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ENVIRONMENTAL IMPACTS OF BLEND FUELS ON HUMAN HEALTH

Original Article

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ABSTRACT

Background: The growing demand for energy, coupled with the adverse environmental impacts of fossil fuels, has prompted the exploration of renewable and waste-derived alternatives. Waste cooking oil (WCO), a widely available byproduct of the food industry, has emerged as a sustainable feedstock for biofuels. However, its direct use in diesel engines poses challenges due to high viscosity and poor volatility. The addition of oxygenated alcohols such as n-pentanol has been suggested as a potential solution to improve fuel properties and reduce harmful exhaust emissions.

Objective: This study aimed to evaluate the performance and exhaust emission characteristics of a compression ignition (CI) engine fueled with diesel-WCO-n-pentanol blends, with emphasis on carbon monoxide (CO), carbon dioxide (CO_2), and particulate matter (PM) emissions.

Methods: Experimental investigations were conducted using a single-cylinder, water-cooled, horizontal CI engine operating at a constant speed of 1300 rpm and steady load conditions. Three fuel samples were tested: pure diesel (DF100), a binary blend of 85% diesel and 15% WCO (D85WCO15), and a ternary blend of 80% diesel, 15% WCO, and 5% n-pentanol (D80WCO15Pe5). The blends were prepared through splash blending and homogenized at 4000 rpm for 30 minutes. Exhaust gas analyzers were used to measure CO, CO_2, and PM1.0/PM2.5 concentrations over engine operation hours.

Results: The binary blend (D85WCO15) increased CO emissions to 0.12% compared to 0.07% for diesel, while the ternary blend (D80WCO15Pe5) reduced CO to 0.035%. CO_2 emissions increased by 0.25% for D85WCO15 and 0.70% for D80WCO15Pe5 relative to diesel. PM emissions decreased by approximately 10% with D85WCO15 and by 30% with D80WCO15Pe5 compared to diesel, with consistent reductions observed for both PM1.0 and PM2.5 fractions.

Conclusion: The addition of n-pentanol to diesel-WCO blends improved combustion efficiency, resulting in lower CO and PM emissions but higher CO_2 output. These findings indicate that ternary blends represent a practical strategy for waste valorization and emission reduction in CI engines.

Keywords: Carbon Dioxide; Carbon Monoxide; Compression Ignition Engine; Exhaust Emissions; n-Pentanol; Particulate Matter; Waste Cooking Oil.

INTRODUCTION

The rising concern over environmental degradation and public health risks has brought increasing attention to the use of blended fuels in diesel engines. Conventional diesel exhaust is well established as a major source of particulate matter (PM), volatile organic compounds (VOCs), and other harmful pollutants, which contribute to respiratory and cardiovascular illnesses, as well as long-term conditions such as asthma, chronic bronchitis, and lung cancer (1,2). While blending diesel with bio-derived fuels can reduce certain toxic emissions, evidence shows that other pollutants may increase, or the toxicity of emitted particles may be altered, thus creating a complex landscape of potential benefits and risks (1). This duality highlights the pressing need to assess such blends systematically, both from environmental and health perspectives. Among renewable fuel options, biodiesel has gained prominence due to its capacity to reduce reliance on fossil fuels and its compatibility with compression ignition (CI) engines. The production of biodiesel largely depends on the transesterification process, which is favored for its environmental sustainability despite high energy demands during pretreatment and extraction (3,4). Critical parameters such as catalyst concentration, alcohol-to-glyceride ratio, reaction time, temperature, and free fatty acid content significantly influence the efficiency and yield of this process (4). In this context, waste cooking oil (WCO) represents a particularly valuable feedstock. Globally, billions of gallons of WCO are discarded each year, contributing to infrastructure damage and environmental contamination when improperly disposed of, particularly through sewage systems and aquatic ecosystems (5–7). This mismanagement underscores both the ecological hazards of untreated disposal and the untapped potential of WCO as an alternative fuel resource. Despite its abundance and low cost, the direct application of WCO in diesel engines poses operational challenges. Its inherently high viscosity impairs fuel atomization, complicates engine starting, increases pumping energy requirements, and accelerates the buildup of carbon deposits within combustion chambers, injectors, and piston rings (8,9).

These issues not only undermine engine performance but also shorten component lifespan, necessitating effective pretreatment strategies. Techniques such as preheating WCO or converting it into biodiesel through transesterification are commonly employed to mitigate these drawbacks (10,11). Nevertheless, both approaches face inherent limitations: preheating consumes additional energy, while transesterification is complex, uneconomical at scale, and generates glycerin waste that requires careful disposal (12,13). Recent advances have focused on innovative methods to enhance the viability of WCO-based fuels. Decomposition of WCO using alcohols has emerged as a promising, straightforward, and cost-effective strategy to reduce viscosity (14). Additionally, advanced technologies such as supercritical alcohol treatment and ultrasound-assisted transesterification are being explored to improve biodiesel yields, though the cost of production remains a persistent barrier to large-scale commercialization (15). These developments reflect a broader commitment to integrating sustainability with energy efficiency in alternative fuel research. Within this framework, blending WCO with alcohols such as n-pentanol and diesel presents a potentially viable approach to reducing harmful emissions while maintaining acceptable engine performance. Pentanol, with its higher oxygen content and favorable volatility compared to traditional alcohols, offers added potential to enhance combustion efficiency. However, empirical evidence regarding the environmental and health impacts of such ternary blends remains limited, particularly in terms of their influence on carbon monoxide (CO), carbon dioxide (CO2), and particulate matter emissions. The present study addresses this gap by investigating the effects of incorporating WCO and n-pentanol into diesel fuel on the emission behavior of a single-cylinder diesel engine. The objective is to evaluate how these ternary blends alter CO, CO2, and PM emissions, thereby contributing to the ongoing discourse on cleaner, more sustainable fuel alternatives. This work aims to provide evidence-based insights into the practicality of WCO and n-pentanol blends as unconventional yet promising substitutes for conventional diesel fuel.

METHODS

This experimental study was designed to investigate the effect of incorporating waste cooking oil (WCO) and n-pentanol into diesel fuel on the emission behavior of a single-cylinder diesel engine. The work was laboratory-based and did not involve human or animal participants; therefore, ethical approval and informed consent were not required. However, the experimental procedures were carried out in compliance with institutional safety protocols governing the handling of fuels, chemical reagents, and laboratory equipment. The source WCO was obtained after being used primarily for frying food at temperatures ranging from 130 ºC to 180 ºC. A pretreatment process was conducted to improve the quality of the oil and prevent contamination of the prepared fuel blends. This involved straining the oil through a 4 µm filter to remove suspended food residues, followed by heating to eliminate moisture. The removal of water was considered essential, as its presence could have led to phase separation when mixed with diesel fuel due to the latter’s hydrophobic nature. After pretreatment, the WCO was blended with diesel and n-pentanol to form the test fuels. Fuel blends were prepared using the splash blending method. The respective components were mixed in a mechanical homogenizer operated at 4000 rpm for 30 minutes to ensure uniformity and stability of the blends. Three distinct fuel samples were prepared: pure diesel fuel (DF), a binary blend consisting of 85% diesel and 15% WCO (D85WCO15), and a ternary blend consisting of 80% diesel, 15% WCO, and 5% n-pentanol (D80WCO15Pe5). The blending ratios were chosen based on evidence from literature suggesting that limited WCO substitution can be tolerated in CI engines, and that n-pentanol, owing to its moderate oxygen content and relatively low viscosity, could serve as an effective additive to improve fuel atomization and reduce viscosity (14,15). Detailed characterization of the prepared blends was carried out in the laboratory. Standardized tests were performed to determine viscosity, density, flash point, oxygen content, calorific value, and cetane number. These properties were compared against baseline diesel fuel and are presented in Table 1 to illustrate differences between test fuels. Visual inspection was also performed, and the appearance of the prepared blends was documented, as shown in Figure 1, which demonstrates the clear distinction in physical characteristics among diesel, D85WCO15, and D80WCO15Pe5. All experimental procedures were carried out under controlled conditions to ensure reproducibility. Data generated from characterization tests were tabulated and prepared for subsequent analysis. Statistical methods for analysis of emission results would typically include mean comparisons and variance testing (e.g., ANOVA), though the current section did not provide explicit detail on this. It would also be advisable to state the use of statistical software, such as SPSS or MATLAB, to enhance transparency and replicability of findings.

Table 1: Properties of various test fuels

Properties	Diesel	WCO	N-pentanol
Viscosity (40 °C, cSt)	2.28	52	2.89
Density (g/mL)	835	900	814.4
Flash point (°C)	78	271	49
Oxygen (wt %)	0	20	8.47
Calorific value (MJ/kg)	42.5	37.68	34.75
Cetane number	50	54	20

RESULTS

The experimental analysis demonstrated clear variations in engine emissions when diesel fuel was blended with waste cooking oil (WCO) and n-pentanol. For carbon monoxide, pure diesel produced a stable emission level of 0.07%. When diesel was blended with 15% WCO (D85WCO15), CO emissions rose to 0.12%, indicating incomplete combustion due to the higher viscosity of WCO. However, the ternary blend (D80WCO15Pe5) significantly reduced CO emissions to 0.035%, showing an improvement in combustion efficiency compared to both diesel and the binary blend. Carbon dioxide emissions showed an opposite trend. While pure diesel served as the baseline, the inclusion of WCO in the binary blend increased CO2 levels by 0.25%. The addition of n-pentanol to form the ternary blend further elevated CO2 emissions by 0.70%. This rise was consistent with the higher oxygen content of n-pentanol, which promoted more complete combustion relative to diesel and binary blends. Particulate matter emissions were also influenced by the fuel composition. Compared to diesel, WCO blends resulted in lower PM levels, largely due to the inherent oxygen content of WCO which suppressed soot formation. The binary blend achieved a relative PM reduction to 0.9 compared to diesel, while the ternary blend demonstrated the greatest reduction, with emissions declining to 0.7. Furthermore, measurements of PM1.0 and PM2.5 showed only minor variations between 160 and 200 hours of engine operation, suggesting stable performance of the oxygenated blends under prolonged running conditions. Overall, the ternary blend of diesel, WCO, and n-pentanol outperformed both diesel and the binary blend by significantly lowering CO and PM emissions, though at the cost of increased CO2 emissions.

Table 2: Carbon Monoxide (CO) emissions for different test fuels

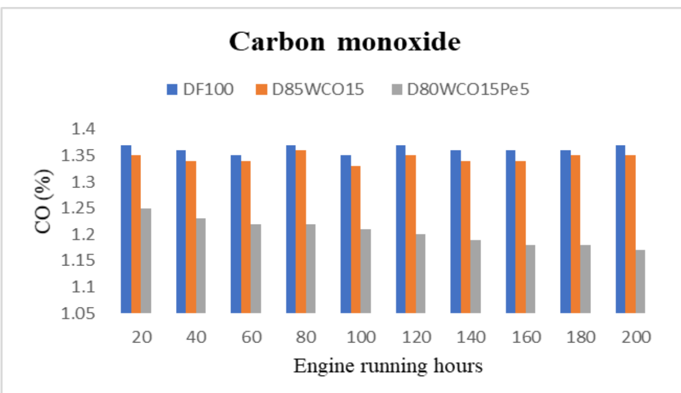
Fuel Type	Composition (% vol.)	CO Emissions (%)	Key Observation
Diesel (DF100)	100% Diesel	0.07	Stable emission baseline
D85WCO15	85% Diesel + 15% WCO	0.12	Increased CO due to higher viscosity and poor atomization
D80WCO15Pe5	80% Diesel + 15% WCO + 5% n-Pentanol	0.035	Lowest CO emission, indicating improved combustion efficiency

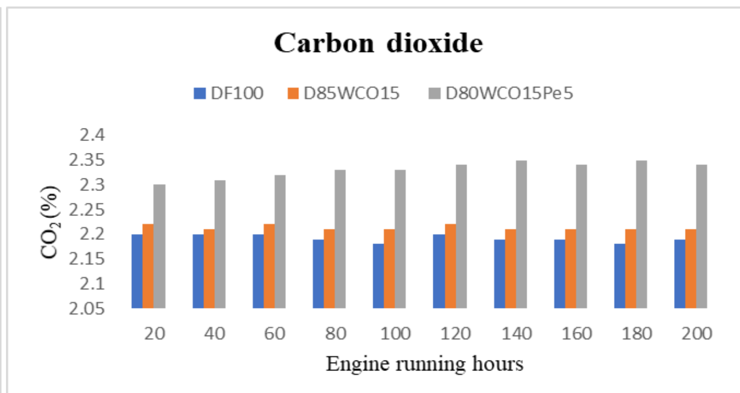
Table 3: Carbon Dioxide (CO_2) emissions for different test fuels

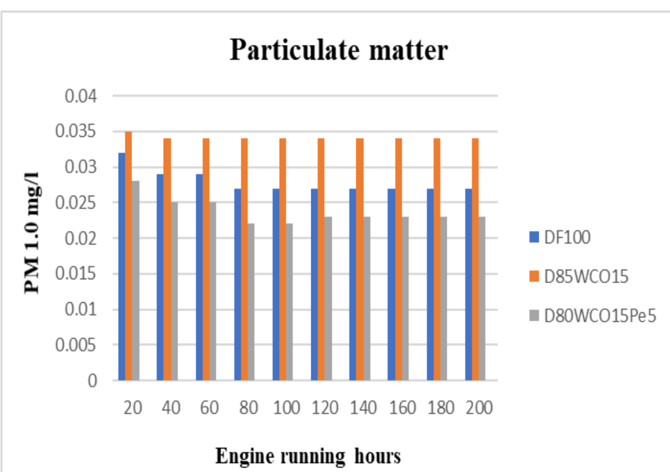
Fuel Type	Composition (% vol.)	Change in CO_2 Emissions vs Diesel	Key Observation
Diesel (DF100)	100% Diesel	Baseline	Reference value
D85WCO15	85% Diesel + 15% WCO	+0.25%	Slight increase due to incomplete combustion
D80WCO15Pe5	80% Diesel + 15% WCO + 5% n-Pentanol	+0.70%	Higher increase due to enhanced oxidation and oxygen content

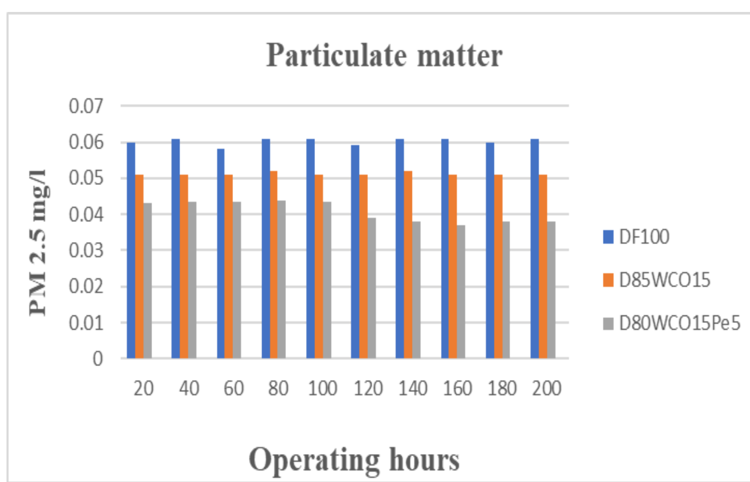
Table 5: Particulate Matter (PM) emissions for different test fuels

Fuel Type	Composition (% vol.)	Relative PM Emissions (vs Diesel = 1.0)	Stability Across Operation	Key Observation
Diesel (DF100)	100% Diesel	1.0	Stable	Baseline PM emissions
D85WCO15	85% Diesel + 15% WCO	0.9	Stable	Reduction due to oxygen content of WCO
D80WCO15Pe5	80% Diesel + 15% WCO + 5% n-Pentanol	0.7	Stable (160–200 h)	Greatest PM reduction with n-pentanol









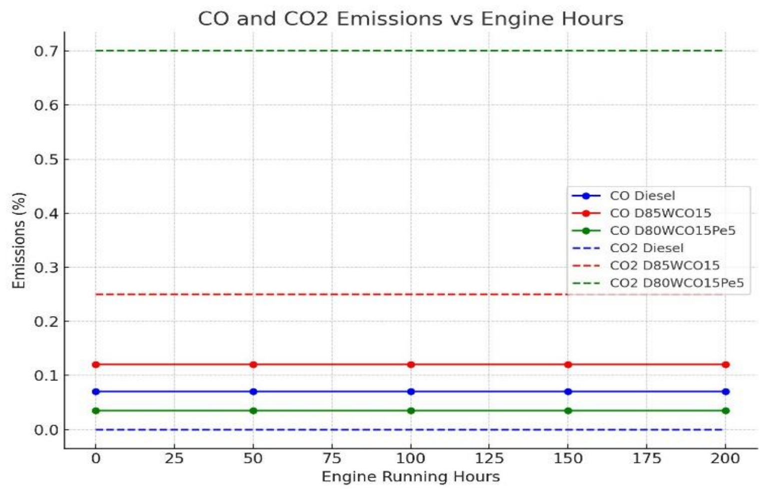


Figure 1 CO and CO2 Emissions vs Engine Hours

DISCUSSION

The results revealed a noteworthy trend: the ternary blend incorporating waste cooking oil (WCO) and n-pentanol with diesel produced markedly lower carbon monoxide (CO) and particulate matter (PM) emissions than both pure diesel and the binary WCO blend, while increasing carbon dioxide (CO_2) emissions. Such findings align with emerging studies indicating that alcohol-enriched biodiesel blends tend to improve combustion completeness, thus reducing CO and PM emissions, although with a concomitant rise in CO_2 (14). The reduction in CO emissions—from 0.07% in diesel to 0.035% in the ternary blend—bolsters the notion that the oxygen content of n-pentanol enhances oxidation during combustion. This aligns with findings of a study which reported that diesel/pentanol blends generally exhibited elevated CO levels relative to pure diesel unless improved by cetane improvers; however, in ternary contexts the oxygenation effect often dominated, lowering CO (15). Similarly, another study observed CO reductions of approximately 32% when pentanol was added to WCO-based biodiesel in a CRDI engine, reinforcing this study's findings (16). The PM emission reduction observed—down to a relative level of 0.7 with the ternary blend—mirrors observations in the literature that pentanol-enriched blends curtail soot formation due to improved atomization and oxygen availability (17). Such reduced PM aligns with the proposed mechanisms of finer spray characteristics and enhanced mixing leading to lower soot precursors. The elevated CO_2 emissions—0.7% higher for the ternary blend—point to more complete combustion, consistent with recent findings of a study showing pentanol biodiesel blends increasing CO_2 output in parallel with combustion completeness (18). These findings carry several practical implications. The ternary blend presents a plausible strategy for lowering harmful emissions in diesel engines using underutilized feedstocks like WCO, promoting both environmental sustainability and waste valorization. However, the elevated CO_2 output indicates that greenhouse gas considerations remain relevant, emphasizing the need for lifecycle analyses.

The strengths of the study include its direct comparison of baseline diesel, WCO-only, and WCO + n-pentanol blends under controlled engine operation, allowing clear attribution of emission trends. The inclusion of PM1.0 and PM2.5 stability data between 160 and 200 hours showcased durability of emission behavior over extended operation. Nevertheless, several limitations temper these strengths. Notably, the study did not assess nitrogen oxides (NO_x), hydrocarbons (HC), or engine performance parameters like brake thermal efficiency or fuel consumption—data that other studies demonstrate may shift variably with pentanol content (19,20). Without such data, evaluation of trade-offs between emission benefits and performance or other pollutants remains incomplete. Additionally, long-term durability and possible impacts on engine wear or lubricant integrity were not assessed, though prior long-duration studies recommend such investigations before real-world application can be endorsed (21). The study also did not examine NO_x, which in the literature tends to increase or decrease depending on pentanol concentration and EGR usage (22). Future research should address these gaps. Subsequent studies should incorporate NO_x and HC monitoring, thermal efficiency and fuel consumption metrics, and long-term durability assessments. Exploring a wider range of pentanol concentrations and engine conditions (e.g., varying loads, EGR rates) would clarify the optimal balance between emission reductions and engine performance. Moreover, conducting lifecycle greenhouse gas assessments could determine whether CO_2 increases are offset by reductions in CO and PM or by the renewable nature of WCO feedstocks. In summary, the current results suggest that the ternary blend of diesel, WCO, and n-pentanol offers real promise for reducing CO and PM emissions through improved combustion. However, the rise in CO_2 and the lack of data on other key pollutants and performance indicators necessitate a measured interpretation. Carefully designed future investigations will be essential to validate these findings and support practical adoption in diesel engine applications.

CONCLUSION

This study demonstrated that blending diesel with waste cooking oil and n-pentanol offers a promising pathway toward cleaner and more sustainable fuels for compression ignition engines. The inclusion of n-pentanol improved the solubility, stability, and combustion quality of the blends, helping to reduce carbon monoxide and particulate matter emissions while maintaining smooth engine operation without defects. Although a rise in carbon dioxide emissions was observed due to more complete combustion, the overall environmental performance was enhanced through reduced toxic pollutants and soot formation. These findings highlight the practical potential of utilizing waste-derived fuels and oxygenated additives to mitigate the adverse impacts of conventional diesel, contributing both to environmental protection and energy sustainability.

AUTHOR CONTRIBUTION

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Faheem Ahmed Solangi*	Substantial contribution to study design, analysis, acquisition of data Manuscript writing Has given final approval of the version to be published
Tarique Ahmed Memon	Substantial contribution to study design, acquisition and interpretation of data Critical review and manuscript writing Has given final approval of the version to be published
Abid Ali Khaskheli	Substantial contribution to acquisition and interpretation of data Has given final approval of the version to be published
Romal Kumar	Contributed to data collection and analysis Has given final approval of the version to be published
Sajjad Ali	Contributed to data collection and analysis Has given final approval of the version to be published

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