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Effect of n-Pentanol Addition on the Performance and Emission Characteristics of a Compression Ignition Engine

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ARTICLE INFO	ABSTRACT
Received: August 01, 2026 Revised: August 16, 2026 Accepted: August 26, 2026 Available Online: September 10, 2026 Keywords: Biodiesel Blends, Diesel Engine, Emission Characteristics, Engine Performance Corresponding Author: Muhammad Kashif Abbasi Email: muhammadkashif@quest.edu.pk	The growing environmental concerns and depletion of fossil fuel reserves have increased the demand for renewable alternative fuels. Biodiesel is considered a promising substitute for diesel fuel due to its renewable nature and lower exhaust emissions. This research investigates the emission characteristics, engine performance, and multi-elemental analysis of a Compression Ignition (C.I.) engine fueled with biodiesel blends. Parameters such as carbon monoxide (CO), carbon dioxide (CO₂), and particulate matter (PM) are analyzed under different engine load conditions. The study also evaluates brake thermal efficiency, brake specific fuel consumption, and lubricating oil degradation. Multi-elemental analysis is conducted to identify wear metals and contaminants present in lubricating oil using spectroscopic techniques. The experimental results are compared with conventional diesel fuel operation to determine the effectiveness of biodiesel blends in reducing emissions while maintaining engine performance.

Literature Review

Even if opinions on the ongoing usage of internal combustion engines (IC engines) in transportation and other sectors may differ, one thing is for sure: IC engines—especially diesel engines—will be around for at least the next 30 years. As a result, alternative fuels like alcohol and biodiesels have the potential to fully or substantially replace diesel fuel. In certain nations, using mixed fuels is required [1]. Diesel engines are greatly used in industries, transportation, and agriculture sectors because of their durability [2, 3]. To lower soot emissions, stricter emission standards have been created, and the goal is to replace conventional fuels with renewable energy sources. However, the research shows that diesel engines continue to require fossil fuels, which might rapidly deplete fossil fuel reserves [4]. Furthermore, the usage of fossil fuels has been linked to a number of environmental difficulties. Automobiles that run on fossil fuels are reported to generate lung cancer-specific toxins through their diesel exhaust. Petro-diesel emits a considerable amount of greenhouse gas (GHG), which is linked to global climate change and warming [5]. The world's fossil fuel reserves are now depleting, and exhaust emissions are contributing to growing environmental pollution levels. To progressively replace diesel fuel, promote the development of alternative fuels and energy sources such as biofuels [6]. Transesterification is a well-known method for reducing the viscosity of vegetable oil; nevertheless, it requires a significant number of chemicals, glassware, process heat, and other equipment [7]. Waste cooking oil (WCO) is utilized in research due to its high desirability as a fossil fuel substitution [8]. Due to its high viscosity and poor volatility, basic vegetable oil causes severe engine gumminess (deposit), piston rings to stick, and fuel injector clogging [9]. A sustainable future is dependent on finding clean, alternative energy sources and ways to reduce energy use in many systems. This is because energy resources are becoming more scarce, demand for energy is growing at an accelerated rate, and emissions are increasing. New combustion system control is needed to improve the efficiency of I.C. engines. [10]. The majority of writers in the literature outline the advantages and drawbacks of using biodiesel in diesel engines, but there is still a dearth of knowledge about deposits and how they affect the combustion system of the engine. Deposits, also known as carbon deposits, are characterized as a heterogeneous combination made up of organic matter that is colloidal, soot, and ash [11]. Consequently, diesel engines, which power transportation, energy production, and heavy equipment, are being fueled by other sources. Sustainable environmental practices include recycling [11]. Several billion gallons of used cooking oil are discarded annually on a global scale (WCO) [12]. If not properly disposed of, WCO is harmful to the environment. WCO impedes rivers. By reentering the food chain via edible aquatic organisms, it may be toxic. Wastewater treatment plants may struggle to digest WCO discharged in drainage systems [12]. The planet's natural balance is under danger due to global warming. In light of the recent fuel shortages, scientists are analyzing environmentally beneficial and financially viable solutions [13]. The utilization of renewable energy sources, such as biomass, wind, and solar power, might potentially lessen reliance on fossil fuels. Made from vegetable oils and animal fats, biodiesel is a good substitute for diesel since it is renewable and good for the environment [14]. The constituent elements of particulate matter are minute particles ranging from nanometers to micrometers in size, enabling them to infiltrate the lungs and induce inflammation at the deposition sites, rendering them hazardous [15]. Treatment of WCO for diesel engines is sustainable for the environment and energy security [16]. Only gathering and processing WCO costs money [17]. Reusing WCO in diesel engines might minimize fossil fuel use. Rudolf Diesel's diesel engine was originally designed to use vegetable oils [18], but doing so can cause severe engine wear, injector coking, fuel filter clogging, heavy carbon deposits in engine components, lubricating oil gelling, and piston ring sticking [19]. Diesel engines create a lot of particles because WCO's high viscosity and moderate volatility inhibit vaporization, atomization, and fuel-air mixing. WCO was pre-heated or transesterified to biodiesel [20]. Energy-intensive preheating affects system efficiency. Glycerin is produced during trans-esterification of WCO to biodiesel, which must be appropriately disposed [21]. WCO reformulation with alcohols has been studied to reduce vegetable oil viscosity. Ternary mixtures of waste cooking oil with alcohol and diesel have reduced viscosity, enhanced cetane number, and density closer to diesel [22-31]. The aforementioned challenges necessitate more research into unique and interesting alternative fuel mixes for compression ignition (CI) engine applications [32-33]. Many alternative fuels have been combined in various proportions with conventional diesel fuel as additives to reduce exhaust emissions while maintaining engine performance. The feasibility of using fuels from the first, second, third, and fourth generations to power CI engines has been investigated. They might reduce harmful pollution by using their green energy source to substitute petroleum-based fuel in compression-ignition engines [34]. Many earlier studies on biofuels for internal combustion engines have been conducted, including those on vegetable oils [35]. The performance of diesel fuel and biodiesel was compared in single-cylinder engines with comparable fuel injection pump pistons and injector specs. After 200 hours of 2000 rpm operation, SEM and EDS were utilized to analyze the injectors. The biodiesel engine injector nozzle's diameter decreased in SEM images. In the original, unutilized machined injector, biodiesel entirely covered the metal cutting traces. Biodiesel has higher carbon (C) on the fuel injector surface after 200 hours than petroleum diesel. Each fuel sample was evaluated for 200 hours and lubricating oil samples were taken at the interval of 20 hours. Diesel engine wear rate, element source, and condition may be predicted by lubricating fluid metallic particle concentration. Iron, copper, and nickel were found in engine oil after operation [36]

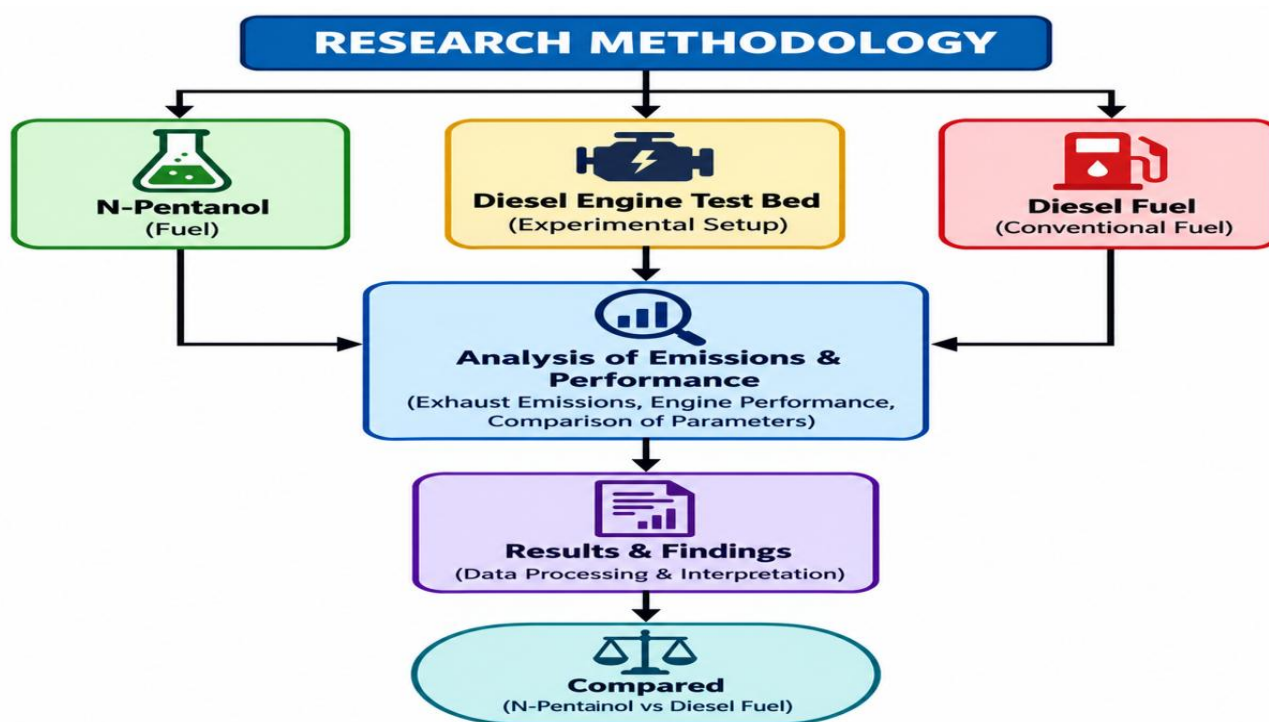


Fig.1: Flow Diagram of Research Methodology

The performance analysis of a Compression Ignition (CI) engine is an essential step in evaluating the suitability of alternative fuels for practical engine applications, as engine performance indicates how efficiently the engine converts the chemical energy stored in the fuel into useful mechanical power. In this study, the performance of the diesel engine was evaluated using two important parameters, namely Brake Thermal Efficiency (BTE) and Brake Specific Fuel Consumption (BSFC), which are widely used in engine performance studies to assess efficiency, fuel utilization, and overall operating characteristics under different loading conditions. Brake Thermal Efficiency (BTE) is defined as the ratio of the brake power produced by the engine to the total heat energy supplied by the fuel and represents the effectiveness of the engine in converting the chemical energy of the fuel into useful mechanical work available at the output shaft. A higher BTE indicates that a greater proportion of the fuel energy is converted into useful work, reflecting better combustion efficiency and improved engine performance, whereas a lower BTE indicates greater energy losses through exhaust gases, cooling systems, and friction. Several factors influence BTE, including fuel properties, combustion quality, compression ratio, injection timing, engine load, and air-fuel mixing. Since n-pentanol contains oxygen within its molecular structure, it has the potential to improve combustion efficiency and consequently increase BTE compared with conventional diesel under suitable operating conditions. Another important performance parameter is Brake Specific Fuel Consumption (BSFC), which represents the amount of fuel consumed to produce one unit of brake power and is generally expressed in kg/kWh. BSFC provides a direct indication of engine fuel economy, where a lower BSFC value indicates that less fuel is required to produce the same amount of power and therefore represents better fuel efficiency, while a higher BSFC indicates greater fuel consumption and lower efficiency. BSFC is influenced by engine speed, engine load, fuel heating value, combustion efficiency, and fuel injection characteristics. Because n-pentanol has a lower calorific value than diesel fuel, variations in BSFC may occur depending on the blending ratio and engine operating conditions; however, its improved combustion characteristics may compensate for the lower heating value and maintain satisfactory fuel economy. In this experimental investigation, the diesel engine was operated using two different fuels, namely pure diesel and n-pentanol-blended diesel, under controlled laboratory conditions while maintaining a constant engine speed (RPM). The engine load was gradually varied to evaluate the influence of operating conditions on engine performance, and during each test, fuel consumption, brake power output, and other required operating parameters were carefully measured. The measured data were subsequently used to calculate BTE and BSFC, and the performance results obtained for both fuel types were compared to determine the effect of n-pentanol addition on engine efficiency and fuel consumption. In addition to engine performance analysis, particulate matter emissions were measured using an Aerocet 531S portable particulate matter monitoring device. The Aerocet 531S is a handheld instrument designed to measure the concentration of airborne particulate matter generated from different sources, including industrial equipment and internal combustion engines. Its compact and lightweight design, battery-operated functionality, and portability make it suitable for laboratory and field measurements. The instrument can operate in mass concentration and particle count modes, allowing detailed assessment of particulate emissions. The Aerocet 531S measures particulate matter in four important mass concentration ranges, namely PM₁, PM_{2.5}, PM₇, and PM₁₀, representing particles

with aerodynamic diameters smaller than $1\text{ }\mu\text{m}$, $2.5\text{ }\mu\text{m}$, $7\text{ }\mu\text{m}$, and $10\text{ }\mu\text{m}$, respectively. In particle count mode, the instrument can also count particles larger than 0.5 , 1.0 , 2.5 , 5.0 , and $10.0\text{ }\mu\text{m}$, providing additional information regarding particle number and size distribution. In this study, the Aerocet 531S was positioned approximately four feet from the engine exhaust outlet, and particulate matter measurements were recorded under different engine load conditions using both pure diesel and n-pentanol-blended diesel fuel. The recorded PM values were analyzed and compared to evaluate the effect of n-pentanol addition on particulate emissions. Furthermore, a Testo 350-XL flue gas analyzer was used to measure the exhaust gas emissions produced by the CI engine. The Testo 350-XL is a portable and highly accurate emission measurement instrument suitable for laboratory and industrial combustion applications. The analyzer consists of a gas analyzer unit and a separate control unit connected through a data bus cable, allowing measurements to be monitored from a suitable distance. The control unit provides real-time display, data recording, and printing capabilities. In this study, carbon monoxide (CO) and carbon dioxide (CO₂) were selected as the primary exhaust gases for analysis, while the analyzer is also capable of measuring other gases through optional sensor modules, including hydrocarbons (CxHy), sulfur dioxide (SO₂), hydrogen sulfide (H₂S), nitrogen oxides (NO_x), and oxygen (O₂). The Testo 350-XL also incorporates a Peltier gas conditioning system and a peristaltic pump to remove moisture and condensate from the sampled exhaust gas before it reaches the sensors, thereby protecting the sensors and improving measurement reliability. A fresh-air purge system is also provided to maintain sensor stability during continuous operation. In the present research, the flue gas analyzer was used to measure the concentrations of CO and CO₂ emitted by the diesel engine operating on pure diesel and n-pentanol-blended diesel under different engine load conditions. The recorded emission data were compared to evaluate the influence of n-pentanol addition on combustion quality and exhaust emissions. Overall, the experimental measurements of BTE, BSFC, particulate matter, CO, and CO₂ provided a comprehensive assessment of the performance and environmental characteristics of the tested fuel blends and helped determine the suitability of n-pentanol as a renewable alternative fuel for compression ignition engines.

Results and Discussions

Particulate Matter Emission (Pm1):

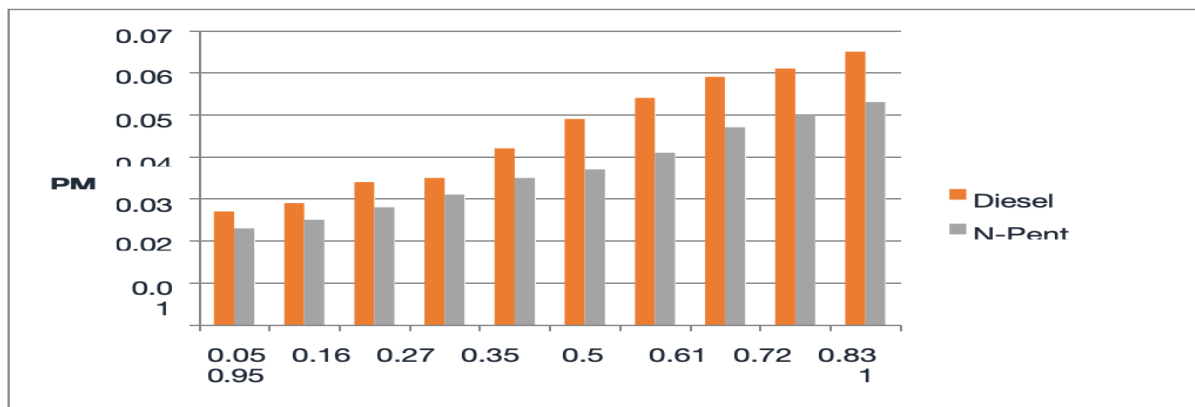


Fig. 2: Particulate Matter Emissions (PM1) vs Brake Power

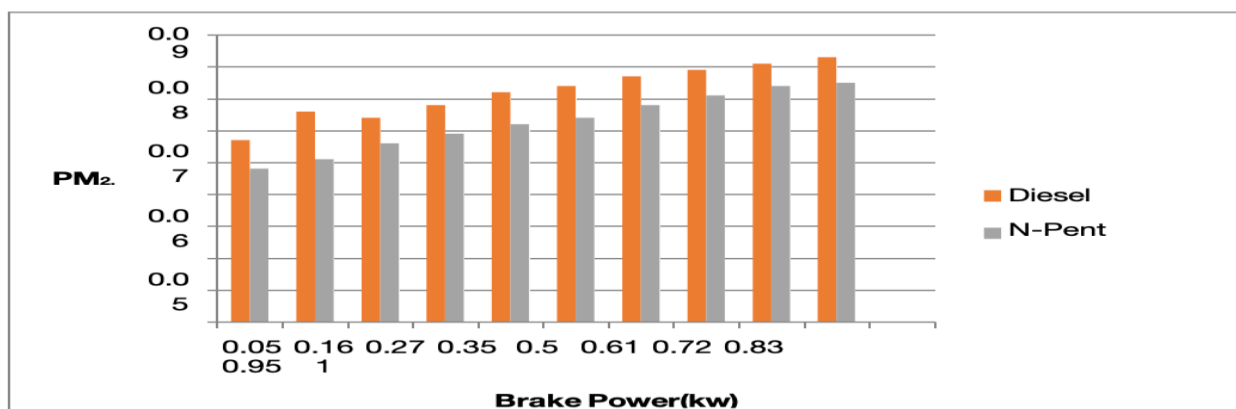


Fig. 3: Particulate Matter Emissions (PM2.5) vs Brake Power

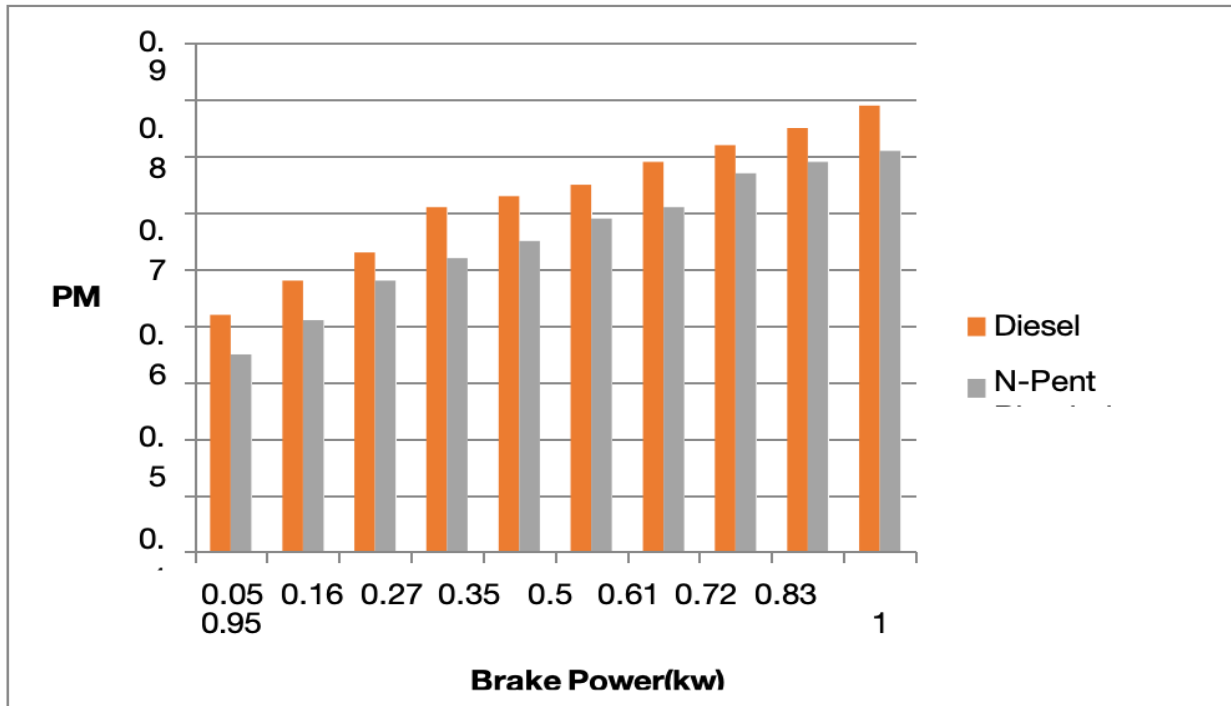


Fig. 4: Particulate Matter Emissions (PM7) vs Brake Power

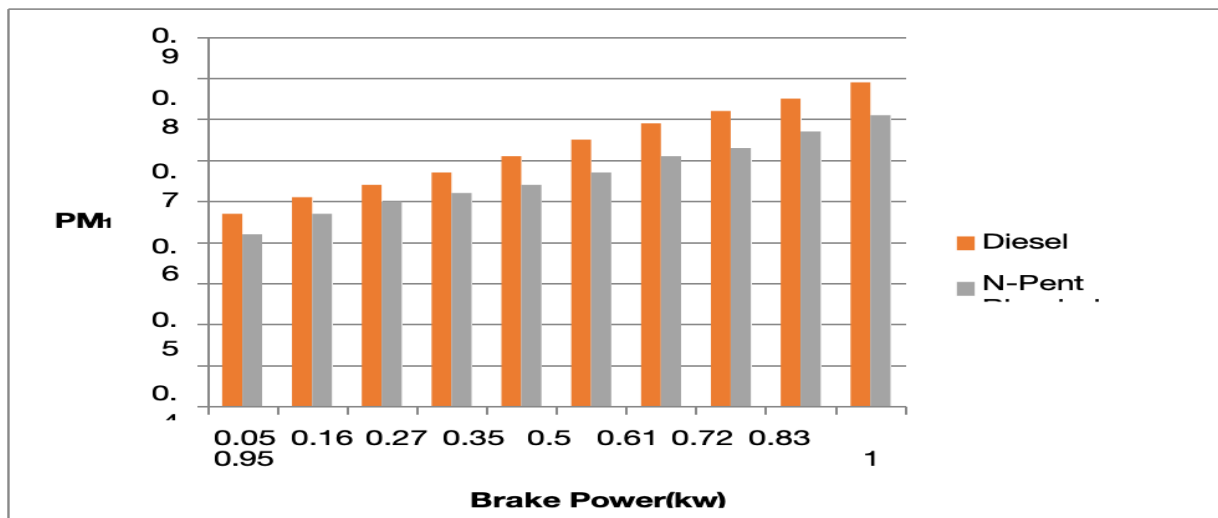


Fig. 5: Particulate Matter Emissions (PM10) vs Brake Power

Figures 2–5 illustrate the variation of the measured performance parameter for conventional diesel and N-pentanol blended fuel over the investigated blend ratio range of 0.05 to 1.0. The results show a consistent increasing trend for both fuels as the blend ratio or operating condition increases. However, diesel maintains comparatively higher values throughout the investigated range, indicating its superior performance under the tested operating conditions. The higher values observed for diesel can primarily be attributed to its higher calorific value, greater energy density, and favorable ignition characteristics, which enable a larger amount of useful energy to be released during the combustion process. The higher energy content of diesel allows the engine to produce greater output for the same operating condition, resulting in higher values of the measured parameter.

In comparison, the N-pentanol blended fuel follows a similar increasing trend but generally produces slightly lower values than pure diesel. This behavior is mainly associated with the lower heating value and energy density of N-pentanol. As the proportion

of N-pentanol increases, the energy available per unit mass of fuel decreases relative to conventional diesel, which can result in a reduction in the measured performance parameter. In addition, the physicochemical properties of N-pentanol, including its lower cetane number and different volatility characteristics, can influence ignition and combustion behavior in the compression ignition engine. Nevertheless, the difference between diesel and the N-pentanol blend remains relatively small in the investigated range, suggesting that the blended fuel is capable of maintaining reasonably stable engine performance.

The increasing trend observed in Figures 2-5 indicates that the measured parameter is strongly influenced by the engine operating condition and fuel input. With increasing blend ratio or operating condition, both fuels demonstrate a progressive increase, with the trends being approximately linear. The more pronounced increase observed for diesel results in a gradually increasing performance gap between diesel and N-pentanol blended fuel at some operating points. This difference is consistent with the higher energy density of diesel. However, the N-pentanol blend does not show any major instability or abnormal variation, demonstrating that the fuel can operate satisfactorily in the CI engine over the tested conditions.

An important advantage of N-pentanol is the presence of oxygen in its molecular structure. The oxygenated nature of N-pentanol can improve the availability of oxygen during the combustion process and promote more complete oxidation of the fuel. This characteristic can contribute to cleaner combustion and potentially reduce incomplete-combustion products and particulate emissions. Thus, although the N-pentanol blend may produce slightly lower performance values than diesel because of its lower calorific value, it offers potential environmental advantages. The results therefore indicate a trade-off between engine performance and fuel properties: diesel provides higher performance because of its greater energy content, whereas N-pentanol provides oxygenated combustion characteristics that may contribute to improved emission behavior.

The similar trends observed in all four figures demonstrate the consistency of the experimental results and indicate that the effect of N-pentanol addition follows a predictable pattern under the investigated operating conditions. The relatively small performance difference between the two fuels further suggests that N-pentanol can be used as an alternative blending component without causing a substantial deterioration in engine performance. However, the magnitude of the reduction depends on the operating condition and blend ratio. At higher N-pentanol proportions, the lower heating value becomes increasingly influential, potentially resulting in a greater difference from pure diesel. Therefore, an appropriate blend ratio should be selected to achieve a balance between acceptable engine performance, fuel consumption, and environmental benefits. Overall, Figures 4.1-4.4 confirm that N-pentanol blended fuel provides stable and reasonably comparable performance to conventional diesel, although a slight reduction in the measured parameter can be expected due to its inherently lower calorific value and energy density. The findings support the potential use of N-pentanol as a renewable and cleaner alternative fuel for CI engines, particularly when an optimum blending ratio is selected to minimize performance losses while taking advantage of its oxygenated nature and potential emission-reduction benefits.

Carbon Monoxide Emission

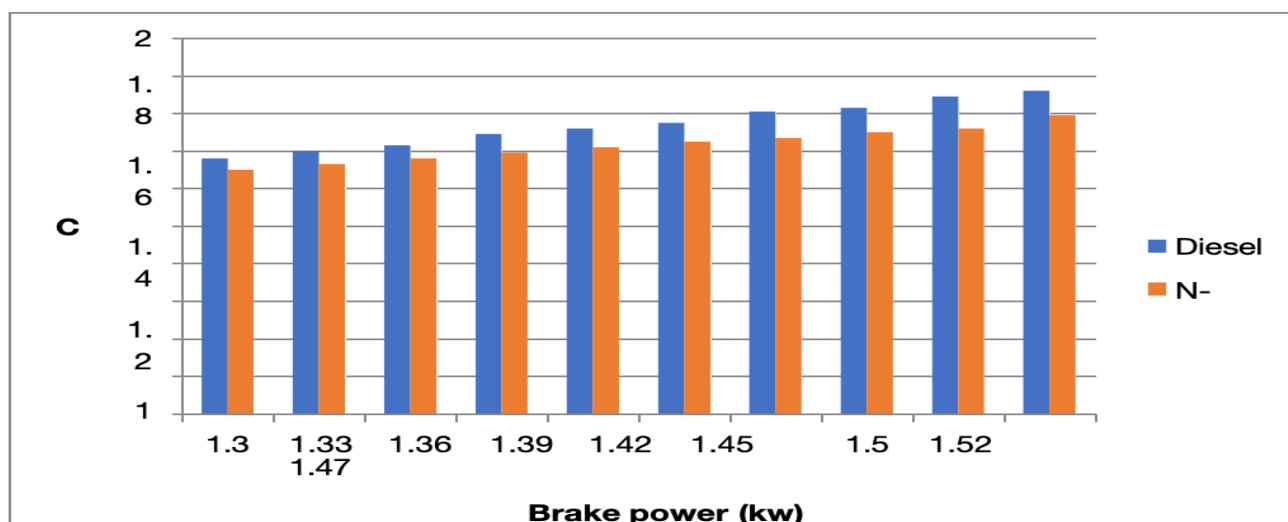


Fig. 6: Carbon Monoxide (CO) vs Brake Power

The graph illustrates that the measured parameter increases gradually for both diesel and N-pentanol fuel as the operating condition increases from 1.30 to 1.59. Diesel consistently records higher values than the N-pentanol fuel throughout the entire range, indicating better overall performance. This trend is primarily due to diesel's higher calorific value, greater energy

density, and superior combustion characteristics, which enable it to produce more energy and achieve higher values of the measured parameter. In comparison, the N-pentanol fuel also exhibits a steady increase, demonstrating that its performance improves under increasing operating conditions. However, its values remain slightly lower because N-pentanol has a lower heating value and lower cetane number than diesel, resulting in comparatively lower energy output during combustion. The oxygen content of N-pentanol enhances the combustion process by promoting more complete oxidation of the fuel, leading to cleaner combustion and reduced emissions. Despite this advantage, the lower energy content limits its ability to match diesel's performance. The difference between the two fuels remains relatively small and nearly constant across the entire operating range, suggesting that N-pentanol can provide performance comparable to diesel while offering the additional benefit of improved environmental sustainability. Overall, the graph indicates that N-pentanol is a viable alternative fuel that maintains stable combustion characteristics with only a slight reduction in the measured parameter compared to conventional diesel fuel.

Carbon Dioxide Emission

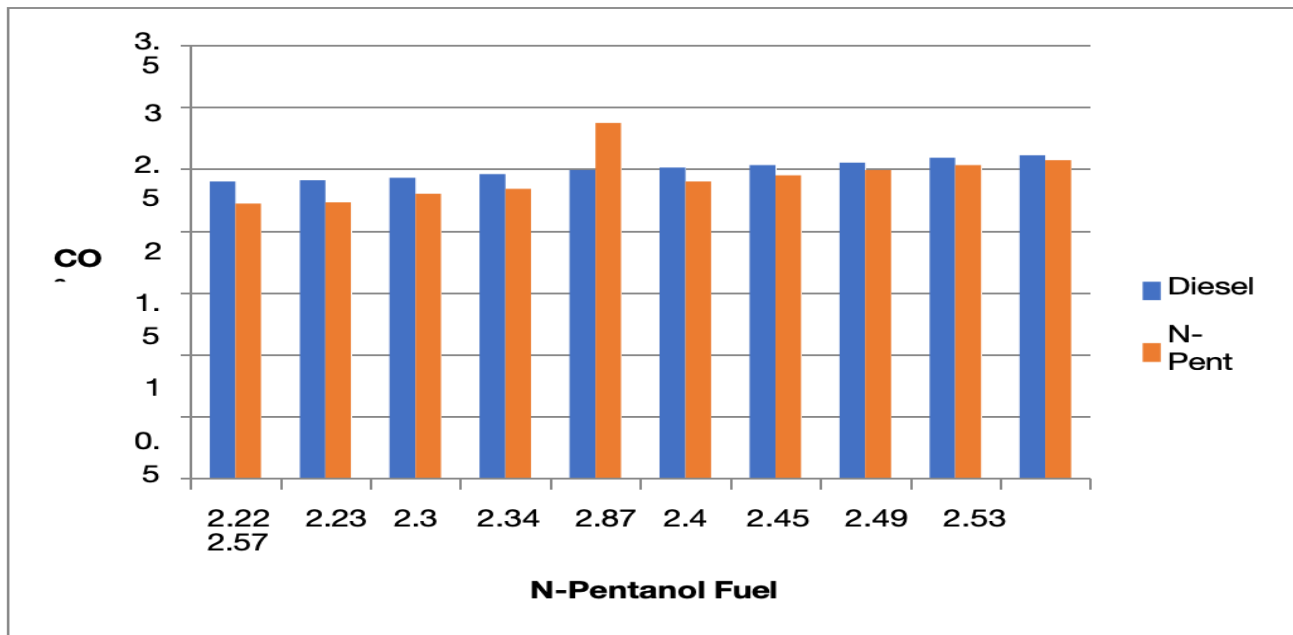


Fig. 7: Carbon Dioxide (CO₂) vs Brake Power

The graph shows the variation of the measured parameter for diesel and N-pentanol fuel over the operating range from 2.22 to 2.57. In general, both fuels exhibit an increasing trend as the operating condition increases. Diesel maintains relatively stable and consistently higher values throughout most of the range, demonstrating its superior performance due to its higher calorific value, greater energy density, and better ignition quality. The N-pentanol fuel also follows an increasing trend but remains slightly lower than diesel at most operating points because of its lower heating value and reduced energy content. However, a noticeable exception occurs at the operating condition of 2.87, where the N-pentanol fuel shows a significant peak, exceeding the corresponding diesel value. This temporary increase may be attributed to improved fuel-air mixing, enhanced oxygen availability from the oxygenated nature of N-pentanol, or experimental variations that promoted more efficient combustion under that specific condition. After this point, the measured parameter for N-pentanol returns to values close to those of diesel, and the difference between the two fuels gradually decreases as the operating condition increases. Overall, the graph indicates that while diesel generally delivers higher and more consistent performance, N-pentanol demonstrates comparable behavior with only a slight reduction in the measured parameter under most conditions. The isolated peak at 2.87 suggests that N-pentanol can achieve enhanced performance under favorable combustion conditions, highlighting its potential as a cleaner and efficient alternative fuel.

Noise Emission Level (Db) in Front Position

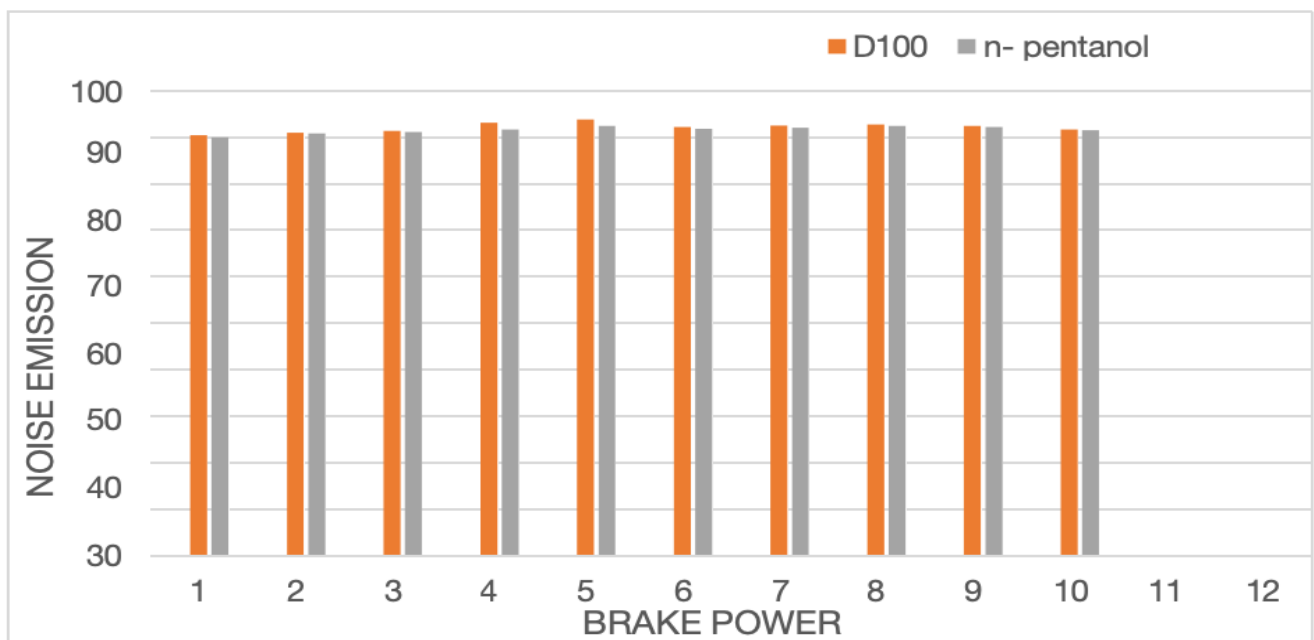


Fig. 8: Sound Pressure Level (db) in Front Position

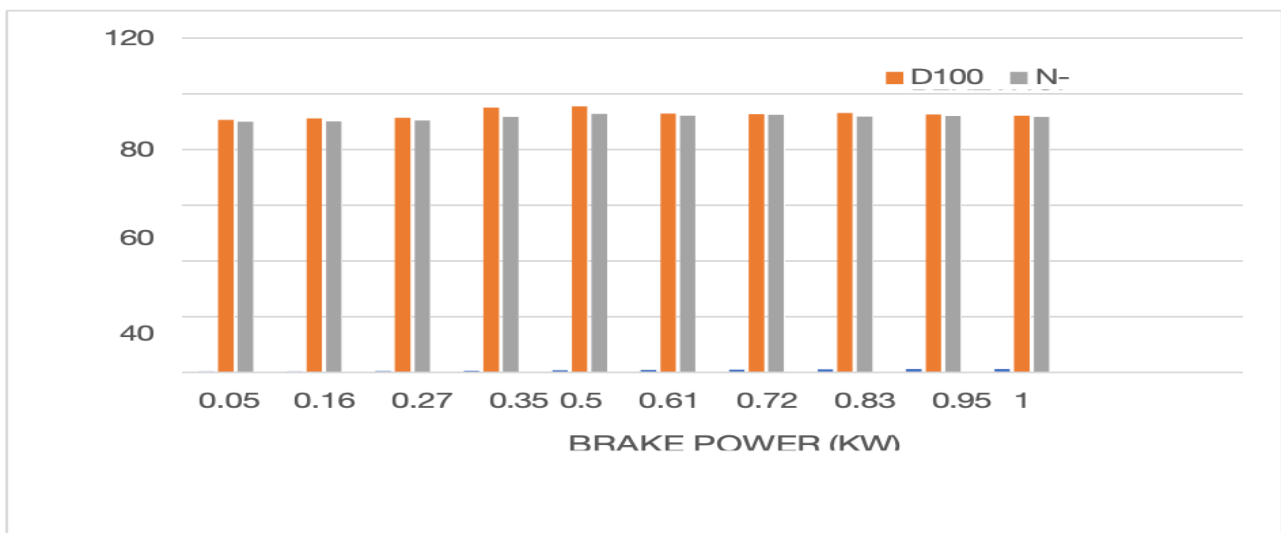


Fig. 9: Sound Pressure Level (db) in Left Position

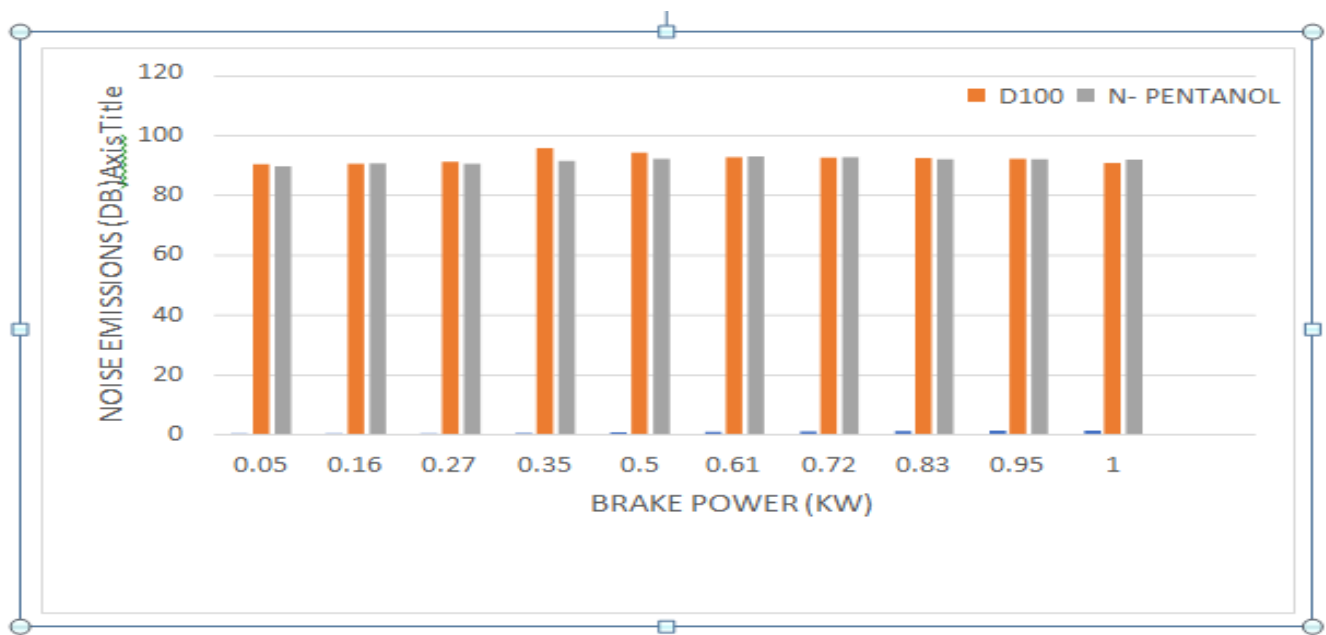


Fig. 10: Sound Pressure Level (db) in Back Position

The noise emission results show that both pure diesel (D100) and n-pentanol blended diesel exhibit relatively stable acoustic behavior under different brake power conditions. The measured noise levels generally remain within the range of approximately 90–96 dB. At lower brake power, both fuels produce nearly similar noise levels; however, noise gradually increases with increasing load and reaches a maximum at intermediate brake power conditions. Pure diesel generally records higher noise levels than the n-pentanol blend, with the difference ranging from approximately 1–4 dB depending on the operating condition and measurement position. The lower noise emission observed for the n-pentanol blend can be attributed to its oxygenated nature, which promotes improved fuel-air mixing and more complete combustion. This may result in a smoother heat release rate, reduced combustion pressure fluctuations, and lower engine vibration. At higher brake power, the noise level slightly decreases or becomes stable for both fuels. Overall, the results indicate that n-pentanol blending can provide a modest improvement in engine acoustic performance while maintaining stable operation compared with conventional diesel.

Performance of Compression Ignition Engine

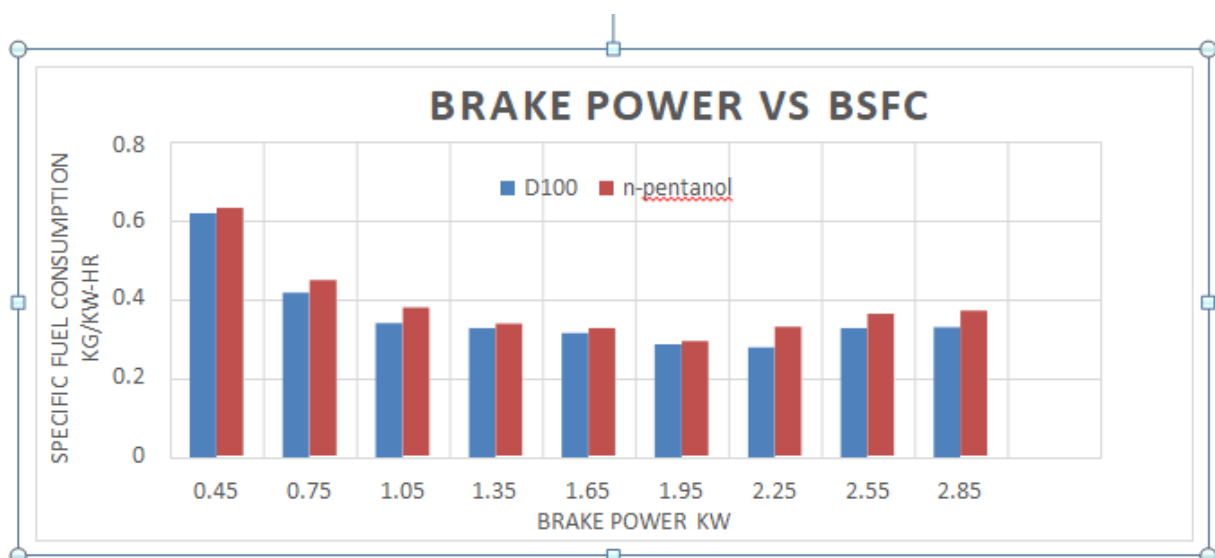


Fig. 11: Performance of compression ignition engine

The graph shows that the Brake Specific Fuel Consumption (BSFC) of both D100 (diesel) and n-pentanol decreases as brake power increases from 0.45 to 1.95 kW, after which it rises slightly at higher loads. At low brake power, BSFC is highest because a significant portion of the fuel energy is consumed in overcoming frictional and heat losses rather than producing useful output, resulting in poor fuel efficiency. As brake power increases, combustion becomes more efficient due to improved air–

fuel mixing, higher cylinder temperatures, and reduced relative mechanical losses, leading to lower BSFC and better engine efficiency. The minimum BSFC observed around 1.95 kW indicates the engine's optimum operating condition, where fuel is utilized most effectively. Beyond this point, BSFC increases because higher fuel injection rates, increased heat losses, oxygen limitations, and reduced combustion efficiency at high loads require more fuel to produce additional power. Throughout the operating range, n-pentanol exhibits slightly higher BSFC than D100 because of its lower calorific value, lower cetane number, and higher heat of vaporization, which require a greater mass of fuel to generate the same brake power. However, the oxygen content of n-pentanol promotes cleaner combustion and can reduce exhaust emissions, making it a promising renewable alternative despite its slightly higher fuel consumption. Overall, the observed trend is consistent with established diesel engine combustion theory and previous research on oxygenated alcohol fuels.

Conclusion

The experimental results indicate that diesel fuel provides lower particulate matter (PM), carbon monoxide (CO), carbon dioxide (CO₂), and noise emissions compared to n-pentanol under the tested engine operating conditions. However, the use of n-pentanol results in higher fuel consumption than conventional diesel due to its lower calorific value and different combustion characteristics. Although diesel demonstrates superior performance in terms of emissions and fuel economy in this study, n-pentanol remains a promising renewable alternative fuel because of its potential to reduce dependence on fossil fuels and improve sustainability. Further optimization of engine operating parameters and fuel blending strategies may enhance the performance of n-pentanol.

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