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Experimental investigation of waste cooking oil and karanja oil biodiesel–diesel blends in a single-cylinder four-stroke compression ignition engine

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Abstract

The growing demand for sustainable fuels has created opportunities to explore biodiesel as a substitute for conventional diesel fuel. In this study, we investigated the engine performance and emission characteristics of biodiesel blends derived from waste cooking oil (WCO) and karanja oil (KO) using a single-cylinder, four-stroke compression ignition engine. The emission characteristics of WCO and KO diesel blends were analyzed at different engine loads (0–12 kg), corresponding to 25% (3 kg), 50% (6 kg), 75% (9 kg), and 100% (12 kg) of the maximum load. The biodiesel blend ratios of 5%, 10%, 15%, and 20%, and compared with pure diesel operation. Biodiesels were produced through transesterification and tested under varying engine loads at a constant speed. Parameters such as brake thermal efficiency and mechanical efficiency were measured and compared. No substantial variations in brake thermal efficiency or mechanical efficiency were observed between pure diesel and the biodiesel blends; therefore, this study primarily focused on evaluating the emission characteristics. Emission parameters, such as carbon monoxide, hydrocarbons, nitrogen oxides, and smoke, were analyzed. The results indicate that both WCO and KO blends can be effectively utilized in compression ignition engines. Compared with pure diesel, biodiesel blends produced lower carbon monoxide, hydrocarbons, and smoke emissions, although a slight increase in nitrogen oxide emissions was observed. WCO- and KO-derived biodiesels show promise as sustainable alternatives to diesel fuel for compression ignition engines.

Keywords: Waste cooking oil; Karanja oil; Biodiesel–diesel blends; Compression ignition engine; Engine performance; Emission characteristics

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1. Introduction

The increase in pollution levels in cities across the globe is an increasing environmental concern. Diesel engines are widely used in transportation, agriculture, and power generation. These engines are major contributors to exhaust emissions, including carbon monoxide (CO), unburnt hydrocarbons (HC), nitrogen oxides (NO_x), and particulate matter. Biodiesel derived from vegetable oils and waste oils has emerged as a substitute for conventional diesel fuel due to its favorable combustion characteristics.

Edible oil-based biodiesels initially gained attention; however, their large-scale use raised concerns related to food security and cost. Research has shifted toward non-edible oils and waste-derived feedstocks as alternative biodiesel sources.[1] The environmental and health concerns associated with the improper reuse and disposal of waste oils have increased interest in waste cooking oil (WCO) as a biodiesel blend. WCO is abundantly available from households, hotels, and food-processing industries, and its disposal poses serious environmental challenges.[2] The use of WCO for biodiesel production not only provides a low-cost fuel alternative but also addresses waste management issues.[3] The karanja oil (KO; *Pongamia pinnata*), a non-edible oil obtained from karanja seeds, is widely available in India and is well-suited for biodiesel production due to its high oil content and favorable fatty acid composition.[4]

Researchers have investigated the feasibility of WCO and KO biodiesel in compression ignition (CI) engines.[5] One common type of biodiesel is fatty acid methyl esters (FAME), which are widely used in compression-ignition internal combustion engines in various vehicles (e.g., automotive, rail, and marine). Hydrotreated vegetable oil, another type of biofuel, is also increasingly utilized in diesel engines.

As a general practice, these fuels are used in mixtures with petroleum fuels. Studies have also reported that biodiesel blends result in lower CO, HC, and smoke emissions owing to the inherent oxygen content of biodiesel, which promotes more complete combustion.[6] A slight increase in NO_x emissions has been observed, which may be attributed to higher combustion temperatures and advanced ignition characteristics.[7] Performance parameters such as brake thermal efficiency (BTE) and brake specific fuel consumption (BSFC) were comparable to those of diesel at lower blend ratios, particularly for B10 and B20 blends.[8]

Numerous studies have independently examined WCO and KO biodiesels; however, limited studies have performed a comparative evaluation of these biodiesel blends under identical engine operating conditions.[9] The present study aims to experimentally investigate and compare the performance and emission characteristics of WCO and KO diesel blends in a single-cylinder, four-stroke CI engine.[10] Previous studies on WCO biodiesel blends have reported comparable engine performance with pure diesel operation.[11] Furthermore, the reduced pollutant emissions observed with biodiesel blends indicate their potential as environmentally favorable alternatives to conventional diesel fuel.[12] Diesel engines remain dominant in transportation, agriculture, and power generation due to their high efficiency and durability. These engines are significant contributors to air pollution and greenhouse gas emissions.[13] Biodiesel derived from renewable feedstocks has emerged as a promising substitute for petroleum diesel.[14]

In the early stages of biodiesel research, edible vegetable oils were extensively investigated. Their large-scale utilization raised concerns related to food security, land use, and fuel cost.[15] This led to a growing shift toward non-edible oils and waste-derived feedstocks. WCO has gained considerable attention because of its low cost, wide availability, and the environmental problems associated with its improper disposal.[16] Recycling WCO into biodiesel or using it in blended form with diesel not only reduces fuel cost but also addresses waste management and environmental pollution issues.[17]

2. Literature review

The shift toward renewable and sustainable fuels has driven extensive research into biodiesel production and its application in CI engines.[18] Biodiesel can be produced from various feedstocks, including edible oils, non-edible oils, and waste oils, with WCO and KO emerging as attractive low-cost, non-food alternatives that mitigate food–fuel competition and environmental waste disposal concerns.[19] WCO biodiesel has been widely investigated due to its economic and environmental benefits.[20] Several studies[21-26] demonstrated that WCO methyl ester (WCOME) results in BTE values comparable to those of diesel, although BSFC tends to increase with higher biodiesel fractions because of its lower calorific value compared with conventional diesel. Performance tests on single-cylinder and multi-cylinder diesel engines using WCO biodiesel blends (B10–B50) have shown reduced emissions of CO, HC, and smoke particulate due to the higher oxygen content of biodiesel. A B10 blend indicates that 10% biodiesel is mixed with 90% diesel. The major limitation of adding higher biodiesel blending ratios is the reduction in thermal efficiency.[27]

Test results of KO and WCO as biodiesel feedstocks are presented in Table 1.

2.1. Karanja oil

Karanja oil, a non-edible seed oil, has also been studied for biodiesel production and engine applications.[28] KO is obtained from the seeds of *Pongamia pinnata* (also known as *Pongamia glabra*). KO consists primarily of triglycerides, which are esters formed from glycerol and long-chain fatty acids. The general molecular structure of triglycerides can be represented as $C_3H_5(OOC\text{-}R)_3$, where R denotes HC chains of varying lengths and degrees of saturation. The dominant fatty acids present in KO include oleic acid (C18:1), linoleic acid (C18:2), palmitic acid

(C16:0), and stearic acid (C18:0). Oleic acid constitutes the highest proportion, ranging from 45%–70%, which contributes to better oxidative stability and ignition quality of the resulting biodiesel. Oleic and stearic acids, which are found in KO, reduce friction losses in both high-pressure fuel injection systems and diesel engine cylinders. This is an additional benefit of using KO.[29-32]

Table 1. Summary of reported test results for karanja oil and waste cooking oil as biodiesel feedstocks

Oil blend	Karanja oil	Waste cooking oil (mix of sunflower and groundnut oil after cooking multiple times)
Feedstock type	Non-edible vegetable oil	Recycled edible oil waste
Botanical/source	*Pongamia pinnata* seeds	Used cooking oils (e.g., soybean, palm, and sunflower oils)
Free fatty acid content (mg KOH/g)	8.8	11
Density (kg/m^3 at 15 °C)	878	882
Kinematic viscosity (mm^2/s at 40 °C)	5.2	5.16
Calorific value (MJ/kg)	37.9	38.2
Cetane number	51	51
Flash point (°C)	170	170
Brake thermal efficiency	Same as diesel	Same as diesel
CO and HC emissions	Lower than diesel	Lower than diesel
Smoke opacity	Reduced	Reduced
Nitrogen oxide emissions	Higher than diesel	Higher than diesel
Availability	Highly available in South Indian forests	Widely available urban waste
Sustainability aspect	Non-edible, grows on wasteland	Waste recycling, low cost

Due to its relatively high free fatty acid (FFA) content, crude KO is not directly suitable for alkaline transesterification. The FFA value may range from 4–12 mg potassium hydroxide (KOH)/g, depending on seed quality and storage conditions. Biodiesel production involves a two-step process, including acid esterification followed by alkaline transesterification. FFAs react with methanol (CH_3OH) in the presence of an acid catalyst such as sulfuric acid to form FAME and water, thereby reducing the FFA level below 2 mg KOH/g. Alkaline transesterification converts triglycerides into biodiesel using CH_3OH and catalysts such as sodium hydroxide (NaOH) or KOH. The FAME compounds produced include methyl oleate ($C_{19}H_{36}O_2$), methyl linoleate ($C_{19}H_{34}O_2$), and methyl palmitate ($C_{17}H_{34}O_2$).[33]

The KO methyl ester (KOME) exhibits characteristics comparable to conventional diesel fuel. The density of KOME is approximately 860–890 kg/m^3, while its kinematic viscosity at 40 °C ranges from 4.5 to 5.5 mm^2/s, which satisfies ASTM D6751 and EN 14214 standards.[34] The cetane number of karanja biodiesel is relatively high (around 50–52), indicating good ignition quality. The calorific value of KOME is slightly lower than diesel, in the range of 37–39 MJ/kg, due to the presence of oxygenated compounds. The flash point of karanja biodiesel exceeds 160 °C, making it safer for storage and handling.

The biodiesel produced from KO was characterized according to ASTM D6751 standards. The measured fuel properties indicated a density of approximately 870–890 kg m^{-3}, kinematic viscosity of 4.5–5.8 mm^2/s, calorific value of 37–40 MJ/kg, cetane number of 51–58, and a flash point of 160 °C–180 °C. The higher oxygen content (10%–12%) and negligible sulfur content contribute to improved combustion and lower exhaust emissions. Karanja trees are widely distributed across India and other tropical regions. They are hardy, drought-resistant, and capable of growing on marginal and wasteland areas without competing with food crops.[34] These trees grow in wastelands with limited water availability. The oil content of karanja seeds ranges from 27%–39%, making it a sustainable and economically viable feedstock for large-scale biodiesel production.[35] KO biodiesel is considered a promising alternative fuel for diesel engines, particularly in blends such as B20.

2.2. Waste cooking oil

Waste cooking oil consists mainly of triglycerides, which are esters of glycerol and long-chain fatty acids, represented by the formula $C_3H_5(OOC–R)_3$, where R denotes HC chains of varying saturation and length.[22] The fatty acid composition of WCO depends on the original edible oil source, such as soybean, palm, sunflower, or groundnut oil, and the extent of thermal degradation during repeated frying.[29] The fatty acids present in WCO include oleic acid (C18:1), linoleic acid (C18:2), palmitic acid (C16:0), and stearic acid (C18:0), along with oxidized and polymerized compounds formed during cooking.[3]

Waste cooking oil contains a high level of FFA, often ranging from 10–20 mg KOH/g. This elevated FFA content makes direct alkaline transesterification unsuitable, as it leads to soap formation and reduced biodiesel yield. A two-step conversion process is commonly adopted. In the first step, acid esterification is carried out using CH_3OH and an acid catalyst such as sulfuric acid to reduce the FFA content below 2 mg KOH/g. In the second step, alkaline transesterification is performed using NaOH or KOH as catalysts, converting triglycerides into FAME and glycerol ($C_3H_8O_3$) as a by-product. Major FAME compounds in WCO biodiesel include methyl oleate ($C_{19}H_{36}O_2$), methyl linoleate ($C_{19}H_{34}O_2$), and methyl palmitate ($C_{17}H_{34}O_2$).[8]

Waste cooking oil was produced through transesterification and characterized according to ASTM D6751 standards. The fuel exhibited a density of approximately 870–890 kg m^3 and a kinematic viscosity of 4.0–5.5 mm^2/s at 40 °C. The calorific value was found to be in the range of 37–40 MJ/kg, while the cetane number varied between 50 and 58. The flash point of WCO biodiesel was significantly higher (140 °C –175 °C) than that of conventional diesel, improving fuel handling safety.[15]

The fuel properties of WCO biodiesel (WCOME) are comparable to those of conventional diesel fuel and meet international biodiesel standards such as ASTM D6751 and EN 14214. The density of WCOME range of 850–885 kg/m^3, while the kinematic viscosity at 40 °C ranges from 4.2–5.8 mm^2/s.[36] The calorific value of WCO biodiesel is slightly lower than diesel, usually between 38 and 40 MJ/kg, due to the presence of oxygenated compounds. The cetane number of WCOME varies between 48 and 51. WCO biodiesel exhibits a high flash point above 150 °C, ensuring safer handling and storage.

Moreover, WCO is abundantly generated from households, restaurants, and food-processing industries, particularly in urban areas. Engine studies have shown that WCO biodiesel blends, especially B20, exhibit BTE values comparable to those of diesel fuel. These fuels have significant reductions in CO, unburnt HCs, and smoke emissions, although a slight increase in NO_x emissions is commonly observed.[26]

3. Methodology

Waste cooking oil was collected from a local food hotel and was filtered to remove food residues, moisture, and suspended impurities. KO was extracted from karanja seeds. The oils were converted into biodiesel using a transesterification process with CH_3OH and an alkaline catalyst (NaOH). The biodiesel was allowed to settle, then washed with warm distilled water to remove residual catalyst and glycerol, followed by drying. The diesel engine test rig is shown in Figure 1. The engine specifications are provided in Table 2.

Table 2. Engine specifications used to test both karanja oil and waste cooking oil biodiesel blends

Parameter	Specification
Number of cylinders	Single cylinder
Number of strokes	4-stroke Kirloskar engine
Engine speed	1,500 rpm
Type of cooling	Water-cooled engine
Power output	3.50 kW
Cylinder bore	87.50 mm
Stroke length	110.00 mm
Connecting rod length	234.00 mm
Compression ratio range	12.00–18.00
Swept volume	661.45 cc
Adiabatic index (γ)	1.41
Air density	1.17 kg/m^3
Polytropic index (n)	1.18
Cylinder pressure	6 bar
Orifice diameter	20.00 mm

Experiments were conducted on a single-cylinder, four-stroke, water-cooled CI engine operated at a constant speed. The engine was coupled with a current dynamometer to apply varying loads. Standard instrumentation was used to measure fuel consumption, airflow, exhaust gas temperature, and engine speed. The engine was initially run with pure diesel to establish baseline data. WCO and KO biodiesel blends were tested under identical operating conditions at different load levels. At each load, the engine was allowed to reach a steady-state condition before measurements were recorded. Performance parameters, such as BTE and BSFC, were calculated, while exhaust emissions, including CO, HC, NO_x, and smoke emissions, were measured using a calibrated gas analyzer and smoke meter.

4. Results

4.1. Brake thermal efficiency versus load

Brake thermal efficiency increases with load for both biodiesel blends and reaches maximum values at high load conditions. This improvement is due to reduced heat losses and better utilization of supplied fuel energy at higher loads. KO shows marginally higher BTE at full load compared to WCO, which may be attributed to its higher

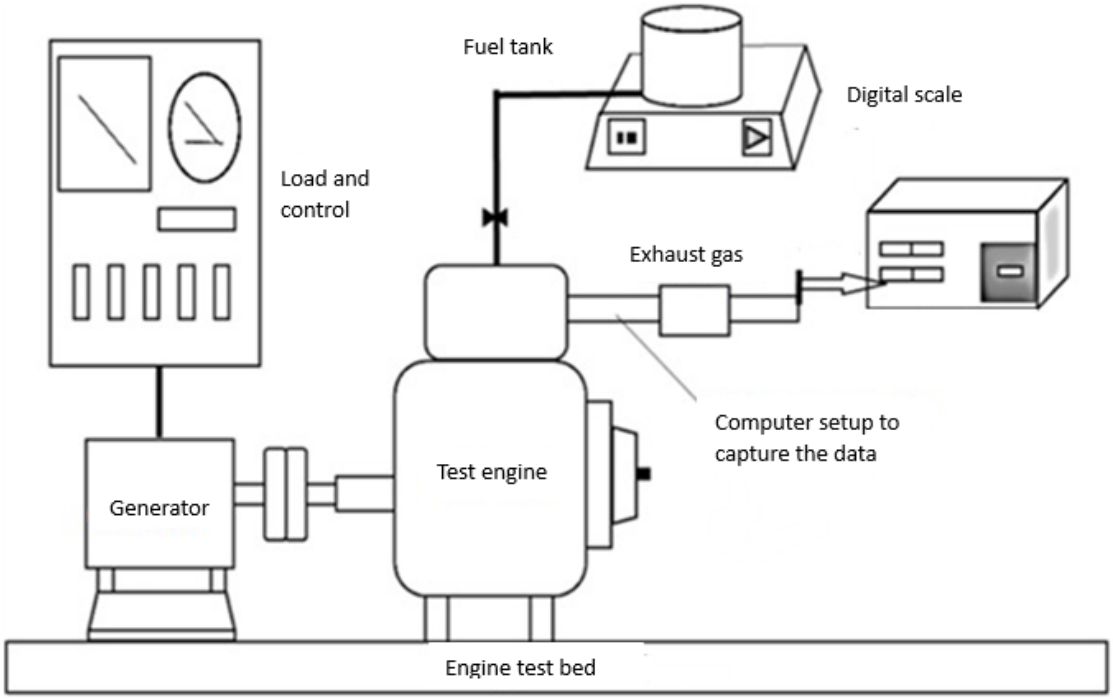

Figure 1. Diesel engine test rig

cetane number and improved combustion stability. The difference between the two fuels remains small, indicating comparable thermal efficiency performance.

Mechanical efficiency increases substantially with increasing load for both biodiesel blends. At low loads, mechanical efficiency is minimal due to dominant frictional losses and lower combustion efficiency. As the load increases, the proportion of useful power output increases, leading to higher mechanical efficiency. WCO shows marginally higher mechanical efficiency values at higher loads, indicating lower relative friction losses and improved engine operation.

Both KO and WCO biodiesel blends have comparable engine performance characteristics, with WCO showing slightly better torque and brake power output, while KO exhibits marginally higher thermal efficiency. These results indicate that WCO biodiesel has potential as an alternative fuel for CI engines without requiring engine modifications.

Figures 2 and 3 show that BTE increases steadily with load for pure diesel and all WCO and KO blends. At lower loads, slight variations are observed among the fuels; however, as the load increases, the efficiency values converge closely. At full load, most blends exhibit BTE values comparable to those of pure diesel, with only marginal differences of about 1%–2%. No consistent or substantial reduction in performance was observed for blended fuels.

Figure 4 shows that there is no substantial variation observed in mechanical efficiency between pure diesel and blended diesel. The main focus of this study is the comparison of emission characteristics among diesel blends. The results indicate that blending WCO and KO with diesel does not adversely affect engine performance under the tested conditions, and the blends demonstrate performance characteristics similar to conventional diesel under all tested load conditions.

4.2. Pollution analysis

The emission characteristics of WCO and KO biodiesel–diesel blends were analyzed at different engine loads (0–12 kg) for blend ratios of 5%, 10%, 15%, and 20%, and compared with pure diesel operation. The measured parameters include CO, HC, oxygen (O_2), NO_x, and smoke opacity.

4.2.1. Carbon monoxide

Carbon monoxide emissions for both WCO and KO biodiesel–diesel blends were higher than those of pure diesel at low and medium engine loads, as shown in Figure 1. Under the present experimental conditions, pure diesel exhibited the lowest CO emissions, indicating more

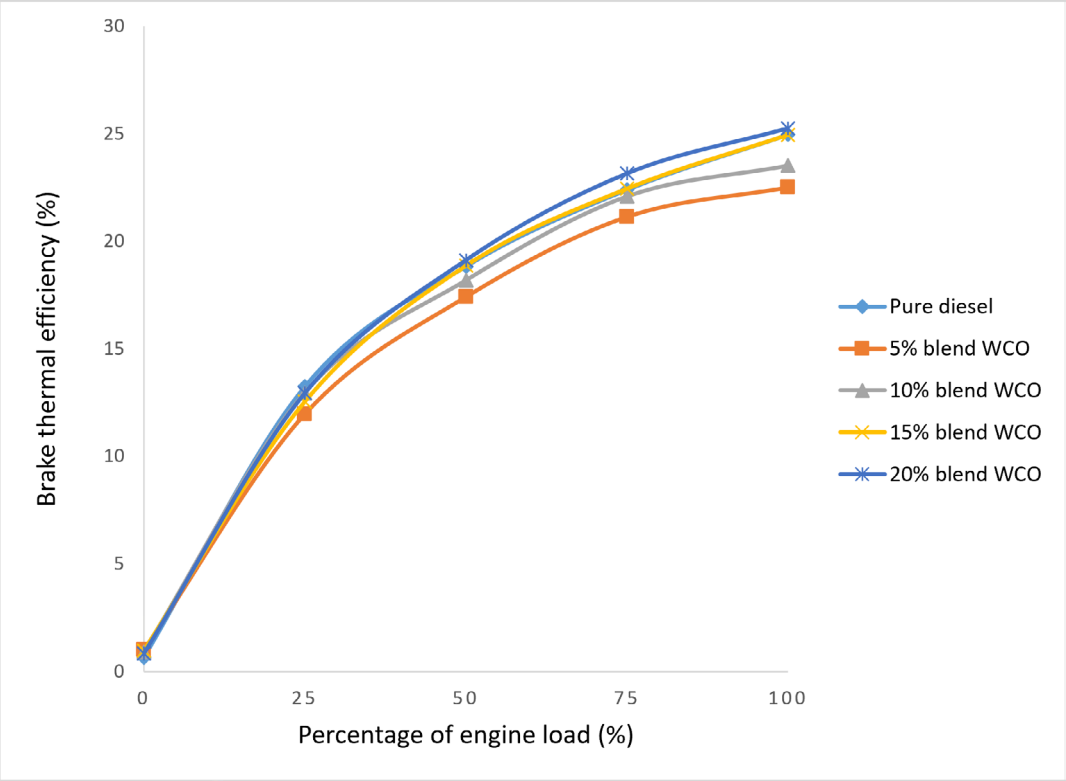

Figure 2. Comparison of brake thermal efficiency of waste cooking oil (WCO) biodiesel–diesel blends and pure diesel

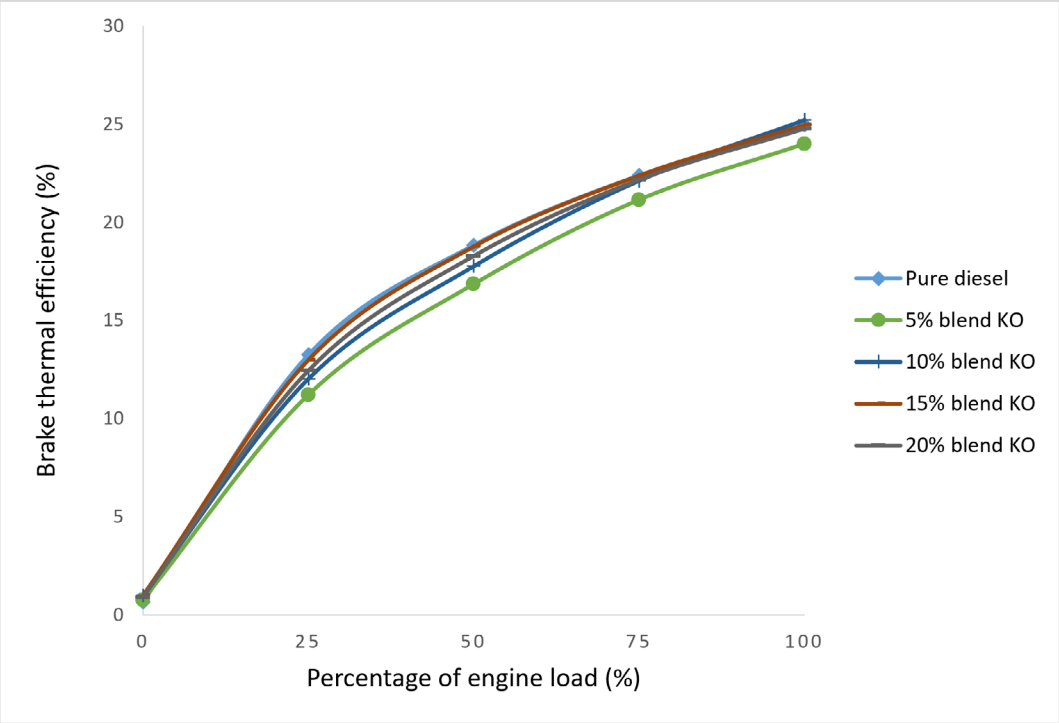

Figure 3. Comparison of brake thermal efficiency of karanja oil (KO) biodiesel–diesel blends and pure diesel

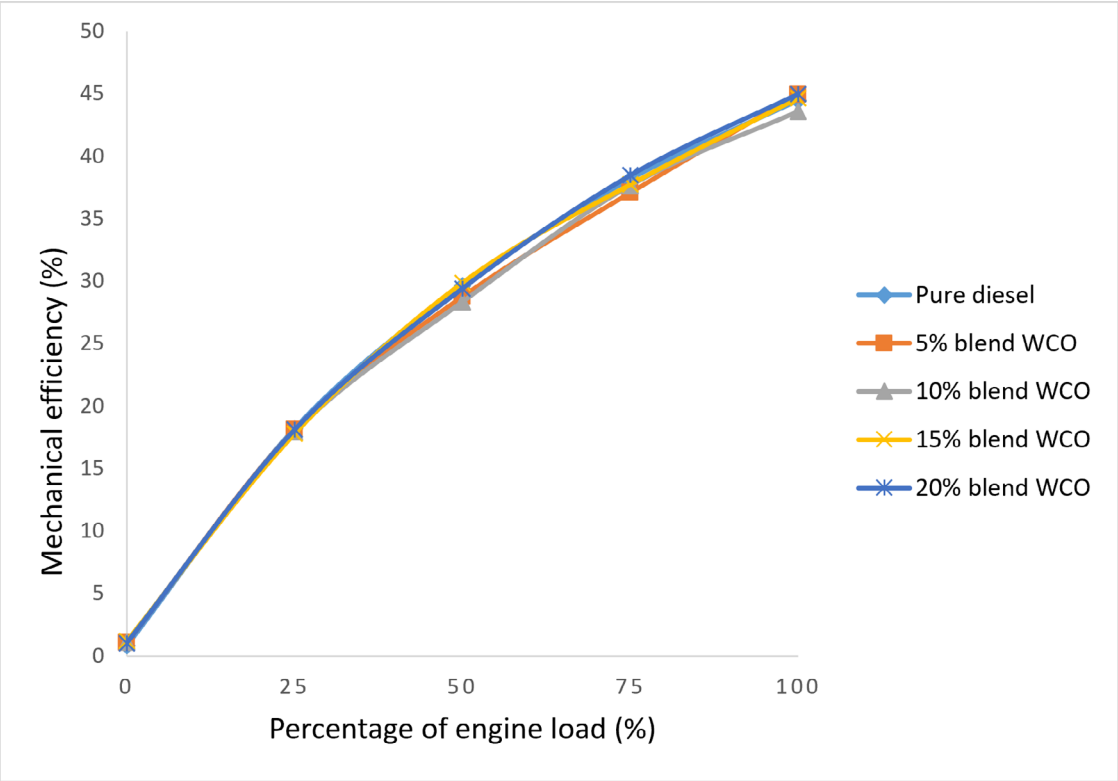

Figure 4. Comparison of mechanical efficiency of waste cooking oil (WCO) biodiesel–diesel blends and pure diesel

complete combustion than the biodiesel–diesel blends. As the engine load increased, the differences in CO emissions among the fuels became less pronounced due to improved combustion efficiency at higher loads.

Based on Figures 5 and 6, the 15% and 20% blends exhibited the lowest CO emission values at medium loads (3–9 kg) compared with the other biodiesel–diesel blends. KO blends showed a similar trend, with the 20% KO blend recording the lowest CO emissions across the tested load range. At full load (12 kg), a marginal increase in CO was observed for all blends, which may be attributed to incomplete combustion under higher fuel supply conditions.

4.2.2. Hydrocarbons

Hydrocarbon emissions increased with load for all fuel blends, including pure diesel. WCO biodiesel–diesel blends showed higher HC emissions at higher loads compared with pure diesel, particularly for the 5% and 10% blends, which may be attributed to less effective fuel atomization. KO blends exhibited lower HC emissions than pure diesel across the tested load range, especially at 15% and 20% blend ratios, suggesting improved combustion stability. The comparison of HC emissions is shown in Figures 7 and 8.

4.2.3. Oxygen

As shown in **Figures 9** and **10**, the exhaust O_2 concentration decreased with increasing engine load, indicating greater O_2 utilization during combustion at higher loads. WCO biodiesel–diesel blends showed lower O_2 concentrations when compared with pure diesel (Figure 9), whereas KO blends exhibited a lower O_2 concentration as the load increased (Figure 10).

4.2.4. Nitrogen oxide

Nitrogen oxide emissions increased with increasing load for all biodiesel blends. WCO blends, particularly at 5% and 10%, showed higher NO_x emissions at full load compared with the corresponding KO blends, which may be attributed to higher combustion temperatures and O_2 availability in the combustion environment (Figure 11). KO blends exhibited relatively lower NO_x emission levels than WCO blends at corresponding blend ratios, especially for 15% and 20% blends, indicating a lower NO_x formation tendency during combustion (Figure 12).

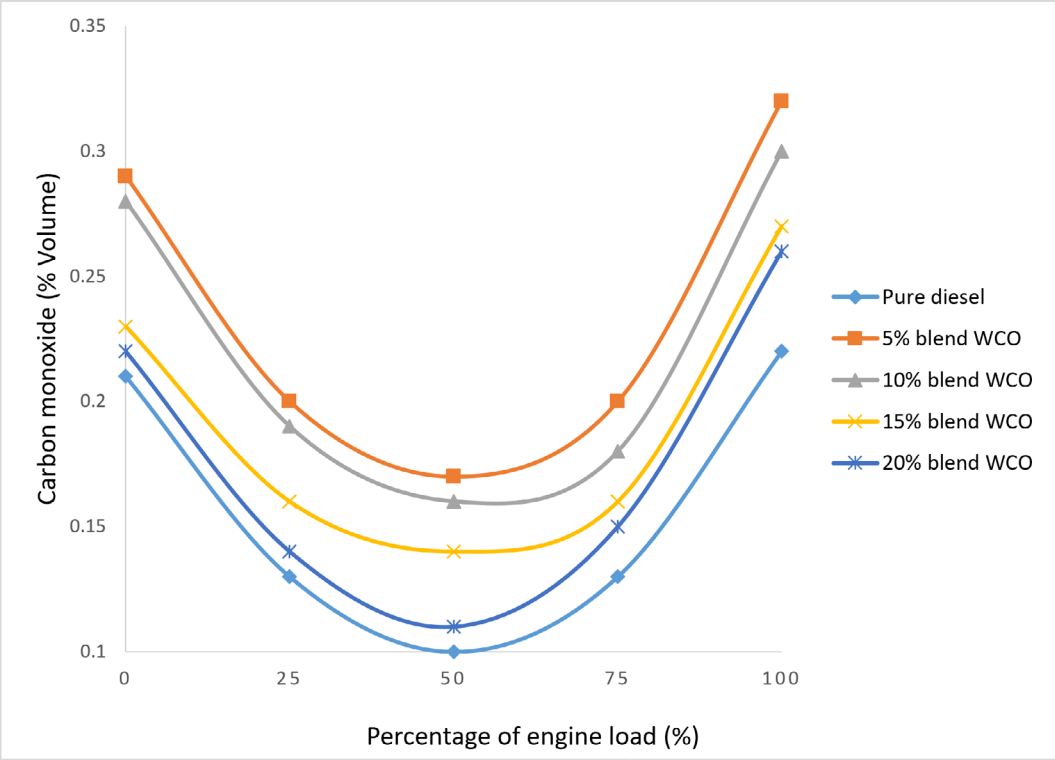

Figure 5. Comparison of carbon monoxide emissions from waste cooking oil (WCO) biodiesel–diesel blends and pure diesel

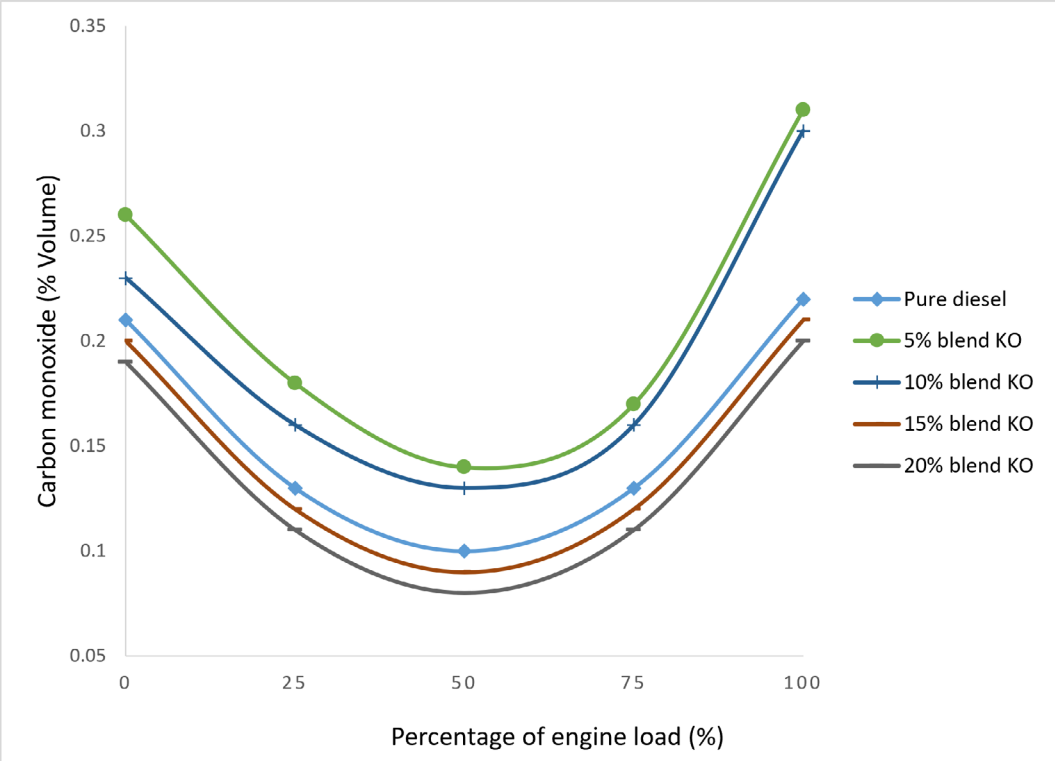

Figure 6. Comparison of carbon monoxide emissions from karanja oil (KO) biodiesel–diesel blends and pure diesel

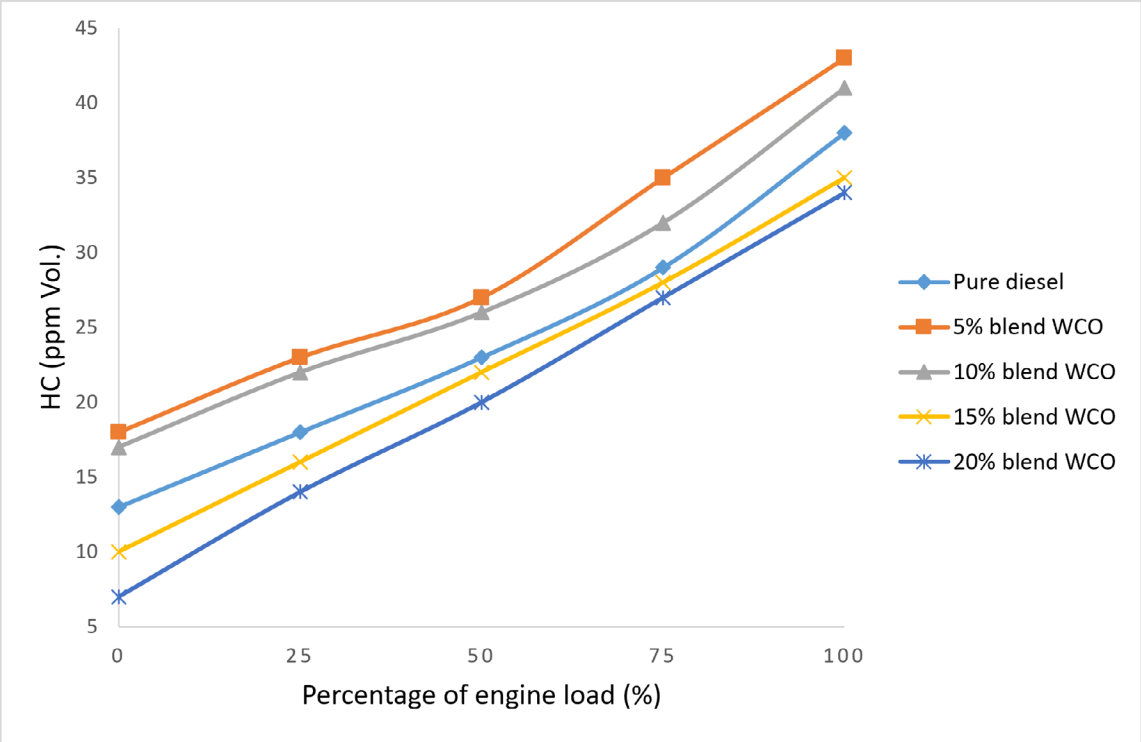

Figure 7. Comparison of HC emissions from WCO biodiesel–diesel blends and pure diesel
Abbreviations: HC: Hydrocarbon; WCO: Waste cooking oil.

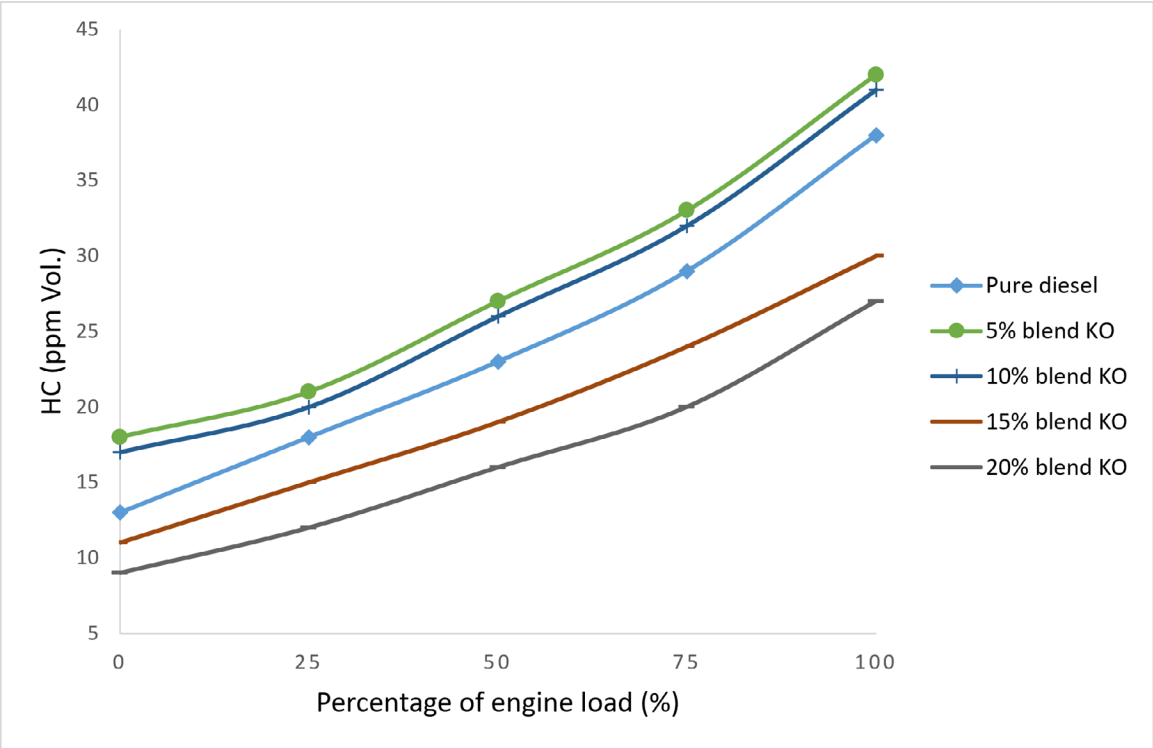

Figure 8. Comparison of HC emissions from KO biodiesel–diesel blends and pure diesel
Abbreviations: HC: Hydrocarbon; KO: Karanja oil.

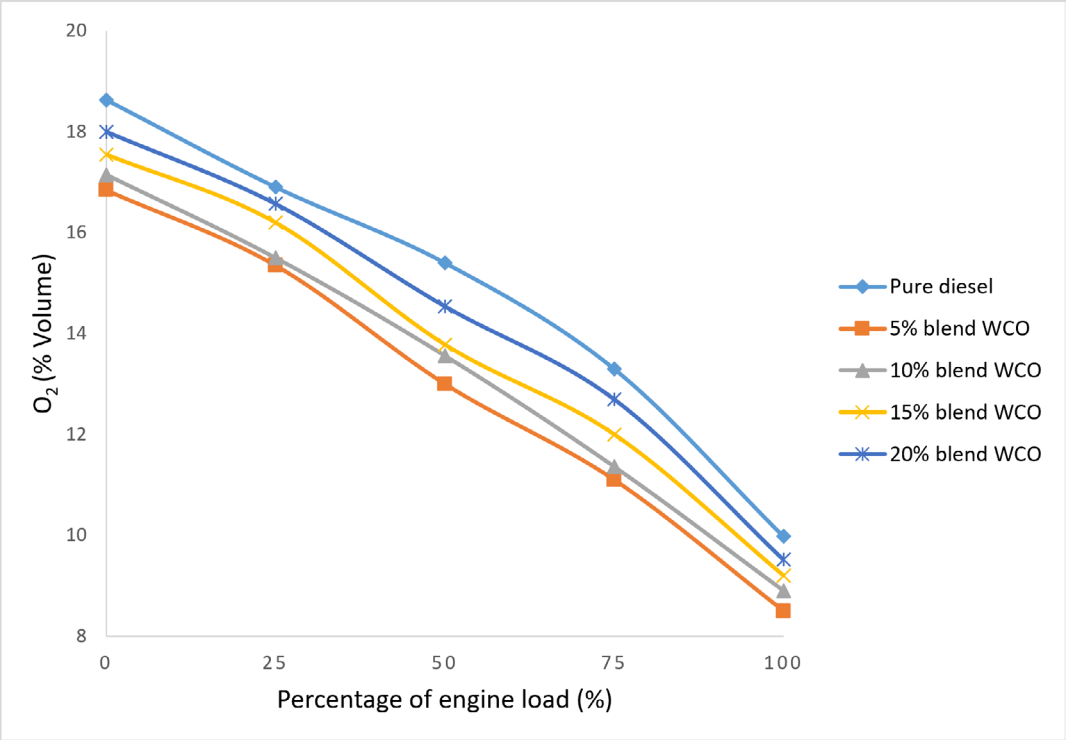

Figure 9. Comparison of exhaust O_2 concentration of WCO biodiesel–diesel blends and pure diesel
Abbreviations: O_2: Oxygen; WCO: Waste cooking oil.

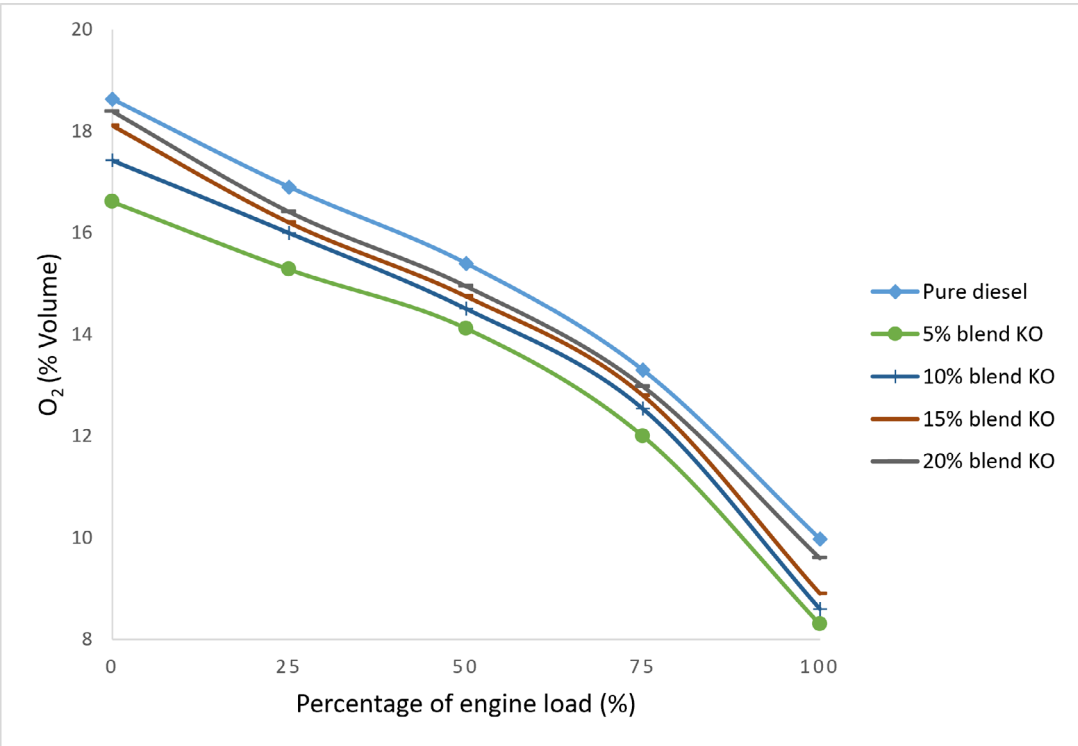

Figure 10. Comparison of exhaust oxygen (O_2) concentration of karanja oil (KO) biodiesel–diesel blends and pure diesel
Abbreviations: KO: Karanja oil; O_2: Oxygen.

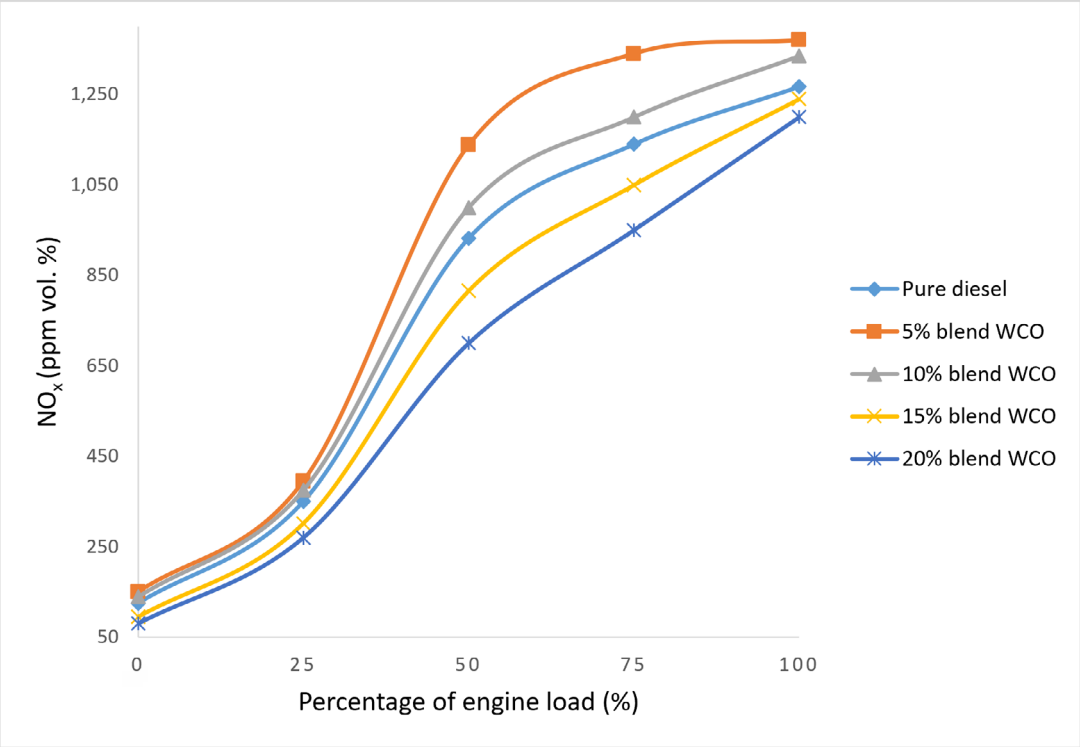

Figure 11. Comparison of NO_x emissions from WCO biodiesel–diesel blends and pure diesel
Abbreviations: NO_x: Nitrogen oxide; WCO: Waste cooking oil.

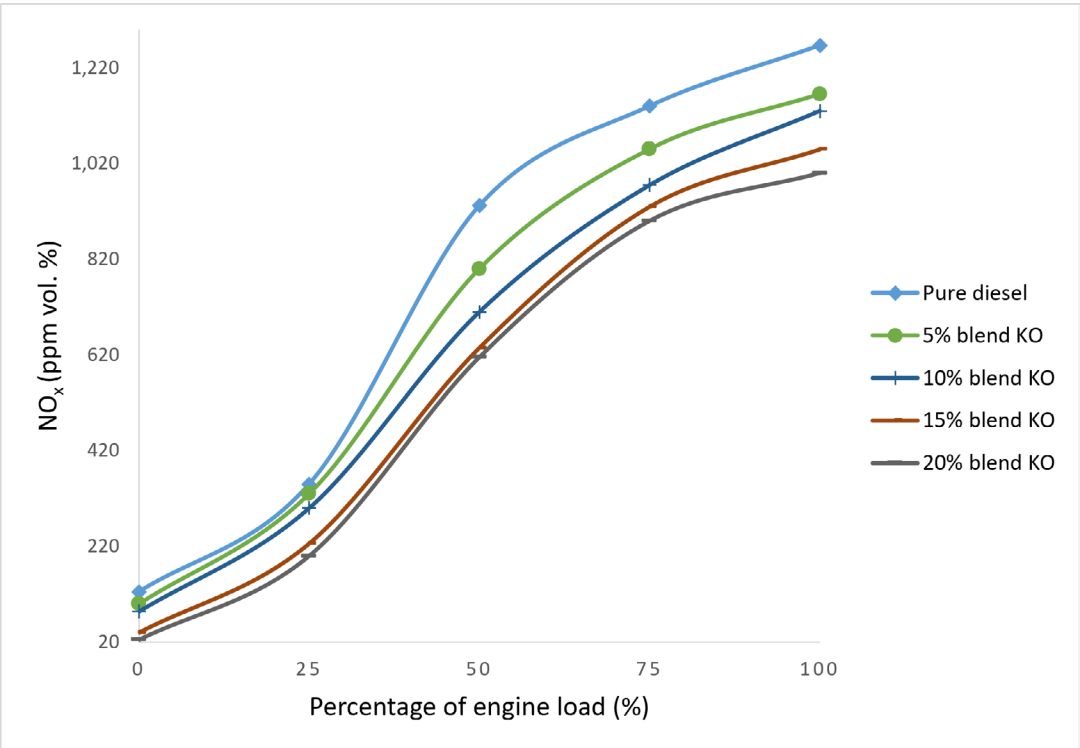

Figure 12. Comparison of NO_x emissions from KO biodiesel–diesel blends and pure diesel
Abbreviations: KO: Karanja oil; NO_x: Nitrogen oxide.

4.2.5. Smoke opacity

Smoke opacity increased with load for both WCO and KO biodiesel–diesel blends. Higher biodiesel blends (10%, 15%, and 20%) produced lower smoke opacity than diesel. Smoke opacity increased for all blends; however, KO blends consistently showed lower smoke opacity than WCO blends, indicating improved combustion characteristics.

Based on Figures 13 and Figure 14, the results indicate that WCO blends and KO blends up to 15% demonstrated favorable emission characteristics at all loads. Among all tested fuel blends, the 20% WCO blend and 5% KO showed potential as an alternative fuel blend, offering reduced CO, HC, and smoke opacity with comparatively moderate NO_x emission levels, indicating its potential suitability for CI engine applications.

5. Comparative study

The proposed experimental study was compared with recent related studies, and the results are presented in Table 3.

The findings indicate reductions in CO, HC, and smoke opacity, accompanied by a marginal increase in NO_x emissions. These observations are consistent with recent studies published in journals such as *MDPI Energies*[37], *International Journal of Hydrogen Energy* [38], and *Scientific Reports* [39], which reported that oxygenated biodiesel fuels can improve combustion characteristics while slightly increasing NO_x formation.

Table 3. Comparison of recent studies with the experimental results

Parameter	The present study (WCO and KO blends)	Wcisło *et al.*[37]	Pullagura *et al.*[38]	Azarudeen *et al.*[39]
Feedstock	WCO and KO	WCO, palm, soybean biodiesel	Karanja, jatropha, mixed oils	WCO and non-edible oils
Engine type	Single-cylinder, 4-stroke CI engine	Single-cylinder CI engine	CI engine (mostly single-cylinder)	CI engine (laboratory-scale setups)
Blend ratios	B5, B10, B15, B20	B5–B30	B10–B20	B5–B20
Operating conditions	Load: 0–12 kg, constant speed	Variable load, constant speed	Variable load and speed	Mostly constant speed, varying load
Biodiesel production	Transesterification	Transesterification	Transesterification	Transesterification
Brake thermal efficiency	Slightly lower than diesel; improves with load	Slight decrease (2%–8%) vs. diesel	Comparable at low blends (B10–B20)	Slight reduction
Brake specific fuel consumption	Higher than diesel	Higher due to lower calorific value	Higher (5%–15%)	Increased brake specific fuel consumption was observed
Exhaust gas temperature	Increases with load	Similar trend	Higher for biodiesel blends	Slightly higher
Carbon monoxide emissions	Reduced	Reduced significantly	Reduced	Reduced
Hydrocarbon emissions	Reduced	Reduced	Reduced	Reduced
Nitrogen oxide emissions	Slight increase	Increase (common trend)	Increase (due to oxygen content)	Slight increase
Smoke opacity	Reduced	Reduced	Reduced	Reduced
Engine modification required	No major modification	No modification needed	No modification needed	No modification needed
Key conclusion	WCO and KO show potential as alternative fuels for CI engines	Biodiesel blends demonstrate potential for reducing exhaust emissions	Biodiesel blends demonstrate potential for reducing exhaust emissions	Biodiesel blends demonstrate potential for reducing exhaust emissions

Abbreviations: CI: Compression ignition; KO: Karanja oil; WCO: Waste cooking oil.

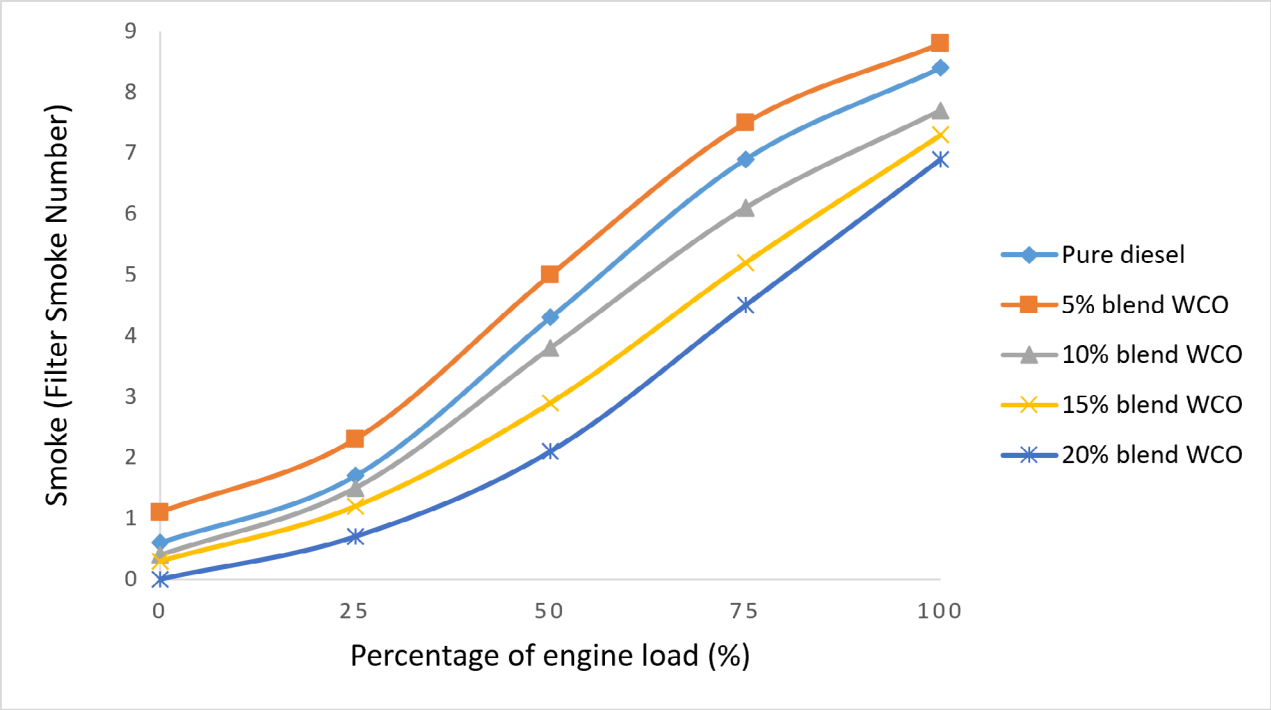

Figure 13. Comparison of smoke opacity from waste cooking oil (WCO) biodiesel–diesel blends and pure diesel

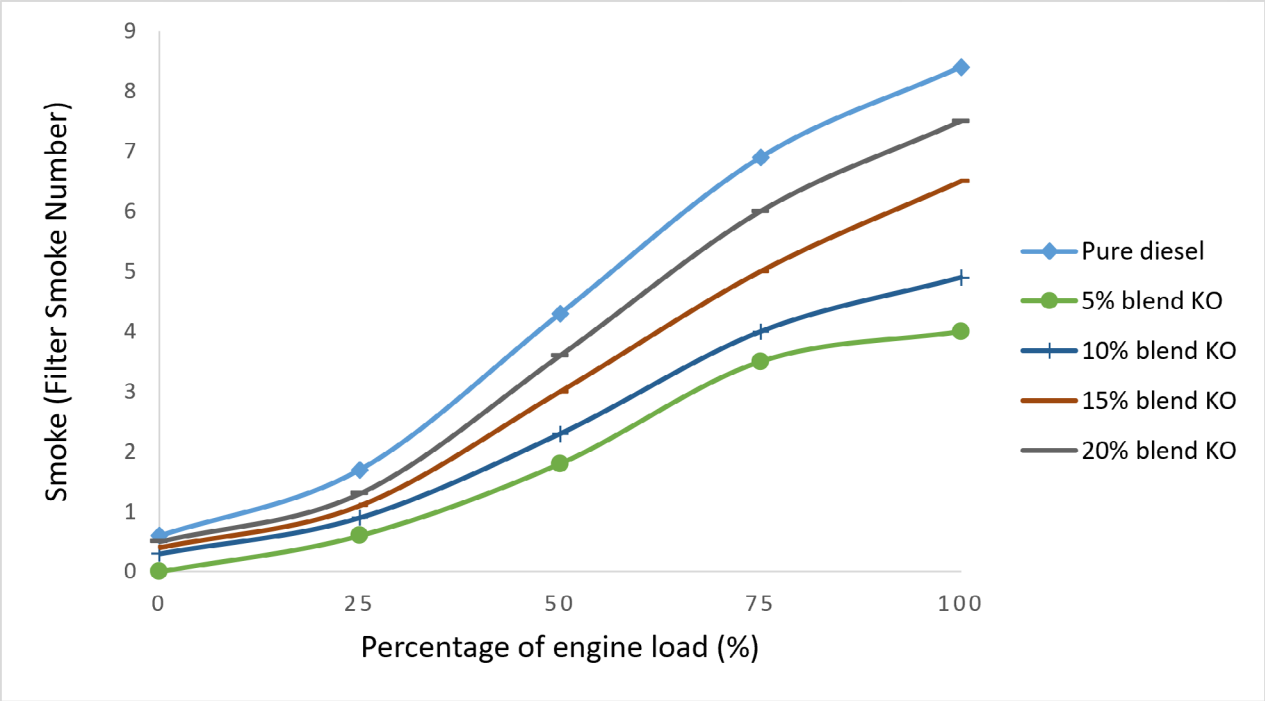

Figure 14. Comparison of smoke opacity from karanja oil (KO) biodiesel–diesel blends and pure diesel

6. Conclusion

This experimental study was conducted to evaluate the performance and emission characteristics of WCO and KO biodiesel–diesel blends in a single-cylinder, four-stroke CI engine under varying load conditions at constant speed. The emission characteristics of WCO and KO biodiesel–diesel blends were analyzed at different engine loads (0–12 kg) for blend ratios of 5%, 10%, 15%, and 20%, and compared with pure diesel operation. The measured parameters included CO, HC, CO_2, NO_x, and smoke opacity. The results indicate that both biodiesel blends demonstrated potential for use in CI engines without engine modifications. Engine performance parameters, such as torque and brake power, increased with increasing load for all test fuels. WCO blends produced marginally higher torque and brake power at medium and full loads, whereas KO blends exhibited slightly higher BTE at higher loads due to improved ignition quality and stable combustion. BSFC decreased with increasing load for both biodiesel blends, with higher values than diesel at low loads, attributed to their lower calorific value and higher viscosity. Mechanical efficiency improved with increasing load, with WCO blends showing marginally higher values at full load.

Emission analysis revealed substantial reductions in CO, unburnt HCs, and smoke opacity for both biodiesel fuels compared to diesel, which may be attributed to the oxygenated characteristics of biodiesel that promote more complete combustion. NO_x emissions increased with load for all blends. KO blends consistently exhibited lower NO_x levels than WCO at higher blend ratios due to relatively lower combustion temperatures. WCO blends at blend ratios 5%–15%, and KO blends at blend ratios of 5%–20% demonstrated a balance between performance and emissions. The 15% KO blend showed potential as a suitable fuel blend. WCO and KO biodiesel blends are technically viable alternative fuel options for CI engine applications. Their adoption may contribute to waste valorization and reduced fossil fuel dependency, although further lifecycle assessments are required to evaluate overall environmental benefits.

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Conflict of interest

The authors declare they have no competing interests.

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Availability of data

Data are available from the corresponding author upon reasonable request.

References

1. Abdul Hakim Shaah M, Hossain MS, Salem Allafi FA, *et al.* A review on non-edible oil as a potential feedstock for biodiesel: physicochemical properties and production technologies. *RSC Adv*. 2021;11(40):25018-25037.

   doi: 10.1039/d1ra04311k

2. Awogbemi O, Kallon DVV. Conversion of hazardous waste cooking oil into non-fuel value-added products. *Int J Ambient Energy*. 2024;45(1).

   doi: 10.1080/01430750.2024.2345253

3. Idris M, Abdul Rasid AF, Mohd Zamberi M, Zhang Y. Biodiesel production from waste cooking oil: a review of prospects and challenges. *J Adv Res Fluid Mech Therm Sci*. 2024;124(1):28-52.

   doi: 10.37934/arfmts.124.1.2852

4. Panwar S, Chaithra, Namita, *et al.* Karanja Seeds (Pongamia pinnata). In: *Underutilized Seeds*. Springer Nature Singapore; 2026:107-139.

   doi: 10.1007/978-981-95-4802-6_5

5. Patel C, Chandra K, Hwang J, *et al.* Comparative compression ignition engine performance, combustion, and emission characteristics, and trace metals in particulates from waste cooking oil, Jatropha and Karanja oil-derived biodiesels. *Fuel*. 2019;236:1366-1376.

   doi: 10.1016/j.fuel.2018.08.137

6. Qi DH, Chen H, Geng LM, Bian YZ. Experimental studies on the combustion characteristics and performance of a direct injection engine fueled with biodiesel/diesel blends.

Energy Convers Manag. 2010;51(12):2985-2992.

doi: 10.1016/j.enconman.2010.06.042

7. Nabi MN. Theoretical investigation of engine thermal efficiency, adiabatic flame temperature, NOx emission and combustion-related parameters for different oxygenated fuels. *Appl Therm Eng*. 2010;30(8-9):839-844.

doi: 10.1016/j.applthermaleng.2009.12.015

8. Bietresato, M., & Friso, D. Durability test on an agricultural tractor engine fuelled with pure biodiesel (B100). *Turk J Agric For*. 2014;38(2):214-223.

doi: 10.3906/tar-1302-51

9. Bidir MG, Narayanan Kalamegam M, Adaramola MS, Hagos FY, Chandra Singh R. Investigation of combustion, performance, and emissions of biodiesel blends using graphene nanoparticle as an additive. *Int J Engine Res*. 2022;24(11):4459-4469.

doi: 10.1177/14680874221097574

10. Agarwal AK, Rajamanoharan K. Experimental investigations of performance and emissions of Karanja oil and its blends in a single cylinder agricultural diesel engine. *Appl Energy*. 2009;86(1):106-112.

doi: 10.1016/j.apenergy.2008.04.008

11. Gad MS, Ismail MA. Effect of waste cooking oil biodiesel blending with gasoline and kerosene on diesel engine performance, emissions and combustion characteristics. *Process Saf Environ Prot*. 2021;149:1-10.

doi: 10.1016/j.psep.2020.10.040

12. Attia AMA, Hassaneen AE. Influence of diesel fuel blended with biodiesel produced from waste cooking oil on diesel engine performance. *Fuel*. 2016;167:316-328.

doi: 10.1016/j.fuel.2015.11.064

13. Elkelawy M, Draz AM, Seleem HE, Hamouda MA. Performance characteristics of diesel engine power plants: efficiency, emissions, and operational flexibility. *Pharos Eng Sci J*. 2025;2(1):1-11.

doi: 10.21608/pesj.2025.352971.1009

14. Ajala OE, Aberuagba F, Odetoye TE, Ajala AM. Biodiesel: sustainable energy replacement to petroleum-based diesel fuel—a review. *ChemBioEng Rev*. 2015;2(3):145-156.

doi: 10.1002/cben.201400024

15. Naylor RL, Higgins MM. The rise in global biodiesel production: implications for food security. *Glob Food Secur*. 2018;16:75-84.

doi: 10.1016/j.gfs.2017.10.004

16. Zhao Y, Wang C, Zhang L, Chang Y, Hao Y. Converting waste cooking oil to biodiesel in China: environmental impacts and economic feasibility. *Renew Sustain Energy Rev*. 2021;140:110661.

doi: 10.1016/j.rser.2020.110661

17. Ng JH, Ng HK, Gan S. Advances in biodiesel fuel for application in compression ignition engines. *Clean Technol Environ Policy*. 2009;12(5):459-493.

doi: 10.1007/s10098-009-0268-6

18. Luque R, Melero JA. *Advances in Biodiesel Production: Processes and Technologies*. Elsevier; 2012.

19. Fayaz U, Bashir I, Fayaz J, *et al.* Food processing byproducts: their applications as sources of valuable bioenergy and recoverable products. In: *Integrated Waste Management Approaches for Food and Agricultural Byproducts*. Apple Academic Press; 2023:25-80.

doi: 10.1201/9781003282327-2

20. Friso D. Brake thermal efficiency and BSFC of diesel engines: Mathematical modeling and comparison between diesel oil and biodiesel fueling. *Appl Math Sci*. 2014;8:6515-6528.

doi: 10.12988/ams.2014.46444

21. Ali N, Maki DF. Combustion characteristics of CI engine fueled with WCO biodiesel/diesel blends at different compression ratios and EGR. *Heat Trans.* 2023;52(6):3953-3966.

doi: 10.1002/htj.22859

22. Elkelawy M, Bastawissi HAE, Shams M. Influence of diesel engine load, waste cooking oil biodiesel blend percentage, and nanoparticles concentrations on brake thermal efficiency and NOx emissions using response surface methodology. *Pharos Eng Sci J*. 2025;2(1):59-74.

doi: 10.21608/pesj.2025.354280.1015

23. Samanta A. Experimental Investigation & Thermodynamic Modeling of a Diesel Engine to Analyze Performance, Energy, Emission and Exergy Using Edible and Inedible Biodiesel Blends. PhD Thesis. Jadavpur University; 2021.

24. Prasad T. *Study of the Effect of Di Butyle Ether Additive on Combustion and Emission Characteristics of Diesel and Honge Biodiesel Run IC Engine*. Master's thesis. ATMECE; 2016.

25. Wu G, Ge JC, Choi NJ. A comprehensive review of the application characteristics of biodiesel blends in diesel engines. *Appl Sci*. 2020;10(22):8015.

doi: 10.3390/app10228015

26. Sharma A, Pali HS, Kumar M, Singh NK, Singh Y, Singh D. Study the effect of optimized input parameters on a CRDI diesel engine running with waste frying oil methyl ester-diesel blend fuel with ZnO nanoparticles: a response surface methodology approach. *Biomass Conv Bioref*. 2023;13(14):13127-13152.

doi: 10.1007/s13399-021-02158-6

27. Habibullah M, Rizwanul Fattah IM, Masjuki HH, Kalam MA. Effects of palm-coconut biodiesel blends on the

performance and emission of a single-cylinder diesel engine. *Energy Fuels*. 2015;29(2):734-743.

doi: 10.1021/ef502495n

28. Ibrahim SMA, Abed KA, Gad MS, Hashish HMA. Performance and emissions of a diesel engine burning blends of Jatropha and waste cooking oil biodiesel. *Proc Inst Mech Eng Part C J Mech Eng Sci*. 2023;238(4):1157-1169.

    doi: 10.1177/09544062231181809

29. Kumar Naik M, Charan Meher L, Kumar Dalai A, Narayan Naik S. Biodiesel production using Karanja (Pongamia pinnata) and Jatropha (Jatropha curcas) seed oil. In: *Handbook of Plant-Based Biofuels*. CRC Press; 2008:255-266.

    doi: 10.1201/9780789038746.ch18

30. Hassan RK, AlDakrany AM, Aref MA, Ghallab AO, Salatein NM, Fahim IS. Valorization of sugarcane bagasse and spent coffee grounds for biodiesel production: a comparative study of solvent extraction methods. *Discov Chem*. 2025;2(1).

    doi: 10.1007/s44371-025-00401-x

31. Sousa ARD. *Análise numérica da cinética química da combustão de n-dodecano e metil oleato: uma abordagem com modelos detalhados* [*Numerical analysis of the chemical kinetics of n-dodecane and methyl oleate combustion: an approach with detailed models*]. Dissertation. Universidade Federal de Santa Catarina; 2025. [In Portuguese]. https://repositorio.ufsc.br/handle/123456789/270769

32. Masjudin, Chang WC. Comparative study on saturated and unsaturated fatty acid methyl esters (FAME) composition in biodiesel production from waste soybean, sunflower, and canola oils. *Biofuels*. 2025;17(5):998-1021.

    doi: 10.1080/17597269.2025.2564500

33. Daji GA, Green E, Akanni GB, Adebo OA. GC-MS-based metabolomics elucidates the impact of cereal-based microbial starters on the metabolite profile of mahewu prepared from yellow maize. *Int J Food Sci Technol*. 2023;59(6):4268-4280.

    doi: 10.1111/ijfs.16667

34. Patel RL, Sankhavara CD. Biodiesel production from Karanja oil and its use in diesel engine: A review. *Renew Sustain Energy Rev*. 2017;71:464-474..

    doi: 10.1016/j.rser.2016.12.075

35. Prakash Varma PS, Subbaiah KV. Biofuel blends and nano-additives: a sustainable approach to diesel engine performance and emissions improvement. *Eng Res Express*. 2024;6(4):045533.

    doi: 10.1088/2631-8695/ad88da

36. Abuhabaya A. Investigation of Engine Performance and Exhaust Gas Emissions by Using Bio-Diesel in Compression Ignition Engine and Optimisation of Bio-Diesel Production From Feedstock by Using Response Surface Methodology. Doctoral dissertation. University of Huddersfield; 2012. https://eprints.hud.ac.uk/id/eprint/14064/

37. Wcisło G, Leśniak A, Kurczyński D, Pracuch B. Experimental Investigation of Physicochemical Properties of the Produced Biodiesel from Waste Frying Oil and Its Blend with Diesel Fuel. *Energies*. 2024;17(16):4175.

    doi: 10.3390/en17164175

38. Pullagura G, Vanthala VSP, Vadapalli S, *et al.* Enhancing performance characteristics of biodiesel-alcohol/diesel blends with hydrogen and graphene nanoplatelets in a diesel engine. *Int J Hydrog Energy*. 2024;50:1020-1034.

    doi: 10.1016/j.ijhydene.2023.09.313

39. Azarudeen JM, Anish M, Babu LG, *et al.* Performance and emission characteristics of waste cooking oil biodiesel blends in sustainable fuel applications. *Sci Rep*. 2025;15(1).

    doi: 10.1038/s41598-025-19130-3