Nigerian Journal of Engineering Science Research (NIJESR).
Copyright@ Department of Mechanical Engineering, Gen. Abdusalami Abubakar College of Engineering, Igbinedion University, Okada, Edo State, Nigeria.
ISSN: 2636-7114
Journal Homepage: https://nijesr.iuokada.edu.ng/

Diesel Engine Performance Evaluation and Emission Analysis Using Waste Cooking Oil Biodiesel

[1]Jude Ebieladoh Sinebe, [2]Wisdom Chukwuemeke Ulakpa, and [3]Emmanuel Tega Erokare

[1]Department of Mechanical Engineering, Delta State University, Abraka, Nigeria,
jesinebe@delsu.edu.ng

[2]Department of Chemical Engineering, Southern Delta University Ozoro, Delta State, Nigeria,
ulakpa.wisdom@yahoo.com, wisdomcu@sdu.edu.ng

[3]Department of Agricultural and Biosystem Engineering, Southern Delta University, Ozoro, Nigeria
erokaretega.e@gmail.com

**Corresponding Author: Wisdom C. Ulakpa; ulakpa.wisdom@yahoo.com*

Manuscript History
Received: 30/06/2026
Revised: 24/07/2026
Accepted: 30/07/2026
Published: 03/08/2026
https://doi.org/10.5281/zenodo.21838911

Abstract: *The increasing energy demand in the world and the environmental impact of fossil diesel have resulted in the search for sustainable alternatives such as biodiesel from waste cooking oil (WCO). This study discusses the generation of WCO biodiesel by alkaline transesterification and performance and emission characteristics of blends (B0, B20, B40, B60, B80, B100) in a Perkins 4:108 diesel engine. WCO was pre-treated and transesterified under optimal circumstances (methanol to oil ratio of 6:1, 1 wt % NaOH, 60 °C, 90 min) with a yield of 92 %. The blends were tested at constant 1500 rpm with variable load. The main performance parameters (BP, BTE, BSFC) and emissions (CO, HC, NOx, smoke) were determined. The results showed minor reductions in BP and BTE with increasing biodiesel ratio due to lower calorific value but significant reductions in CO and HC emissions. NOx increased somewhat. The measured fuel qualities were within the limits of the ASTM D6751 and EN 14214. Moderate mixes (B20-B40) produce the best performance-emission balance. Recommendations include NOx abatement and long term engine durability testing.*

Keywords: *Waste Cooking Oil Biodiesel, Transesterification, Engine performance, Emission characteristics, Biodiesel blends, Sustainable fuel*

INTRODUCTION

Growing worries about the environmental damage from burning fossil fuels have made the search for cleaner, renewable energy sources more pressing than ever, especially as global energy needs continue to rise. Diesel engines, prized for their strong torque and high efficiency, power many heavy-duty trucks, farming equipment, and electricity generators. However, they also remain a leading cause of urban air pollution and greenhouse gas emissions. Biodiesel, produced from renewable materials, offers a practical substitute that can cut these harmful effects while supporting a circular economy by turning waste into useful fuel (Yaqoob et al., 2021; Mengistu et al., 2024). Among available options, waste cooking oil (WCO) stands out as an excellent feedstock for biodiesel. As a discarded product from homes and restaurants, it helps tackle waste disposal issues and avoids the food-versus-fuel conflict linked to fresh vegetable oils. Through transesterification, WCO can be converted into biodiesel with properties very close to regular diesel, allowing it to be used in existing compression ignition engines with almost no changes. Recent studies indicate that blending WCO biodiesel with petroleum diesel can sharply lower emissions of particulate matter, carbon monoxide, and unburned hydrocarbons, although it sometimes leads to a slight rise in nitrogen oxides because of the fuel's oxygen content and altered burning behavior (Lee and Cho, 2024; Mengistu et al., 2024).

This research brings fresh insight by carrying out a full assessment of WCO biodiesel's engine performance and exhaust emissions. It goes beyond standard testing by applying multi-objective approaches that carefully balance thermal efficiency, fuel consumption, and pollutant levels. Drawing on the latest understanding of how different blends behave during combustion, the work provides useful guidance for putting sustainable fuels into practice. Comparative analyses show that well-chosen WCO biodiesel blends can achieve major cuts in CO and HC emissions while preserving competitive power output, which helps reduce the overall carbon footprint over the fuel's lifetime (Alotaibi et al., 2024; Biberci et al., 2025). The real novelty lies in linking effective waste management with detailed engine testing. This approach could encourage wider use of the fuel in places that produce large amounts of WCO. By transforming a problematic waste into a high-value, cleaner-burning fuel, the strategy strengthens energy security and supports international sustainability goals. The following sections describe the experimental methods, key findings, and broader implications, underlining the strong potential of WCO biodiesel as a future renewable option for diesel engines.

MATERIALS AND METHODS

2.1 Preparation of Waste Cooking Oil

Waste cooking oil (WCO) was collected from local restaurants and households within the study area. The oil was first filtered using a 20 µm mesh to eliminate solid food residues and other impurities. It was subsequently preheated to 110 °C for 30 minutes to remove moisture and volatile compounds. The acid value of the filtered WCO was determined to be 2.8 mg KOH/g, indicating a low free fatty acid (FFA) content and making it suitable for single-step base-catalyzed transesterification.

2.2 Production of Waste Cooking oil Biodiesel oil by Transesterification

Biodiesel production was carried out via alkaline transesterification in a 5 L batch reactor equipped with a mechanical stirrer, thermometer, and reflux condenser. Methanol (99.8% purity) and sodium hydroxide (NaOH, 98% purity) were used as alcohol and catalyst, respectively. The reaction conditions were optimized at a 6:1 methanol-to-oil molar ratio, 1 wt.% catalyst concentration, 60 °C reaction temperature, and 90 minutes reaction time with constant stirring at 600 rpm. After completion, the mixture was allowed to settle in a separating funnel for 24 hours, where the glycerol layer was removed from the bottom. The upper biodiesel layer was washed repeatedly with warm distilled water (50–60 °C) until neutral pH was achieved and then dried by heating to 110 °C under vacuum to remove residual moisture and methanol. The final yield of WCO biodiesel (B100) was approximately 92% by volume.

2.3 Fuel Blends Preparation

Test fuels were prepared by blending the produced WCO biodiesel with commercial ultra-low sulfur diesel (B0) on a volume basis. The following blends were formulated: B0: 100% diesel, B20: 20% biodiesel + 80% diesel, B40: 40% biodiesel + 60% diesel, B60: 60% biodiesel + 40% diesel, B80: 80%, biodiesel + 20% diesel,B100: 100% biodiesel. Blending was performed by mechanical stirring for 30 minutes at room temperature to ensure homogeneity. All blends were stored in airtight containers and used within one week of preparation. Experimentally measured fuel properties for the produced WCO biodiesel included density 882 kg/m^3, kinematic viscosity 4.8 mm^2/s at 40°C, calorific value 38.2 MJ/kg, flash point 162°C, cetane number 55, and acid value 0.3 mg KOH/g, all complying with ASTM D6751 and EN 14214 standards. Measurement uncertainties were ±0.5% for density, ±1% for viscosity.

Sinebe *et al.*, (2026). *Diesel Engine Performance Evaluation and Emission Analysis Using Waste Cooking Oil Biodiesel. Nigeria Journal of Engineering Science Research (NIJESR).*, *9*(2), 41-50. https://doi.org/10.5281/zenodo.21838911

2.4 Test Engine and Experimental Setup

The engine performance and emission tests were conducted on a four-cylinder, four-stroke, water-cooled, direct injection (DI) compression ignition diesel engine (Perkins 4:108). Prior to the commencement of the experiments, all measuring instruments were meticulously calibrated according to the manufacturers' guidelines and standard laboratory protocols to ensure accuracy, reliability, and traceability of the collected data. The digital tachometer was calibrated against a standard reference frequency generator and verified at multiple speed points across the operating range (1000–4000 rpm) to confirm precise engine speed measurement.

Fuel consumption measurement, performed using the burette and stopwatch method, was calibrated by comparing volumetric readings against a precision electronic balance for mass flow determination. The burette was cleaned, checked for leaks, and its volume markings were verified using certified volumetric glassware. The eddy current dynamometer was calibrated using known torque standards and a certified load cell. Torque and power readings were validated at various load levels to ensure accurate brake power measurements. The multi-gas analyzer was calibrated daily before testing using certified zero and span calibration gases for CO, HC, NOx, and CO_2. A two-point calibration procedure was followed for each gas component, and the analyzer's response time and linearity were verified. The Hartridge smoke meter was calibrated using standard filter papers of known opacity values provided by the manufacturer. Zero adjustment was performed with clean air, and the instrument's accuracy was cross-checked against reference opacity standards. These calibration procedures were repeated at regular intervals throughout the experimental period to maintain measurement integrity and minimize uncertainties. All calibration records were documented for quality assurance purposes.

2.5 Experimental Procedure

All tests were performed at a constant engine speed of 1500 rpm, with brake load varied from 0% to 100% of the engine's full capacity. The engine was initially warmed up on diesel fuel for 15–20 minutes until the exhaust gas temperature stabilized. For each fuel blend, the engine was allowed to run for 10 minutes to achieve steady-state conditions before any measurements were taken. To ensure reliable and repeatable results, each test condition was conducted three times, and the average values were used in the analysis. Fuel consumption was determined volumetrically, while brake thermal efficiency (BTE) and brake specific fuel consumption (BSFC) were calculated using standard equations. Emission measurements were taken concurrently with the performance data. All experiments were carried out under controlled ambient conditions, with temperature maintained between 25 and 30 °C and relative humidity between 50 and 60 %. After switching to a different test fuel, the fuel lines and injection system were thoroughly flushed with the new fuel for 15 minutes to eliminate any residual effects from the previous blend. No modifications were made to the engine's original hardware. This systematic approach enabled a direct and fair comparison of the performance and emission characteristics of the various WCO biodiesel blends against baseline diesel operation.

Table-1 Engine Specifications

Description	Specification
Make and model	Perkins 4:108
Type	Four cylinder, vertical, direct injection, variable speed, water cooled stroke diesel engine
Bore	79.735mm
Stroke	80.9mm
Swept volume	1.76 L/cycle
Swept length	0.089m
Compression ratio	22:1
Oriffice diameter	58.86cm
Maximum HP	38 hp
Maximum speed	1500-4000rpm
Loading device	Eddy current dynamometer
Injection pressure	0.95bar

Number of cylinder head	4
Exhaust pipe diameter	3/2″
Coefficient discharge	0.6
Dynamometer capacity	112 kW/150 hp
Dynamometer Max. Speed	7500 rpm
guage	50-100cc
Baracharach	PCA2 No. 235, P/N 24-7305

Plate-1Perkins 4:108 diesel engine test bed

RESULTS AND DISCUSSION

3.1 Fuel Properties of WCO Biodiesel and its Blend with Diesel

Waste cooking oil (WCO) biodiesel consists mainly of fatty acid methyl esters (FAME) and possesses physicochemical characteristics that generally meet international standards such as ASTM D6751 and EN 14214. These properties allow it to serve as a viable renewable substitute or blending component with conventional petroleum diesel.

The produced WCO biodiesel satisfies or exceeds most key requirements of the ASTM D6751 and EN 14214 specifications, confirming its suitability for direct use or blending. Compared with petroleum diesel, it typically shows higher density and viscosity due to the presence of longer-chain fatty acid esters. While these differences can slightly affect fuel injection and atomization, they also enhance lubricity. When adequately processed, the kinematic viscosity falls well within the acceptable ranges of 1.9–6.0 mm²/s (ASTM) and 3.5–5.0 mm²/s (EN) (Suherman et al., 2023).

One notable advantage is the significantly higher flash point of WCO biodiesel, often exceeding 150 °C, which substantially improves safety during storage, handling, and transport compared to regular diesel (55–66 °C). Additionally, its cetane number is generally higher than that of conventional diesel, resulting in shorter ignition delay, smoother engine operation, and reduced noise levels (Etim et al., 2025).

However, cold flow properties—including cloud point, pour point, and cold filter plugging point—present a challenge for WCO biodiesel because of its higher saturated fatty acid content. These properties are often poorer than those of petroleum diesel, which may require the use of additives or blending for use in colder climates. After proper purification, the acid value remains low, thereby minimizing risks of corrosion in the fuel system (Suherman et al., 2023).

The lower heating value of WCO biodiesel, arising from the oxygen content in the FAME molecules, can lead to slightly higher fuel consumption when used in its pure form (B100). Nevertheless, lower blends such as B20 frequently achieve efficiency levels comparable to diesel (Camur et al., 2021).

Table 1: Fuel Properties of WCO Biodiesel along with Corresponding Test Methods

Property	Unit	Typical Value (WCO Biodiesel)	ASTM Standard	EN Standard
Density (at 15°C)	kg/m³	870–895	ASTM D4052 / D1298	EN ISO 3675 / 12185
Kinematic Viscosity (at 40°C)	mm²/s	4.0–5.5	ASTM D445	EN ISO 3104
Cetane Number	-	52–60	ASTM D613	EN ISO 5165

Flash Point	°C	120–180	ASTM D93	EN ISO 3679
Pour Point	°C	0 to 12	ASTM D97	EN ISO 3016
Cloud Point	°C	5 to 15	ASTM D2500	EN ISO 23015
Acid Value	mg KOH/g	0.1–0.5	ASTM D664	EN 14104
Calorific Value	MJ/kg	37–39	ASTM D240 / D4809	-

3.2 Engine Performance Evaluation of Diesel, WCO FAME and the Blends

Engine performance parameters were calculated from the raw experimental data, which included the volume of fuel consumed, the time taken for consumption, mass flow rate, torque, and the measured physicochemical properties of both diesel and WCO biodiesel. These measurements formed the basis for determining the key indicators: brake power (BP), brake thermal efficiency (BTE), and brake specific fuel consumption (BSFC). The calculated performance values for pure diesel (B0), pure WCO biodiesel (B100), and the various blends (B20, B40, B60, and B80) were then plotted against engine speed. This graphical representation allowed for clear observation of how different fuel formulations behaved under varying speeds and loads. Finally, the performance curves of the biodiesel and its blends were directly compared with those of baseline diesel fuel to assess their relative effectiveness and potential as a practical alternative for compression ignition engines.

3.3 Effect of Engine Speed on Engine Performance and Emission Evaluation Characteristics

3.3.1 Effect of Engine Speed on Brake Power for Diesel, WCO FAME and Blends

Brake power (Fig.1) increased with engine speed up to around 2000–2500 rpm, after which it stabilized or showed only slight variations. This trend aligns with the typical operating characteristics of diesel engines. Pure diesel (B0) consistently delivered the highest brake power across the tested speed range. Higher biodiesel blends (B80 and B100), however, produced noticeably lower power output, with the differences becoming more pronounced at both lower (1000 rpm) and higher (3000 rpm) speeds. The primary cause of this reduction is the lower calorific value of WCO biodiesel, which delivers less energy per unit mass compared to conventional diesel. These findings are consistent with recent studies reporting modest decreases in brake power and torque when using WCO biodiesel blends (Gaur *et al.,* 2025).

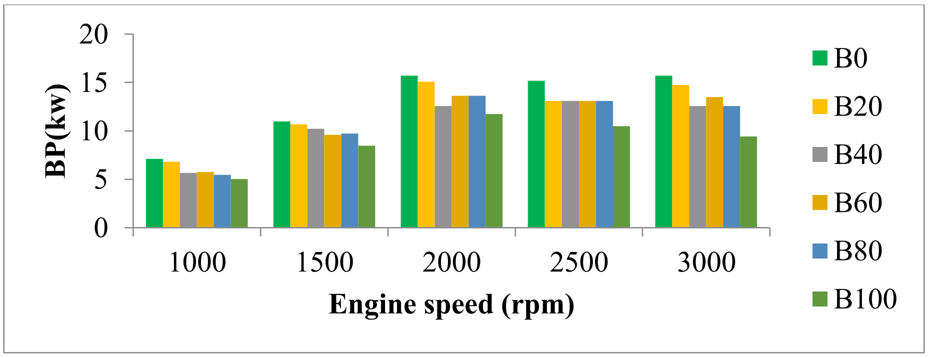

Fig. 1 Effect of Engine Speed on Brake Power for Diesel, WCO FAME and the Blends

3.3.2 Effect of engine speed on brake thermal efficiency for diesel, WCO FAME and blends

BTE (Fig.2), followed a characteristic pattern, peaking near 2000 rpm for most blends due to optimal combustion phasing and reduced relative heat losses at mid-range speeds. B20 demonstrated competitive or occasionally superior BTE compared to B0 at certain speeds, suggesting that low-level blending can maintain thermal efficiency through improved combustion completeness enabled by fuel-bound oxygen (Ulakpa *et al.,* 2020). In contrast, B100 showed the lowest BTE, particularly at lower and higher speeds. These results corroborate findings that moderate WCO biodiesel blends (up to B20–B30) often provide a favorable balance, whereas higher blends incur efficiency penalties due to increased fuel consumption to compensate for lower energy density (Alotaibi et al., 2024).

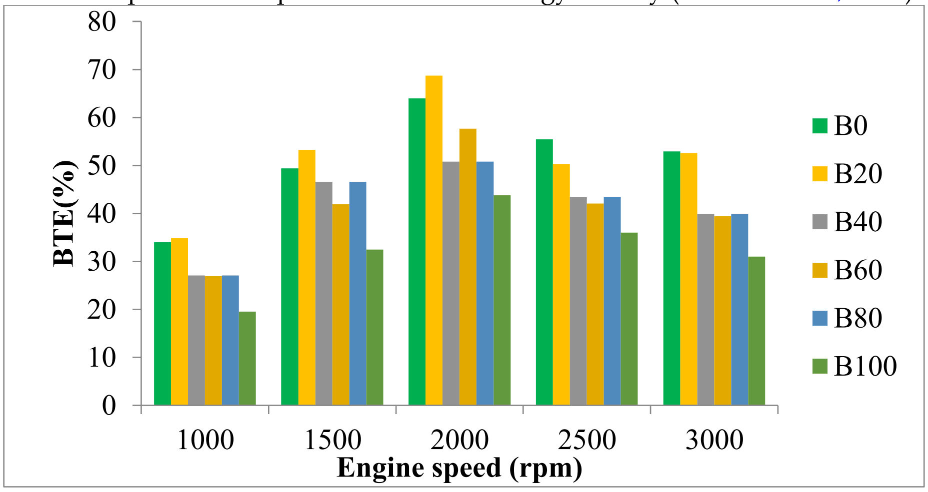

Fig.2**:** Effect of Engine Speed on BTE for Diesel, WCO FAME and Blends

3.3.3 Effect of Engine Speed on Brake Specific Fuel consumption (BSFC) for Diesel, WCO FAME and the Blends

BSFC (Fig. 3) varied with engine speed for all the fuels tested. The lowest values occurred around 2000 rpm, which matched the point of highest brake thermal efficiency. As the proportion of biodiesel in the blend increased, BSFC also rose steadily, with B100 showing the highest consumption rates — particularly at 1000 rpm. This happens because WCO biodiesel contains less energy per kilogram than regular diesel, so the engine needs more fuel to produce the same power. The data suggests that the B20 blend offers a good balance in practice: it causes only a small increase in fuel use while delivering clear improvements in emissions. Other recent studies have also shown that BSFC goes up with higher biodiesel content, though carefully chosen lower blends help keep this effect under control (Mengistu *et al.,* 2024).

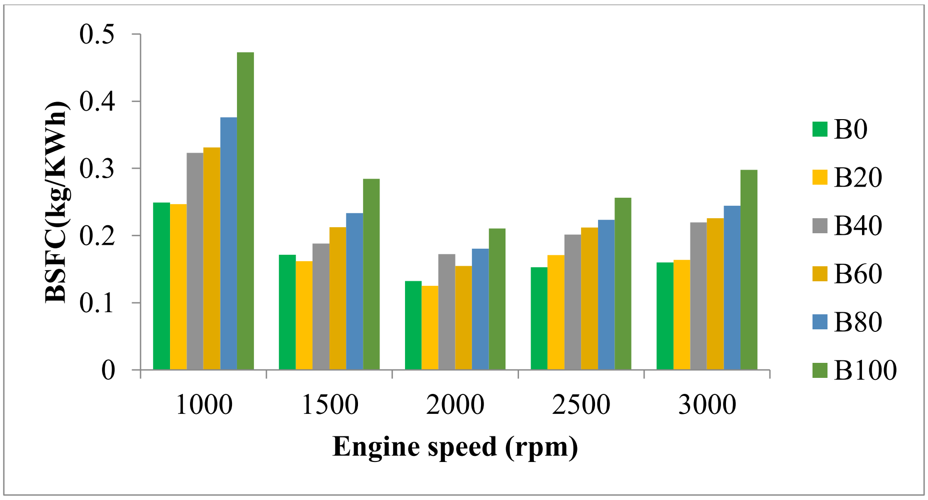

Fig. 3 Effect Engine Speed on BSFC for Diesel, WCO FAME and Blends

3.3.4 Effect of Engine Speed on CO Emission of Diesel, WCO FAME and the Blends

Across the entire speed range, carbon monoxide (CO) emissions (Fig. 4) were markedly lower with higher biodiesel blends, especially with B100. This improvement comes from the oxygen-rich nature of WCO biodiesel, which promotes more complete combustion and reduces the formation of CO. The reduction was particularly evident at higher engine speeds, where air-fuel mixing is more effective. Other studies have reported CO reductions of 20–70% with WCO biodiesel blends, highlighting their potential for controlling products of incomplete combustion (Lee *et al.,* 2024).

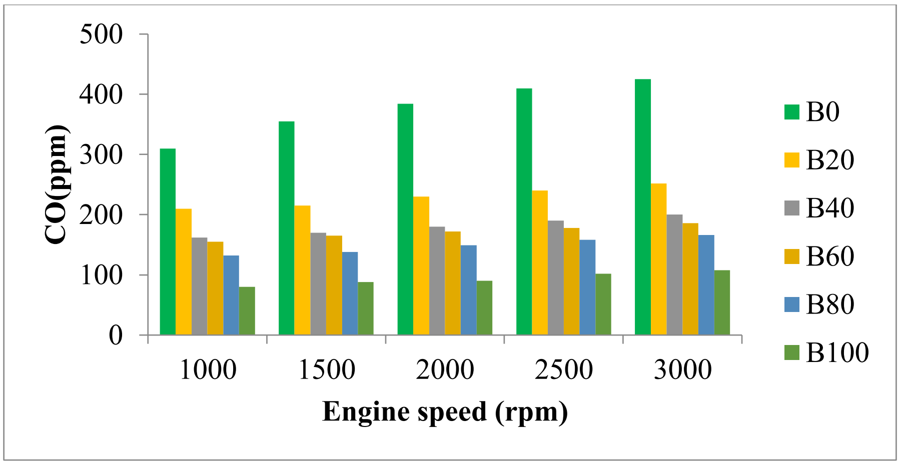

Fig.4 Effect of Engine Speed on CO Emission for Diesel, WCO FAME and their Blends

3.3.5 Effect of engine speed on NOx emission of diesel, WCO FAME and the blends

Nitrogen oxides (NOx) emissions (Fig.5) increased with higher biodiesel blend ratios and generally rose with increasing engine speed. This well-known trade-off is primarily attributed to elevated combustion temperatures resulting from the oxygen content in biodiesel and altered combustion phasing. Pure diesel (B0) exhibited the lowest NOx emissions, whereas higher blends such as B100 produced significantly higher levels, particularly at elevated speeds. For practical implementation, mitigation strategies including exhaust gas recirculation (EGR) and optimization of injection timing are commonly recommended (Ulakpa *et al.,* 2020; Mengistu *et al.,*2024).

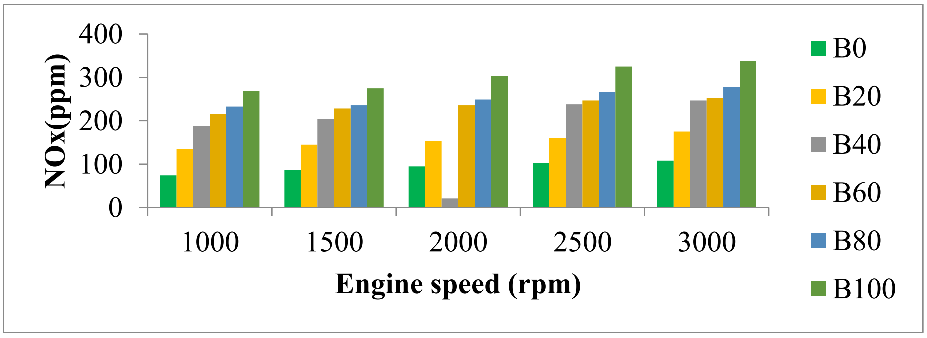

Fig.5: Effect of Engine Speed on NOx Emission for Diesel, WCO FAME and their Blends

3.3.6 Effect of engine speed on HC emission of diesel, WCO FAME and the blends

Fig. 6 illustrates the variation in unburned hydrocarbon (HC) emissions (in ppm) for diesel (B0) and WCO biodiesel blends (B20, B40, B60, B80, and B100) across engine speeds from 1000 to 3000 rpm. Pure diesel consistently produced the highest HC emissions at every speed tested, while emissions decreased steadily as the biodiesel content increased, with B100 recording the lowest values. Although HC emissions tended to rise with higher engine speeds for all fuels, the biodiesel blends maintained a clear advantage (Khujamberdiev *et al.,* 2023). This trend reflects the superior combustion characteristics of WCO biodiesel. The oxygen naturally present in fatty acid methyl esters promotes more complete burning, which reduces the amount of unburned hydrocarbons. Higher cetane numbers in the blends also contribute to shorter ignition delays and better oxidation of fuel molecules. As the biodiesel proportion increases from B20 to B100, HC emissions drop noticeably compared with pure diesel, with greater reductions observed at higher blend ratios (Yaqoob et al., 2021).

At lower speeds (1000–1500 rpm), the difference between pure diesel and higher blends (B80–B100) is particularly clear, indicating improved combustion efficiency under these conditions. As speed approaches 3000 rpm, HC levels rise across all fuels due to shorter time available for complete combustion; however, the biodiesel blends continue to outperform conventional diesel. This behavior is consistent with findings from several other studies on WCO-derived fuels (Ojapah *et al.,* 2023). The observed reductions in HC emissions highlight the environmental advantages of utilizing WCO biodiesel. By recycling waste cooking oil, these blends help address disposal challenges while lowering pollutant levels and producing cleaner exhaust. Although higher blends deliver stronger emission benefits, moderate ratios such as B20–B40 often provide the best overall balance between engine performance, fuel properties, and compatibility with existing diesel engines (Mengistu *et al.,* 2024).

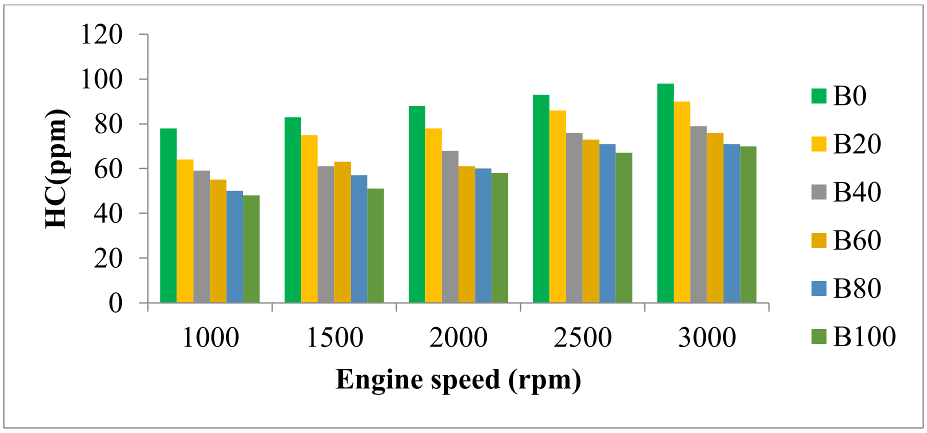

Fig.6 Effect of Engine speed on HC emission for Diesel, WCO FAME and their Blends

CONTRIBUTION TO KNOWLEDGE

This study advances the field of sustainable biofuel utilization by providing a comprehensive experimental investigation into the production and application of waste cooking oil (WCO) biodiesel in a Perkins 4:108 diesel engine, with a detailed performance and emission characterization across multiple blend ratios (B0 to B100) under varying engine loads at constant speed. The research demonstrates an optimized single-step alkaline transesterification process achieving a high 92% biodiesel yield from locally sourced WCO, while confirming that the resulting fuel and its blends fully comply with ASTM D6751 and EN 14214 standards. Key original insights include the identification of moderate blends (B20–B40) as offering the most balanced trade-off between acceptable brake power and brake thermal efficiency with substantial reductions in CO and HC emissions, despite the expected modest increases in NOx and BSFC associated with higher biodiesel content. By bridging waste valorization with practical engine diagnostics in a Nigerian context, this work contributes actionable data on real-world applicability, highlights the environmental benefits of recycling abundant WCO resources, and offers targeted recommendations for NOx mitigation and durability testing to support scalable adoption of WCO biodiesel in compression ignition engines, thereby supporting circular economy principles and reduced reliance on fossil diesel.

CONCLUSION

This study successfully produced biodiesel from waste cooking oil through base-catalyzed transesterification and comprehensively evaluated its blends with petroleum diesel in a diesel engine. The produced WCO biodiesel exhibited physicochemical properties that largely satisfied ASTM D6751 and EN 14214 requirements, confirming its suitability as a drop-in fuel. Engine tests revealed that while higher biodiesel blends led to modest reductions in brake power and brake thermal

efficiency alongside increased brake specific fuel consumption primarily due to lower energy content, they delivered substantial improvements in exhaust emissions.
Notably, CO and unburned HC emissions decreased significantly with increasing WCO biodiesel content across the tested speed range, attributed to the oxygen-rich nature of fatty acid methyl esters and improved combustion completeness. Although NOx emissions rose with higher blend ratios, the overall emission profile supports the environmental advantages of WCO biodiesel. Moderate blends such as B20 demonstrated the best compromise, maintaining acceptable performance while providing meaningful emission reductions and promoting waste recycling. The findings reinforce the potential of WCO biodiesel to contribute to energy security, circular economy principles, and reduced environmental impact in diesel engine applications. Future work should focus on NOx mitigation strategies, long-term durability studies, and economic optimization for large-scale implementation. This research provides valuable insights for advancing sustainable biofuel adoption in regions with abundant waste cooking oil resources.

CONFLICT OF INTEREST

There is no conflict of interest for this research work.

ACKNOWLEDGEMENT

The authors gratefully acknowledge the support provided by the Department of Mechanical Engineering, University of Nigeria, Nsukka, and the Department of Chemical Engineering, Southern Delta University, Ozoro, for providing laboratory facilities and equipment used in this study. Special thanks are extended to laboratory technologists and colleagues for their technical assistance during the experimental work. This research received no specific external grant from any funding agency.

REFERENCES

Alotaibi, J. G., Alajmi, A. E., Alsaeed, T., Al-Lwayzy, S. H., & Yousif, B. F. (2024). On the influence of engine compression ratio on diesel engine performance and emission fueled with biodiesel extracted from waste cooking oil. *Energies, 17*(15), Article 3844. https://doi.org/10.3390/en17153844

Biberci, M. A., Çelik, M. B., & Ozhuner, E. (2025). Engine performance and emission optimization with waste cooking oil biodiesel/diesel blend using ANN and RSM techniques coupled with ACKTR-DE and HHO algorithms. *BMC Chemistry, 19*, Article 137. https://doi.org/10.1186/s13065-025-01512-3

Chukwumela Ajie, A., Moore Ojapah, M., & Ogheneruona Diemuodeke, E. (2023). Effects of waste cooking oil biodiesel on performance, combustion and emission characteristics of a compression ignition engine. *Journal of Energy and Power Technology, 5*(2), Article 020. https://doi.org/10.21926/jept.2302020

Etim, A. O., & Bwapwa, J. K. (2026). Optimization, economic assessment, and quality analyses of waste-based biodiesel fuel production: A case study of waste cooking oil and a seashell synthesized catalyst. *Energies, 19*(1), Article 48. https://doi.org/10.3390/en19010048

Gaur, R. K., & Goyal, R. (2025). Performance, emission, combustion and economics analysis of CI engine fueled with mixed oil biodiesel blends from waste cooking oil and pongamia oil. *Discover Applied Sciences, 7*, Article 609. https://doi.org/10.1007/s42452-025-07150-7

Khujamberdiev, R., & Cho, H. (2023). Impact of biodiesel blending on emission characteristics of one-cylinder engine using waste swine oil. *Energies, 16*(14), Article 5489. https://doi.org/10.3390/en16145489

Lee, K., & Cho, H. (2024). Comparative analysis of performance and emission characteristics of biodiesels from animal fats and vegetable oils as fuel for common rail engines. *Energies, 17*(7), Article 1711. https://doi.org/10.3390/en17071711

Mengistu, N. G., Mekonen, M. W., Ayalew, Y. G., et al. (2024). Experimental investigation on diesel engine performance and emission characteristics using waste cooking oil blended with diesel as biodiesel fuel. *Discover Energy, 4*, Article 26. https://doi.org/10.1007/s43937-024-00051-7

Suherman, S., Abdullah, I., Sabri, M., & Silitonga, A. S. (2023). Evaluation of physicochemical properties composite biodiesel from waste cooking oil and *Schleichera oleosa* oil. *Energies, 16*(15), Article 5771. https://doi.org/10.3390/en16155771

Ulakpa, W. C., Onukwuli, D. O., & Ude, C. N. (2020). Performance and emission characteristics of neem oil methyl ester and its blends with diesel fuel. International Journal of Advances in Engineering and Management (IJAEM), 2(7), 192–198. https://doi.org/10.35629/5252-0207192198

Yaqoob, H., Teoh, Y. H., Sher, F., Farooq, M. U., Jamil, M. A., Kausar, Z., Sabah, N. U., Shah, M. F., Rehman, H. Z. U., & Rehman, A. U. (2021). Potential of waste cooking oil biodiesel as renewable fuel in combustion engines: A review. *Energies, 14*(9), Article 2565. https://doi.org/10.3390/en14092565

Sinebe *et al*., (2026). *Diesel Engine Performance Evaluation and Emission Analysis Using Waste Cooking Oil Biodiesel. Nigeria Journal of Engineering Science Research (NIJESR).*, *9*(2), 41-50. https://doi.org/10.5281/zenodo.21838911