014; Buono et al. 2012). However, the DPFs must be regenerated in order to ensure optimum filtration efficiency and prevent high back pressures. However, the regeneration process affects the DPF loading. During the regeneration process, heat is released due to exothermal reactions and conversion of chemical species (Torregrosa et al. 2011). Therefore, various schemes have been developed for regeneration of DPFs, such as microwave heating and catalytic regeneration (Benaqqa et al. 2014; Deng et al. 2017b). The regeneration temperature as well as materials and structures of DPFs will affect the performance of the DPFs in the long term, leading to thermal aging and filter clogging (Zhang et al. 2017).

Regeneration temperature of DPFs

The regeneration temperature of DPFs should reach the temperature for soot oxidation (Benaqqa et al. 2014). The optimum regeneration temperature is defined as the break-even temperature (BET), which is the temperature where the deposition of particulates on the filter is balanced by particulate oxidation (Buono et al. 2012). The BET depends on the soot reactivity and oxidation rate in the DPF. According to Rodríguez-Fernández et al. (2017), the temperature for soot oxidation is 525 and 575 °C for the diesel engine fueled with biodiesel and diesel, respectively. For a diesel engine equipped with SCR system, the increase in EGT during regeneration of DPF can be reduced up to 400 °C (Chen and Wang 2014). Continuous regeneration technology (CRT) is a recent technology which enables DPFs to be regenerated at normal operating temperatures as low as 250 °C (Deng et al. 2017b; Liu et al. 2016). A low-temperature regeneration process assisted by nitrogen dioxide (NO_2) has also been developed for DPFs. Jiaqiang et al. (2016d) found that there is an increase in the regeneration speed for continuous regeneration of DPF assisted by NO_2 due to the increase in the exhaust gas volume, EGT, and concentrations of NO_2 and O_2 in the exhaust gas (Jiaqiang et al. 2016d). The presence of NO_2 accelerated soot oxidation within a low temperature range of 250–400 °C due to the increase in surface functionalization with oxygen groups and subsequent decomposition. However, there are a number of parameters that need to be considered in order to prevent significant pressure drop in CRT, which include the length, wall thickness, diameter, and thermal conductivity of the filter, as well as diameter of the channel (Deng et al. 2017b; Jiaqiang et al. 2016e).

Regeneration methods and catalysts of DPFs

The use of microwave heating during DPF regeneration enables instantaneous and selective soot oxidation process, especially for high concentrations of oxygen in the exhaust gas and high EGTs in diesel engines (Zuo et al. 2016). Palma et al. (2007) found that the soot oxidation is high when the microwave irradiation-assisted DPF regeneration process is facilitated by a catalyst. This is likely because the microwave energy is able to heat the carbon particulates rapidly and the silicon carbide (SiC) foams coated with iron/vanadium/potassium (Fe/V/K) and copper/vanadium/potassium (Cu/V/K) catalysts can strongly absorb microwaves (Palma et al. 2007). In another research, Palma et al. (2015) found that the copper ferrite ($CuFe_2O_4$) catalyst improves the regeneration of the DPF by promoting soot oxidation and reaction rate, increasing the specific surface area and bending strength, and decreasing the median pore diameter and total pore volume (Palma et al. 2015).

Materials and structures of DPFs

DPFs are designed to operate at the working conditions of diesel engines which include uncontrolled burning at engine idle, filter temperature peaks, pressure drop due to ash accumulation, and filtration efficiency due to mileage. During the thermal regeneration process, the DPF can melt or crack due to excessive thermal stresses. The temperature of the DPF during the thermal regeneration process increases from the filter section to the contraction section along the axial direction, and the maximum temperature occurs in the rear end of the monolith (Deng et al. 2017a; Jiaqiang et al. 2016a). Large temperature gradients are formed in the DPF carrier due to the uneven distribution of combustion temperature. The regeneration optimization area ratio increases with an increase in velocity. According to Deng et al. (2017a), the regeneration process is optimum at a particle load and flow rate of 5 g/L and 30 g/s, respectively. It has been proposed that SiC is a suitable material for DPFs because it shows medium isotropic grain and porosity, and the material has high thermal stability during the filtration process (Benaqqa et al. 2014).

According to Bogdanić et al. (2008), the reaction kinetic parameters of soot are sensitive to the pressure drop and temperature within the pores of the DPF based on their shape correction and slip flow. It shall be noted that slip flow refers to the zone where the flow transits from continuous flow to free molecular flow. Based on the simulation and experimental results of Bogdanić et al. (2008), the shape correction model only has a slight effect on the results, but the slip flow factor decreases with an increase in the solid temperature, which reduces pressure losses. Zhang et al. (2016) found that the regeneration efficiency increases by 17.3% when the pressure drop of the DPF decreases by 14.5%.

Low-temperature combustion technology

Low-temperature combustion technology is an advanced combustion technology for internal combustion engines. There are various types of low-temperature combustion technologies: (1) homogeneous charge compression ignition (HCCI), (2) premixed charge compression ignition (PCCI), (3) partially premixed combustion (PPC), (4) reactivity controlled compression ignition (RCCI), (5) high-efficiency clean combustion (HECC), (6) spark-assisted low-temperature combustion, and (7) laser-assisted low-temperature combustion (Agarwal et al. 2017). Low-temperature combustion technology increases the ignition delay, which improves the premixed combustion phase and reduces the diffusion flame combustion phase. This, in turn, significantly reduces the overall in-cylinder temperature (Jiaqiang et al. 2017). With low-temperature combustion technology, it is possible to achieve high thermal efficiency and low NO_x and PM emissions (Agarwal et al. 2017).

Conclusions

A review on the engine performance and exhaust emission characteristics of diesel engines fueled with biodiesel–diesel blends, exhaust aftertreatment systems (EGR systems and DPFs), and low-temperature combustion technology has been presented in this paper. The following conclusions can be drawn based on the literature survey:

- Much effort has been made to produce biodiesel blends by blending biodiesels with other types of fuels, such as diesel, biodiesels from different types of feedstocks, biooils, WTLs, and GTLs. Biodiesel blends are also blended with nano-additives in order to improve the engine performance and exhaust emission characteristics of diesel engines.
- For biodiesel–diesel blends, the BP and BSFC tend to increase while the BTE tends to decrease with an increase in the percentage of biodiesel in the blend. The THC tends to decrease with an increase in the percentage of biodiesel in the blend. However, these results should be interpreted with caution because it is not possible to generalize the trends based on the results available in the existing literature. For example, the CO emissions decrease with an increase in the percentage of palm oil biodiesel in the blend, but the CO emissions increase with an increase in

the percentage of *C. inophyllum* biodiesel in the blend. In general, the extent to which the engine performance and exhaust emission parameters increase or decrease depends on the type of biodiesel and the composition of biodiesel and diesel in the blend.

- For mixed biodiesel–diesel blends, the BP, ET, and BTE tend to be lower while the BSFC tends to be higher for these blends compared with those for diesel. However, the differences are not significant, typically within a range of 3–10%. The CO and THC emissions tend to be lower for mixed biodiesel–diesel blends compared with diesel. However, the NO_x emissions are still higher for these blends with a difference of 5–7%, which is characteristic of biodiesel blends.
- Attempts have been made to blend biodiesels with biooils, WTLs, GTLs, alcohols, and nano-additives in order to improve the engine performance and exhaust emission characteristics of diesel engines with varying degrees of success due to variations in the physicochemical properties of the fuel blends.
- In general, there is no one-size-fits-all solution. In other words, there is no ideal biodiesel blend that has favorable physicochemical and cold flow properties while producing optimum engine performance and minimum vehicle exhaust emissions. For this reason, exhaust aftertreatment systems, such as EGR systems and DPFs, and low-temperature combustion technology play an important role in reducing vehicle exhaust emissions. For engines equipped with EGR systems, care should be taken on the EGR rate and engine speed because both of these parameters influence the BSFC and NO_x emissions. For diesel engines equipped with DPFs, one should note that the type of regeneration method, regeneration temperature, and type of catalyst used for the regeneration process play a crucial role on the effectiveness of soot oxidation, which will affect the filtration efficiency of DPFs. Progress is now underway to develop technologies such that soot oxidation can take place at low temperatures (250–400 °C), which will facilitate the regeneration of DPFs. Optimizing the IT and CR is also important because these parameters will affect the BSFC, BTE, and EGT of diesel engines.
- Various biodiesel property improvement and diesel engine modification methods have been developed to enhance engine performance and to reduce exhaust emissions. However, each method has privileges and drawbacks that depend on environmental condition, government policy, and natural potency of biodiesel implementation area. Therefore, in the future study, the cost-effectiveness of each method may help in the choosing and optimizing the engine performance improvement, and in reducing exhaust emissions.

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