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Optimization and Performance Analysis of Microalgae Oil-Derived Biodiesel/Diesel Blends: An Emission Test Study

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Abstract: The deleterious environmental impacts of crude oil, notably significant pollution and escalated greenhouse gas emissions, necessitate alternative fuels. In this context, biodiesel, particularly when blended with diesel, emerges as a viable substitute. This study investigates the emissions and performance characteristics of diesel-biodiesel blends, utilizing microalgae oil-based biodiesel. Variations in the catalyst (potassium hydroxide, KOH), reaction duration (30-110 minutes), and temperature (30-70°C) were explored to determine their influence on biodiesel yield. The biodiesel produced was characterized using Fourier-transform infrared spectroscopy (FTIR), revealing distinct absorption bands indicative of various functional groups present. Furthermore, emission testing was conducted on a TecQuipment TD202 diesel engine, a naturally aspirated, single-cylinder, four-stroke, direct-injection, air-cooled model. Optimization studies revealed that the optimal biodiesel yield was achieved using 2g of KOH, at a temperature of 60°C, and within a reaction time of 90 minutes. Emission testing demonstrated a decrease in exhaust gas temperature (EGT) with reduced biodiesel blend ratios and an increase with engine speed across all blends. Carbon monoxide (CO) emissions diminished with lower biodiesel concentrations, whereas carbon dioxide (CO_2) and nitrogen oxides (NO_x) emissions escalated. Total hydrocarbons (THC_S) emissions increased with reduced biodiesel content, and smoke opacity escalated with lower biodiesel blend ratios. This investigation methodically examines the emissions from various biodiesel blends, underscoring their potential as a cleaner, more sustainable option for the transportation sector.

Keywords: Microalgae biodiesel; Emission analysis; Diesel-biodiesel blends; Transesterification optimization; Sustainable fuel alternatives

1 Introduction

The increasing appeal of renewable energy sources is primarily attributed to factors such as the depletion of petroleum reserves, escalating oil costs, and the imperative to mitigate greenhouse gas emissions. Biodiesel development stands out as a key strategy to diminish reliance on petroleum resources [1]. Biodiesel has garnered international attention due to its compatibility and favourable characteristics as a fuel. Globally, crops like soybean, sunflower, and mustard seed oil predominantly serve as biodiesel sources. However, considering the existing deficits in edible oil supplies, the production of biodiesel from these edible oils is not a viable option [2]. First-generation biodiesel technologies are limited by their dependence on edible feedstocks, which poses a threat to food availability for both humans and animals, and their reliance on feedstocks that are inadequate to replace the energy currently provided by petroleum. Consequently, harnessing non-edible feedstocks for biofuel production emerges as a sustainable approach to fulfilling future global energy demands [3–5].

Biodiesel, a renewable fuel, demonstrates potential in reducing pollution and carcinogenic substances. Its compatibility with existing diesel engines negates the need for technological modifications and, due to its photosynthetic carbon origin, results in higher quality exhaust gas emissions. Biodiesel use does not contribute to atmospheric carbon dioxide concentrations, thereby circumventing the exacerbation of the greenhouse effect. Its combustion has been observed to reduce emissions of CO, CO_2, HC, and smoke, albeit with an increase in NO_x emissions compared to petrodiesel [6]. Biodiesel boasts several superior qualities: it is renewable, exhibits higher biodegradability than petroleum and its derivatives, is non-toxic, provides effective lubrication, and is virtually free from aromatics and sulfur [1].

The primary impediment to biodiesel's commercial viability lies in its higher production costs relative to fossil fuel-derived diesel [7]. The cost of production is substantially influenced by the price of raw materials or feedstock. Factors contributing to these elevated costs include the high expenses of energy and fertilizers, a low yield of biofuel from the feedstock, and the limited availability of resources for biofuel production [8]. From a safety standpoint, biodiesel is one of the safest alternative fuels due to its exceptionally high flash point. Notably, biodiesel's cetane index surpasses 51, enhancing fuel ignition efficiency and diminishing idle noise in vehicles. The practice of blending diesel with biodiesel to enhance performance has been widely researched, with the most common blend being 20% vegetable oil ester (referred to as B20, signifying 20% biodiesel content) and 80% conventional diesel [9].

Additionally, it has been noted that the consumption of biodiesel blends only results in a marginal 5%-7% increase in fuel consumption compared to traditional diesel. Investigations into biodiesel blended with ethanol have shown that a 20% blend can reduce CO and NO_x emissions, albeit with an increase in HC emissions [9]. Despite this, research on emissions from diesel blended with biodiesel derived from microalgae oil remains sparse. Therefore, the aim of this study is to explore the emissions and performance characteristics of diesel-biodiesel blends, specifically those made from microalgae oil. This research endeavors to aid the shift from conventional fuels to cleaner alternatives by providing valuable insights into the application of microalgae-based biodiesel. The findings of this study are vital for policymakers, researchers, and industries in search of sustainable alternatives to conventional fossil fuels, contributing to the broader objectives of sustainable energy and environmental preservation.

2 Materials and Methods

2.1 Sample Collection, Production and Analysis of Biodiesel

Microalgae oil, serving as the feedstock, was sourced from the BioEnergy Research Lab at the Chemical Sciences Department, Achievers University Owo, Nigeria. A precise volume of 50 mL of this oil was heated within a temperature range of 30 to 70°C and subjected to continuous stirring using a magnetic stirrer. Varying amounts of KOH catalyst, ranging from 0.5g to 3.0g, were weighed and dissolved in 25 mL of methanol [4]. This methoxide solution was subsequently introduced into the heated oil, followed by stirring for a duration ranging from 30 to 110 minutes. Post-reaction, the mixture was allowed to cool to ambient temperature and then transferred to a separating funnel for phase separation. To purify the biodiesel fraction, 10 mL of ethyl acetate was added, followed by three successive washings with 10 mL of distilled water to remove impurities such as excess methanol, glycerol, and solid residues including dirt, debris, or catalyst remnants. The resultant biodiesel was labelled appropriately and stored for subsequent analysis [10].

Biodiesel characterization was conducted in accordance with the official methods prescribed by the Association of Official Analytical Chemists [11]. FTIR spectroscopy was performed using a Varian 660 MidIR Dual MCT/DTGS equipment. All analyses were executed in triplicate.

2.2 Performance and Emission Test of Biodiesel/Diesel Blend

The performance and emission characteristics of various biodiesel-diesel blends were examined. These blends, prepared in different ratios as outlined in Table 1, were tested using a TecQuipment TD202 diesel engine. This engine, a naturally aspirated, single-cylinder, four-stroke, direct-injection, and air-cooled model, was connected to a small engine test bed. Engine speeds ranged from 1000 to 3000 rpm, with all data meticulously recorded and monitored via a computer system.

Table 1. Key parameters of our model

	Ratio (%)		
S/N	**Biodiesel**	**Diesel**	**Name**
1	100	0	B
2	80	20	B80
3	60	40	B60
4	40	60	B40
5	20	80	B20
6	0	100	D

2.3 Statistical Analysis

To assess experimental reproducibility, optimization tests and physicochemical analyses of biodiesel were conducted in triplicate, with results expressed as Mean ± Standard Deviation Data analysis involved one-way analysis of variance (ANOVA) utilizing SPSS version 21. Duncan's multiple range test was applied to identify statistically significant differences among means at a significance level (a) of 0.05.

3 Results and Discussion

3.1 Optimization of Biodiesel Production Process

The influences of catalyst concentration, reaction temperature, and reaction time on biodiesel yield were explored, as depicted in Figure 1, Figure 2 and Figure 3 respectively.

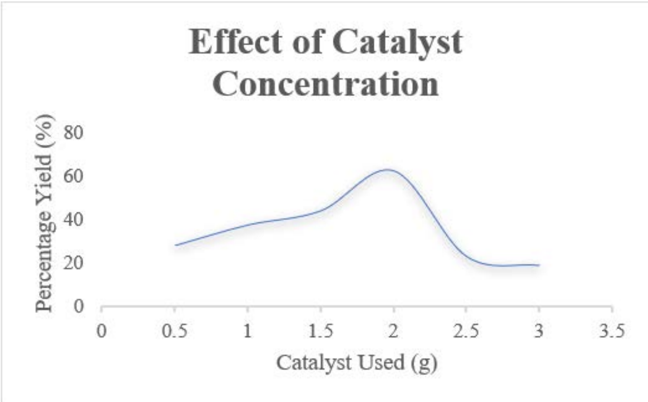

Figure 1. Effect of catalyst concentration on biodiesel yield

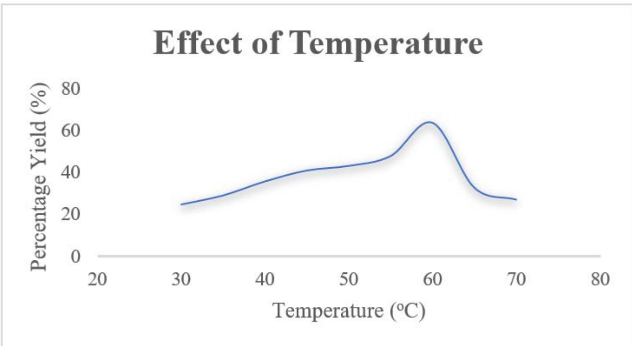

Figure 2. Effect of temperature on biodiesel yield

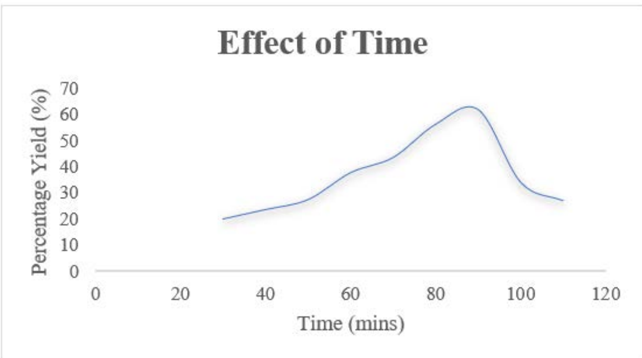

Figure 3. Effect of time on biodiesel yield

Variations in the concentration of KOH from 0.5g to 3g were analyzed to determine its impact on biodiesel yield. An initial increase in yield was observed when the concentration was elevated from 0.5g to 2g, followed by a notable decline at concentrations of 2.5g and 3g. The optimal yield was recorded at a concentration of 2g of KOH. Similarly, the reaction temperature was varied from 30 to 70℃ to identify the optimal condition for biodiesel production. A marked increase in yield was observed from 30℃ to 60℃, beyond which a decrease was noted at 70℃. The peak yield was achieved at 60℃. Furthermore, the effect of reaction time, ranging from 30 to 110 minutes, was examined. A progressive increase in biodiesel yield was observed up to 90 minutes, which represented the optimum reaction time, as yields diminished beyond this duration. These findings are consistent with those reported by Efavi et al. [12] in their study utilizing Citrullus vulgaris (watermelon) seeds as a feedstock for biodiesel production.

3.2 Physicochemical Analysis of Biodiesel

Table 2 shows the physicochemical analysis results of the produced biodiesel.

Table 2. Physicochemical analysis results of biodiesel

Parameters	Biodiesel	ASTM Standard
Specific gravity	0.725 ± 0.01	0.95 max
Viscosity	2.95 ± 0.5	1.90 to 6.00
Acid value $\mathrm{mg\ KOH/g}$	0.51 ± 0.01	0.60
Cetane number	47.82 ± 1.5	46 to 52
Flashpoint $(^{\circ}\mathrm{C})$	135 ± 3.20	$130\ \mathrm{min}$
Cloud point $(^{\circ}\mathrm{C})$	4.87 ± 0.05	4.80 to 5.30
Water by distillation $(\%)$	ND	$0.5\mathrm{max}$
Ash content $(\%)$	ND	$0.1\mathrm{max}$

The specific gravity of the produced biodiesel was determined to be 0.725, falling within the ASTM standards, which stipulate a maximum of 0.95. This value is notably lower than the 0.91 reported in previous research [13]. Specific gravity, a dimensionless unit comparing the density of a substance to that of a reference (typically water), is pivotal in biodiesel production for quality assurance and control. It provides insights into the composition and purity of biodiesel. Deviations from the standard range of specific gravity may indicate the presence of contaminants or impurities, potentially affecting the fuel's functionality and compatibility with engines. The energy content and combustion properties of biodiesel are significantly influenced by its specific gravity. This parameter is crucial for engine manufacturers and users in determining the optimal fuel-air mixture for efficient engine performance. Discrepancies in specific gravity can lead to issues such as elevated emissions, reduced engine efficiency, or potential engine damage [13].

The viscosity of the biodiesel was measured at 2.95, aligning with ASTM standards ranging from 1.90 to 6.00. This viscosity is slightly higher than the 2.65 value reported in the study [13]. Viscosity plays a critical role in fuel injection and atomization within the engine combustion chamber. Effective atomization is essential for the fuel to mix efficiently with air, thus promoting optimal combustion. Excessively high viscosity may lead to diminished engine performance, increased emissions of particulate matter, and incomplete combustion. Compared to conventional diesel, biodiesel generally exhibits a higher cloud point and pour point, affecting its flow characteristics at lower temperatures.

The acid value of the biodiesel produced was determined to be 0.51, well within the ASTM standard limit of 0.60. This value differs significantly from the 1.3 KOH/g observed in biodiesel derived from alkaline-treated waste cooking oil [14]. The acid value is a critical parameter for assessing biodiesel stability and quality. It indicates the amount of KOH required to neutralize the acids in one gram of biodiesel, reflecting the concentration of free fatty acids. High acid values in biodiesel signify increased levels of free fatty acids, which can lead to corrosion of engine and fuel system components. Additionally, elevated acidity may result in the formation of deposits and sludge, potentially clogging injector nozzles and fuel filters, thereby impairing engine performance and increasing the risk of mechanical failures [15].

The cetane number was recorded at 47.82, aligning with the ASTM standard range of 46 to 52. The cetane number is an essential indicator of diesel fuel ignition quality, including biodiesel. It directly influences the efficiency, emissions, and performance of diesel engines. This number signifies the time lapse between fuel injection and the commencement of combustion in the engine cylinder, known as ignition delay. Fuels with higher cetane numbers have shorter ignition delays, facilitating more rapid and efficient ignition. Consequently, higher cetane number biodiesel improves overall engine performance, contributing to quieter, smoother operation, and reducing vibration, noise, and knocking during combustion [15].

The flashpoint of the biodiesel was measured at 135℃, which is within the ASTM stipulation of a minimum of 130℃. This value is lower than the 174.15℃ reported for biodiesel from alkaline-treated waste cooking oil [14].

The flashpoint, indicating the lowest temperature at which a liquid emits sufficient vapor to ignite in the presence of an open flame or spark, is a vital property for biodiesel's safety and handling. Higher flashpoints denote reduced flammability and a lower risk of ignition at lower temperatures, crucial for the safe storage, handling, and transportation of biodiesel. Conversely, fuels with lower flashpoints are more susceptible to fire or explosion, especially near ignition sources [16].

The cloud point of the biodiesel was recorded at 4.87℃, fitting within the ASTM standard range of 4.80 to 5.30℃. The cloud point refers to the temperature at which biodiesel begins to form solid particles or crystals, causing it to appear cloudy. Biodiesel with a high cloud point may experience flow issues in cold conditions, potentially leading to fuel gelling or clogging in injectors, filters, and fuel lines. If the temperature drops below the cloud point, the biodiesel may gel or solidify, rendering it unusable until it is reheated [17].

3.3 FTIR Spectrum of Biodiesel from Microalgae Oil

The FTIR spectrum of the biodiesel produced from microalgae oil, as illustrated in Figure 4, provides an intricate view of its molecular structure and chemical composition. The spectrum revealed several prominent absorption bands, each indicative of specific functional groups present in the biodiesel molecules. Strong and broad peaks observed in the 2700-3000 cm^{-1} range are characteristic of the long hydrocarbon chains in the biodiesel. These peaks are attributed to the stretching vibrations of the C-H bonds in the alkyl chains. Moreover, the presence of a carbonyl group (C=O), a pivotal functional group in biodiesel, was identified, resulting from the esterification process. This is evidenced by the strong peak for C=O stretching vibration observed at approximately 1745-1755 cm^{-1}. Ester linkages (C-O) in the biodiesel are indicated by absorption bands in the 1052-1253 cm^{-1} region. These bands are generally sharper and more defined compared to other peaks in the spectrum. Additionally, the spectrum displayed medium to strong peaks in the 1398-1469 cm^{-1} range, which are attributed to the bending and rocking vibrations of the $\mathrm{CH_2}$ groups in the fatty acid chains. The methyl ($\mathrm{CH_3}$) groups in the fatty acid chains also contribute to the spectrum, producing distinctive peaks in the 1201-1372 cm^{-1} range, owing to their bending and rocking vibrations.

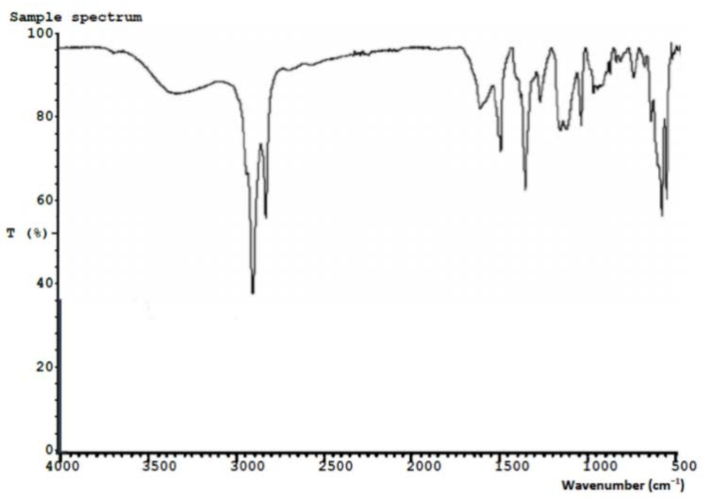

Figure 4. FTIR spectrum of biodiesel from microalgae oil

3.4 Performance and Emission Test

Figure 5, Figure 6, Figure 7, Figure 8, Figure 9 and Figure 10 display the results of the EGT, CO emission, $\mathrm{CO_2}$ emission, $\mathrm{NO_x}$ emission, THC emission, and smoke opacity emission for various diesel/biodiesel blends.

The EGT of diesel/biodiesel blends was varied with engine speeds ranging from 1000 rpm to 3000 rpm. The data indicated a decrease in EGT as the proportion of biodiesel in the blend was reduced, and conversely, an increase in EGT with rising engine speeds across all blends. The lowest EGT values were observed in pure diesel at all engine speeds, while the highest were recorded for 100% biodiesel. EGT is a critical parameter in fuel performance testing for different types of internal combustion engines, providing vital insights into fuel efficiency and combustion characteristics [18]. EGT reflects the temperature of the exhaust gases from the combustion process, serving as a direct indicator of the quality of internal combustion in the engine. Monitoring EGT is essential for assessing the complete and efficient combustion of fuel during performance tests [19].

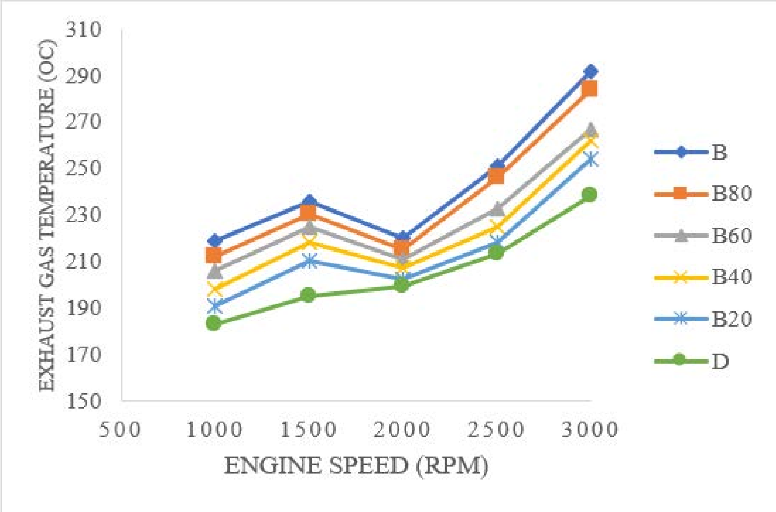

Figure 5. Exhaust gas temperature of diesel/biodiesel blend

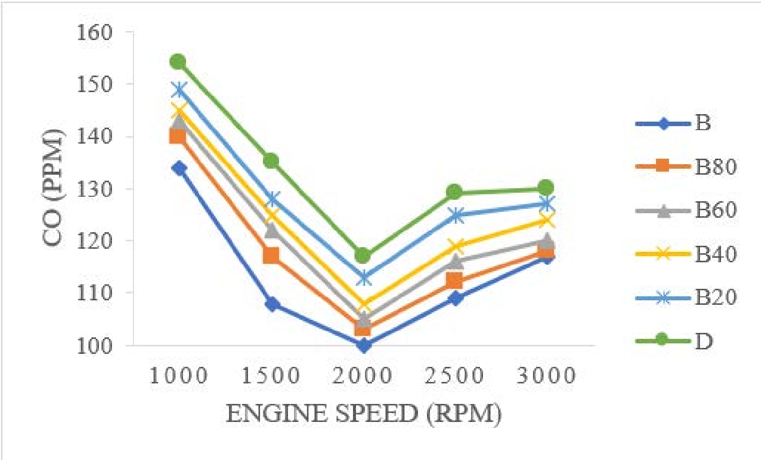

Figure 6. Carbon monoxide emission of diesel/biodiesel blend

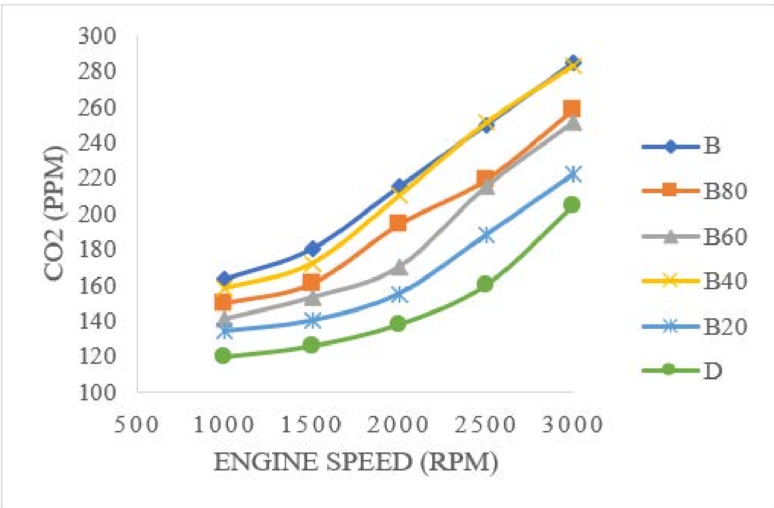

Figure 7. Carbon dioxide emission of diesel/biodiesel blend

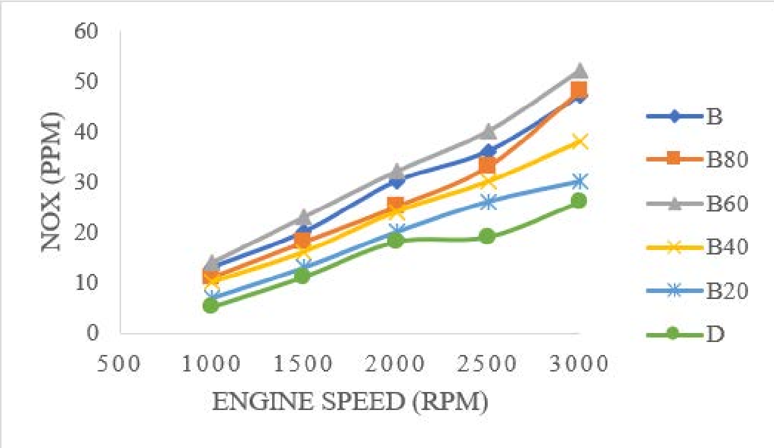

Figure 8. Nitrogen oxide emission of diesel/biodiesel blend

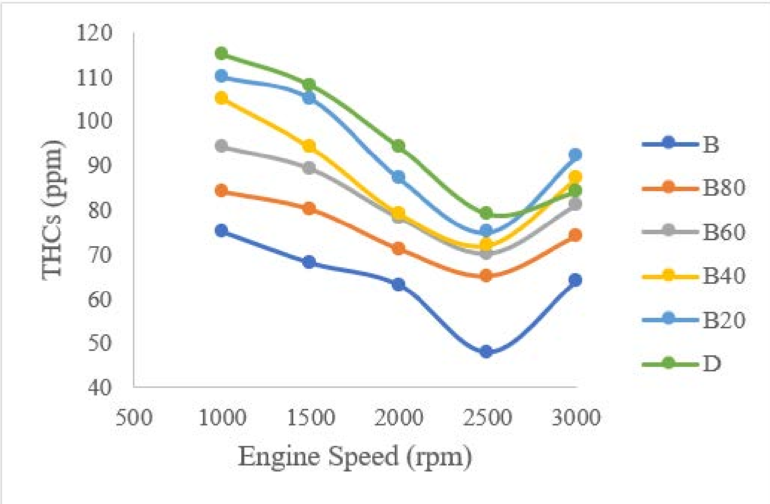

Figure 9. Total hydrocarbons emission of diesel/biodiesel blend

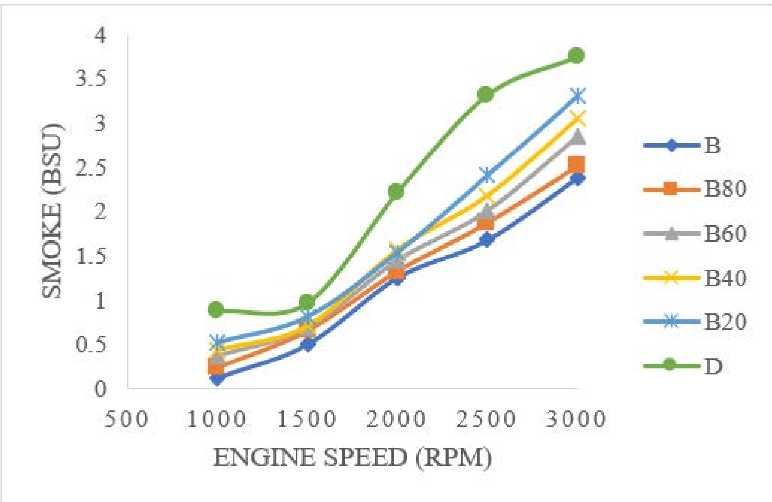

Figure 10. Smoke opacity emissionof diesel/biodiesel blend

Regarding CO emissions, a similar variation with engine speed was observed, ranging from 1000 rpm to 3000 rpm. The results showed a decrease in CO emissions as the biodiesel concentration in the blend decreased. The lowest CO emission levels were observed in 100% biodiesel at all engine speeds, while the highest were noted in pure diesel. Carbon monoxide is a hazardous gas that can cause significant health issues upon inhalation, as it binds more strongly to hemoglobin than oxygen, reducing the blood's ability to transport oxygen to vital organs. Therefore, reducing CO emissions in exhaust gases is crucial to mitigate potential health risks to both the environment and individuals [20].

The CO_2 emissions of diesel/biodiesel blends were examined across engine speeds ranging from 1000 rpm to 3000 rpm. The analysis demonstrated an increase in CO_2 emissions as the biodiesel concentration in the blend increased. The lowest CO_2 emission levels were recorded for 100% diesel at all engine speeds, while the highest CO_2 emissions were observed in 100% biodiesel, with an overall increase in CO_2 emissions across all blends as engine speed increased. While CO_2 is a well-known greenhouse gas linked to climate change and global warming, high levels of CO_2 emissions in fuel emission tests can be indicative of more complete combustion. In scenarios where complete combustion occurs, all available carbon in the fuel is converted to CO_2, which, despite its environmental impact, is less harmful than other byproducts of incomplete combustion [21].

The NO_x emissions of diesel/biodiesel blends were similarly varied with engine speeds within the 1000 rpm to 3000 rpm range. The results indicated an increase in NO_x emissions as the biodiesel concentration in the blend increased. The lowest NO_x emission values were observed in 100% diesel for all engine speeds, while the highest values were noted in blends with 60% biodiesel. Excessive NO_x emissions are detrimental to the environment, adversely affecting the quality of soil, water, and ecosystems. Elevated levels of NO_x emissions can harm plant life and contribute to the eutrophication of water bodies, thereby impacting biodiversity [22].

The THC emissions of diesel/biodiesel blends were evaluated across engine speeds from 1000 rpm to 3000 rpm. The analysis revealed an increase in THC emissions as the biodiesel concentration in the blend decreased. The lowest THC emission levels were recorded in 100% biodiesel at all engine speeds, while the highest values were observed in 100% diesel. Hydrocarbons, particularly in their unburned form, have a negative environmental and air quality impact, contributing to the formation of ground-level ozone and smog. Lowering THC emissions is critical for reducing air pollution and its associated environmental damage. Unburned hydrocarbons are also implicated in climate change due to their role in generating greenhouse gases. Reducing THC emissions is a crucial part of broader efforts to limit pollutants that contribute to global warming. These emissions are known to have adverse health effects, exacerbating respiratory conditions and other health issues [23].

The smoke opacity emissions of diesel/biodiesel blends were also varied with engine speeds in the range of 1000 rpm to 3000 rpm. The results indicated an increase in smoke opacity emissions as the biodiesel concentration in the blend decreased. The lowest smoke opacity emission values were observed in 100% biodiesel for all engine speeds, while the highest values were noted in 100% diesel. Smoke opacity is a direct indicator of particulate matter emissions, which are significant contributors to air pollution. Elevated smoke emissions can degrade air quality, posing environmental and health hazards. Particulate matter, particularly from smoke emissions, is associated with various health issues, including respiratory problems. The inhalation of particulate matter can be especially harmful to individuals with existing respiratory disorders. Thus, reducing smoke opacity emissions is crucial for diminishing health risks and enhancing air quality, ultimately contributing to the protection of public health [24].

4 Conclusion

This research, focusing on the emission characteristics of biodiesel/diesel blends, has yielded significant insights into the environmental implications of these alternative fuels. Exhaust emissions from various blends were meticulously analyzed, highlighting their potential as cleaner and more sustainable options for the transportation sector. It has been observed that blends of biodiesel and diesel can markedly reduce certain noxious emissions in comparison to conventional diesel fuel. The noted reductions in particulate matter, nitrogen oxides, and other pollutants underscore the potential of biodiesel integration into diesel fuel blends to enhance air quality and mitigate the detrimental effects of traditional diesel combustion.

However, it is imperative to acknowledge that emission characteristics are influenced by the blend ratio and the specific attributes of the biodiesel utilized. Future research endeavors should be directed towards optimizing blend formulations, taking into account variables such as feedstock, production methodologies, and fuel properties. Long-term studies are also paramount to evaluate the durability and reliability of engines operating on biodiesel blends over extended periods. This study underscores the importance of ongoing efforts to explore and implement sustainable alternatives to conventional fossil fuels.

Biodiesel/diesel blends emerge as a promising approach to reduce the environmental impact of transportation, aligning with global initiatives to combat climate change and improve air quality. The findings from this research provide crucial insights that can inform future developments and policies in the quest for a more sustainable and eco-friendly transportation sector. As policymakers, industries, and consumers navigate the challenges associated with fuel emissions, the knowledge gleaned from this study is invaluable in guiding future strategies and decisions.

Data Availability

The data used to support the research findings are available from the corresponding author upon request.

Conflicts of Interest

The authors declare no conflict of interest.

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