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Impact of Oxygenated Fuels on Dry Soot Emissions in Diesel Engines

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ABSTRACT – *Dry Soot emissions pose a significant challenge for diesel engines, as they can severely impact human health and the environment. This study investigates the impact of oxygenated fuels on Dry Soot emissions from a TF120 YANMAR direct injection compression ignition diesel engine. Tests were conducted at engine speeds ranging from 1200 to 2400 rpm under no load, 50% of load, and 100% of load conditions. Diesel fuel was used as a comparison between two types of biodiesel blend fuels and two types of water-in-biodiesel blend fuels. The biodiesel blends included 5% biodiesel with 10% methanol (B5M10) and 10% biodiesel with 10% methanol (B10M10). The water-in-biodiesel blends included 3% water in the B5M10 blend (B5M10E3) and 3% water in the B10M10 blend (B10M10E3). The results indicate that the water-in-biodiesel blend fuel produced lower dry soot emissions than biodiesel blends and conventional diesel, highlighting their potential as environmentally friendly fuel alternatives.*

KEYWORDS: Emulsion, diesel engine, biodiesel fuel, water-in-biodiesel fuels, dry soot

1. INTRODUCTION

Diesel engines are widely used in automotive systems because of their high fuel efficiency. However, in diesel engines, the fuel and air mixture do not mix thoroughly. This incomplete blending creates fuel-rich pockets, leading to soot formation during combustion. Although most soot is expelled through the exhaust, some passes through the piston rings and contaminates the engine oil. The release of soot into the atmosphere is a significant environmental concern, contributing to emissions of nitrogen oxides (NOx) and particulate matter.

Particulate matter is a complex mixture composed of soot, liquid droplets, and solid-phase substances, with soot particles typically ranging in size from 1.0 to 7.5 µm (Wang, & Chen, 2021). The formation of soot particles from liquid hydrocarbons occurs in six stages: pyrolysis, nucleation, surface growth, coalescence, agglomeration, and oxidation (Johansson et al., 2023). As these processes conclude near the exhaust tailpipe, the gas temperature decreases. This cooling effect causes low-volatility hydrocarbons, sulfates, and water-bound sulfuric acid to condense, leading to the formation of particulate matter (Li & Wang, 2018).

Various strategies can be employed to mitigate diesel engine pollution and reduce dry soot emissions. One effective approach is optimizing engine parameters, as engine performance is significantly influenced by changes in altitude and temperature conditions (Zhao et al., 2023). Another method is the use of turbocharged engines, which enhance the combustion process by increasing the intake of oxygen-rich air into the combustion chamber. Raising the air pressure intake further energizes the molecules within the combustion chamber, while higher injection pressure improves fuel atomization (Zhang et al., 2022). Additionally, applying thermal barrier coating can boost molecular activity in the combustion chamber. Exhaust gas recirculation is also beneficial, as it recycles heat to support the combustion process (Hoseini et al., 2017; Gandolfo et al., 2023).

Enhancing the design of the combustion chamber improves air-fuel mixing, while fine-tuning the injection timing ensures an optimal combustion duration. Injecting oxygen directly into the intake valve further supports the combustion process. Adjusting chamber pressure helps optimize the mixing and ignition of fuel molecules. Additionally, using oxygen-rich biodiesel fuels enhances combustion efficiency (Wang et al., 2024). Incorporating biodiesel additives such as butanol, ethanol, and diethyl ester can further increase molecular reactivity (Hosseini et al., 2017). Moreover, after-treatment technologies play a vital role in emission control, including lean NOx traps for capturing and converting NOx, selective catalytic reduction for transforming NOx into nitrogen, and Diesel Oxidation Catalysts for reducing overall emissions (Hoseini et al., 2017).

In addition, diesel engine pollution and dry soot emissions can be reduced through pre-combustion control methods. This approach consists of two primary strategies: modifying the fuel itself (Zhang et al., 2022), and making adjustments within the engine cylinder (Gandolfo et al., 2023). Fuel modifications can be categorized into three main types: utilizing biodiesel as a fuel, incorporating oxygenated fuel additives, and using emulsified fuel.

Biodiesel, also known as fatty acid methyl or ethyl ester, is derived from sources such as vegetable oils and animal fats. It can be used directly in diesel engines without modification because its properties are similar to those of conventional diesel fuel (Hagos et al., 2017; Kumar & Sharma, 2023). Recent studies have demonstrated that biodiesel can significantly reduce emissions of carbon monoxide, unburned hydrocarbons and particulate matter from diesel engines (Sharma et al., 2020). However, several studies have shown that biodiesel combustion may result in higher NOx emissions (Ayhan & Tunca, 2018; Mikulski & Wierzbicki, 2023).

Adding oxygenated fuel additives provides a solution to some of the challenges associated with biodiesel, particularly in reducing NO_x emissions. Incorporating methanol into biodiesel fuel can enhance engine performance. Additionally, water-in-biodiesel fuel is effective in controlling both particulate matter and NOx emissions. This fuel consists of two primary components: a primary fluid (dispersed phase) and a secondary, immiscible fluid, which is stabilized by selected surfactants. The micro-explosion process resulting from water-in-biodiesel fuel improves combustion, leading to a reduction in particulate emissions (Al-Esawi & Tsolakis, 2023; Zhang, & Zhang, 2022). The water content in fuel also helps lower combustion chamber temperatures, further reducing NOx emissions.

Further research is required to explore the impact of biodiesel blend fuels and water-in-biodiesel blend fuels on diesel engine emissions. Therefore, focus studies need to investigate and compare the emission characteristics of particle-phase compounds produced by diesel engines when fueled with various biodiesel blends and water-in-biodiesel blends. With this in mind, the current study focuses on two biodiesel blend fuels: 5% biodiesel with 10% methanol (B5M10) and 10% biodiesel with 10% methanol (B10M10). Additionally, water-in-biodiesel blends, including 3% water in the B5M10 blend (B5M10E3) and 3% water in the B10M10 blend (B10M10E3), were selected as the target fuels. The aim of this paper is to evaluate the impact of these fuels on the particle-phase compounds emitted by diesel engines, including dry soot.

2. EXPERIMENTAL EQUIPMENT AND PROCEDURE

The methodology outlined below details the systematic measurement and analysis of CO, NOx emissions, and smoke opacity using the RTES device.

2.1 Design of Experiment

The investigation engine used in this study is a YANMAR TF120M four-stroke, single-cylinder, water-cooled, and direct fuel injection. The diagram of the test platform and sampling system is given in Figure 1. Two base fuels were used during the engine testing. The first was diesel fuel, obtained from a commercial petrol station, and the second was palm-based biodiesel. Both fuels adhered to the European standard EN14214, which outlines the specifications and test methods for producing fatty acid methyl esters for use as diesel fuel or as a blending component with diesel fuel. The engine lubrication oil used was Delta Super HD40, a German-engineered product with a capacity of four liters.

The process begins with selecting the diesel fuel with the lowest calorific value, i.e., B5M10, to determine the maximum load capacity of the diesel engine. Figure 2 shows the experimental process for testing under three different load conditions: 100% load (high load), 50% load (partial load), and 0% load (low load). For each load condition, tests were performed sequentially at five speeds: 2,400, 2,100, 1,800, 1,500, and 1,200 rpm. The data were collected over three separate cycles to analyze engine performance.

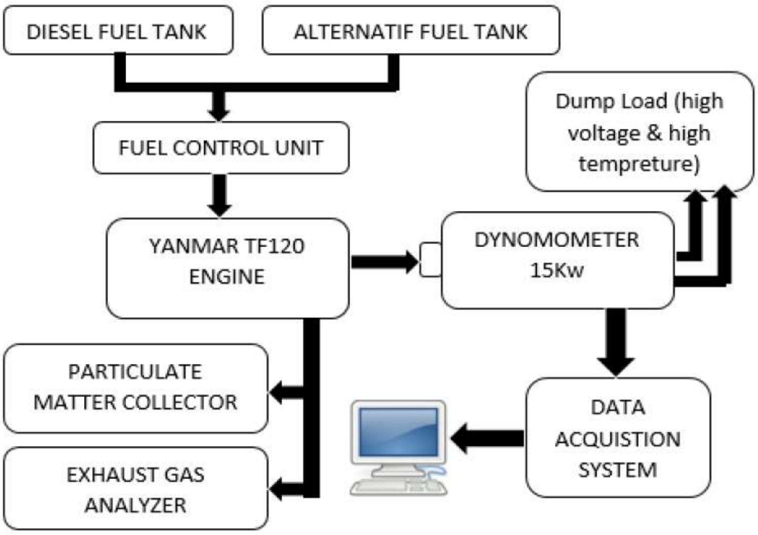

FIGURE 1: Schematic diagram of test platform and sampling system

B5M10					
1	High Load	Speed	Design of Experiment		
			Cycle 1	Cycle 2	Cycle 3
	20	2400	↓	↑	↓
		2100			
		1800			
		1500			
		1200			
2	Partial Load	Speed	Design of Experiment		
			Cycle 1	Cycle 2	Cycle 3
	10	2400	↑	↓	↑
		2100			
		1800			
		1500			
		1200			
3	Low Load	Speed	Design of Experiment		
			Cycle 1	Cycle 2	Cycle 3
	0	2400	↓	↑	↓
		2100			
		1800			
		1500			
		1200			

FIGURE 2: Test operating cycle schedule for each fuel

The engine must be preheated for 15 minutes using diesel fuel under partial loads to ensure stable efficiency. During this process, the throttle is alternately adjusted to increase and decrease the speed over one to two minutes, preventing sudden velocity shocks. For the first cycle of operation, it is necessary to start at high speed first to obtain the momentum of the engine and fuel efficiency to be tested. Each interval is five minutes for the data to be taken, so that the situation is ready. The operation study process will take seven to eight hours to complete the full three cycles of any type of fuel. After completion of the oil test process, the diesel engine should clean the fuel path of diesel fuel for 20 minutes at partial load and with a speed of 1,800 rpm. This process is carried out on all five fuels, which include diesel fuel, B5M10, B10M10, B5M10E3, and B10M10E3. The engine specification is shown in Table 1.

TABLE 1: Research engine specification

Engine parameters	Specifications
Engine type	Diesel 1-cylinder
Stroke type	Four – stroke
Cylinder bore x stroke (mm)	92 x 96
Injection timing (deg.)	btdc 17°
Compression ratio	17.7
Displacement (lit.)	0.638
Maximum torque (kgf.m / rpm)	4.42 / 1800
Specific fuel consumption (gr / hp. h)	169
Fuel injection pump	Bosch Type
Injection pressure (kg /cm^2)	200

2.2 Sample Preparation

The four alternative diesel-based fuel types formulated are B5M10, B10M10, B5M10E3, and B10M10E3. In these formulations, "B" represents biodiesel, "M" denotes methanol, "E" stands for emulsion fuel, and the numbers specify their respective ratios. A 5% biodiesel ratio was selected because it is commonly used at gas stations. It also contains oxygen, which aids in achieving complete combustion. Furthermore, a new blend with 10% biodiesel and 10% methanol was introduced to enhance the compatibility of biodiesel and diesel, leveraging methanol's higher cetane number. The inclusion of 3% water in the fuel helps to lower the engine cylinder temperature, promoting optimal combustion conditions and reducing emissions.

The material was blended using the IKA RW20 digital mechanical stirrer. The mixing process was conducted in a sealed beaker for 25 minutes at a speed of 600 rpm, followed by a 30-minute resting period at room temperature. The UP400S ultrasonic emulsifier, operating at 400W power and a frequency of 24 kHz, was subsequently employed to improve stabilization by enhancing the breakdown of fuel and water molecules. The operation was conducted for 10 minutes, with the sonotrode centrally positioned within the fuel to ensure a uniform mixture. Figure 3 illustrates the diesel and four fuel types, while the properties of these fuels are summarized in Table 2.

FIGURE 3: Fuel type

TABLE 2: The properties of the diesel and four alternative diesel-based fuels

Types of Properties	Fuel					
	Diesel	B5M10	B10M10	B5M10E3	B10M10E3	Unit
Cetane Number	50	51.6	51.9	52.3	53.9	-
Calorific Value	42.7	34.22	35.27	41.69	42.74	MJ/kg
Density at 25°C	0.84	0.86	0.84	0.92	0.83	g/cm^3
Kinematic Viscosity at 40°C	5	5.69	5.71	5.25	5.25	mm^2/s
Flash Point	80	100-105	95-100	90-95	105-110	°C
Boiling Point	149	268.2	191.7	105.2	73	°C

2.3 Particulate Matter Measurement

This process involves measuring particulate matter to evaluate the dry soot emission rate from diesel engines, aiming to highlight the differences in emissions between alternative diesel-based fuels. The PG-60 composite filter was used to trap the particulate matter. With a 0.6 mm diameter, the composite filter trapped the particulate matter samples collected from the exhaust pipe using a stainless-steel probe connected to a vacuum pump system. The composite filter was used to trap particulate matter. In this experiment, only a single filter was used to collect particulate matter for each fuel. The process was repeated until three sample filters were obtained for each fuel. An aluminum filter holder, measuring size of 47 mm^2, was used to hold the composite filter, as shown in Figure 4.

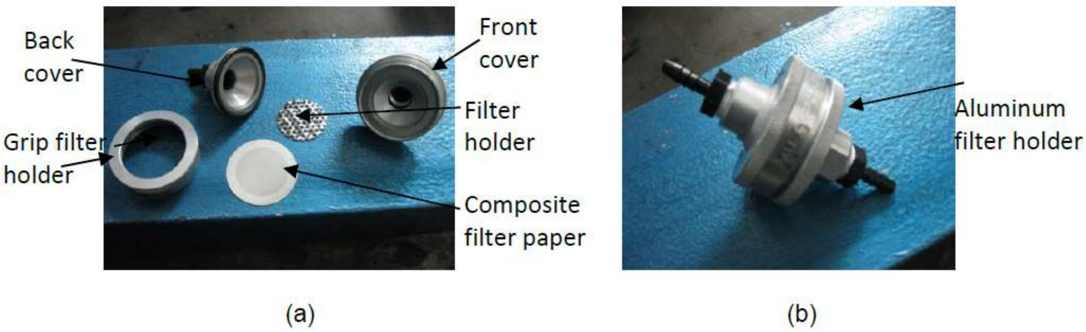

FIGURE 4: Component Filter holder (a); Filter holder (b)

2.4 Dry Soot Analysis

Next, the filter paper that's contains particulate matter were heated in oven at 50 °C for 2 hours to remove the moisture content absorbed from the exhaust gas. The dry mass of the particulate matter on filter is then weighed using a high precision electric balance types Sartorius BSA 224S-CW. Therefore, the density of particulate matter, d (g/m^3) is calculated by using formula below,

$$d = a - b$$

where a (g) and b (g) are mass of composite filter paper after extraction and mass of composite filter before extraction, respectively. In this study, the proportion of soluble organic fraction in the particulate matter was analyses using the dichloromethane solution. Therefore, the sample of filter papers that contain particulate matter is immersed in dichloromethane solution for 24 hours as illustrated in Figure 5.

Next, the composite filter paper are heated again by using oven for 2 hours to obtain the weight of dichloromethane solution, e (g). Then, the soluble organic fraction, f (g) is calculated using Equation below,

$$f = a - e$$

where, e is mass of the dichloromethane solution. The density, g ($gm3⁄$) of soluble organic fraction are calculated using equation below,

$$g = (f/20\ L)\ X\ 1000$$

The density of dry soot, h ($gm3⁄$) can be calculated using Equation below,

$$h = d - g$$

where d is a density of particulate matter. All the results that obtained will be plotted in the graph to do the analysis and determine the different between those conditions that was set up.

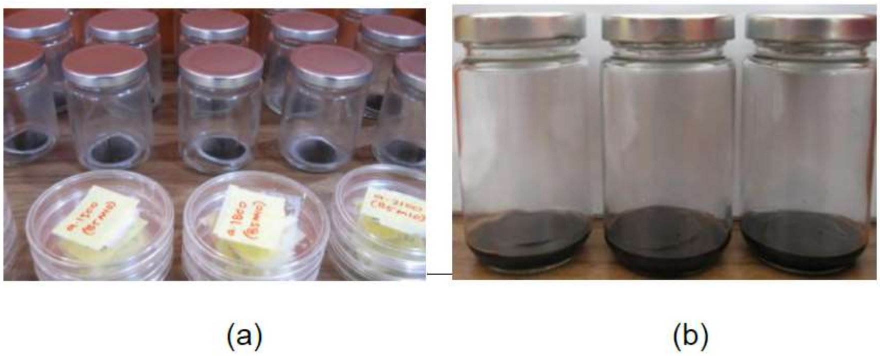

FIGURE 5: Particulate matter sample: before extraction (a); after extraction (b)

3. RESULTS AND DISCUSSION

This section will show the result of dry soot concentration, measured across various types of fuel, including Diesel, B5M10, B10M10, B5M10E3, and B10M10E3, at different operational engine speeds. The combustion process in diesel engines generates dry soot, which consists of solid carbon particles, metals, and sulfates. As shown in Figure 6, diesel fuel produces the highest dry soot concentration under low-load conditions, with 0.2000 kg/m³ at a speed of 1,200 rpm. In comparison, the alternative fuels of B5M10, B10M10, B5M10E3, and B10M10E3 show significantly lower dry soot concentrations, with reductions of 10%, 17.5%, 72.5%, and 65%, respectively, under the 1,200 rpm and load conditions. At 2,400 rpm, the dry soot concentration for water-in-biodiesel fuel increases compared to the biodiesel blends, likely due to incomplete combustion. Notably, under optimal engine conditions at 1,800 rpm, water-in-biodiesel fuel achieves the lowest dry soot levels among all tested fuels, surpassing both biodiesel blends and diesel. This indicates that water-in-biodiesel fuel has significant potential as an environmentally friendly alternative due to its lower dry soot emissions under optimal engine conditions.

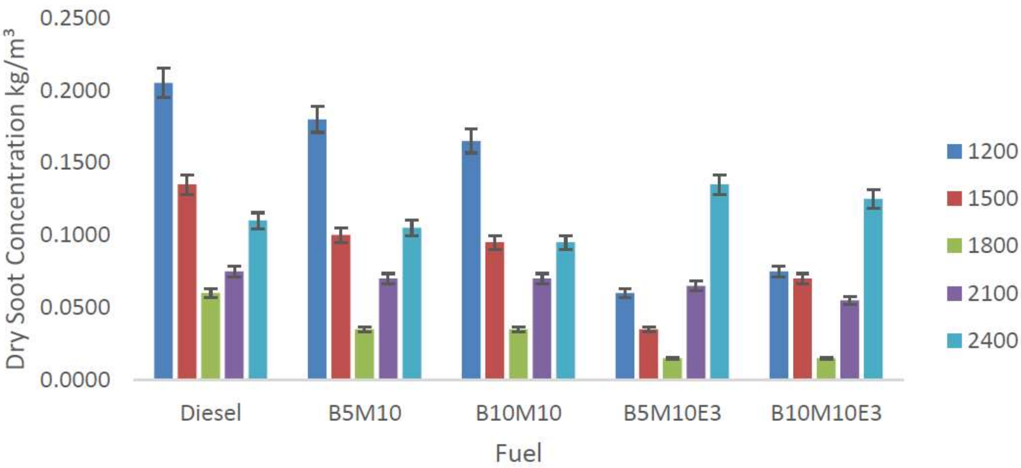

FIGURE 6: Dry soot at Low Load (0%)

On a 50% of load state shown in Figure 7, the dry soot produced by diesel fuel over other alternative fuel at all speed. The inclusion of biodiesel B5M10 and B10M10 leads to a noticeable reduction in soot concentration compared to diesel at lower RPMs, i.e., 1,200 to 1,800 rpm. This is attributed to the oxygen content in biodiesel and methanol, which enhances combustion efficiency and reduces soot formation. The addition of water further decreases the soot concentration, especially at speed of 1200 to 1800 rpm. Water's high oxygen content contributes significantly to cleaner combustion. Among the fuels tested, B5M10E3 shows the lowest soot concentrations, demonstrating the combined effectiveness of biodiesel, methanol, and water. The water-in-biodiesel fuel produces the lowest dry soot of 0.03 kg/m^3 for both B5M10E3 and B10M10E3 at 1800 rpm speeds compared to diesel fuel, B5M10 and B10M10 with high dry soot percentages of 266%, 166%, 133% respectively. For all fuels, the dry soot concentration increases with higher speed. This trend aligns with the higher fuel injection rates and shorter combustion times at elevated engine speeds, which can lead to incomplete combustion.

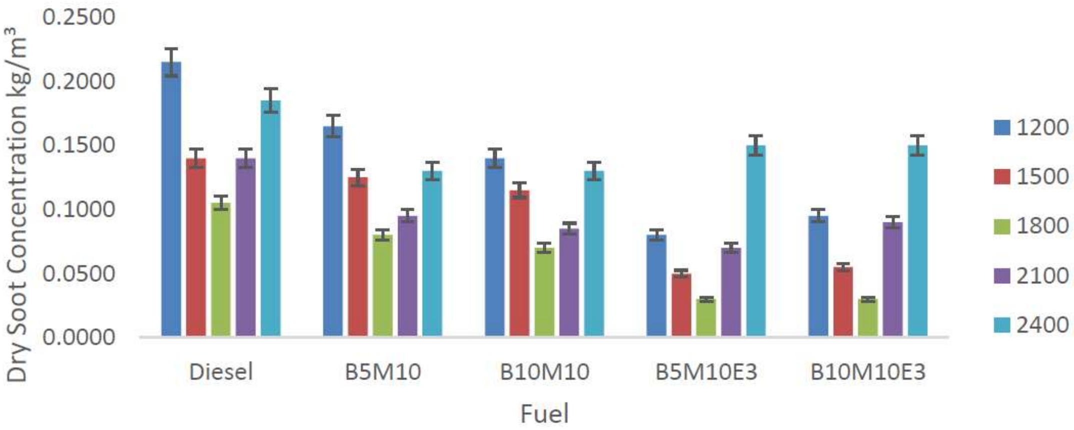

FIGURE 7: Dry soot at 50% of load

Under the 100% load condition, the results in Figure 8 indicate that diesel fuels exhibit the highest soot concentrations across all speeds. The lowest dry soot is water-in-biodiesel fuels at a speed of 1,800 rpm, which the B5M10E3 and B10M10E3 with values of .004 kg/m3 by low dry soot percentages are 63.63% for both fuels compared to diesel fuel. While the low dry soot percentages of B5M10 and B10M10 are 36.36% and 27.27%, respectively, compared to diesel fuel at 1,800 rpm. The addition of 5-10% methanol significantly reduces soot concentrations compared to diesel.

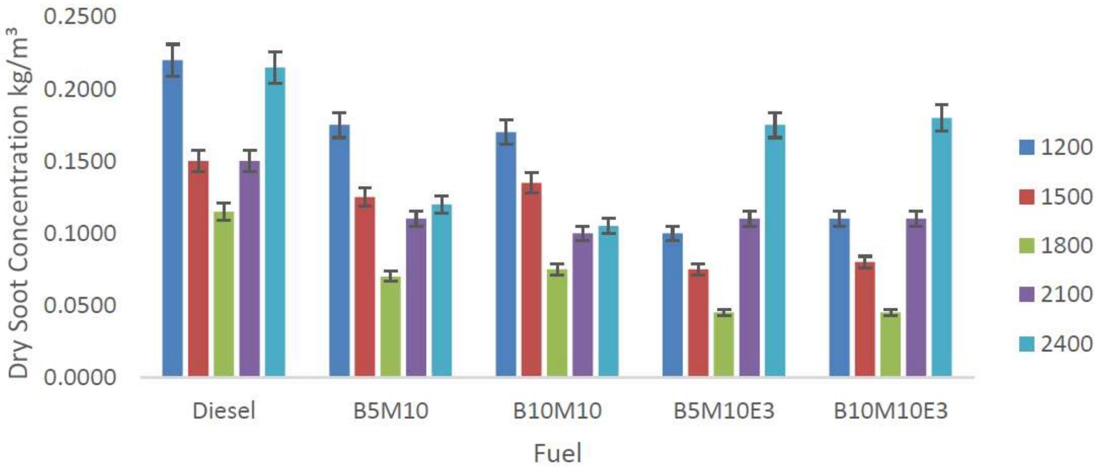

FIGURE 8: Dry soot at High Load (100%)

Adding 3% of water in B5M10E3 and B10M10E3 further lowers soot emissions, at 1,800 rpm. It shows the lowest concentration among all fuel blends, showcasing the effectiveness of combining biodiesel, methanol, and water. Water's high oxygen content and low carbon-to-hydrogen ratio are likely contributors to these reductions. Water-in-biodiesel fuel helps to complete combustion at an ideal speed of 1800 rpm engine with a micro-explosion phenomenon that can reduce dry soot production. However, the soot concentrations rise with increasing speed after 1,800 rpm, with the highest values observed at 2,400 rpm. This increase is attributed to the higher fuel injection rates and shorter time for combustion at higher engine speeds, which can lead to incomplete combustion and soot formation.

4. CONCLUSION

This study investigates the effectiveness of biodiesel blends and water-enriched biodiesel fuels in lowering air pollution by analyzing dry soot emissions from diesel engines. Biodiesel has flammability, short ignition delay, higher viscosity, and higher cetane number. Therefore, Biodiesel fuel produces lower heating value, lower brake thermal efficiency, and higher brake specific fuel consumption. Biodiesel blends offer the advantage of being compatible with diesel engines without requiring modifications while also lowering emissions. The water-in-biodiesel blend fuel, classified as an oxygenated fuel due to the oxygen present in water aiding complete combustion, demonstrated improved performance in this study. The findings revealed that the biodiesel blend generated less dry soot compared to diesel fuel but produced slightly more dry soot than the water-in-biodiesel blend.

The observation concludes that for all fuel types under various load conditions, the diesel engine produces a high rate of dry soot at the initial speed of 1,200 rpm. This concentration gradually decreases until it reaches the low speed of 1,800 rpm, after which it begins to rise again up to 2,400 rpm. Additionally, biodiesel fuels generate less dry soot compared to diesel fuel. However, water-in-biodiesel blend fuels exhibit an even better reduction in dry soot concentration than pure biodiesel fuels.

The findings reveal that water-in-biodiesel blends considerably decrease soot output, emphasizing their promise as cleaner alternatives to traditional diesel. It encourages further exploration of fuel blends with varying ratios of biodiesel, methanol, and water to optimize performance and reduce emissions. This research aims to support a pollution-free world by promoting eco-friendly alternative fuels to replace diesel. Experimental results show that water-in-biodiesel blend fuel is more effective in reducing dry soot compared to both diesel fuel and biodiesel blends. Looking ahead, biodiesel blends and water-enhanced biodiesel fuels are promising eco-friendly alternatives that could play a significant role in minimizing dry soot emissions.

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