

Impact of Emulsion Fuels on Particulate Surface Morphology and Implications for Air Quality

H. A. Hassan*¹ and N. Aliman²

¹ Department of Mechanical Engineering, Politeknik Sultan Azlan Shah, 35950 Behrang, Perak

² Center of Autonomous Vehicle Technology (CAVTech), Politeknik Sultan Azlan Shah, 35950 Behrang, Perak

*Corresponding author: hazmanpts@gmail.com

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ABSTRACT – *Emulsion fuels have emerged as promising alternatives for cleaner and more efficient combustion technologies. These fuels offer a sustainable pathway to reducing environmental impact through enhanced energy efficiency, improved torque, superior engine performance, and lower pollutant emissions. This study focuses on analyzing the surface morphology of particulates formed during the combustion of emulsion fuels to better understand the mechanisms underlying particulate matter (PM) formation in exhaust emissions. A multifaceted research approach was adopted, including the preparation of materials and experimental equipment, as well as the formulation of fuel blends, namely B5M10, B10M10, B5M10E3, and B10M10E3, where B represents biodiesel, M denotes methanol, E indicates an emulsion fuel, and the numbers correspond to blend ratios. The findings provide critical insights into how different fuel compositions influence particulate characteristics and emission behavior. The results support the viability of emulsion fuels and biodiesel as renewable, environmentally friendly alternatives capable of significantly reducing PM emissions, thereby contributing to improved air quality and sustainable energy solutions.*

KEYWORDS: Surface morphology, emulsion fuel, renewable fuel, environmental

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1. INTRODUCTION

The transformation of diesel fuel into unwanted particulate matter exhaust is a major problem in combustion and clean emissions. Diesel engines also release harmful gases like HC, CO, and NO_x into the atmosphere. Biodiesel has the potential to reduce CO₂ emissions over the long term, although its impact may be marginal at the initial stage of implementation (Kumar et al., 2025; Masera et al., 2025). The overall effect on CO₂ emissions is strongly influenced by the rate of adoption and the blending ratio with conventional diesel (Solaymani, 2024). Hassan et al. (2024) mentioned that blends of biodiesel with diesel have many benefits, such as reduction in emissions, lower engine wear, reduced engine fuel consumption, and appropriate thermal efficiency.

In 2012, the United States Environmental Protection Agency (EPA, 2025) revised the National Ambient Air Quality Standards (NAAQS) for PM_{2.5}, reducing the annual limit from 15 µg/m³ to 12 µg/m³. More recently, the standard was further tightened to 9 µg/m³ in 2024, reflecting increasing concerns regarding the health impacts of fine particulate matter (Jin et al., 2016; Wu et al., 2017). Nevertheless, the impact of alternative fuels on particulate matter emissions requires further investigation, as studies have shown that particle toxicity tends to increase with decreasing particle size (Garcia et al., 2023).

A few studies have investigated emissions from emulsion fuels in diesel engines; however, detailed analysis of particulate matter (PM) is still limited. Emulsion fuel requires a suitable ratio of water and fuel to ensure stability (Hassan et al., 2025). Surfactants are used to stabilize the mixture by improving the dispersion of water droplets in fuel based on hydrophilic-lipophilic balance (HLB). Common surfactants used include Tween 80 and Span 80. Emulsion fuel can generally be used in diesel engines with little or no modification, making it a promising alternative fuel.

The performance of a diesel engine increases with the occurrence of the micro-explosion phenomenon. This leads to more complete combustion and results in a reduction in PM and emissions. This study focuses on investigating the emissions and PM characteristics of the fuels to be tested, namely emulsion fuels and biodiesel blends, and comparing them with conventional diesel. The main aim of this study is to determine the impact of fuel additives, i.e., biodiesel, methanol, and water on the emitted carbonaceous particles. Furthermore, it aims to examine the formation process of exhaust pollutants, including PM concentration, PM size distribution, and elemental composition in diesel engines

2. METHODOLOGY

2.1 Particulate Matter Measurement

This study's methodology below shows the systematic measurement to measure particulate matter and determine the smoke emission rate from diesel engine exhaust to prove that the difference of various alternative fuels versus diesel was sufficient.

2.2 Experimental of Particulate Surface Morphology

The experiment to evaluate the performance of five types of fuel was conducted in a single-cylinder engine laboratory. The YANMAR TF120M diesel engine was used as the test engine, and all experimental equipment was properly prepared prior to testing. The experimental setup consisted of a 15-kW eddy current dynamometer for engine load control, a data acquisition system for real-time measurement and recording of engine parameters, a high-voltage dump load for energy dissipation, a ventilation system equipped with a blue container for exhaust handling, and two oil barrels for fuel storage and management. Proper maintenance of the engine and all equipment was ensured to guarantee safe and stable operation throughout the experiment. The schematic diagram of the test bench and sampling system for this four-stroke, water-cooled, direct fuel injection engine is shown in Figure 1.

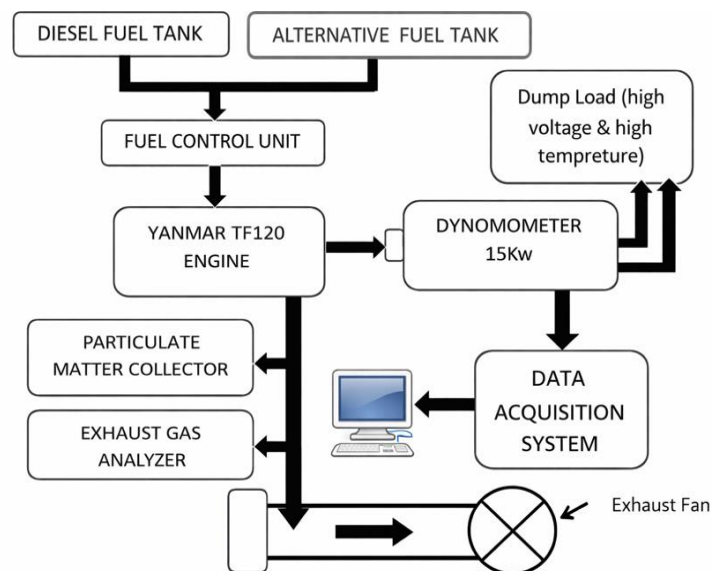


FIGURE 1: Block diagram of the test platform and sampling system

2.2.1 Preparing the Filter Paper

Composite filter paper was used to trap the PM. The composite filter is placed in a gas line connected to the metal sampler. This type of filter uses a composite with a diameter of 0.6 mm. The engine is fitted to a 50 cm length stainless steel probe in the exhaust pipe for the sampling of PM. The stainless-steel probe is connected to a vacuum pump for the stability of the flow rate of the sampling process. A composite filter was used to retain particulate matter, accompanied by the other PM components. An aluminum filter holder was used in this experiment to hold the composite filter with a stainless-steel

support screen. The size of the filter holder is 47 mm. A single filter was used for all runs of the experiment, and the mass of the filter was measured after each run under regulated atmospheric conditions. Table 1 demonstrates the specifications of the filter paper. Figure 2 illustrates the detailed composite filter paper PG-60 and components of the filter holder.

TABLE 1: Specifications of filter paper

Detail	Specification
Material	Composite filter (PTFE coated)
Trademark	ADVANTEC
Type	PG-60
Size	47 mm ²
Lot Number	20919702
Manufacturer	Toyo Roshi Kaisya, Ltd.

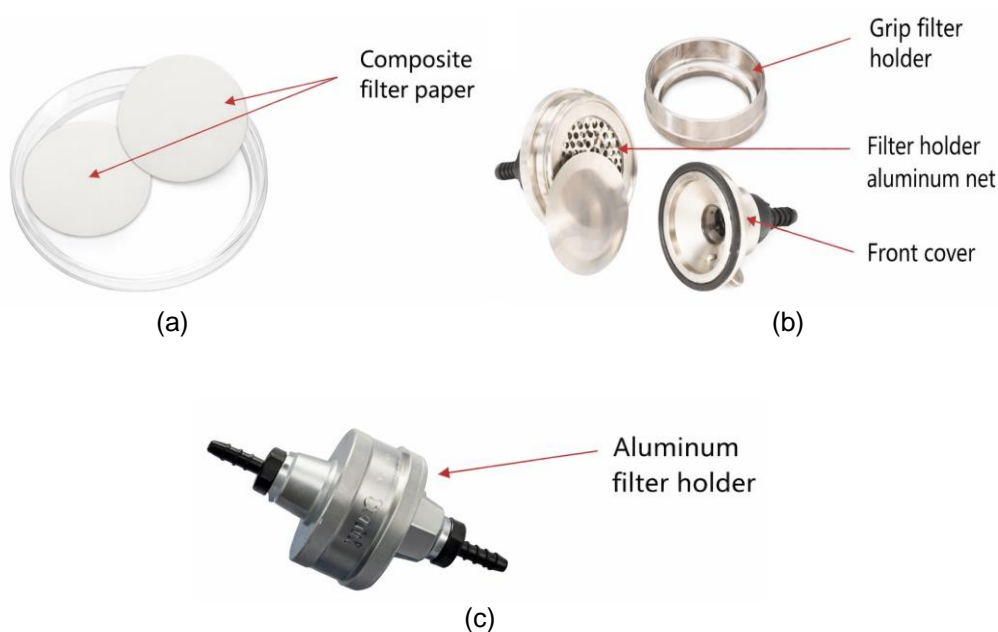


FIGURE 2: Filter materials are soft, and care must be taken when using them: (a) composite filter paper PG-60 (b) component filter holder (c) filter holder

Before running the experiment and collecting data, the filter paper must be heated, and its original weight must be measured. The composite filter paper is then heated in a Redline convection oven for 2 hours at 50 °C. Clippers are used to handle the filter paper so that no other elements get attached to it. After two hours, the filter paper is weighed using a high-precision electric balance. A gravity convection oven is a tool that is used to heat the filter before the data collection. The aim is to eliminate the moisture in the filter paper. The heater is equipped with a digital temperature display and controller with a sensitivity of 1 °C. Exposure time display of the oven was up to 0-9999 minutes, and high temperature safety controls by high-grade thermostats are included. Behind the oven, there is a duct exhaust of diameter (∅ 50) which can be manually adjusted. In the oven, there are 4 chrome-plated shelves. To have the same flow rate, a vacuum pump was used to maintain the flow of the exhaust gas up to 20 L/min. In this study, the proportion of soluble organic fraction (SOF) in the particulate was analyzed using the Dichloromethane solution extraction method. Table 2 demonstrates the specifications of the dichloromethane chemical employed in the investigation. A precision weighing balance was employed to obtain an accurate measurement. Table 3 demonstrates the specifications of the precision weighing balance.

TABLE 2: Specifications of dichloromethane chemical

Detail	Specification
Grade	ACS, ISO, Reag. Ph Eur
Synonyms	DCM, Methylene chloride, Methylene dichloride
Chemical formula	CH ₂ Cl ₂
HS Code	2903 12 00
EC number	200-838-9
Weight (Molar mass)	84.93 g/mol
EC index number	602-004-00-3
CAS number	75-09-2
Ignition temperature	605 °C DIN 51794
Solubility	20 g/l (20 °C)
Melting point	-95 °C
Density	1.33 g/cm ³ (20 °C)
pH value	(H ₂ O, 20°C) neutral
Boiling point	40 °C (1013 hPa)
Vapour pressure	475 hPa (20 °C)
Explosion limit	13 – 22% (V)
Refractive index	1.42
Evaporation	1.9

TABLE 3: Specifications of the Precision Weighing Balance

Detail	Specification
Brand	Sartorius BSA224S-CW
Size	90 mm
No. Of item	1
Repeatability	<+ 0.1 mg
Readability	0.0001 G-0.1 mg
Standard	ISO 9001
Linearity	<+ 0.2 mg

2.2.2 Platinum Sputter Coater

Platinum sputter coats are used to obtain quality images before samples are viewed using the scanning electron microscope (SEM). The sample should be small in size (5 mm) and affixed to the FESEM stub using a double-sided tape. The sample is then placed into a sputter coater platinum pot and processed for 10-15 minutes. This is done to ensure that dirty coatings on the sample surface are cleaned off. The process is repeated if the image is still unclear. The sample can then be used to view the images on the SEM. Figure 3(a) shows the JFC-1600 Auto Fine Coater, and Figure 3(b) shows a schematic diagram of the Auto Fine Coater (Hassan et al., 2018).

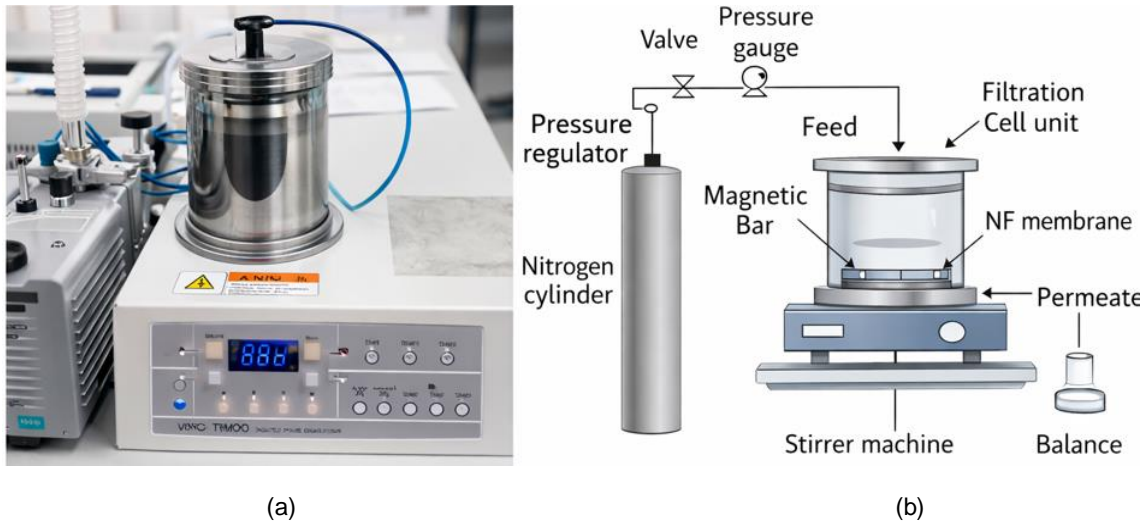


FIGURE 3: JFC-1600 Auto Fine Coater is intended mainly for preparing specimens for SEM observation: (a) JFC-1600 Auto Fine Coater, and (b) Schematic diagram of Auto Fine Coater

2.2.3 Scanning Electron Microscope (SEM)

The samples were cleaned using the platinum sputter coater that incorporated an image shelf on the SEM. The samples that were included in the image shelf appeared in the computer display. The particle size image was selected based on the study requirements. Spot images can also be selected based on the objective of the study. The contents of the sample can be evaluated by selecting the sample portion to be studied. The number of elements found in the spot area can be measured using the SEM. The concentration of particles that agglomerate on the sample fiber is observed clearly. Figure 4(a) illustrates the Quanta 450 scanning electron microscope; and 4(b) the schematic diagram of the SEM. Table 4 demonstrates the specification of the Quanta 450 SEM.

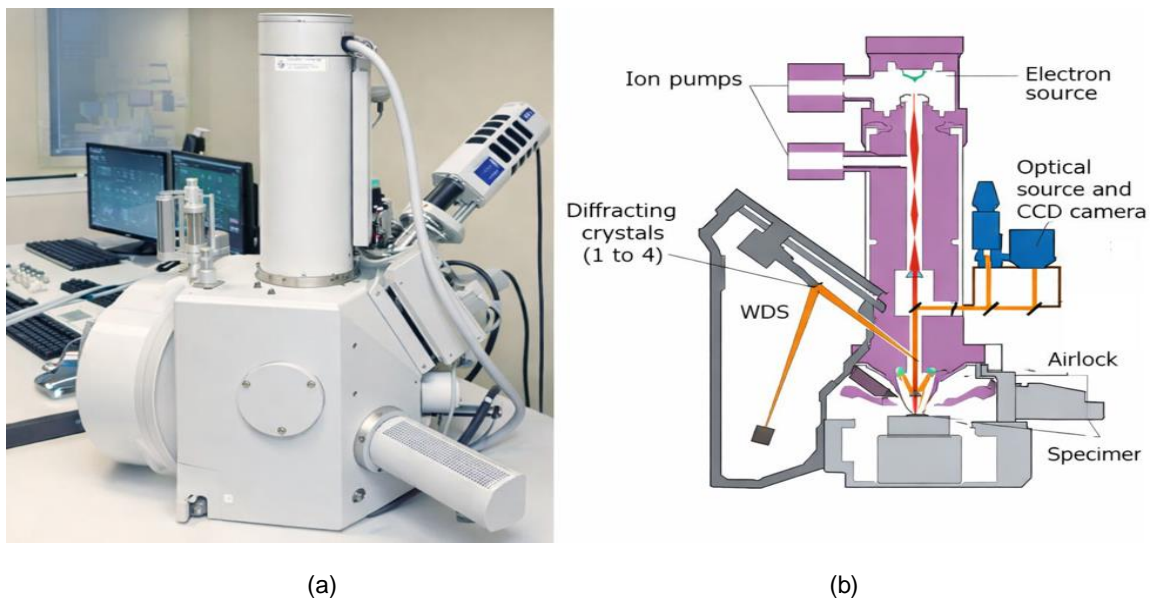


FIGURE 4: (a) Quanta 450 scanning electron microscope is a type of electron microscope that produces images of a sample; (b) The schematic diagram of Quanta 450 scanning electron microscope.

TABLE 4: Quanta 450 scanning electron microscope specification

Detail	Specification
High vacuum	3.0 nm at 30 kV SE
	4.0 nm at 30 kV BSE
	10.0 nm at 3 kV SE
High vacuum with beam deceleration	6.2 nm at 3 kV BD mode* +vCD*
Extended vacuum mode ESEM	3.0 nm at 30 kV SE

The preparation of fuels in accordance with prescribed procedures and proper standards of accuracy, as well as the use of quality tools, will produce the expected fuel composition. The fuel produced in a real state, as required, helps the analyst to compare the quality of fuel properties well.

3. RESULTS AND DISCUSSION

3.1 Particulate Surface Morphology

Particulate surface morphology is a method of identifying the particulate accumulation rate tested on five types of test fuels, namely diesel, B5M10, B10M10, B5M10E3, and B10M10E3. Particulate matter is collected using a fiber filter placed on the exhaust. All samples of diesel, B5M10, B10M10, B5M10E3, and B10M10E3 were collected at 1800 rpm speed and partial engine load conditions. A Scanning Electron Microscope (SEM) was used to view particulate matter morphology. Figure 5 demonstrates the particulate surface morphology for diesel, B5M10, B10M10, B5M10E3, and B10M10E3 at 1800 rpm and partial engine load conditions.

3.2 Analysis of Particulate Surface Morphology

There was a particle state that was ripped and stacked to illustrate many of the collected particles for diesel samples. The morphology of Figure 5(b) (B5M10) particulate matter was slightly lower than that of diesel at 1800 rpm speed and partial load conditions. The B5M10 sample had no particle conditions that were split and overlapped, where the collected particles were less than diesel. Figure 5(c) (B10M10) was found to have no ripped particles, and the cylinder fiber shape indicates that the particles collected were fewer than those in the diesel and B5M10 samples.

Particulate surface morphology for Figure 5(d) (B5M10E3) was found to have less particulate matter compared to the other three samples, namely diesel, B5M10, and B10M10. The shape of the cylinder fiber was visible, and there was a space between the cylinders, which demonstrated that the particles collected were lower than those of diesel, B5M10, and B10M10. Particulate surface morphology for Figure 5(e) (B10M10E3) was found to collect the least particulate matter as compared to the other four samples. The form of the cylinder fiber was visible, and there were black spaces between the cylinders, indicating that the particles collected were lower than the others. The results are in full agreement with Figure 5. The attributes are high fuel oxygen content and the occurrence of the micro-explosion phenomenon with emulsion fuels (Elsanusi et al., 2017).

The morphology of the particulate surface for B10M10E3 was found to have the least amount of particulate matter compared to the other fuel samples. The form of cylinder fiber was visible, and there was a black space between the cylinders, indicating the particles collected are less than diesel, B5M10, B10M10, and B5M10E3 samples at 1800 rpm and partial load conditions. The surface morphology of B5M10 and B10M10 was found to have particulate matter concentrations that are less than diesel due to the high oxygen content, and a better mixture resulting from micro-explosions. Therefore, fuel modification with both oxygenation and water emulsion is found to limit the emissions of particulate matter. However, the reduction should be further evaluated for on-road conditions, considering all the variables that might affect particulate matter formation.

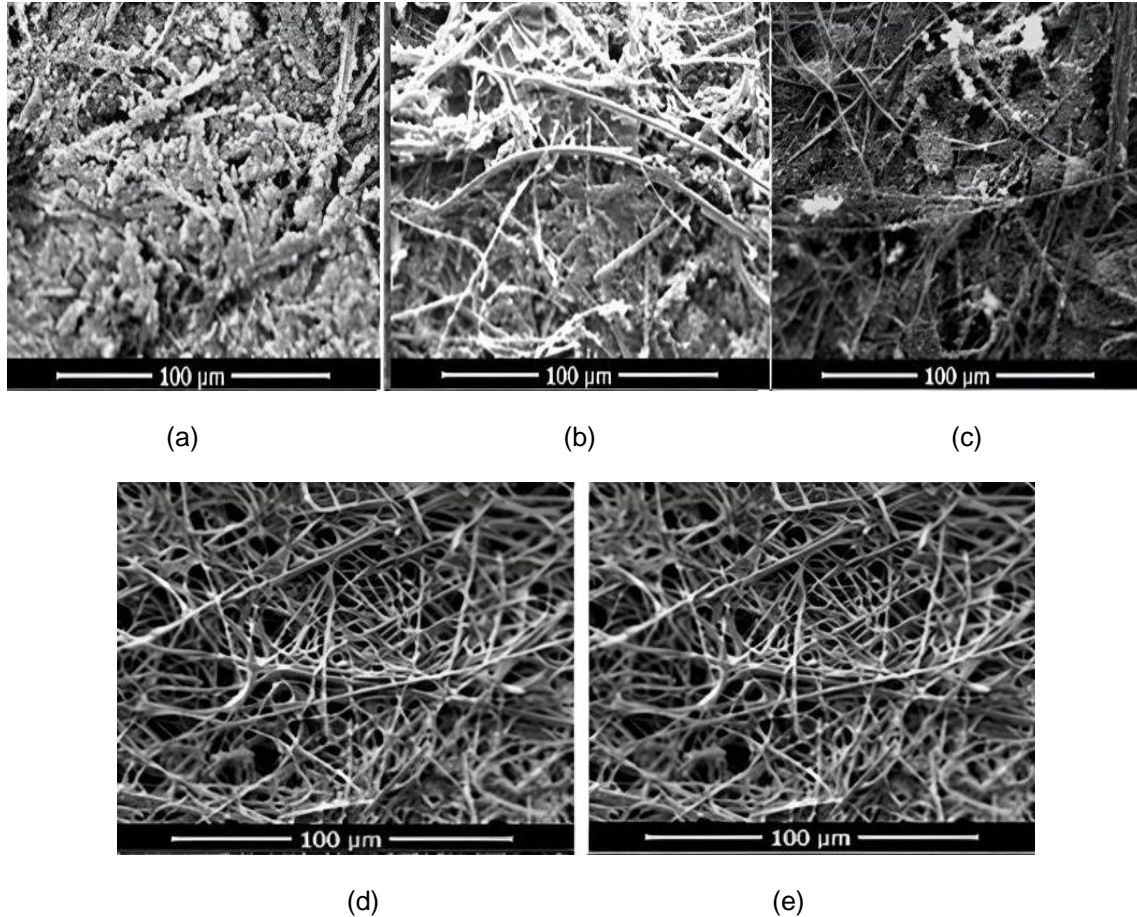


FIGURE 5: Scanning electron microscope images for particulate samples at 100 μm : (a) Diesel 1800 rpm 50% load, (b) B5M10 1800 RPM 50% load, (c) B10M10 1800 rpm 50%, (d) B5M10E3 1800 rpm 50% load, (e) B10M10E3 1800 RPM 50% load

4. CONCLUSION

PM concentration reduces natural visibility. Acid rain, which results when sulfur dioxide (SO_2) and nitrogen oxides (NOX) are emitted into the atmosphere, damages buildings and structures because it dissolves the stone or corrodes the metal that is exposed to the weather. The combination of 10% methanol and 10% biodiesel (B10M10) effect is also observed to reduce PM concentration considerably, lower than B5M10 due to high cetane. Diesel fuel was found to have high PM in all engines compared to alternative fuels, as it tends to be less efficient. The addition of 3% water and 10% biodiesel in B10M10E3 enables it to have the lowest PM concentration compared to diesel, B5M10, B10M10, and B5M10E3 due to micro-explosions leading to secondary fuel atomization. Overall, biodiesel blends produce lower PM, SOF, and DS compared to diesel due to high oxygen content and lower cetane number. Meanwhile, emulsion fuel produces lower PM, SOF, and DS compared to diesel or biodiesel blends due to the micro-explosion phenomenon and high cetane number. Morphology for B10M10E3 was low for particulate concentration compared to other tested fuels due to high oxygen content and high combustion efficiency. The B10M10E3 is recommended as among the best fuels in terms of fuel properties, performance, emissions, and particulate matter tested.

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