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Emission characteristics of a compression ignition engine using biodiesel and clove oil antioxidant blends

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ABSTRACT

The growing environmental concerns associated with fossil fuel combustion have intensified the search for sustainable alternatives, particularly in the transportation sector. Biodiesel, derived from renewable biological sources, offers a promising substitute for conventional diesel due to its potential to reduce greenhouse gas and particulate emissions. However, its use in compression ignition (CI) engines presents challenges, including oxidative instability and inconsistent performance. This study investigates the impact of biodiesel blends, with and without antioxidant additives, on engine emissions in a single-cylinder CI engine. Three fuel types were evaluated: pure diesel (D100), a biodiesel blend (B30: 70 % diesel, 30 % biodiesel), and a modified blend incorporating 3 % clove oil antioxidant (D67+B30+3Cl). Emissions of particulate matter (PM), carbon monoxide (CO), carbon dioxide (CO_2), and noise levels were measured under controlled operating conditions. The results reveal a 14.6 % reduction in PM emissions with B30 compared to D100, and a further 28.1 % reduction with the clove oil-enhanced blend. Additional decreases in CO, CO_2, and noise emissions were also recorded, highlighting the benefits of antioxidant-enriched biodiesel in enhancing combustion efficiency. These findings underscore the potential of biodiesel-antioxidant blends to improve environmental performance while suggesting directions for future research in fuel stability and long-term engine compatibility.

1. Introduction

An important determinant of a country's economic standing is the growth in foreign exchange outflow coinciding with the rising demand for conventional fuel [1]. As industrialization and population growth accelerate, the use of petroleum-derived fuels is increasing. To mitigate the severe environmental impact of diesel engine emissions, control measures must be implemented.

To enhance performance and reduce emissions, researchers are exploring alternative fuels. Studies on Annona Methyl Ester (AME) [2–5] have shown that while blending it with diesel reduces Brake Thermal Efficiency (BTE), which is the ratio of useful engine power to total fuel energy input, the A20 blend's BTE is comparable to diesel. Moreover, adding oxygen to biodiesel blends significantly reduces CO, HC, and smoke emissions. Although biodiesel blends emit more NOx, the A20 blend can be used without engine modifications [6].

Various vegetable oils, including Calophyllum inophyllum, Ficus elastica, Nicotiana tabacum, Madhuca indica, Pongamia pinnata, and Jatropha curcas, have been explored as potential diesel substitutes. Researchers have investigated different transesterification techniques to improve biodiesel's viscosity and other properties [7–10].

Studies on biodiesel derived from rice bran, neem, and cottonseed oil [11–14] have shown that these blends exhibit higher Exhaust Gas Temperature (EGT) and lower BTE compared to diesel. While biodiesel increases NOx emissions, it reduces CO, HC, and smoke. Tests on diesel and 100 % Jatropha biodiesel [13,15–17] revealed that the pure Jatropha blend has a BTE of 21.2 % at maximum load, lower than diesel's 29.6 %. Although Jatropha biodiesel emits higher NOx and CO_2, it significantly reduces smoke, HC, and CO emissions. Research on Palm Methyl Ester (PME) and its impact on CI engine performance [18] has shown that PME reduces CO and HC emissions by 8.2 % and 8.9 %, respectively, while significantly lowering NOx emissions. However, it leads to a 2.4 % decrease in thermal efficiency and a 4.2 % increase in Brake Specific Fuel Consumption (BSFC).

Studies on Mango Seed Methyl Ester (MSME) and L-ascorbic acid (LAA) [19] have shown that MSME increases specific fuel consumption (SFC) and decreases BTE under all load conditions. While MSME reduces

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Nomenclature:

PM	Particulate Matter
CO	Carbon Mono Oxide
CO_2	Carbon Di Oxide
D100	Diesel 100 %
B30	Biodiesel 30 %
BTE	Brake Thermal Efficiency
EGT	Exhaust Gas Temperature

CO, HC, and smoke emissions compared to diesel, adding LAA increases these emissions. However, LAA scavenges free radicals in MSME blends, reducing NOx emissions.

Biodiesel, derived from renewable sources like vegetable and animal fats, offers an environmentally friendly alternative to conventional diesel fuel. It reduces reliance on petroleum, lowers greenhouse gas emissions, and is safer and more biodegradable. Government incentives, rising demand for renewable energy, and technological advancements have driven the growth of biodiesel production and use [20,21].

While soybean oil was historically the primary feedstock, a shift towards sustainable sources like used cooking oil, algae, and waste fats and oils is underway. Technological advancements have improved biodiesel production efficiency and reduced costs. Blending biodiesel with conventional diesel further enhances performance and reduces emissions. Government support and incentives worldwide are driving the expansion of the biodiesel industry [22–25]. The global biodiesel industry is indeed experiencing significant growth, driven by supportive government policies and incentives. According to International Energy Agency and the Renewable Energy Policy Network for the 21st Century, renewables supplied 30 % of global electricity, 10 % heating, and 3.5 % of transport fuels in 2023 [26]. It strongly maintained in the report that to meet the target of 11 TW by 2030, there is a requirement of almost 1 TW per year of accelerated capacity additions. In 2023, investment in renewable energy and related technologies expanded 70 %, with solar PV and battery storage being at the forefront. Still, the IEA says current trends will not be sufficient to meet the United Nations' goal of tripling renewable capacity by 2030. This would require further efforts in integrating renewables into the grids by building and upgrading as many as 25 million kilometres of electricity networks and deploying 1500 GW of storage capacity. Solar PV will contribute with 80 % of that new capacity, while the wind sector will grow at twice its previous pace. Findings from IEA and REN21 point to an enormous progress in the deployment of renewables but also a critical further need for policy support and infrastructure so that global energy and climate targets can be reached [27,28].

Biodiesel production promotes energy diversification, which mitigates the vulnerabilities associated with excessive reliance on petroleum. It also is consistent with global renewable energy targets and domestic policies to decarbonize transportation. Biodiesel blends, such as B20 (20 % biodiesel, 80 % petroleum diesel) are compatible with current diesel engines, and can be used with little if any modifications to existing fuel infrastructures.

Further, on a macro level, biodiesel generation will encourage technology development and skill in the field of renewable energy technologies. It is an enabler to mature catalyst development and to optimize production processes like transesterification to achieve higher yield and lower cost. In addition, biodiesel technology is more beneficial in food-energy balance that can also utilize marginal lands to plant non-consumable feedstocks and not being a competition for food crops.

From an energy transition perspective, biodiesel is part of the bridge that needs to be built between oil and gas and newer technologies such as electric vehicles. It also assists other renewable energy systems by offering a dependable, low-carbon fuel source for applications that may not be suitable for electrification at this time, such as heavy-duty transportation and aviation.

Despite these advantages, challenges remain, including the availability of feedstock, production costs, and lifecycle emissions from land use change. Hence, ongoing research and policy measures are necessary to promote feedstock diversification, refining technologies, and enabling sound sustainability frameworks. However, with some solutions already identified, addressing these challenges will help biodiesel reach its full potential – as an important part of a growing, renewable energy portfolio for sustainable development and global energy resilience.

Although biodiesel is a promising and potentially renewable energy source, the performance and emissions profile of compression ignition engines using biodiesel remains relatively under-researched. Despite the demonstrated greenhouse gas (GHG) emissions benefits of biodiesel, elevated NOx emissions and lower brake thermal efficiency (BTE) present challenges to widespread adoption. Additionally, limited studies have been conducted on the effect of mixing biodiesel with antioxidants to decrease emissions and improve engine performance, especially regarding particulate matter (PM), carbon monoxide (CO), and noise emissions. The present study tries to fill this gap with systematic investigation on emissions and performance in CI engine operated on biodiesel–antioxidant blend to assist in optimizing biodiesel as a potential sustainable substitute for petroleum-based fuels.

The literature review indicates that significant research has been conducted to investigate the performance and emissions of compression ignition engines using various fuels. However, very few studies have explored the use of clove oil in such investigations. Additionally, limited information is available regarding carbon monoxide and carbon dioxide emissions when using clove oil. Therefore, a detailed investigation into the performance and emissions, including carbon monoxide and carbon dioxide, of compression ignition engines is essential to better understand engine behaviour and enhance engine longevity.

2. Methodology

2.1. Examine emission of particulate matter (PM)

To investigate the impact of biodiesel blends on particulate matter (PM) emissions from diesel engines, a comprehensive experimental study was conducted. The study focused on PM emissions under various engine operating conditions, including varying speeds and loads, while utilizing different biodiesel blends. The experimental setup consisted of a diesel engine coupled to an eddy current dynamometer, the parameters are described in Table 1. Properties of Fuel Samples D100, B30, and B30+CL3000PPM are described in Table 2. The experimental setup is shown in Fig. 1. The speed, load, and fuel quality of an engine all affect how much pollution it emits. The pollutants from an engine depend on many things, like the engine speed, load, and the type of fuel. Under a

Table 1
Engine specifications.

Parameter	Value
Stroke	80 mm
Speed	2600 RPM
Displacement	0.353 L
Compression Ratio	21–23
Brake Mean Effective Pressure (BMEP)	576 kPa
Piston Mean Speed	6.93 m/s
Specific Fuel Consumption	278.8 g/kWh
Specific Oil Consumption	4.08 g/kWh
Cooling Water Consumption	1360 g/kWh
Injection Pressure	14.2 ± 0.5 MPa
Inlet Valve Clearance	0.15–0.25 mm
Maximum Engine Power	7.7 kW
Maximum Engine Torque	80 Nm

Table 2
Properties of fuel samples: D100, B30, and B30+CL3000PPM.

Parameter	D100	B30	B30+CL3000 PPM	Method
Viscosity (mm^2/s)	2.91	3.92	2.89	ASTM D445
Density (g/m^3)	0.830	0.858	0.829	ASTM D941
Calorific value (MJ/kg)	43	43.5	43.10	ASTM D240
Flash point (°C)	71	84	70	ASTM D93
Cetane number	49	53	55	ASTM D613

long-term engine operation scenario, the effects of these parameters were evaluated by measuring exhaust particulate matter (PM) emissions in a controlled study. In detail, a 10-h continuous test was performed at a constant engine speed with both diesel fuel and biodiesel-blended fuels.

To assess the particulate emissions, the PM was characterised according to its particle size distribution. The exhaust emission measurement was classified into four different particle size categories, in microns, and was conducted periodically throughout the test period. Through this, exhaust particulate matter emissions were collected and analysed at the end of every 10-h cycle, assessing fuel type and operating condition individually, coupled with the model to provide a detailed understanding of their effects on emission characteristics.

These findings were able to provide important insights into the fuel quality and particulate emissions relationship. The data collated may confirm that biodiesel blends assist with reducing some particulate sizes, which ultimately improves air quality and lowers the impact on the environment. The results emphasize the need for developing optimal fuel strategies and the tuning of engine parameters to mitigate polluting emissions in practical scenarios.

2.2. *Engine sound pressure level*

The study analysed the noise levels of a CI engine running on different fuel samples at various loading conditions and constant speed. The sound pressure level was measured from four different directions, including front, back, top, and left, using microphones installed at 1 m from the test bed at each location. The sound pressure level was measured after every 10 h during an endurance test. The measurements were taken using a Benetech GM1356 Digital sound level meter, which measures the sound pressure level in decibels (dB). Table 3 provides detailed specifications of the sound level meter used in the study. This analysis can provide valuable insights into the impact of different fuel samples on the noise levels of CI engines and can help in identifying ways to reduce noise pollution from engine operations.

2.3. *Carbon dioxide and carbon monoxide*

In this experiment, researchers tested the performance and emissions of a specific type of diesel engine, which is a single-cylinder, 4-stroke, water-cooled, direct-injection model, as given in Table 1. The setup included specialized measuring equipment (Testo 350- XL) that tracked important data throughout the test. Operating the engine at a steady speed of 1500 rpm allowed for controlled conditions, making it easier to observe how the engine behaved over time. The focus was on emissions, specifically the levels of carbon dioxide (CO_2) and carbon monoxide (CO), which were measured after the engine had been running for a continuous 10-h period. Monitoring these gases is essential for understanding how efficiently the engine burns fuel, as well as for evaluating its environmental impact. CO_2 is a common byproduct of combustion, while CO indicates incomplete combustion and is a concern for both efficiency and environmental safety. By running the engine over an extended time, researchers could assess both the stability of emissions over time and the potential buildup of these gases during prolonged operation.

3. Results

3.1. *Particulate matter emissions*

The increase in particulate matter emissions with running hours is common due to factors such as carbon deposit buildup, reduced combustion efficiency, and engine wear. However, the rate of increase differs between fuel types, which is crucial for assessing long-term environmental impacts. DF100 (Pure Diesel): The steady rise in PM emissions is expected, given that pure diesel lacks oxygenate, leading to

Table 3
Detailed Specification of sound pressure level meter.

Type	Electric Condenser Microphone
Range of dB Level	35 dB–150 dB
Accuracy	±1.5 dB
Resolution	0.1 dB
Microphone diameter	½ inch
Dynamic Range	55 dB

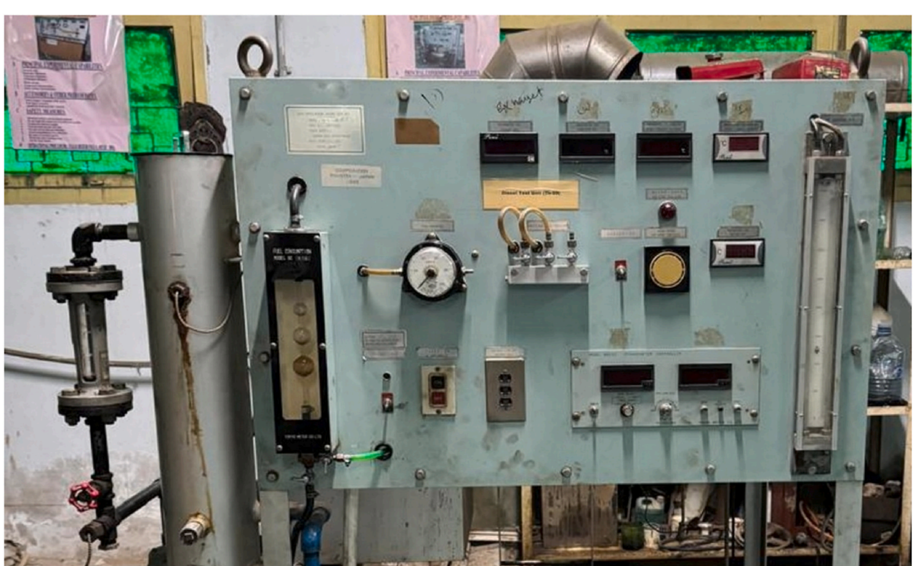

Fig. 1. Experimental setup of Diesel Engine.

incomplete combustion and more soot formation. It appears that after the 100-h mark, emissions escalate more sharply, reflecting potential engine degradation or incomplete fuel burns as shown in Fig. 2. The slower rate of PM increase in B30 indicates that biodiesel's oxygen content enhances combustion. However, it still experiences a rise in emissions over time, suggesting that while biodiesel improves performance, it does not fully prevent carbon deposit buildup, especially as the engine ages. Further, adding clove oil to biodiesel blended fuel resulted in the slowest increase in emissions. The PM slowest increase in emissions with clove oil highlights its potential to improve combustion efficiency over time, due to its antioxidant properties. It suggests that clove oil may also help mitigate engine wear or fouling, keeping emissions low for a longer duration.

While pristine biodiesel (B30) is an improvement over pure diesel, it is not sufficient by itself to reduce particulate matter emissions, especially over extended engine running hours. The use of natural antioxidants like clove oil as additives offers a promising strategy for improving combustion efficiency and reducing emissions. Its renewable nature and effectiveness make it an attractive alternative to chemical additives, contributing to both emission control and sustainability goals. Further studies should explore the optimization of clove oil concentration and investigate the use of other natural antioxidants. Additionally, long-term engine testing could provide insights into how clove oil affects engine wear and overall durability in biodiesel-powered engines.

3.2. CO emissions

Fig. 3 shows that the in-diesel fuel exhibits the highest CO emissions due to incomplete combustion, stabilizing but slightly increasing after 50 h, indicating reduced combustion efficiency when biodiesel blend with diesel Shows lower CO emissions initially, aided by biodiesel's oxygen content. However, CO levels converge with DF100 after 100 h, suggesting diminishing combustion advantages over time. Further clove oil added the lowest CO emissions at all intervals, indicating enhanced combustion efficiency. CO emissions increase gradually over time, reflecting sustained combustion quality. Clove Oil (3 %) is the most effective additive for reducing CO emissions compared to DF100 and B30, demonstrating improved combustion stability and significantly lower CO formation without additives, highlighting the need for supplemental solutions like clove oil. The reduction in CO emissions not only enhances engine performance but also provides critical health and environmental benefits. Future research may explore other natural antioxidants to further improve combustion in fuel technologies.

3.3. CO_2 emissions

DF100 consistently exhibits the highest CO_2 emissions across all operating hours, which can be attributed to the incomplete combustion of diesel fuel that results in elevated carbon dioxide levels. This phenomenon occurs when there is insufficient oxygen available to fully oxidize carbon to carbon dioxide (CO_2), a characteristic typical of diesel combustion. While CO_2 emissions remain relatively stable, they show a slight increase after 100 h, indicating a gradual decline in combustion efficiency as the engine runs longer. In comparison, CO_2 emissions for B30 are lower than those of DF100, particularly during the initial operating hours (from 10 to 100 h) as shown in Fig. 4. The higher oxygen content in biodiesel aids in achieving more complete combustion, thereby reducing CO_2 formation. However, after 10 h of operation, CO_2 levels for B30 begin to converge with those of DF100, suggesting that the combustion advantage of biodiesel diminishes with prolonged engine operation.

Clove oil at a 3 % concentration consistently shows the lowest CO_2 emissions at all intervals. This suggests that clove oil's antioxidant properties contribute to a more complete and stable combustion process, limiting the formation of carbon dioxide. Unlike the other two fuel types, CO_2 emissions from the clove oil blend increase very gradually over time, demonstrating a consistent reduction in CO_2 formation even during extended operation. This indicates that clove oil effectively enhances combustion quality over time, likely by reducing carbon buildup and improving oxygen availability during combustion.

Carbon dioxide is formed when carbon in fuel is not fully oxidized to CO_2, primarily due to insufficient oxygen, lower combustion temperatures, or inefficient fuel mixing. Diesel engines, particularly under load or during cold starts, are prone to CO_2 formation because diesel fuel burns at a slower flame speed compared to gasoline. Biodiesel, such as B30, introduces oxygen into the fuel, which helps achieve more complete combustion and reduces CO_2 formation compared to pure diesel. However, the results indicate that biodiesel alone is insufficient to maintain low CO_2 levels consistently, especially as engine running hours increase.

The clove oil blend demonstrates the lowest CO_2 emissions, highlighting that clove oil's antioxidant properties not only reduce particulate matter but also enhance the combustion process by mitigating incomplete fuel burning. By preventing the oxidation of fuel molecules and ensuring fuel stability, clove oil promotes a more uniform and thorough burn. Its ability to maintain low CO_2 emissions over extended running hours is a significant advantage, suggesting that clove oil helps sustain combustion efficiency and reduces the likelihood of carbon buildup, which can impair air-fuel mixing and oxygen availability during prolonged engine operation. Diesel fuel exhibits the highest CO_2

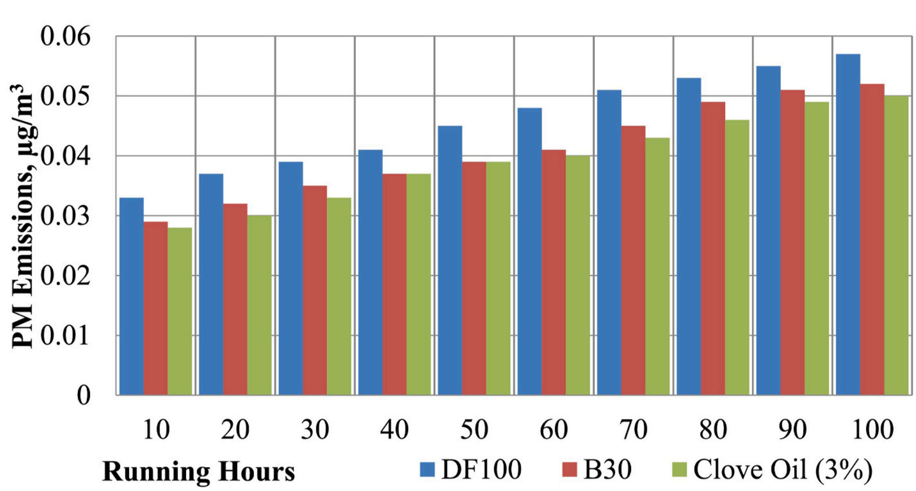

Fig. 2. Variation of particulate matter emissions over time for different fuel blends.

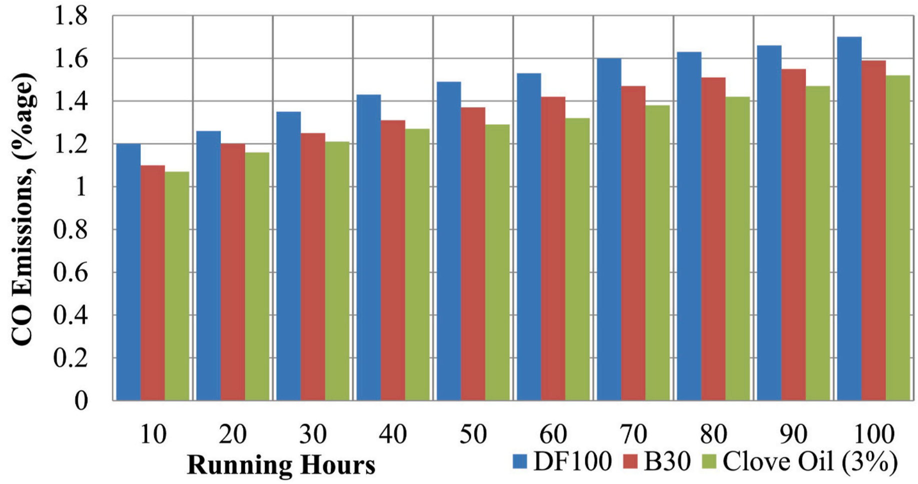

Fig. 3. Carbon monoxide emissions trends for diesel, biodiesel, and biodiesel with antioxidant blends.

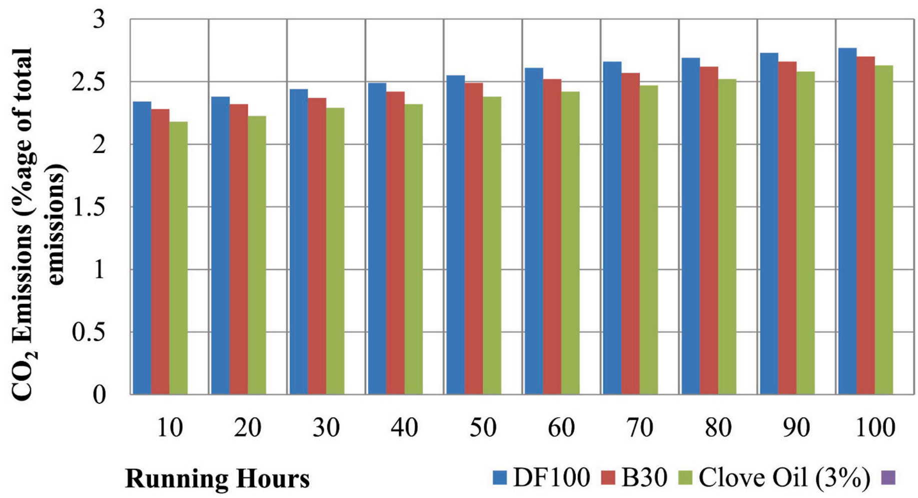

Fig. 4. Carbon dioxide emissions from compression ignition engine fuelled with diesel, biodiesel, and biodiesel–clove oil blends.

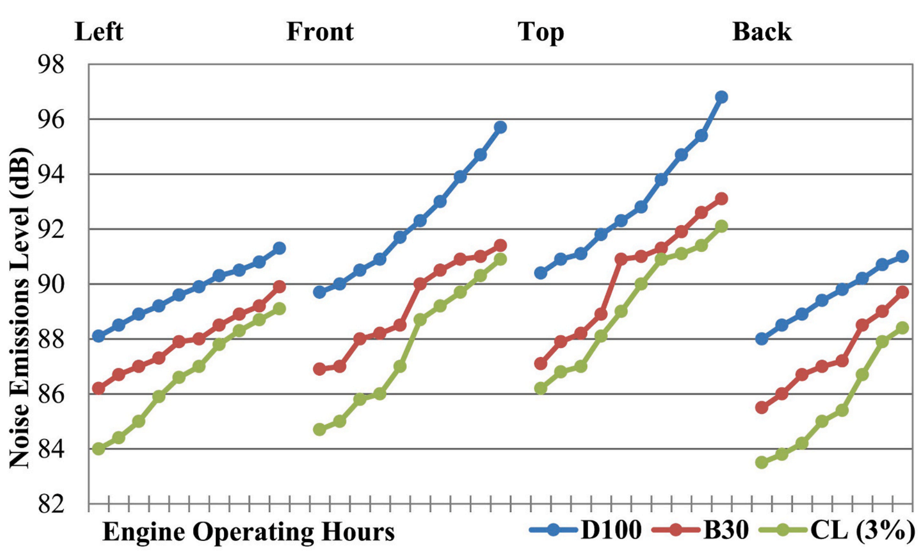

Fig. 5. Noise emissions level at different positions.

emissions due to its lower oxygen content and incomplete combustion characteristics. Over time, the disparity between DF100 and the other two fuel types becomes more pronounced, underscoring diesel's inefficiency in reducing harmful emissions like CO_2. While B30 initially offers a reduction in CO_2 emissions compared to DF100, its advantage appears to diminish with longer engine running hours. Although the oxygenated nature of biodiesel improves combustion efficiency initially, it may lose effectiveness as the engine ages or operates for extended periods. This decline could be linked to carbon deposits, injector fouling, or reduced combustion temperatures over time.

The substantial reduction in CO_2 emissions associated with clove oil not only enhances engine performance but also presents significant environmental and health benefits by minimizing the release of toxic gases and secondary pollutants. The consistent performance of clove oil as an additive provides an opportunity for further research into other natural antioxidants or additive combinations that could sustain or enhance combustion performance in both biodiesel and diesel engines. This research could pave the way for cleaner and more sustainable fuel technologies.

3.4. Noise Emissions Level at Different Positions

Fig. 5 shows the noise emission levels measured at the left side of a compression ignition engine running on pure diesel (DF100), a biodiesel blend (B30), and a biodiesel blend with the addition of 3 % clove oil as an antioxidant additive. The data indicate that pure diesel fuel exhibits the highest noise levels at the left measurement position, attributed to its conventional combustion characteristics which inherently produce more acoustic emissions. In contrast, the biodiesel blend (B30) demonstrates a notable reduction in noise emissions. This improvement is likely a result of biodiesel's higher oxygen content, which contributes to a more complete combustion process, thereby reducing noise intensity.

The addition of clove oil to the biodiesel blend further decreases noise emissions beyond what is achieved with biodiesel alone. Clove oil's antioxidant properties enhance fuel stability and promote smoother combustion, which likely mitigates irregular combustion events that contribute to higher noise levels. This trend suggests that incorporating natural additives like clove oil into biodiesel not only improves combustion efficiency but also provides a sustainable solution for noise reduction in engine operations. The findings underscore the potential of biodiesel-clove oil blends as a dual-purpose strategy to decrease both noise pollution and particulate emissions from diesel engines, advancing environmental and public health goals.

In this critical investigation of noise emissions from a compression ignition engine using biodiesel and clove oil as additives, the data reveals a noticeable reduction in noise emissions from the left position when biodiesel-blended fuel is used, as shown in Fig. 5. Moreover, the addition of clove oil to the biodiesel-blended fuel leads to a further reduction in noise levels, surpassing the performance of both conventional diesel and biodiesel-blended fuel alone. This suggests that the biodiesel-clove oil combination may be an effective strategy for mitigating noise emissions in such engines. The diesel fuel has higher particulate matter emissions of the compression ignition engine. When biodiesel (B30 %) blends with diesel fuel the particulate matter emissions are reduced as compared with the diesel fuel. Further addition of clove oil as an antioxidant in biodiesel blended fuel the particulate matter emissions reduced as compared with the diesel fuel and biodiesel blended fuel.

4. Discussion

This study provides a comprehensive analysis of the emission characteristics of a compression ignition engine when fuelled with pure diesel (D100), a biodiesel blend (B30), and a biodiesel blend enhanced with 3 % clove oil (B30+3Cl). The results consistently demonstrate the positive impact of biodiesel and, more significantly, the antioxidant properties of clove oil in mitigating harmful emissions and improving engine performance.

4.1. Particulate matter (PM) emissions

The findings indicate a clear trend of reduced PM emissions with the use of biodiesel and further reduction with the addition of clove oil. Pure diesel (DF100) consistently exhibited the highest PM emissions due to its inherent lack of oxygenate, leading to incomplete combustion and increased soot formation. The B30 blend showed a 14.6 % reduction in PM compared to D100, which can be attributed to biodiesel's oxygen content enhancing combustion. The most notable improvement was observed with the clove oil-enhanced blend, achieving a 28.1 % reduction in PM emissions. This significant decrease highlights clove oil's potential to improve combustion efficiency over time, likely by mitigating engine wear or fouling and maintaining lower emissions for a longer duration. The study underscores that while biodiesel is an improvement, it is not sufficient on its own to significantly reduce PM emissions over extended running hours, making natural antioxidants like clove oil a promising strategy.

4.2. Carbon monoxide (CO) emissions

Similar to PM, CO emissions were highest for pure diesel, indicating incomplete combustion. While the biodiesel blend (B30) initially showed lower CO emissions due to its oxygen content, its advantage diminished over time, converging with D100 after 100 h. This suggests a potential decline in combustion advantages with prolonged use of B30 alone. In contrast, the clove oil blend consistently maintained the lowest CO emissions across all intervals, showcasing enhanced combustion efficiency and stability. The reduction in CO emissions is crucial for both engine performance and for mitigating critical health and environmental concerns.

4.3. Carbon dioxide (CO_2) emissions

D100 exhibited the highest CO_2 emissions, a characteristic of incomplete diesel combustion where insufficient oxygen hinders full carbon oxidation. The B30 blend initially presented lower CO_2 levels than D100, owing to biodiesel's higher oxygen content promoting more complete combustion. However, this advantage also diminished with extended operation, as CO_2 levels for B30 started to converge with those of D100 after 10 h. The clove oil blend consistently demonstrated the lowest CO_2 emissions at all measurement intervals. This strong performance suggests that clove oil's antioxidant properties contribute to a more complete and stable combustion process, effectively limiting carbon dioxide formation and sustaining combustion efficiency even during prolonged engine operation. The consistent reduction in CO_2 emissions with clove oil offers significant environmental and health benefits by minimizing the release of toxic gases.

4.4. Noise Emissions Level

The study also observed a reduction in engine noise levels with the use of biodiesel blends, particularly when combined with clove oil. Pure diesel generated the highest noise levels. The B30 blend showed a notable reduction, likely due to more complete combustion facilitated by biodiesel's higher oxygen content. The most significant noise reduction was achieved with the addition of clove oil, further decreasing noise emissions beyond what was seen with B30 alone. This effect is attributed to clove oil's antioxidant properties, which enhance fuel stability and promote smoother combustion, thereby mitigating irregular combustion events that contribute to higher noise levels. These findings highlight a dual benefit of biodiesel-clove oil blends in reducing both noise pollution and particulate emissions.

4.5. Implications and future directions

The consistent superior performance of the biodiesel-clove oil blend across all measured emission parameters (PM, CO, CO_2, and noise) underscores its strong potential as a sustainable and environmentally friendly alternative to conventional diesel fuel. These results have practical implications for fuel formulation, engine design, and emissions control strategies, supporting the integration of such blends into existing fuel infrastructures. From a policy perspective, the demonstrated emissions benefits align with global sustainability targets and strengthen the case for promoting biodiesel adoption through regulatory incentives.

Despite these promising results, further research is crucial. Future studies should focus on optimizing clove oil concentrations and investigating other natural antioxidants. Long-term engine testing is necessary to assess the impact of these blends on engine durability, carbon deposition, and maintenance requirements under real-world operating conditions. Additionally, economic analyses of scaling antioxidant-enhanced biodiesel production and exploring engine calibration strategies will be vital for widespread adoption and achieving sustainable, low-emission transportation systems.

5. Conclusion

This study provides a detailed assessment of the emission characteristics of a compression ignition engine fuelled with various biodiesel–antioxidant blends, offering critical insights into their environmental and operational performance. The most significant finding is that the use of biodiesel leads to a 14.6 % reduction in particulate matter (PM) emissions compared to conventional diesel, while the incorporation of clove oil as an antioxidant further enhances this reduction to 28.1 %. These results demonstrate the strong potential of biodiesel–antioxidant blends in mitigating harmful particulate emissions, thereby contributing to improved air quality and public health.

Additionally, the study reveals substantial reductions in carbon dioxide (CO_2) and carbon monoxide (CO) emissions with these blends, reinforcing their role as viable alternatives to fossil fuels in the pursuit of decarbonizing the transportation sector. The observed decrease in engine noise emissions also indicates ancillary benefits for urban environments, where noise pollution is a growing concern.

These findings have practical implications for fuel formulation, engine design, and emissions control strategies, supporting the integration of biodiesel blends into existing fuel infrastructures. From a policy perspective, the demonstrated emissions benefits align with global sustainability targets and strengthen the case for promoting biodiesel adoption through regulatory incentives and investment in renewable fuel technologies.

Future research should aim to evaluate the long-term impacts of biodiesel–antioxidant blends on engine durability, carbon deposition, and maintenance requirements under real-world operating conditions. Additionally, optimizing antioxidant concentrations, particularly clove oil, and scaling up production processes will be crucial to improving the economic and environmental feasibility of these fuels. These next steps will contribute to the broader transition toward sustainable, low-emission transportation systems. For future recommendations, consider increasing the percentage of clove oil in the biodiesel blend to further analyse its impact on engine performance and carbon deposition in a compression ignition engine. Also, long-duration engine tests to assess wear and deposit formation, field trials under real driving cycles, economic analyses of scaling antioxidant-enhanced biodiesel, and engine calibration or additive strategies to overcome performance limitations.

CRediT authorship contribution statement

Sher Muhammad Ghotto: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Sajjad Bhangwar:** Writing – review & editing, Writing – original draft, Validation, Supervision, Resources, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Ramez Raja:** Writing – review & editing, Investigation, Formal analysis. **Muhammad Kashif Abbasi:** Writing – review & editing, Visualization, Investigation, Formal analysis. **Gordhan Das Valasai:** Writing – review & editing, Writing – original draft, Validation, Supervision, Resources, Project administration, Methodology, Investigation, Formal analysis. **Muhammad Ramzan Luhur:** Writing – review & editing, Writing – original draft, Project administration, Methodology, Investigation, Formal analysis, Conceptualization. **Stefano Landini:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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