Case Studies in Thermal Engineering 76 (2025) 107408

Contents lists available at ScienceDirect

Case Studies in Thermal Engineering

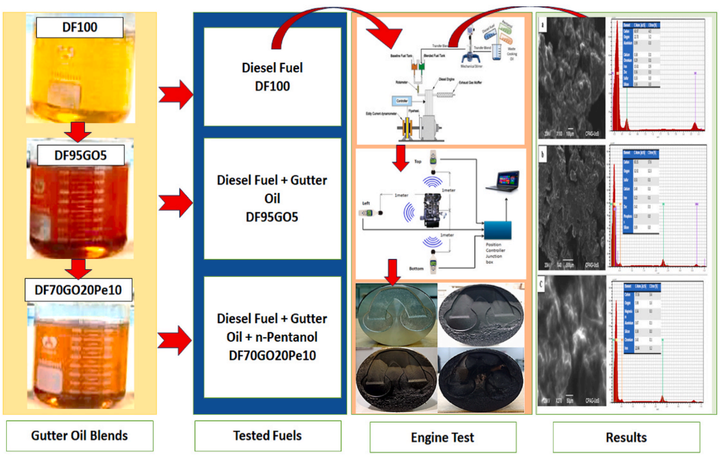
journal homepage: www.elsevier.com/locate/csite

Debris accumulation, acoustic and wear analysis of compression ignition engine using bio alcohols blends

Faheem Ahmed Solangi [a], Ali Murtaza Ansari [b], Altaf Alam Noonari [c], Fayaz Hussain [d,*], Bo Zhang [e,**], Nazmi Mat Nawi [d], C Ahamed Saleel [f,g]

[a] Department of Mechanical Engineering, Quaid-e-Awam University of Engineering Science and Technology, Nawabshah, Sindh, Pakistan
[b] Department of Mechanical Engineering Technology, Faculty of Engineering Science & Technology (FEST), Hamdard University North Nazimabad Campus, Karachi, Sindh, Pakistan
[c] Department of Environmental Sciences, Arror University of Art, Architecture, Design and Heritage, Sukkur, 65170, Pakistan
[d] Department of Biological and Agricultural Engineering, Faculty of Engineering, Universiti Putra Malaysia, Selangor, Malaysia
[e] School of Mechanical Engineering, Ningxia University, China
[f] Central Labs, King Khalid University, AlQura'a, Abha, P.O. Box 960, Saudi Arabia
[g] Department of Mechanical Engineering, College of Engineering, King Khalid University, PO Box 394, Abha, 61421, Saudi Arabia

GRAPHICAL ABSTRACT



* Corresponding author.
** Corresponding author.
E-mail addresses: fayazhussain@upm.edu.my (F. Hussain), zhangb@nxu.edu.cn (B. Zhang).

https://doi.org/10.1016/j.csite.2025.107408
Received 28 May 2025; Received in revised form 1 November 2025; Accepted 12 November 2025
Available online 19 November 2025
2214-157X/

A R T I C L E I N F O

Keywords:
Diesel engine
Endurance
Piston surface deposits
Exhaust emission
Gutter oil
N-pentanol

A B S T R A C T

The use of alternative fuels in diesel engines has become increasingly important in recent years. In this study, deposit development was examined using combinations of n-pentanol, diesel, and gutter oil. Finding out how well adding n-pentanol improves ternary blend performance is the aim of this study. Three test fuels—DF, DF95GO5, and DF70GO20Pn10—were chosen for this purpose. Each fuel sample underwent a separate engine test to examine the surfaces of the piston crowns. The SEM and EDX tests revealed that using DF95GO5 significantly altered the piston's surfaces. The gutter oil binary mix fuel was found to produce carbon deposition more quickly than diesel fuel, with 67.68 % for GO and 60.72 % for D100. However, engine part deposition decreased when 1-pentanol was combined with gutter oil instead of diesel fuel, even though n-pentanol had a 52.90 % deposition rate. To compare to DF, N-pentanol was added as a ternary blend DF70GO20Pn10 for copper (Cu), nickel (Ni) 0.37 ppm, and cadmium (Cd) 8 ppm. The ternary blend gasoline, on the other hand, contained less debris. The results showed that engine noise emissions were generally increased when gutter oil was added to DF95GO5 diesel fuel. However, DF70GO20Pn10 had less of an effect on the engine's noise emissions (86.63 dB) than baseline fuel and gutter oil blend.

Abbreviations

ASTM	American society for testing and materials
Cu	Copper
CI	Compression ignition
DF	Diesel fuel
DI	Direct injection
DF95GO5	Diesel fuel 95 % + Gutter oil 5 %
DF70GO20Pn10	Diesel fuel 70 % + Gutter oil 20 % + N-pentanol 10 %
EDX	Energy dispersive X-ray spectroscopy
Fe	Iron
IC	Internal combustion
Ni	Nickel
O	Oxygen
SEM	Scanning electron microscopy
GO	Gutter oil

1. Introduction

Due to their higher torque, low fuel consumption, and great thermal efficiency, diesel engines distinguish themselves from gasoline engines in the internal combustion engine (ICE) class, which is utilized in a wide range of industries, transportation, agriculture, and the service sector today [1]. The most significant element in our daily lives is energy. Renewable energy sources only make up a small percentage of energy; fossil fuels are the most reliable source [2]. For over a century, fossil fuels have provided the majority of the energy used for industry, transportation, and residential illumination. Over 80 % of the energy we use comes from fossil fuels. The rapid combustion of fossil fuels is a result of industrialization, population growth, and the rise in the number of cars on the road [3]. Urbanization, industry, and population growth are driving a growing need for and search for alternative resources. Fossil fuel supplies used in industry and transportation are thus declining [4]. Diesel fuel is essential for power generation, transportation, and agriculture due to its high energy density and efficiency among the several energy sources. Among the environmental issues brought on by an over-reliance on diesel are resource depletion, greenhouse gas emissions, and air pollution. One major worldwide source of carbon emissions that significantly contributes to climate change is the burning of fossil fuels [5]. The need to find alternative fuels that can address both issues stems from the simultaneous crises caused by the depletion of fossil fuel supply and the increase in pollutants from internal combustion engines [6]. As the number of cars increases, many sectors and researchers are working harder to discover alternative energy sources to lessen our reliance on the dangerous exhaust emissions and petroleum-based fuels that cars generate [7,8]. Recycling is a crucial step in achieving environmental sustainability. Each year, billions of gallons of waste cooking oil (WCO) are disposed of worldwide [9]. However, there is a significant environmental concern associated with inappropriate gutter oil disposal. Streams may get contaminated and blocked by WCO. It may be harmful to human health since it re-enters the human food chain through aquatic edible animals. The overall effectiveness of the system. WCO conversion into biodiesel is an expensive, time-consuming, and complex process. Additionally, it produces glycerine as a byproduct, which needs to be handled carefully once more [10]. Researchers have recently developed an interest in alcohol-based waste oil reformulation because it offers a straightforward and reasonably priced way to lower the viscosity of vegetable oils [11–17]. These alternative fuels can be broadly classified into two groups: diesel-alcohol blends and diesel-biodiesel blends [18,19]. Because alcohols are liquid and have a high oxygen content, they can be used as alternative fuels or as appropriate additions to diesel fuel made from petroleum. Diesel exhaust emissions and petroleum usage are decreased by utilizing an alcohol-diesel blend, which also lessens environmental pollution and dependency on petroleum

[20,21]. This work examines the transesterification of UCO utilizing pentanol as an alcohol. In a Perkins diesel engine, Campos-Fernandez et al. examined diesel fuel blends containing pentanol fractions at 10, 15, 20, and 25 vol %. The results demonstrated that diesel engines can operate on blends containing up to 25 % pentanol without the need for any changes, and these blends displayed characteristics that were similar to petroleum diesel [22]. Combustion produces carbon as a byproduct. Pollution from lubricating oil and incomplete fuel combustion are two factors that contribute to carbon deposition [23,24]. To better determine the wear of different combustion chamber components and materials, Haycock RF et al. examined the percentages of different metal particles in the carbon buildup from each engine. It was anticipated that various components would contribute to the carbon deposit debris because there were so many sliding parts. They recommended a standard metal element level for diesel engines [25]. Long-term lubricating oil pollution is one of the most common issues experiencing diesel engines. The most frequent reasons for lubricating oil contamination are thermal breakdown of oil, oxidation, additive depletion, blow-by from combustion gases, and accumulation of wear debris. [15,26]. Carbon is one of the combustion byproducts. A certain amount of carbon deposition is determined by incomplete fuel combustion and lubricating oil contamination [27]. The concentration of various metal elements in the carbon deposit samples from each engine was examined in order to understand the wear of various parts and materials from the combustion chamber. The debris in the carbon deposit was expected to be produced by multiple components due to the multiple sliding elements involved. Nickel (Ni), copper (Cu), chromium (Cr), aluminum (Al), and lead (Pb) were among the elemental metal concentrations examined in dried deposit samples. The results indicated a typical quantity of each metal element for diesel engines. In this work, experimental experiments were conducted on a single-cylinder diesel engine to investigate deposits buildup on the piston crown during the stationary state for various diesel, waste cooking oil, and n-pentanol fuel mixes. To determine lubricating oil degradation, the test was conducted on each fuel sample at 20-h intervals for 180 h at a constant speed of 1300 rpm. Analyzing the amount of metallic particles in lubricating oil provides sufficient information and forecasts regarding the wear rate, element source, and engine condition of diesel engines. Common metallic elements such as cadmium (Cd), copper (Cu), and nickel (Ni) are present in lubricating oil after the engine runs [28].

This study investigates the significance of gutter oil blend with diesel and n-pentanol in single cylinder diesel engine to examine the appearance of deposits formation on piston crown and degradation of lubricating oil as well as the noise emission. Three test fuels i-e. DF100, DF95GO5, and DF70GO20Pe10 were prepared. An atomic absorption spectrophotometer (AAS) has been employed to measure the engine wear and debris by installing hollow cathode lamps for each element independently.

2. Material and methods

Gutter oil obtained from a nearby restaurant was employed in the experimental study. A thorough literature review revealed an addition—n-pentanol—due to the viscous nature of the GO. The test fuels met the necessary characterization requirements. For frying jobs that needed temperatures between 1300 °C and 180 °C, GO was mostly used. The oil was heated before to mixing in order to eliminate any contaminants. Since diesel repels water and water can eventually cause phase separation, this was created to change the combinations' strength. The properties of the fuel are shown in Table 2.

2.1. Selection of fuels

Reducing the environmental effects of manufacturing processes, both new and old, and optimizing resources are two of the scientific community's top priorities. Because of their detrimental effects on the environment, used vegetable oils (UVOs) fall under the category of hazardous waste, or GCO. The term "used vegetable oils" refers to waste vegetable oils (GVO). In most cases, the first step in processing collected gutter oil GCOs is a coarse filtering procedure intended to eliminate solid particles dispersed throughout the oil. Reliance on depleting fossil oil supplies can be reduced by using GO as a fuel alternative for diesel engines. Because of the low volatility and high viscosity of gutter oil, there is insufficient fuel-air mixing, vaporization, and atomization, which results in higher particulate levels. These issues include deposits accumulating in injectors, fuel filter obstruction, carbon buildup in various engine parts, lubricating oil solidifying, increased engine wear, and piston ring sticking. Techniques like preheating used cooking oil or converting GO into biodiesel were commonly employed to get around these issues. Preheating requires more energy, which lowers the system's efficiency as a whole. Glycerine is a by-product of the time-consuming, costly, and complicated process of trans-esterifying GO into

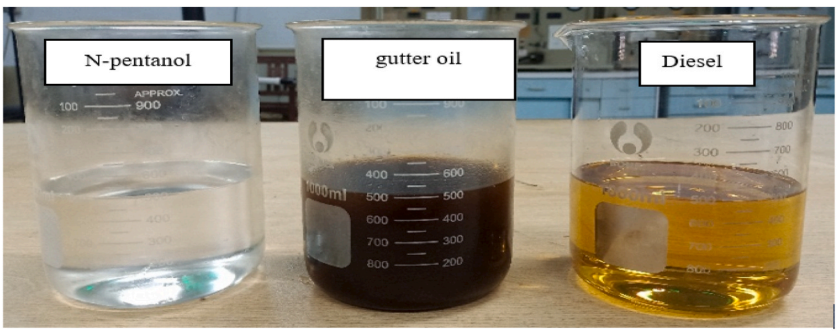


Fig. 1. Selected fuels before blending.

biodiesel, and it must be disposed of properly. When diesel is mixed with n-pentanol and gutter oil under different load situations, positive combustion events are seen. According to the study, performance has increased and smoke emissions have decreased. Fig. 1 depicts the physical characteristics of the selected fuels. In contrast, Table 1 displays the fuel characteristics of n-pentanol, diesel, and gutter oil.

Gutter oil, n-pentanol, and diesel fuel (designated as DF100, DF95GO5, and DF70GO20Pe10) were among the fuels employed in the experiment. The test procedures were carried out three times to ensure that the investigative results were accurate.

2.2. Fuel properties measuring procedure and equipment

Viscosity, cetane number, density, flash point, and heating value were measured using various types of equipment in order to ascertain the primary fuel qualities. The ASTM technique is used for all fuel measurements in Table 2.

2.3. Fuel property measurements

The fuel characteristics experiments were conducted in a chemical laboratory with controlled humidity and temperature to ensure accurate results. The cloud and pour point measurements were carried out using test apparatus manufactured by the Koehler instrument company K46195 (USA) in accordance with ASTM D-2500 and ASTM D-92 standards, respectively. The acid value was determined with the aid of test equipment manufactured by Metrohm 785 (USA) and the ASTM D-664 standard protocol. Kinematic viscosity measurements were performed using a digital constant temperature kinematic viscosity bath in accordance with the ASTM D-445 protocol; density was then determined using a portable density/gravity meter using the ASTM D1298 standard technique.

In this experiment, three test fuels were selected and prepared for the trials. The characteristics of petroleum diesel and its blends were described using the ASTM standards.

2.4. Fuel blending

Fig. 2 depicts the physical characteristics of the chosen fuels. Each fuel sample mixture (% vol) was created before to each engine test run. In this respect, the splash blending method was used to combine all of the fuel components using a mechanical homogenizer machine running at 4000 rpm for 30 min. Table 3 lists the mixture composition of the test fuels.

2.5. Experimental setup and methodology

The investigation was conducted using a compression ignition engine, as shown in Fig. 3, which ran steadily at 1300 rpm with a power rate of 1 kW. Engine test specifications are shown in Table 4. Following the endurance test, piston samples were collected for analysis. The device was started using conductive double-sided carbon solution tape, and the sample stub was then held in its sample chamber by the JEOL JSM-6490 LV type scanning electron microscope, which also has an additional and required bruker EDX (Energy Dispersive X-ray spectrometer) attachment and SEM specification machine. The SEM's operating settings were appropriately adjusted to provide the required level of fine focus at high sample magnifications. For examination and interpretation, the selected locations were photographed under a microscope. Following the analysis, the samples' qualitative and quantitative elemental determinations were made. This triggered the activation of the energy dispersive x-ray Spectrometer (EDX). In addition to tabulating the sample analysis data for the quantitative analysis, peak heights were utilized to ascertain the elemental makeup for the qualitative inquiry.

2.6. Engine sound pressure level emission

Diagrammatic depiction as shown in Fig. 4. This study also assessed the compression ignition engines' noise level, also known as the noise pressure level. The sound pressure levels of three fuels were examined at constant speeds and under constant loading circumstances. Step loads between 1.0 N m. are used by the engine to calculate the results. The front, left, and center orientations of sound pressure measurement are shown in Fig. 4. Three microphones, each 1 m from the test bed, were positioned at four different locations in the area above. Details are provided in Table 5. To measure engine noise, a digital sound level meter is used. Acoustic levels, or

Table 1
Properties of diesel, gutter oil, and n-pentanol.

Properties	Diesel Fuel	GO	N-pentanol
Viscosity 40 °C Cst	2.28	52	2.89
Density g/mL	835	900	814.4
Flash point ^{0}C	78	271	49
Oxygen (wt %)	0	20	8.47
Calorific valve MJ/Kg	42.5	37.68	34.75
Cetane number	50	54	20
C mass fraction (%)	85.4	77.91	60.05
H mass fraction (%)	15	11.69	13.7
Acid value (mg-KOH/g)	0.032	28.7	0.5

Table 2
Fuel characterization.

Properties	D100	D95-GO5	D70-GO20-Pe10	Test method
Calorific valve MJ/Kg	42.5	39	40	ASTM D-240
Viscosity 40C Cst	2.28	2.34	1.95	ASTM D-88
Density g/mL	0.85	0.89	0.84	ASTM D-854
Flashpoint ^{0}C	78	85	94	ASTM D-92
Cetane number	50	53	55.5	ASTM D-613

Fig. 2. Selected fuels used in the experiment before blend.

Table 3
Test fuel composition.

S. No	Fuel sample	Sample description
1	DF 100	Diesel fuel 100 %
2	DF95+GO5	Diesel fuel 95 %+ Gutter oil 5 %
3	DF 70+ GO20 + Pn 10	Diesel fuel 70 % + Gutter Oil 20 %+ Pn10 %

sound waves that move through the atmosphere, are measured with a sound level meter. It is typically a portable instrument that has a microphone. The microphone's diaphragm reacts to variations in air pressure brought on by sound waves. As a result, the device is occasionally called a sound pressure level (SPL) meter. An electrical signal (Volts V) is produced by this diaphragmatic movement, also known as the sound pressure variation (Pascal Pa). The voltage value that results from applying a known, consistent sound pressure can be used to identify a microphone. This is known as the sensitivity of the microphone. The sensitivity of the specific microphone being used must be recognized by the device. The device shows the sound pressure level (in decibels, or dB) and accurately converts the electrical signal back to sound pressure using this data.

2.7. Engine wear analysis and equipment

To qualitatively and quantitatively assess any increase in wear metal proportions, a 180-h durability test was conducted on DF, DF95GO5, and DF70GO20Pe10, respectively, using an atomic absorption spectrophotometer (AAS). For this aim, lubricating oil samples were taken every 20 h obtaining a sample of diesel engine lubricating oil.

The following is the procedure for preparing samples for an atomic absorption spectrophotometer. A representative 0.5 g (0.01 g) sample should be taken and placed in a beaker once the material has been homogenized. Add 0.5 g of potassium permanganate powder. If larger sample sizes are to be utilized, adjust the amount of potassium permanganate to maintain a 1:1 ratio with the oil. Ensure that the oil and potassium permanganate are well combined. The equipment's flame was ignited after the gas supply. Run distilled water as a blank, then 0.2 ppm, 0.3 ppm, and 0.4 ppm standard solutions to create a calibration curve. The following is the sample preparation procedure for an atomic absorption spectrophotometer. Following homogenization, select a representative 0.5 g (0.01 g) sample and place it in a beaker. Half a gram of potassium permanganate powder should be added. If using larger sample sizes, adjust the potassium permanganate quantity to maintain a 1:1 ratio with the oil. Be sure to mix the oil and potassium permanganate well.

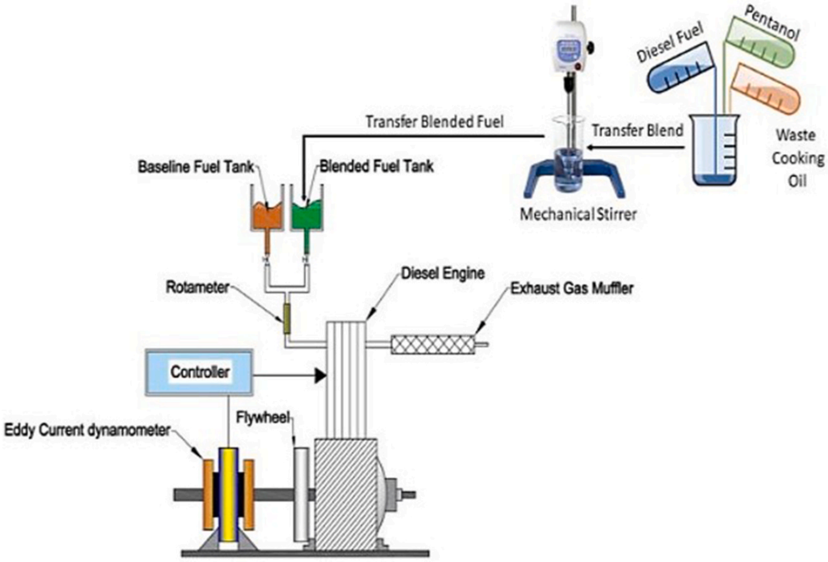


Fig. 3. Schematic diagram of engine test rig.

Table 4
Engine specifications.

Model	Single-cylinder diesel engine
Bore	75 mm
Stroke	80 mm
Mean effective Pressure	576 kPa
Cooling water consumption	1360 m/kW h
Injection Pressure	14.2 + 0.5 MPa
Specific oil consumption	4.08 g/kW h
Output (12 h rating)	4.4 kW/2600r/min
Illuminator	Fly wheel driver
Piston mean speed	6.93 m/s
Specific fuel consumption	278.8 m/kW h
Displacement (L)	0.353
Compression Ratio	21–23
Lubricating oil capacity	About 2L

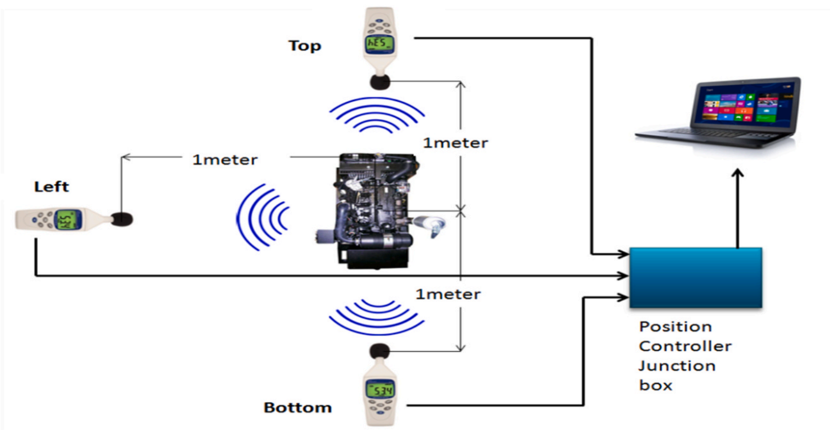


Fig. 4. Schematic diagram of sound pressure level.

Table 5
Detailed Specification of Sound pressure level meter.

Specifications	
Microphone	AWA14425 prepolarized condenser type
Sensitivity	App.40 mV/Pa
Calibration	94 dB@1 KHz
Accuracy	±1.5 dB (ref 94 dB@1 KHz)
Range of measurement	30~130dBA
Frequency response	20Hz ~ 8 KHz
Resolution	0.1 dB
Power	6V
Dimension	210 × 72 × 32 mm
Net weight	10 h (Continuous use)
Over load indication	"OVER" "UNDER" symbol
Frequency weighting	A
Data store	10000 group

To achieve mixing, immiscible thick oils and tars must be heated, and the oil may undergo a slight reaction. Add 1.0 mL of concentrated HSO while using a suitable stirring tool. The amount of sulfuric acid must be adjusted in accordance with the sample size to ensure a more representative sample, keeping the oil to sulfuric acid ratio between 1 g and 2 mL. Tiny droplets of H2SO4 can be introduced gradually. Stir in 2 mL of concentrated nitric acid (HNO). This technique will emit a small amount of heat. Depending on the specific analytical requirements, employing larger sample sizes may not necessarily necessitate a corresponding increase in the volume of HNO3. A reddish-brown gaseous substance, namely nitric oxide (NO), can be produced. Continue the process until the digestate stops releasing odors, which indicates that it is finished. Let the beaker cool as needed. Stir in 10 mL of strong hydrochloric acid after adding. Whether or not a corresponding increase in HCl volume is required when employing larger sample sizes will depend

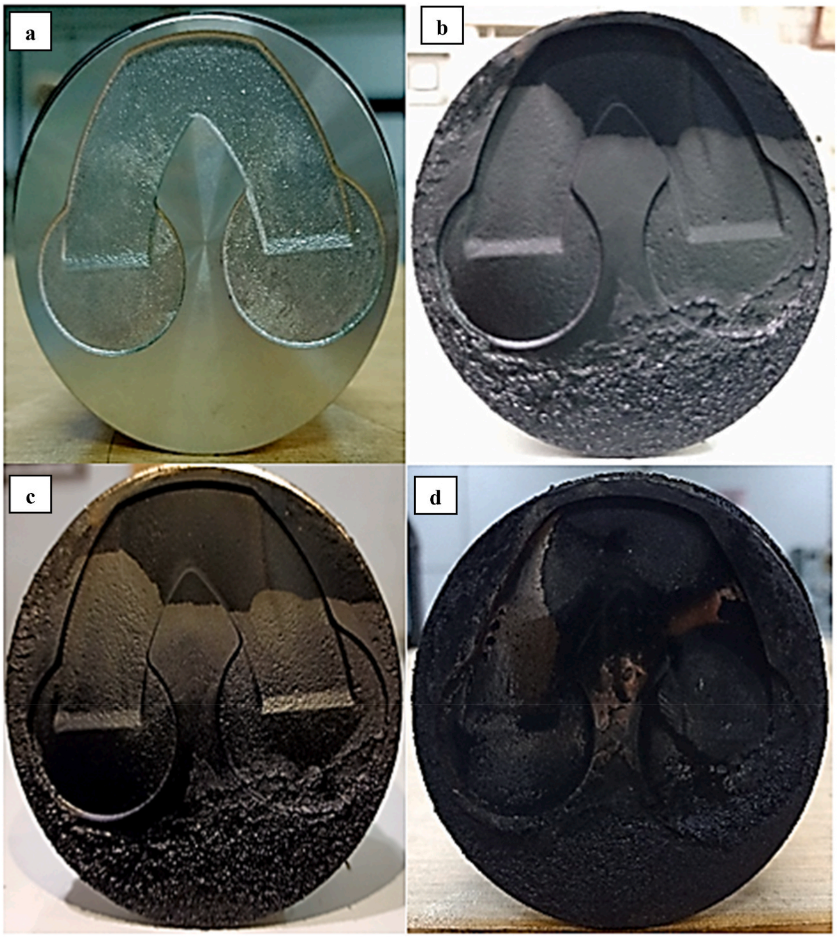


Fig. 5. Visual images of all test fuels (a) 0h (b) DF100, (c) DF95GO5 and (d) DF70GO20Pe10 of piston crown.

on the specific analytical requirements. This reaction will have a little quantity of exothermy, which will result in gas production and foaming. Lighter oils have a higher likelihood of forming foam than heavy ones. To prevent the sample from being lost, add water if the foaming is excessive. If need, allow the beaker to cool. Gather the digestate in a volumetric flask or beaker after filtering it through Whatman 41 filter paper to remove impurities. After the digestion process is complete, cleaning the filter paper and the digestion beaker with a maximum of 5 mL of hot hydrochloric acid while still in the funnel is recommended.

3. Results and discussion

Combustion produces carbon as a byproduct. Pollution from lubricating oil and incomplete fuel combustion are two factors that contribute to carbon deposition [29]. In addition to increasing maintenance expenses, these deposits impair engine performance and efficiency and cause operational issues. Engine failure can also infrequently be caused by large deposits. In addition to the physical deterioration of the components being visible to the naked eye, the carbon deposits may be compared [30]. Examples of the several types of mixes that include carbon deposits include carbon residue, oxygenated resinous organic material, and carbonaceous mixtures [23]. Carbon accumulation on several key engine components was photographed as part of a qualitative investigation. Throughout both trial stages, the engine ran at the same speed and under the same load conditions because the power output was maintained for the endurance test. Samples of piston crowns were photographed after the DF, DF95GO5, and DF70GO20Pn10 mix testing were finished. Visual inspection revealed some deposits on the piston surfaces of both blend fuel samples (Fig. 5(a-d)). However, the DF-powered piston was cleaner than the DF95GO5-powered piston. In addition, it was found that deposits on the piston surface of the piston crown made with the DF70GO20Pe10 blend were dry, while deposits made with DF were greasy or oily.

The thermal cracking of impurities in lubricating oil and incomplete fuel combustion result in heterogeneous mixtures known as carbon deposits [31]. These mixtures consist of oxygenated organic resinous material, carbon residue, and carbonaceous mixtures [32, 33]. The oxygenated fuel has an impact on the soot chemistry as well as the bonding of deposit formation. Incomplete combustion is

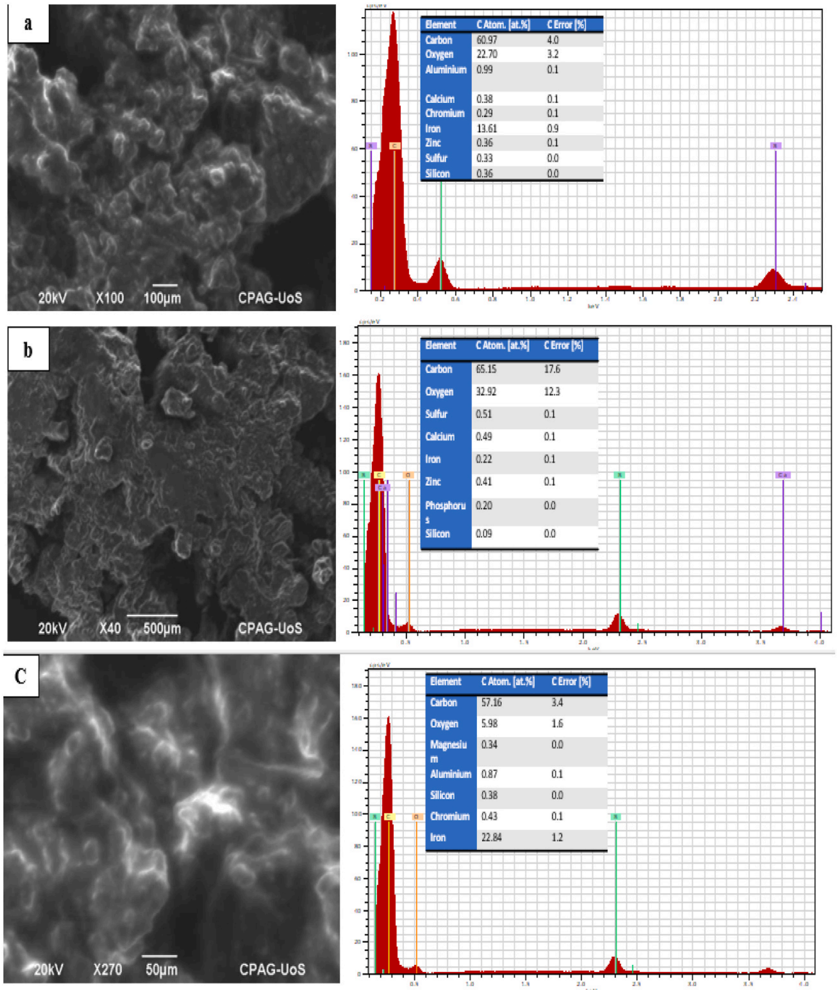


Fig. 6. (a–c). SEM and elemental composition of all tested fuels related to piston surface crown samples.

also caused by inadequate atomization and vaporization formation, while deposit accumulation is caused by viscosity and density. Carbon dioxide is produced as a byproduct of combustion. Part of the reason for the carbon buildup is the incomplete burning of fuels and the pollution caused by lubricating oil [34]. The performance and driveability of the engine can be significantly impacted by carbon buildup. It forms on the cylinder head and piston top surfaces as a result of the discernible rise in surface temperature and compression ratio, which eventually leads to issues for the engine. The unburned fuel pieces did not diffusely burn despite the injector's spray, most likely due to an inadequate air-fuel ratio (AFR). Unburned fuel deposits have been documented [35]. Prior to the engine trials, the engine was warmed up. To ascertain the effect of engine operations on the piston surfaces, tests were conducted on each fuel sample. The development of the deposit was then assessed by scanning the piston surface with SEM and EDX. The EDS spectra on the piston showing DF, DF95GO5, and DF70GO20Pe10 often showed sulfur (S), phosphorus (P), zinc (Zn), and calcium (Ca) in addition to carbon (C), oxygen (O), iron (Fe), and chromium (Cr) (the latter two are from the base material of the piston rings).

These latter elements are frequently present in lubricating oil additive systems for engine crankcases. Following the completion of the studies, it was found that, as Fig. 6(a–c) illustrates, DF70GO20Pn10 generated less deposit formation than the two fuel samples.

Fig. 6(a) illustrates that the carbon (C) and oxygen concentrations in the baseline fuel scenario can both rise to 60.72 percent and 15.75 percent, respectively. The carbon content (67.68 %) and oxygen concentration (19.16 %) are comparatively higher in the upper layer of Fig. 6(b). Fig. 6(c) displays carbon concentrations at a lower level of 52.90 %. The oxygen content in this specific location, however, was determined to be 16.12 %. Carbon deposits appeared on the piston tops of engines that ran on mineral diesel (D100), gutter oil (GO20), and n-pentanol (10), following a 180-h endurance test. The study indicated that engines using gutter oil (GO) had more carbon deposits on their piston tips than engines using mineral diesel and n-pentanol. This suggests that more carbon is deposited on the piston top when GO fuel is burned. All of the fuel types that were examined showed signs of degradation at the piston crown.

Numerous factors, including the particular properties of the fuels or the way they are burned, could cause this erosion. However, engines that used DF70GO20Pn10 fuel resulted the less deposit formation on piston crown than that of DF95GO5 and DF fuel. This implies that gutter oil lubricating qualities are comparable to those of the other fuels evaluated. Scanning electron microscopy (SEM) and energy dispersive microscopy (EDX) were used to look into the carbon deposits on the piston heads in more detail. These methods offer comprehensive details regarding the structure and makeup of the deposited carbon. According to the findings, waste gutter oil is more likely than mineral diesel and n-pentanol to cause carbon deposition. This could be caused by a number of things, including variations in the composition and combustion properties of the fuels. However, the reduced carbon deposition seen in engines that use n-pentanol may be explained by the fact that it was discovered to have strong lubricating qualities and to burn well while operating. Overall, the results indicate that GO fuel results in higher carbon deposits on the piston tops; additionally, n-pentanol has superior combustion and lubrication qualities that lower carbon deposition.

3.1. Sound emission

In addition to studying internal combustion engines' performance and combustion properties, several researchers have also examined its noise and vibration characteristics [36]. Engine noise and vibration can be reduced in two ways. These are modifications made to the fuel or engine [37]. Both the front and rear noise levels were measured using a portable digital sound pressure level dB meter. Sound levels in the left and front directions were measured at a distance of 1 m from the test engine bed. Several scholars have discussed the microphone position selected for this study in greater detail. Figs. 7 and 8 show the sound level in the front and rear directions of the engine test bed as well as the average of both directions when the engine was running on diesel fuel (DF), including blend fuels such DF100 and binary blend DF95GO5. However, a prolonged ignition delay period results in a combustion event that is extremely reliant on the ignition delay. The cetane rating of diesel indicates the quality of its ignition. It therefore influences ignition

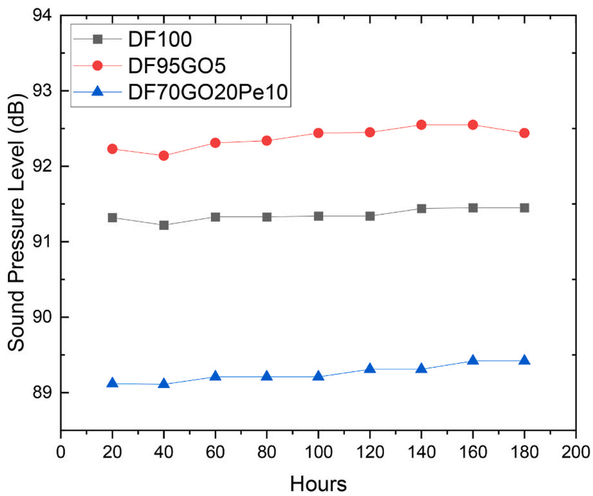


Fig. 7. Sound emission front position versus engine operating hours.

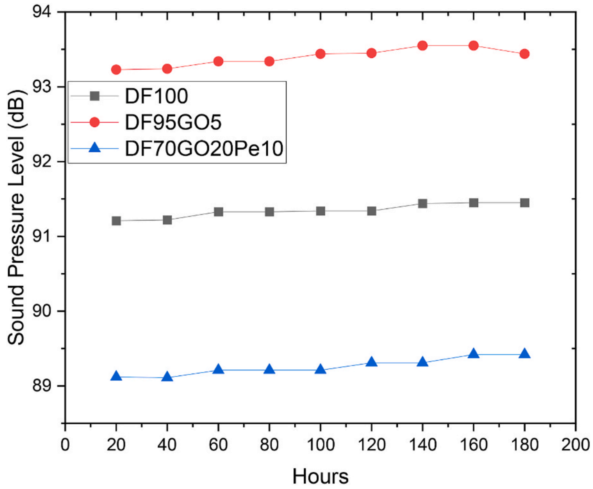


Fig. 8. Sound emission left position versus engine operating hours.

delay; a greater number denotes a shorter ignition delay or an earlier injection timing [38]. The noise level increases when more mass bursts because the combustion pressure increases faster [39]. However, the higher oxygen concentration of emulsion fuels increases the efficiency of burning, which could result in a lower sound level. The amount of aromatic compounds in the gasoline has also been found to enhance the igniting delay. Diesel gasoline will ignite more slowly due to the tiny amount of aromatic chemicals it contains [40,41]. In terms of noise emissions, however, DF70GO20Pe10 as a ternary blend fuel produces the best results; however, using DF95GO5 blend fuel produced higher deviation rates than diesel fuel.

In reaction to load, the injection strategy modifies the timing of injections and the ignition delay, thereby reducing in-cylinder pressure. It is also possible to interpret this as the result of some debris in the blend, which increased the noise emissions, as seen in Figs. 7 and 8.

Conventional diesel fuel shares the same cetane number as n-pentanol and gutter oil. The ternary blend (DF70GO20Pe10), however, has a higher oxygen intake than DF95GO5 and DF100 due to its unique botanical origin. This enables an earlier and more controlled combustion process in the ternary blend, which lessens acoustic disturbances and, consequently, lowers local ambient noise levels. In contrast, incomplete fuel combustion raises noise emissions in the binary blend. The study's findings indicate that a greater gutter oil/n-pentanol concentration in the diesel fuel (DF70GO20Pe10) improved combustion quality by raising the oxygen content. This is corroborated by the accompanying photos, which show an overall decrease in ambient sound pressure. The sound pressure level was measured in this investigation in accordance with ASTM E492-09, which is the ASTM noise detection standard. In addition to providing guidelines for data processing, instrumentation, and calibration, this standard explains how to measure noise levels in various contexts. By adhering to ASTM E492-09, we were able to ensure the accuracy and reliability of our noise measurements, increasing the validity of our findings.

3.2. Lubricating oil analysis

Wear is the degradation of any surface that usually entails a significant loss of materials and can be caused by relative motion between the surfaces and bodies that come into touch with them [42,43]. Lube oil analysis involves a laboratory examination of the properties of a lubricant, suspended impurities, and wear metal debris. To get accurate and vital information on the state of the engine and oil, lubricating oil analysis was performed on an oil sample that was periodically retrieved from the engine oil sump. Atomic absorption spectroscopy (AAS) was used to assess the various metal concentrations discovered in the lubricating oil samples that were collected at 20-h intervals. The metal wear from the engines' major components is fairly summarized in the analysis. In this case, several metal elements were investigated, such as Cd, Cu, and Ni. In this experiment, the density and viscosity of the ternary blend of n-pentanol, diesel, and gutter oil were reduced. It is believed that n-pentanol enhances centane, which encourages engine complete combustion. Debris and engine wear decreased as a result.

3.2.1. Cadmium (Cd)

Fig. 9 displays the graph of various blends that analyzes the cadmium proportions in lubricating oil during long-term endurance testing. The amount of cadmium in engine oil is shown on the graph. This element was found to be more concentrated in the binary blend (DF95GO5) than in the other two blends. The ternary blend has the lowest Cd content compared to DF100 and DF95GO5. Thus, it can be concluded that n-pentanol enhanced the impacts of blends on engine materials and wear when added at a 10 % concentration.

3.2.2. Nickel (Ni)

The concentration of nickel in the shards that landed in the old lubrication oil from the engine sump could have come from

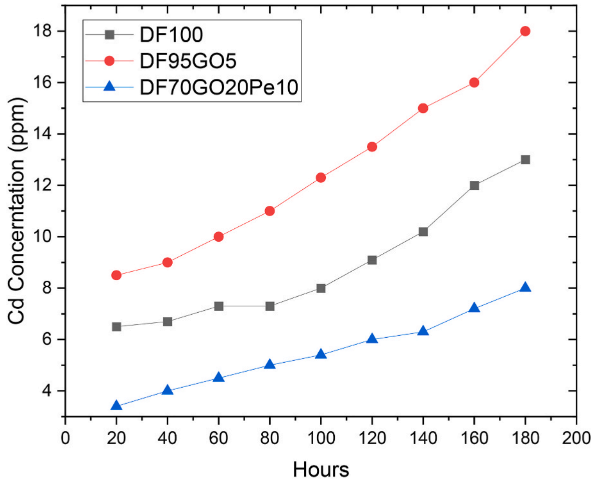


Fig. 9. Cadmium concentration versus engine operating hours.

bearings, gear plates, and valves [44,45]. Fig. 10 shows the nickel concentration of diesel and its mixes. The graph unequivocally shows that mix fuels have a lower nickel concentration than diesel when the amount of hours spent using lubricating oil is taken into consideration. The cobalt comes from the bearings. Gears, crankshaft wear, bearing wear, cylinder linings, or compression rings can all produce nickel wear debris in an internal combustion engine. Even though the cylinder contains relatively little nickel, it is incredibly robust. Thus, only a very small amount was detected in the engine oils, as Fig. 10 illustrates. Compared to the mixed fuels, the diesel-powered engine in Fig. 10 displayed reduced nickel wear. Compared to DF100, higher values were obtained using the binary mix DF95GO5. On the other hand, DF100 yielded more cobalt than the ternary mix DF70GO20Pn10. However, it is clear that the ternary mix DF70GO20Pn10 produced the least quantity of nickel when compared to DF100 and DF95GO5. In summary, the nickel concentration dropped in the following order following the use of mix fuel: DF95GO5 > DF100 > DF70GO20Pn10. The acidity of the blow-by air that entered the oil sump and came into contact with the bearing could be the cause of the increase in nickel wear that occurs when lubricating oil is used. The 180-h engine run produced the least quantity of nickel waste.

3.2.3. Copper (Cu)

The concentration of copper in engine oil is caused by bearing wear [45]. Fig. 11 illustrates the difference in copper concentration between blend fuels and diesel in relation to the number of hours spent using lubricating oil. The figure indicates that the amount of lead found in the lubricating oil samples taken from the DF100, DF95GO5, and DF70GO20Pn10 is increasing with time [46]. When all blends were evaluated, the binary blend (DF95GO5) provided the highest content of Cu, while the ternary blend (DF70GO20Pn10) produced the lowest concentration.

However, even with a little lower percentage of n-pentanol (10 % more) added to the mixture, the ternary blend DF70GO20Pn10 still yielded superior results than engine-operated diesel fuel. Lead is most likely present in grease, paint, coatings, and wear debris.

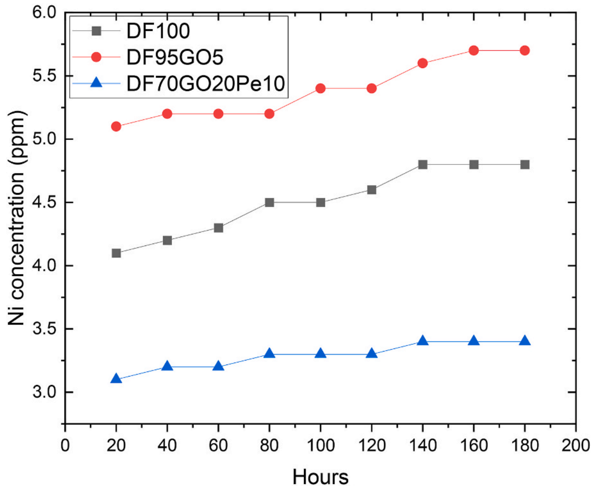


Fig. 10. Nickel concentration versus engine operating hours.

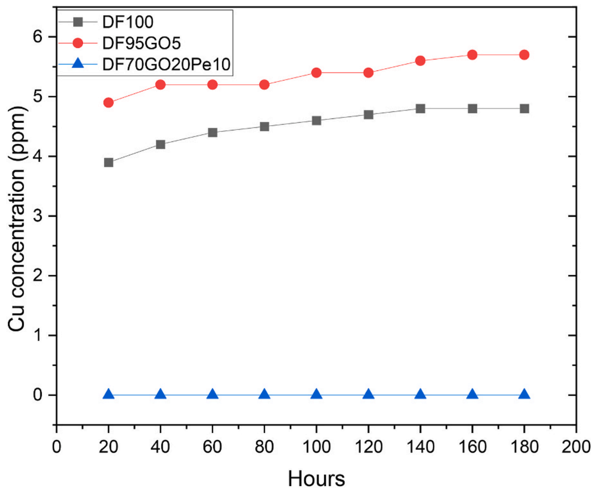


Fig. 11. Copper concentration versus engine operating hours.

4. Conclusion

In order to assess the deposit formation, sound emission and debris present in the lubricating oil of CI engine, a single-cylinder water-cooled horizontal diesel engine has been utilized by considering DF, DF95GO5 and DF70GO20Pe10 fuels. The stability and solubility of diesel blending were improved by the addition of n-pentanol. The physical and chemical properties of DF70GO20Pe10 suggested good potential for application in CI engines, and the engine operated flawlessly and smoothly throughout the test.

- SEM micrographs and a variety of roughness measures show that wear is comparatively greater on the antitrust side. The DF95GO5 engine had more wear overall than the diesel engine, even though their wear patterns were similar.
- According to engine trial testing, DF70GO20Pn10 is a good partial mineral diesel alternative. Gutter oil binary mix fuel was shown to generate carbon deposition at a higher rate than diesel fuel, with 67.68 % for GO and 60.72 % for D100. When n-pentanol was mixed with gutter oil, its deposition rate was 52.90 %, which was lower than that of diesel fuel.
- Furthermore, the current compression ignition engine may easily be converted to run on n-pentanol and gutter oil without requiring significant changes to the engine's internal components. Blend fuel produced lower sound levels than diesel fuel because of a number of characteristics, such as a higher oxygen content, a shorter ignition delay, enhanced viscosity, lubricity, etc. On the other hand, blend fuel DF70GO20Pn10 generated the least amount of noise.
- After analyzing a variety of data (Debris Accumulations, Acoustic and Wear Analysis) collected during the endurance test, the following findings were drawn: The results of the current analysis show that the amount of metal debris in the lubricant oil sample taken from the DF70GO20Pn10-fueled engine is comparatively low, according to the AAS, when compared to diesel-fueled engines. The addition of n-pentanol as a ternary mix DF70GO20Pn10 for copper (Cu), nickel (Ni) 0.37 ppm, and cadmium (Cd) 8 ppm was investigated and contrasted with diesel fuel and gutter oil, respectively. However, it was discovered that the concentration of Cd, Cu, and Ni was reduced in the case of DF70GO20Pn10. According to the results, n-pentanol, diesel fuel, and gutter oil as ternary blend increased engine fuel system lubrication and system component operational life.

4.1. Recommendations for future work

Ternary blends of diesel, gutter oil, and n-pentanol offer better performance and emission characteristics than binary blends of diesel and gutter oil. Compared to using the binary blend and diesel fuel, n-pentanol reduced exhaust emissions. Therefore, further study on ternary mixes of n-pentanol is required in order to use other biofuels in CI engines in the future. Utilizing renewable fuels was shown to enhance engine performance and emissions. Furthermore, for gutter oil to be used as fuel, the smart method of recapture and valuation is required. Last but not least, using GO directly as a binary fuel with diesel and ternary blends with n-pentanol was recommended since it avoided unnecessary physical-chemical processes and had the least detrimental environmental impact. This implied that since GO is a successful waste recovery solution that will reduce future need on fossil fuels, it should be utilized directly in engines.

CRediT authorship contribution statement

Faheem Ahmed Solangi: Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis, Conceptualization. **Ali Murtaza Ansari:** Writing – review & editing, Writing – original draft, Visualization, Validation, Formal analysis, Data curation, Conceptualization. **Altaf Alam Noonari:** Writing – original draft, Validation, Methodology, Investigation. **Fayaz Hussain:** Writing – original draft, Visualization, Project administration, Funding acquisition, Data curation, Conceptualization. **Bo Zhang:** Writing – review & editing, Writing – original draft, Visualization, Supervision, Software, Methodology, Funding acquisition, Formal analysis, Conceptualization. **Nazmi Mat Nawi:** Visualization, Validation, Resources, Project administration, Conceptualization. **C Ahamed Saleel:** Writing – review & editing, Writing – original draft, Resources, Project administration, Methodology, Investigation, Funding acquisition.

Declaration of competing interest

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

Acknowledgments

This work was supported by the Natural Science Foundation of Ningxia under Grant No. 2022AAC2003. The authors extend their appreciation to the University Higher Education Fund for funding this research work under the Research Support Program for Central Labs at King Khalid University through project number CL/CO/A/1.

Data availability

Data will be made available on request.

References

[1] I. Temizer, O. Cihan, B. Eskici, Investigation of lubrication and tribological behaviors in a diesel engine with the new designed flow-guided combustion chamber, Eng. Fail. Anal. 163 (2024) 108592.

[2] S. K, G.N. Kumar, P. Bedar, A novel approach to enhance the combustion quality of C5 alcohol with 2-Ethylhexyl nitrate as a cetane enhancer in common rail direct ignition diesel engine, J. Clean. Prod. 446 (2024) 141314.

[3] B. Musthafa, M. Prabhahar, Experimental and numerical analysis of performance, and emission characteristics of CI engine using Juliflora-Gulmohar Biodiesel/Blends and ANN prediction using MATLAB, Case Stud. Therm. Eng. 72 (2025) 106338.

[4] F.A. Solangi, et al., Study of deposit accumulation and tribological degradation in diesel engine utilizing blend fuels, Energy Convers. Manag. X 26 (2025) 100999.

[5] K.V. Pradeep, et al., Production and evaluation of engine performance and emission characteristics of composite biodiesel from Michelia champaca and amoora rohituka oils in a CRDI VCR diesel engine, Results Eng. 26 (2025) 105172.

[6] K.V. Pradeep, et al., Production and application of Michelia Champaca methyl ester as a novel second-generation biofuel: combustion, performance, and emission analysis in CRDI CI engines, Energy Convers. Manag. 332 (2025) 119774.

[7] D. kumar, S. kachhap, S.S. Thokchom, Numerically comparative assessment of different biodiesel & its blends on performance, combustion and emission characteristics, Ind. Crop. Prod. 209 (2024) 117900.

[8] M.S. Abishek, et al., Alumina and titanium nanoparticles to diesel–Guizotia abyssinica (L.) biodiesel blends on MFVCR engine performance and emissions, Sustain. Energy Technol. Assessments 61 (2024) 103580.

[9] A. Hribernik, B. Kegl, Performance and exhaust emissions of an indirect-injection (IDI) diesel engine when using waste cooking oil as fuel, Energy Fuel. 23 (3) (2009) 1754–1758.

[10] W. Diaz-Felix, et al., Pretreatment of yellow grease for efficient production of fatty acid methyl esters, Biomass Bioenergy 33 (4) (2009) 558–563.

[11] A. Atmanlı, B. Yüksel, E. İleri, Experimental investigation of the effect of diesel–cotton oil–n-butanol ternary blends on phase stability, engine performance and exhaust emission parameters in a diesel engine, Fuel 109 (2013) 503–511.

[12] H. Sharon, et al., Fueling a stationary direct injection diesel engine with diesel-used palm oil–butanol blends–an experimental study, Energy Convers. Manag. 73 (2013) 95–105.

[13] F. Lujaji, et al., Experimental investigation of fuel properties, engine performance, combustion and emissions of blends containing croton oil, butanol, and diesel on a CI engine, Fuel 90 (2) (2011) 505–510.

[14] A. Atmanlı, E. Ileri, B. Yüksel, Experimental investigation of engine performance and exhaust emissions of a diesel engine fueled with diesel–n-butanol–vegetable oil blends, Energy Convers. Manag. 81 (2014) 312–321.

[15] A. Atmanlı, E. Ileri, B. Yüksel, Effects of higher ratios of n-butanol addition to diesel–vegetable oil blends on performance and exhaust emissions of a diesel engine, J. Energy Inst. 88 (3) (2015) 209–220.

[16] A. Atmanli, et al., Extensive analyses of diesel–vegetable oil–n-butanol ternary blends in a diesel engine, Appl. Energy 145 (2015) 155–162.

[17] A. Atmanli, Effects of a cetane improver on fuel properties and engine characteristics of a diesel engine fueled with the blends of diesel, hazelnut oil and higher carbon alcohol, Fuel 172 (2016) 209–217.

[18] D.P. Satsangi, N. Tiwari, Experimental investigation on combustion, noise, vibrations, performance and emissions characteristics of diesel/n-butanol blends driven genset engine, Fuel 221 (2018) 44–60.

[19] A.M. Ansari, et al., Impact of biodiesel blended fuel with nanoparticles on performance and noise emission in compression ignition engine, Int. J. Thermofluids 19 (2023) 100390.

[20] M. Sen, A.O. Emiroğlu, A. Keskin, Production of biodiesel from broiler chicken rendering fat and investigation of its effects on combustion, performance, and emissions of a diesel engine, Energy Fuel. 32 (4) (2018) 5209–5217.

[21] A. Keskin, Two-step methyl ester production and characterization from the broiler rendering fat: the optimization of the first step, Renew. Energy 122 (2018) 216–224.

[22] J. Campos-Fernandez, et al., Performance tests of a diesel engine fueled with pentanol/diesel fuel blends, Fuel 107 (2013) 866–872.

[23] V. Kumbhar, et al., Investigations on durability and lubricating oil degradation of CIDI engine fuelled with tamarind seed oil methyl ester, Int. J. Ambient Energy 43 (1) (2022) 5758–5767.

[24] A.M. Ansari, L.A. Memon, M.Y.E. Selim, Experimental study of particulate matter emission for a diesel engine fueled with nanoparticles and biofuel/diesel blends, Int. J. Thermofluids 23 (2024) 100738.

[25] A.J. Caines, R.F. Haycock, J.E. Hillier, Automotive Lubricants Reference Book, 354, John Wiley & Sons, 2004.

[26] I. Temizer, O. Cihan, Tribological investigation of the new combustion chamber with wall-guided fuel injection in a diesel engine, Int. J. Engine Res. 26 (1) (2025) 27–40.

[27] A. Atmanli, Comparative analyses of diesel–waste oil biodiesel and propanol, n-butanol or 1-pentanol blends in a diesel engine, Fuel 176 (2016) 209–215.
[28] M. Ponnusamy, B. Ramani, R. Sathyamruthy, A parametric Study on a diesel engine fuelled using waste cooking oil blended with Al2O3 Nanoparticle—Performance, emission, and combustion characteristics, Sustainability 13 (13) (2021) 7195.
[29] J. Li, W. Yu, W. Yang, Evaluating performance and emissions of a CI engine fueled with n-octanol/diesel and n-butanol/diesel blends under different injection strategies, Fuel 284 (2021) 119085.
[30] S. Sinha, A.K. Agarwal, Experimental Investigation of the Effect of Biodiesel Utilization on Lubricating Oil Degradation and Wear of a Transportation CIDI Engine, 2010.
[31] A.Z.M. Fathallah, F. Pinto, The Influence of NaCl dissolved on biodiesel of used cooking oil on performance and its degradation of main components of diesel engine, in: IOP Conference Series: Earth and Environmental Science, IOP Publishing, 2022.
[32] M.T. Suryantoro, B. Sugiarto, F. Mulyadi, Growth and characterization of deposits in the combustion chamber of a diesel engine fueled with B50 and Indonesian biodiesel fuel (IBF), Biofuel. Res.J. 3 (4) (2016) 521–527.
[33] F. Solangi, et al., Comparative assessment of head deposition, exhaust gas temperature and sound emission in CI engine using blend fuel, J. Kejuruteraan. 36 (2024) 1321–1327.
[34] S.K. Kurre, R. Garg, S. Pandey, A review of biofuel generated contamination, engine oil degradation and engine wear, Biofuels 8 (2) (2017) 273–280.
[35] O. Morgul, Experimental analysis for assessing noise and vibration of the diesel engine fuelled with a butanol–diesel blend under different injection pressures and engine speeds, Int. J. Environ. Sci. Technol. 18 (2020) 1–12.
[36] J. Borg, A. Watanabe, K. Tokuo, Mitigation of noise and vibration in the high-pressure fuel System of a gasoline direct injection engine, Proced. Soc. Behav. Sci. 48 (2012) 3170–3178.
[37] M. Redel, et al., Bibliometric studies on emissions from diesel engines running on Alcohol/Diesel fuel blends. A case Study about noise emissions, Processes 9 (2021) 623.
[38] X. Li, et al., Impact of lower and higher alcohol additions to diesel on the combustion and emissions of a direct-injection diesel engine, Environ. Sci. Pollut. Control Ser. 26 (2019).
[39] P. Muthaiyan, K. Jeyachandran, Investigations on the performance and exhaust emissions of a diesel engine using preheated waste frying oil as fuel, Renew. Energy 30 (2005) 2189–2202.
[40] Z. Liu, Z. Ni, Effect of biodiesel components on its lubrication performance, J. Mater. Res. Technol. 8 (2019).
[41] A.M. Ansari, et al., Influence of alcohol blend fuels on performance and noise emission in spark ignition engine, Int. J. Thermofluids 26 (2025) 101120.
[42] S. Kurre, et al., Tribology in industry Study of lubricating oil degradation of CI engine fueled with diesel-ethanol blend, Tribol. Industry. (2021) 43.
[43] Analysis of lubricant oil degradation and sound pressure level for CI engine using blend fuels, J. Teknologi (Sci. Eng.) 86 (4) (2024) 131–137.
[44] A.K. Hasannuddin, et al., Performance, emissions and lubricant oil analysis of diesel engine running on emulsion fuel, Energy Convers. Manag. 117 (2016) 548–557.
[45] F. Solangi, et al., Investigation of lubricating oil and exhaust valve deposit formation using blend fuels in CI engine, J. Kejuruteraan. 37 (2025) 287–298.
[46] C.P. García, S. Orjuela Abril, J.P. León, Analysis of performance, emissions, and lubrication in a spark-ignition engine fueled with hydrogen gas mixtures, Heliyon 8 (11) (2022) e11353.