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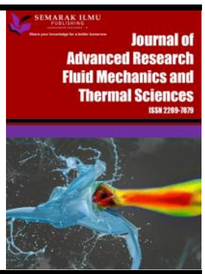

A Review on the Influence of Additive Blended Biodiesel to the Performance and Emission Characteristics of Heavy-Duty Diesel Engines

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ABSTRACT

Modern industrial society is heavily dependent on energy. The amount of energy needed to sustain a society increases as the world's population grows and transportation systems improve. However, the stringent emissions regulations enacted to control the number of harmful exhaust pollutants from heavy-duty diesel engines are likely to gradually phase out internal combustion engines that run solely on petrochemical fuels. This challenge puts constant pressure on researchers to seek improved fuel technologies that meet emission standards while reducing costs and emissions. In this paper, the impact of biodiesel blends, with or without additives was found to have both positive and negative effects on heavy-duty diesel engines. Biodiesel blends with additives such as 50% biodiesel 400mg/l additive and 100 % biodiesel 500mg/l additive have the potential to reduce emissions of harmful pollutants such as particulate matter (PM), carbon monoxide (CO), and hydrocarbons (HC). However, the impact on nitrogen oxide emissions is less clear and may depend on engine type and operating conditions. Regarding engine performance, additive biodiesel blends exhibited lower power and torque output and slightly lower fuel consumption than conventional diesel. On the other hand, non-additive biodiesel blends such as 5%, 10%, and 20% biodiesel in conventional diesel showed higher nitrogen oxide emissions and fuel consumption, but a reduction in HC and CO emissions. Overall, the use of additives in biodiesel blends can improve certain properties, such as cold weather performance and oxidation stability but the effect largely depends on engine design, operating conditions, and the percentage of additives used. Hence, more research is needed to fully understand the effect of biodiesel blends and additives on heavy-duty diesel engines and optimize their use for maximum benefits.

Keywords:
Biodiesel blends; non-additive blends; heavy-duty diesel engines; emissions and combustion

1. Introduction

Heavy-duty trucks powered exclusively by petrochemical diesel remain one of the most important modes of land transportation, especially for haulage services with reference to low- cost, transient times, and reliability compared to rail, water, and air [1]. Road vehicles are classified according to their weight into light, medium, and heavy trucks. Very heavy trucks are used for specialized tasks, such as freight hauling, oversized loads, mining, and off-road services [2]. Light

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trucks fall into the category of mini and medium trucks with a gross vehicle weight of 6,350 kg, such as minivans, pickups, panel vans, etc. Medium trucks, on the other hand, are larger than light trucks but smaller than heavy trucks with a gross weight of 6,351-11,793 kg. This includes vans, box vans, box van chassis, and flatbed trucks. However, heavy trucks are heavier than medium and light trucks and have a gross weight range of 11,794 to 14,196 kg. They include concrete trucks, tractor-trailers, logging trucks, and refuse trucks.

A major challenge to the use of heavy-duty trucks that run exclusively on petrochemical diesel for land transportation is air pollution, especially in highly congested areas, which causes a significant amount of harmful emissions such as HC, CO_2, and NO_X emissions [3]. This was attributed to the use of conventional diesel and non-additive blended biodiesel fuels. As a result, the use of heavy trucks for transportation services has contributed significantly to harmful exhaust emissions that affect human and animal health. Specifically, 25% and 6% of the greenhouse gas (GHG) and NO_X emissions in the European Union (EU) are caused by heavy-duty vehicles and long-distance buses [4].

In order to comply with EU regulations requiring zero-emission heavy-duty vehicles by 2030, new heavy-duty manufacturers are being forced to search for fuel technologies that can reduce harmful emissions from high-performance engines. Light trucks use gasoline, diesel, compressed natural gas, and liquefied petrol gas (LPG) fuels. However, the majority of heavy-duty vehicles used diesel fuel [5]. The damaging pollutants that conventional diesel causes, along with its limited supply and recent, unpredictably rising oil prices, have caused researchers to turn their attention to improved fuel technology for long-term energy security.

2. Biodiesel Blended Fuels

Animal fats, vegetable oils, and used cooking oil can all be used to make biodiesel. It is non-toxic, biodegradable, and effective at lowering diesel-fuelled emissions [6]. In addition, it has the potential to increase the finite supply of pure diesel and reduce exhaust pollutant emissions. A formulated biodiesel blended fuel is denoted by the letter “B” which denotes the proportion by volume (vol%) of the amount of biodiesel contained in the blended fuel. There are numerous concentrations and blends of biodiesel that can be employed in heavy-duty vehicles such as B5, B10, B15, and B20, and other higher concentrations targeted at improving emissions and counteracting fuel depletion [7].

The creation of low-level blended diesel fuels by the America Standard of Testing Material (ASTM) such as ASTM D975 permits diesel fuel with biodiesel percentages up to 5% (B5) to be sold at commercial filling stations without requiring additional labelling. Diesel engines made to run on conventional diesel can as well run on low-level biodiesel blended fuels including B5, B10, and B15 [5]. This is applicable to tractors, heavy-duty vehicles, and light trucks. Low-level biodiesel blended fuels are affordable, have excellent properties in emission reduction and are capable of improving engine performance in cold climate [8]. They are also compatible with different materials and solvent properties.

According to diesel engine original equipment manufacturers (OEMs), low-level blends up to B20 can be utilized in existing diesel engines without modifications, however the user should check the engine warranty for details regarding the maximum permissible volume of biodiesel blends allowed. The fuel consumption, horsepower, and torque of B20-powered engines are comparable to those of petroleum-based diesel engines [9]. Blended fuels with biodiesel provide higher reductions in GHG emissions than regular diesel fuel [10]. The reduction in emissions is roughly proportional to the blend level; for example, B20 would result in a 20% reduction in emissions over regular diesel [11]. There is a significant decrease in GHG emissions when biodiesel replaces petroleum. Specifically, B100 emits 74% fewer greenhouse gases during its entire life cycle than petroleum diesel, according to research by Argonne National Laboratory.

High-grade blends such as B50 and B100 are less commonly used as transportation fuel than B20 and other lower blends because the performance of heavy-duty engines is affected by non-additive high-level fuel blends [12]; when non-additive biodiesel is utilized in high-performance engines, it may significantly affect emissions and performance. Biodiesel is known to have lower emission of PM, CO, and other harmful pollutants compared to traditional petroleum diesel fuel. However, biodiesel can also have distinct physical and chemical characteristics from petroleum-based diesel, which can influence engine performance. Reduced emissions of dangerous pollutants are possible when heavy-duty diesel engines are powered by non-additive biodiesel, as well as improved fuel efficiency and engine performance. However, in a view of Issa *et al.,* [11] and Keihani *et al.,* [13], an effective fuel additive would be a better alternative to counteract deposit formation, abrasion and reduction in exhaust emissions associated with high-dose biodiesel blends than engine modification.

According to research, animal and vegetable crude oils used in biodiesel formulations without proper chemical additive treatment can lead to lubricating oil gelling, ring sticking, persistent engine deposits, and other maintenance issues even at low concentrations of 2% in conventional diesel [14]. This is primarily due to crude oils having a higher viscosity than regular diesel, for which high performance engines are designed. Because of high boiling point of crude oils, blended biodiesel fuels may not vaporize completely, especially during a cold start. However, efficient treatment with chemical additives such as cold flow additives during the conversion of crude oil into biodiesel is expected to lowers the boiling point and viscosity to values comparable to those of standard diesel fuels (see Figure 1). From the above, it can be seen that effect of additive and non- additive in biodiesel blended fuels varied depending on the specific engine and the ratio of the blend fuel used. Hence further studies would be needed to fully understand this phenomenon in fuel science.

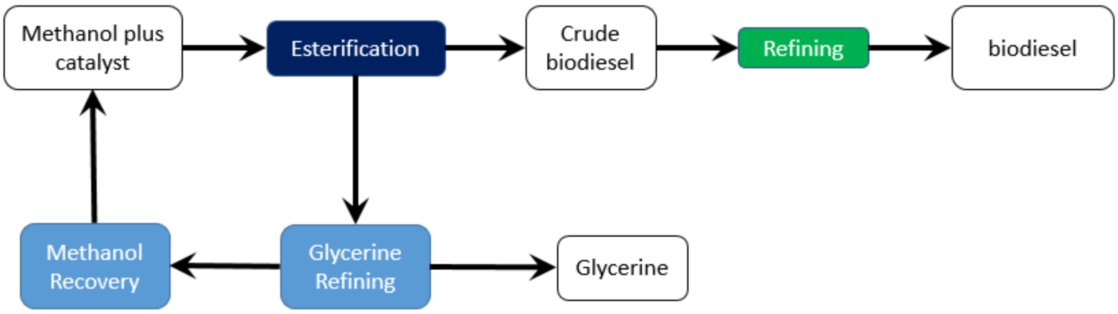

Fig. 1. Esterification process of raw oil into biodiesel [14,15]

2.1 Characteristics of Biodiesel-Based Fuel Blends

The fundamental characteristics of biodiesel blended fuels as it affects light trucks and heavy-duty engines are presented in this section. At low concentration, biodiesel boosts the cetane number of conventional diesel and enhance its lubricity [15]. In contrast to gasoline, biodiesel, and petroleum diesel can gel or freeze at typical wintertime temperatures; however, the cloud point for biodiesel can often exceed that for petroleum products [16]. The fuel can clog filters and eventually thicken to the point where it is impossible to push it from the fuel tank to the engine [17]. But, with effective cold flow additives, B20 can be utilized all year round. There are several different cloud spots in various petroleum diesels. Depending on the season and geographic location, petroleum diesel cloud points can range from -7°C (19°F) to -45°C (-49°F) [18]. The cloud point may rise above that of conventional diesel for blended biodiesel. Table 1 summarizes some of the key properties as approved ASTM necessary in the biodiesel blends to improve engine efficiency and cut emissions.

Table 1
Physical and chemical characteristics of blended fuels [19]

Properties	Diesel	B5	B10	B20	B100
Density (g/cm^3)	0.85	0.88	0.871	0.864	0.9342
Acid value mgKOH/g	0.5	0.3	0.3	0.3	0.5
Kinematics viscosity mm^2/s	3.85	3.5	4.05	3.98	5.75
Flash point (^{0}C)	79.75	52	52	52	103
Cetane number	52	40	40	40	59
Cloud point (^{0}C)	-25	-50	-50	-50	-13.5
Oxidation stability	8	6	6	6	3
Water and sediment	0.125	0.05	0.05	0.05	0.05

2.1.1 Fuel characteristics and their significance on heavy-duty diesel engine performance

(i) Cetane number**:** For an engine to perform well, the cetane number must be sufficient [20]. A minimum cetane number of 40 is required for conventional diesel. With this number, better cold starting characteristics are ensured and the production of white smoke is reduced with higher cetane levels [21]. According to the national conference of weights and measures, 47 cetane number is the minimum amount certified by ASTM for B100. Moreover, out of a vast variety of feedstock currently utilized in the production of biodiesel, the lowest cetane number of biodiesels found is 47 [21].

(ii) Viscosity**:** For some engines, a minimum viscosity is required, as there may be a loss of power caused by leaks from the injectors and fuel pump [22]. This applies not only to B5, B10, B20, and B100, but also to conventional diesel fuels, for which the same minimum standard applies. The layout of the engines' fuel injection systems sets a limit to the maximum viscosity [23]. Higher viscosity fuels carry greater potential for poor fuel combustion, deposit formation, and greater dilution of the engine oil by the fuel as the fuel penetrates more deeply into the cylinder [24]. According to ASTM D975, low -viscosity blends such as B5, B10 and B20 may have a maximum allowable viscosity of 1.4 mm^2/s at 40°C. However, compared to diesel fuel, B100 has a higher viscosity and ASTM D6751 allows higher viscosities than D975. Therefore, low viscosity blends such as B5, B10 and B20 should have a viscosity between 1.9 and 4.1 mm^2/s as allowed by the D975 standard for use in heavy-duty engines.

(iii) Cloud point: Cloud point is the most frequently used metric for low-temperature operability. Typically, fuels are anticipated to function at or below their cloud point. B100 often has a greater cloud point than regular diesel fuel [25].

(iv) Acid value**:** The biodiesel acid number primarily measures the amount of free fatty acids, contained in the raw oil used as biodiesel feed stocks [26]. The acid value may rise if the fuel was made poorly or if it had undergone oxidative degradation. Deposits in the fuel system have been connected to acid values more than 0.50 mg KOH/g and capable of shortened fuel pump and filter lives [27].

(v) Density: High density caused more fuel to be injected into the combustion chamber thereby raising the heat output and carbon level, which will subsequently increase the power of diesel engine [25]. Compared to diesel, biodiesel is denser. which normally ranged from between 0.86g/cm^3 and 0.90g/cm^3 [28]. One of the most crucial characteristics of biodiesel is density, which is necessary for engine injection systems (pumps and injectors) to provide precisely the right amount of fuel for proper combustion with the least amount of greenhouse gas emissions.

(vi) Water and sediment: This is amount of water vapor and sediment granules suspended in biodiesel. Specifically, B100 permissible level is equal to that of conventional diesel fuel. B100 may not meet specifications for water content if improper drying procedures were used during production or if it came into touch with too much water while being transported or stored. A surplus of water can cause corrosion and create a habitat for bacteria.
(vii) Flash point: Diesel fuel must have a minimal flash point in order to be free of danger. The National Fire Protection Association guideline classifies B100 as nonhazardous, and stipulates that its flash point must be at least 93°C in order to guarantee that all of the alcohol produced is eliminated.

3. How Additives in Biodiesel Blends Affect the Performance of Heavy-Duty Engines

Fuel additives impart new chemical properties to hydrocarbons that improve their functionality and performance, enabling fuel manufacturers and users to better secure distribution and improve the overall performance of diesel engines [29]. Filtration points are provided in high-performance fuel lines to clean the fuel before it reaches the fuel injector. However, filter plugging still occurs, especially with highly blended biodiesel fuels, which raise the temperature in the combustion chamber and raise exhaust emissions. Popular additives commonly used to improve the performance of biodiesel blends include cold flow improvers, lubricity enhancer, injectors and fuel system cleaners [30]. Deposit formation and filter plugging are caused by various contaminants such as water, dirt, metal, and salt in the engine environment and have been associated with non-additive high-level biodiesel blends. However, research is increasingly focused on exploring B100, especially for high-performance engines, by incorporating additives in its formulation to counteract harmful emissions and accelerate the transition to 100% biofuels.

3.1 Cold Flow Improver

It works by altering the crystal structure of wax particles. The cold flow improver functions as a nucleator during the crystallization process by co-crystalline with saturated hydrocarbon chains, changing the size and shape of the wax crystals from plate-like to needle-like. Smaller wax crystals are better at navigating filters and less likely to develop the three-dimensional gel formations that obstruct the flow of highly blended fuels in the fuel lines. For a variety of biodiesel blends, cold flow enhancers have numerous advantages, including

(i) Increase the efficiency of the cloud point, pour point, and cold soak filter tests for biodiesel fuel blends made from various feed stocks.
(ii) Enhance the low-temperature handling characteristics of biodiesel while reducing sedimentation and solidification.
(iii) Increase the filterability and cold flow performance of biodiesel and fossil diesel blends to widen the range of blend ratios, such as B5, B10, and B50.
(iv) Permit combinations of Fatty Acid Methyl Ether (FAME) with various degrees of low-temperature performance to satisfy regulatory standards.

3.2 Lubricity Enhancer

These are added to biodiesel fuels to improve their lubricating properties and protect system components. Common lubricity enhancers include FAME, fatty acid ethyl ester (FAEE), and vegetable oil-based additives [31]. The additives not only improve lubricity but can also reduce emissions and improve fuel economy. The specific type and amount of lubricity enhancer needed depends on the fuel blend and requirement of the engine or equipment being used. It is important to follow the recommendations of the fuel and equipment manufacturers when using biodiesel blended fuels.

4. Regulated Emissions from High-Performance Engines

Reducing the amount of harmful exhaust emissions from new heavy-duty vehicles, various parts of the world implemented emission standards. In particular, Japan, Europe, and the United States have enacted some challenging laws regarding the allowable levels of NO_X, HC, PM, and CO. The emission standards imposed by EU is shown in Figure 2. Euro I, set limits on the emissions of CO, HC, and NO_X for gasoline engines, and PM for diesel engines. Euro I required gasoline engines to meet limit shown in Figure 2 for CO, HC, PM, and NO_X [32]. For diesel engines. In addition, Euro II-VI further tightened the limit on CO and introduced advanced exhaust after-treatment system to lower PM and NO_X emissions.

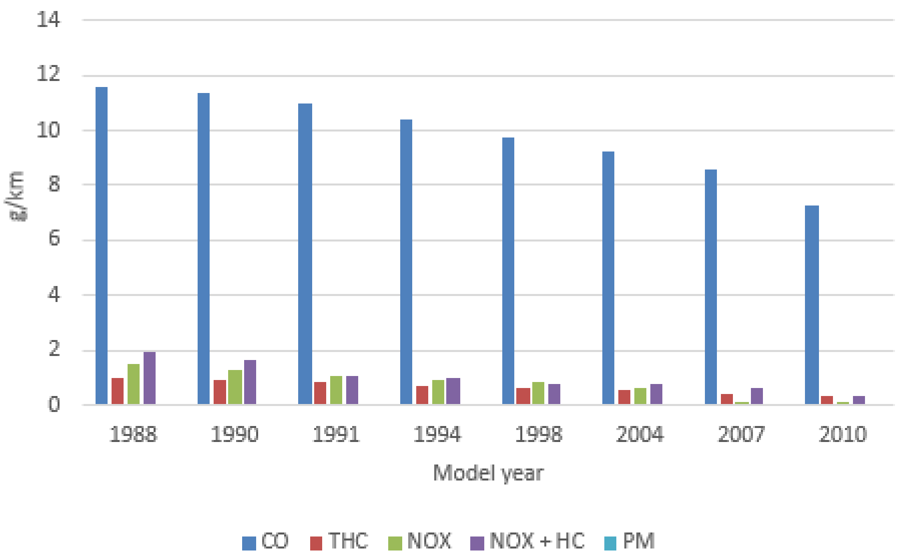

Fig. 2. EU emission regulation from petrol and diesel engines [30,32]

Similarly, Figure 3 presents the United States emission legislation intended to reduce emissions from heavy-duty diesel engines, these regulations include Tier 1-3 standards implemented between 1994 and 2006 aimed at reducing NO_X, PM and other pollutants from diesel engine [33]. The Clean Air Act amendments of 1990 which mandated emission standard from non-road diesel engines. Tier 4 standard implemented in 2010 for non-road diesel engines and 2011 Greenhouse Gas standard for heavy-duty trucks and buses have led to a considerable pollution reduction emitted from heavy-duty diesel engines resulting in better air quality and public health, as well as less environmental impacts from transportation sector.

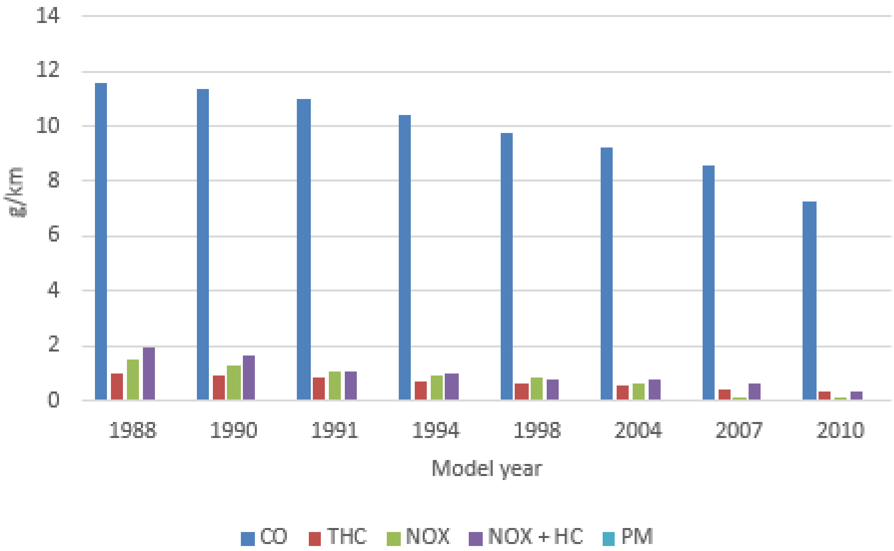

Fig. 3. The United States emission standard from heavy-duty diesel engines [33]

In addition, the Japanese government emission standard for heavy-duty vehicles is presented in Figure 4, these regulations include Japan post new long-term Regulations (PLR) from 2005, Japan new short-term Regulations from 2010, and Japan post new short-term Regulations (PSR) from 2015. The regulations aimed at limit emissions of NO_X, PM and other pollutants from heavy-duty diesel engines leading to a considerable improvement in air quality and public health in Japan [34].

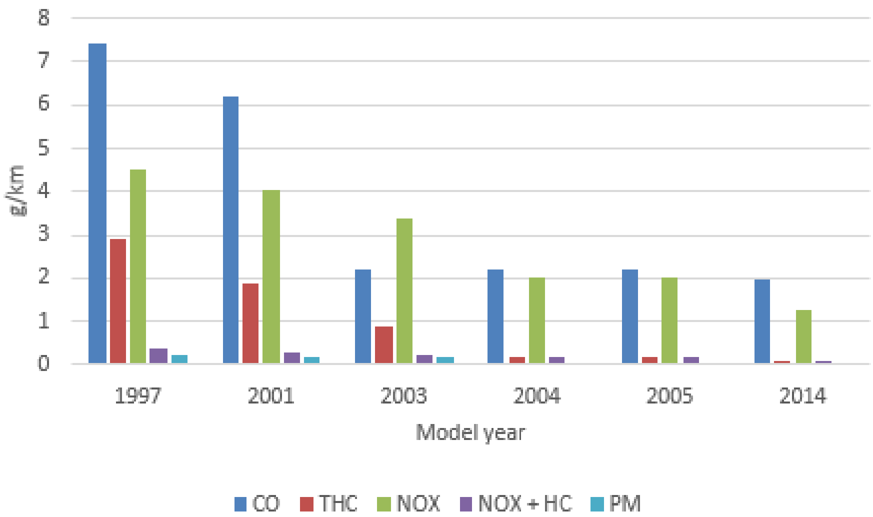

Fig. 4. Japanese regulated emissions from heavy-duty diesel engines [34]

5. Review of Related Study on Non-Additive Fuel Impacts on Heavy-Duty Diesel Engines

In a review by Szabados and Bereczky [35] on the emission of PM from light and heavy-duty diesel engines in Europe, the study draws various sources including measurement of real-world emissions and model predictions, to present a thorough overview of the current situation regarding PM emissions in Europe. The report highlights that heavy-duty diesel engine PM emissions significantly contribute to air pollution especially in urban areas. The authors note that although PM emissions from new vehicles have decreased in recent years due to stricter regulations, there are still many older vehicles on the road that produce high levels of PM. It also discusses different types of particulate matter emitted by vehicles, including particle number (PN) and black carbon (BC) and how they affect health and air quality. Finally, the report provides useful insight into the current status of PM emissions from vehicles in Europe and highlights the need for further efforts to reduce these emissions by introducing stricter regulations and promoting fuel technologies. Un-Noor *et al.,* [36] Examined how a heavy-duty diesel engine's performance and emissions are affected by the use of biodiesel and fuel additives. Their research indicates that some fuel additives enhance engine performance and lower emissions when used with biodiesel. Figure 5 shows that when the biodiesel fuel blends' additive ratio rises, there is a reduction in percentage of emissions. B100A500 additive blended fuel produced the lowest emission of CO, HC, NO_X, and PM emissions. Higher biodiesel fuel such as B50 and B100 support complete combustion and this is evident in the percentage of harmful emissions produced.

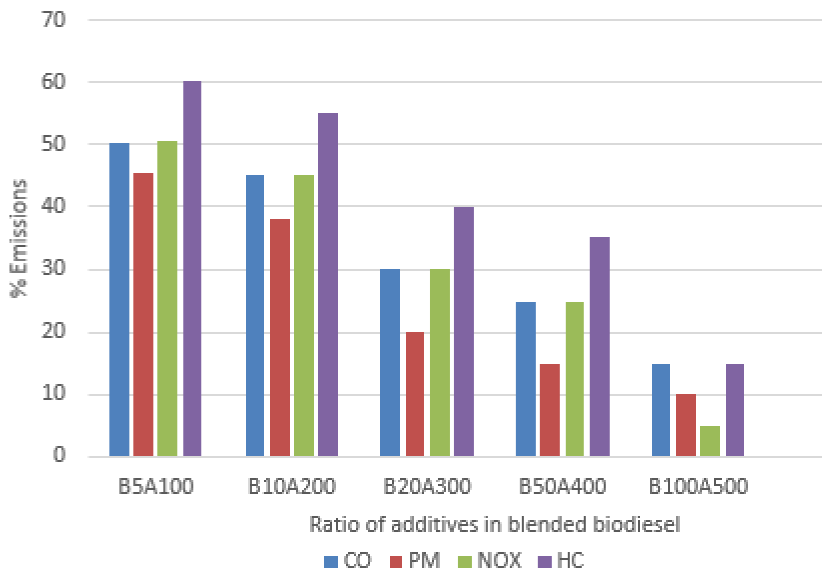

Fig. 5. Impact of additive on biodiesel blended fuel on emissions [36]

Unglert *et al.,* [37] Used biodiesel-diesel mixtures to test the effects of three different additives on the efficiency and emissions of a diesel engine. The three additives tested were a cetane improver, a lubricity enhancer, and a detergent. The tests were conducted using various biodiesel and diesel fuel blends, both with and without the three additives. It was found that the cetane improver improved combustion efficiency and reduced emissions of CO and HC, while the lubricity enhancer reduced engine wear and improved fuel economy. The detergent reduced the formation of deposits in the engine and improved engine performance. The research came to the conclusion that when employing biodiesel-diesel blends, additives can improve engine performance and emissions.

Uyumaz [38] examined how fuel additives affected the operation and emissions of a heavy-duty diesel engine running on soybean biodiesel. The study uses two types of fuel additives namely, cetane improver and antioxidant and compares their effects on engine performance and emissions with those of pure diesel and biodiesel. The result shows that adding a cetane improver to biodiesel improves the engine’s Performance by increasing its power and reducing its fuel consumption. Moreover, cetane improver reduces the emissions of NO_X, CO, and PM compared to pure diesel. On the other hand, adding an antioxidant to biodiesel improves its oxidation stability and reduces NO_X, and CO emissions, but slightly increases PM emissions. According to the study's findings, fuel additives can greatly boost the efficiency and emissions of heavy-duty diesel engines running on soybean biodiesel. However, the effect of fuel additives on emissions depends on the type and concentration of the additives.

Since the Brake Mean Effective Pressure (BMEP) measures the ability of the engine to convert fuel into power. From Figure 6, it can be seen that the higher the proportion of additives and biodiesel concentration in the fuel blends, the higher the engine BMEP at a given engine speed, which improves combustion efficiency and reduces the formation of deposits in the engine [39]. This could be attributed to the higher cetane number and the effect of additives, which can help maintain engine performance over a longer period of time. The effects of additives in biodiesel fuel blends on BMEP depend on a number of factors and may vary from engine to engine [40]. However, fuel blended with biodiesel under the influence of additives can provide several benefits for heavy-duty diesel engines, such as improved combustion efficiency and reduced engine deposits.

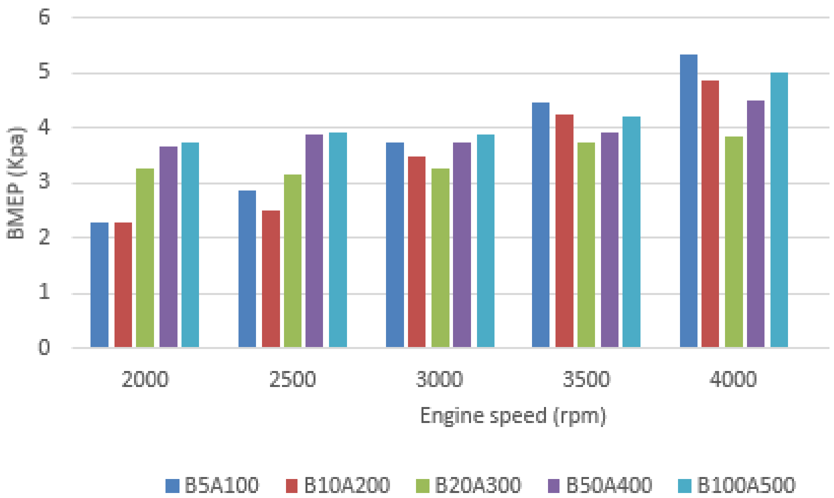

Fig. 6. BMEP and Engine speed for different biodiesel fuel blends [40]

Biodiesel blended fuel depends on several factors such as the percentage of biodiesel fuel, percentage of additives used, engine operating condition, and engine design [41]. Usually, biodiesel blended fuels have a slightly lower energy content than pure diesel, which is capable of increasing BSFC [42]. In Figure 7, additive biodiesel blends are seen to have a positive impact on BSFC by improving combustion efficiency and reducing engine deposit formation. At low engine speeds and loads, additive biodiesel blended fuel showed a significant impact on BSFC due to increased energy content in the fuel blends, however, at high engine speeds and loads, the impact of biodiesel blended fuels on BSFC was less due to an improved combustion efficiency.

In a study conducted by Heidari-Maleni *et al.,* [43] on non-additive fuel mixtures as it affects a heavy-duty diesel engine's output and emissions. The study uses two types of biodiesel blends namely B20 and B40, and compare their effects with those of pure diesel. The results showed that both B20 and B40 blends reduce the engine’s power output and increase its fuel consumption compared to pure diesel. Moreover, both blends increase the emissions of NO_X, CO, and PM compared to pure diesel.

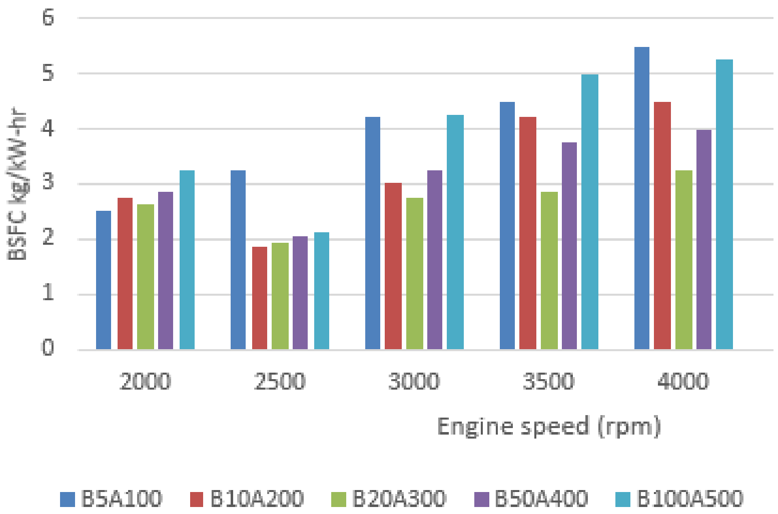

Fig. 7. Effect of additive in biodiesel blends on BSFC at different engine speed [42]

The study attributes the observed effects to the lower energy density and higher oxygen content of biodiesel compared to diesel. The study concludes that non-additive biodiesel fuel blends have a negative impact on the performance and emissions of heavy-duty diesel engines. The authors suggest that future research should focus on optimizing the engine parameter effects of biodiesel blends. In a similar study conducted by Al-Hasan [44] on effects of non-additive biodiesel blended fuel on the emissions, performance and fuel consumption characteristics of a heavy-duty diesel engine. Three different blends B10, B20 and B30 were tested, along with pure diesel fuel as a control. As can be seen in Figure 8 and Figure 9, the result showed that the use of biodiesel blends led to lower CO, HC and PM emissions, while NOX emissions were within acceptable limits. The biodiesel blends also also led to improvements in engine performance, including higher brake thermal efficiency and lower BSFC. In general, the study concluded that non-additive biodiesel blended fuel have the potential to reduce emissions and improve performance in heavy-duty diesel without significantly increasing fuel consumption.

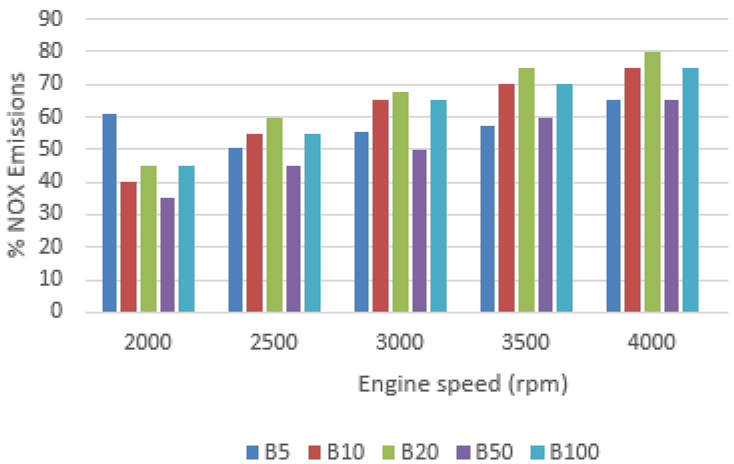

Fig. 8. Effect of non-additive blended biodiesel fuel on NO_X emissions [15]

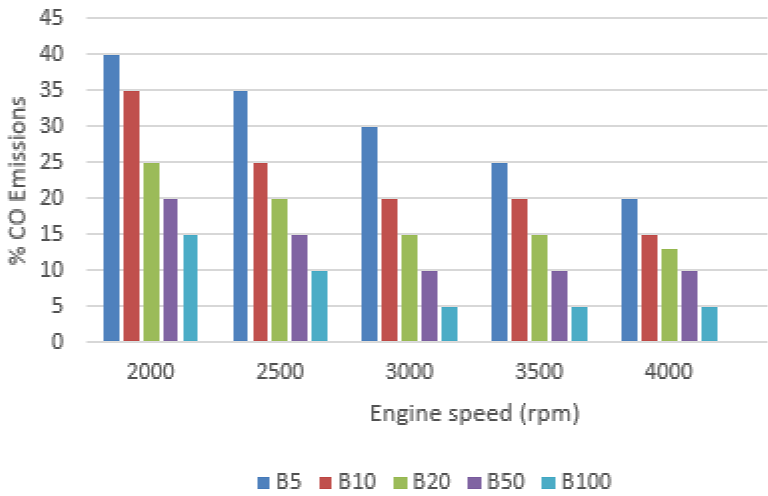

Fig. 9. Effect of non-additive blended biodiesel fuel on CO emissions [15]

6. Conclusions

The focus of this study is on the effects of biodiesel blends with or without additives on the emissions, performance, and fuel economy of heavy-duty diesel engines. The research has shown that biodiesel blends with and without additives can have both positive and negative effects on heavy-duty diesel engines. The identified biodiesel blend additives such as cold flow improvers, lubricants, and fuel system cleaners are capable of reducing CO, HC, and PM emissions, respectively. However, certain additives also resulted in a loss of engine power, an increase in fuel consumption and NO_X emissions. Biodiesel blends without additives are responsible for a significant increase in deposits, ring sticking, and intake system performance degradation in heavy-duty diesel engines. In general, the study found that engine design and operating conditions play a key role in the efficiency of heavy-duty diesel engines, whether or not they are fueled with additive or non-additive biodiesel blends . The use of additive blended fuels such as B20A200, B50A400, and B100A500 are promising alternatives to conventional and non-additive blended fuels, as found in this study. Therefore, this report called for further investigation of lower biodiesel blends and higher percentages of additives such as B5A300, B10A400, and B15A500 to take advantage of abundant biodiesel sources to meet growing energy demand and reduce emissions from heavy-duty engines.

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