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Research Article

Effect of higher alcohol on injector deposit and wear in compression ignition engine

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ABSTRACT

An environmentally friendly and energy-secure approach is to recycle waste cooking oil (WCO) for use in diesel engines. In place of costly pre-heating and trans-esterification, diesel-WCO-alcohol ternary blends offer a simple and affordable way to use both a bio-component and a recycled component to substitute diesel and lower the viscosity of WCO partially. This investigation tested three fuel samples: 20% waste cooking oil, 65% DF, and 15% n-pentanol; diesel fuel, which served as the reference; and 5% waste cooking oil and 95% DF. The 200-hour endurance test was performed on the single-cylinder CI engine. An atomic absorption spectrophotometer equipped with hollow cathode lamps for every element was used to quantify the engine wear debris, and scanning electron microscopy and energy-dispersive X-ray spectroscopy procedures were employed to analyze the elements and measure deposit accumulations. Furthermore, temperatures at and around the injector tip caused by modern diesel injection systems may result in incredibly persistent deposits. After prolonged use, some fuels can damage the engine itself, generate excessive carbon and lacquer buildup, and make an engine operate less efficiently. The proportion of carbon layer on injector surfaces for DF, DF95WCO5, and DF65WCO20Pe15 is 32.54%, 56.17%, and 27.58%, respectively. In this experimental investigation, the fuel DF65WCO20Pe15 showed minimal injector deposit buildup.

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INTRODUCTION

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

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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]. The engine analysis wear/debris was measured using an atomic absorption spectrophotometer (AAS) with hollow cathode lamps for each element. Iron (Fe), copper (Cu), and nickel (Ni) were dissolved in standard solutions.

MATERIAL AND METHODS

This study examined carbon deposition, lubricating oil analysis and wear debris on engine parts using a compression ignition engine. A four-stroke, single-cylinder, water-cooled engine with an eddy current dynamometer attached was chosen to be used in this experiment. Its primary settings are displayed in Table 1.

The endurance test was conducted for 200 h at 1300 rpm and 1 N-m torque on three tested fuels: DF, DF95WCO5 and DF60WCO20Pe15respectively. Figure 1 illustrates the schematic diagram of the engine test bed. Three types of fuel samples were tested: a base fuel with no additions and a fuel blend with waste cooking oil and n-pentanol additives. The engine was run for 200 hours on each fuel sample. After 200 hours of operation, the engine component responsible for carbon deposition, such as the combustion chamber or injector, was removed. Carbon deposition in an engine part was analyzed using SEM and EDX.

The WCO was collected from a nearby eatery. The usual temperature range for frying chips in oil is 130 to 180 degrees Celsius. The oil was heated and filtered before mixing to remove any suspended food and water particles. Given that diesel is water-repellent and the presence of water may cause phase separation, this technique was employed to increase blend stability. Table 2 provides information on blend fuels, whereas Table 3 shows properties of n-pentanol, diesel, and used cooking oil.

Each fuel sample ran through an endurance test lasting 200 hours. After that, the engine was dismantled, and the injector was taken out. The process was repeated for

Table 1. Detailed engine specifications

Model	**Single-Cylinder, Water Cooled Four Stroke Engine**
Bore	75 mm
Stroke	80 mm
Output (12 hours rating)	4.4 kW/2600 r/min
Displacement	0.353 L
Compression Ration	21-23
Means effective pressure	576 kPa
Piston mean speed	6.93 m/s
Specific fuel consumption	278.8 m/kW h
Specific oil consumption	4.08 g/kW h
Cooling water consumption	1360 m/kW h
Injection Pressure	14.2 + 0.5 MPa

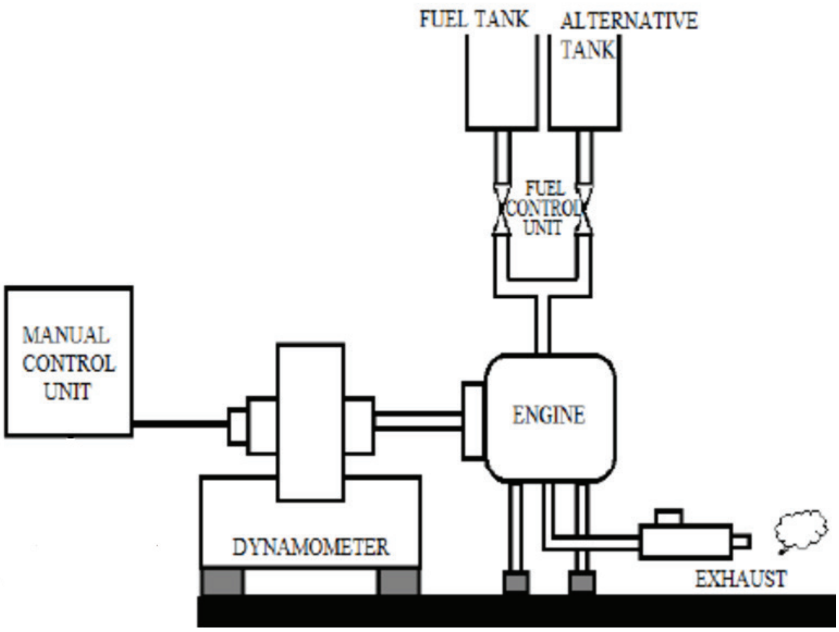

Figure 1. Schematic diagram of the experimental setup.

Table 2. Characterization of diesel, waste cooking oil and n-pentanol

Properties	Diesel fuel	Waste cooking oil	N-pentanol
Viscosity Cst at 40c	2.28	52	2.89
Density g/ml	835	900	814.4
Flash Point ^{o}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

Table 3. Chemical characterization of selected fuels

Properties	D100	D95WC05	D65WC015Pe15	Test Method
Calorific Valve MJ/Kg	42.5	39	40	ASTMD-5468
Viscosity Cst at 40c	2.28	2.338571	1.948706	ASTM D-7042
Density g/ml	0.835	0.836281	0.835178	ASTM D-7042
Flash Point ^{o}C	78	85	94	ASTM D-93
Cetane number	50	53	55.5	ASTMD-6890

the other test fuels. Each and every injector nozzle sample collected in this way was examined using energy dispersive X-ray spectroscopy (EDS) and scanning electron microscopy (SEM). SEM examines deposits both large and small. It can examine minute deposits for elements using EDS. For every fuel sample, injector nozzle photos were obtained at 0 h (Fresh) and 200 h (Endurance test). to investigate the effects on the engine oil of the DF, DF95WCO5, and DF60WCO20Pe15 mixes. For every fuel sample, throughout the engine endurance test, an oil sample was taken every 20 hours. The Saybolt viscometer (two tube type), a glass pycnometer for density assessment, and an atomic absorption spectrophotometer for wear metal debris analysis were used to measure the viscosities of the lubrication oil samples.

RESULTS AND DISCUSSION

Injector Visual Inspection

High heat and mechanical stress are applied to the critical components of diesel engines. Incomplete combustion and pyrolysis, as well as heat and oxidative lubricant degradation, are the main causes of deposits on these components. These deposits decrease engine operation, performance, and efficiency while increasing maintenance expenses. Engine failure might result from large deposits [37]. When compared to mineral diesel (during the performance and emission study completed earlier), a similar trend was detected in exhaust smoke opacity tests on the same engine with different mixes. Soot formation was decreased and combustion was enhanced by the oxygen present in the fuel molecule. When oxygenated fuels are used in diesel engines, fewer smoke and particles are produced [38]. In Figure 2, slanted views of the injectors working at different engine operating hours and with different fuels are displayed during an endurance test. Just looking at injectors utilizing different fuels made it hard to tell them apart. Carbon deposits were photographed and analyzed on key engine components. The engine ran at the same speed and load throughout the endurance test, maintaining power output. A DSLR was used to capture pictures of the injector nozzle both before and after the endurance test in order to compare the carbon deposits. Similar to the injectors utilizing DF, the outer surface of the injectors using DF95WCO5 mixes was also observed to be dirtier.

Scanning Electron Microscopy & Energy Dispersive X-ray Spectroscopy

when each test fuel underwent a 200-hour endurance test. After that, the engine was taken apart in part to look at the deposits that had formed on each injector tip. Figure 3 displays SEM micrographs of deposits on each of the fuels that were evaluated, each at a magnification of 25. Complex diesel injection systems are known to produce more heat at and around the injector tip, which can result in deposits that are especially difficult to remove [39, 40]. DF fuel deposits are much higher than those with DF65WCO20Pe15. Figure 2 (c) illustrates that the injector hole showed much more deposit formation when DF95WCO5 was utilized than the remaining evaluated fuels.

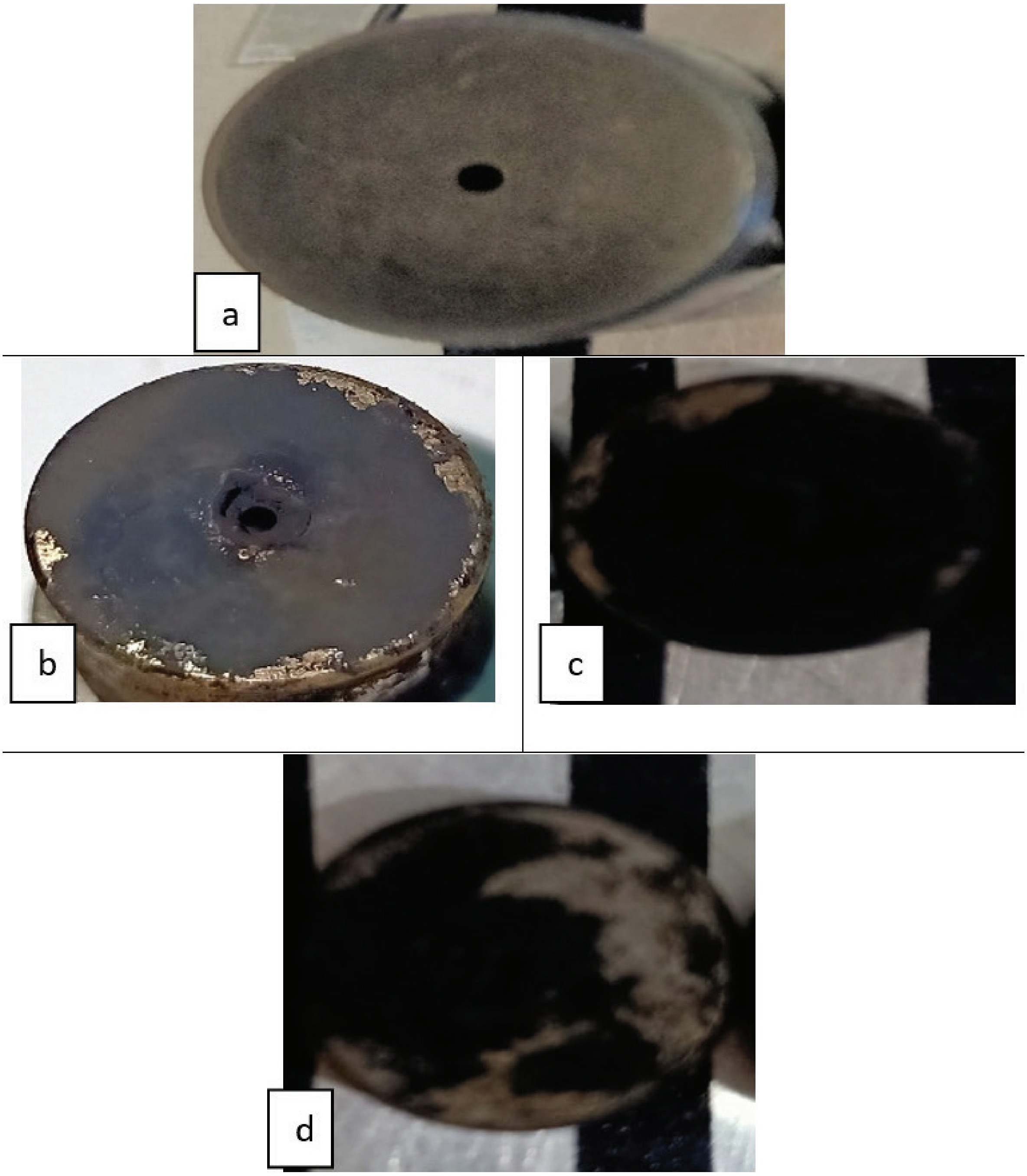

Figure 2. Photographic views of injector nozzles before and after engine operations.

Over time, deposits are supposed to accumulate at the high temperatures at which the sophisticated diesel injection systems' injector tips are exposed [41]. The results show that the elemental composition of the deposits was equal even if the combustion chamber's temperature and pressure were the same. The presence of Fe and Al in all samples may indicate partial wear in some engine components. As an engine runs, metal fragments or organometallic compounds find their way into the lubricant and build up as deposits [42]. All fuels saw an increase in pressure rise rate as the brake load increased because more gasoline is fed into the engine with each cycle. This shortened the delay time and increased the rate of pressure buildup in the diesel engine. When diesel and jatropha were combined, there was a little increase in the ignition delay period, which resulted in a faster rate of pressure rise [43]. The concept of ternary blend formulation was not only attempted with vegetable oils but also extended to biodiesels derived from

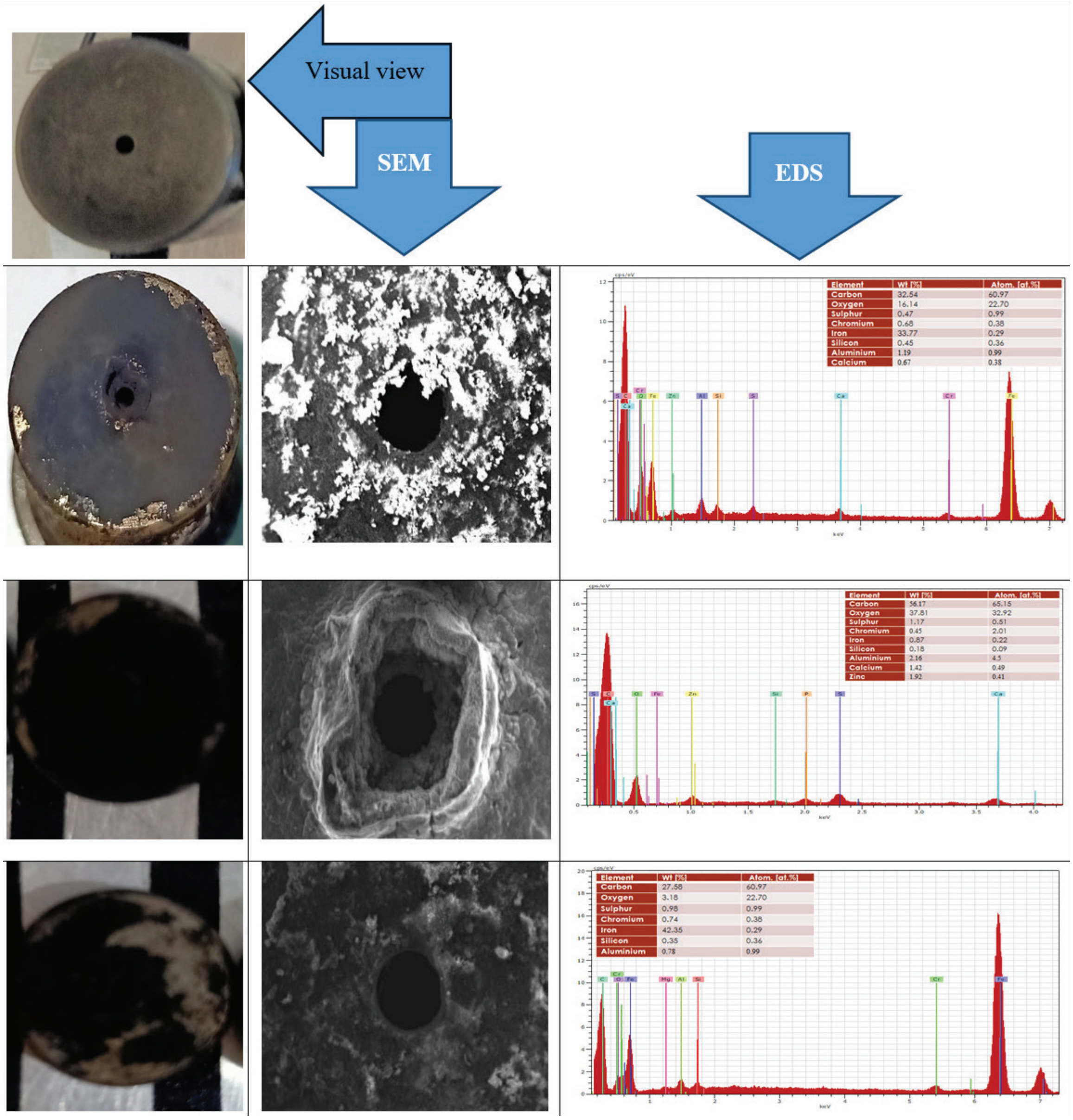

Figure 3. SEM images and related elemental analysis of injector tips operated with DF, DF95WCO5 and DF60WCO20Pe15 respectively.

them and favorable results have been reported [44, 45]. Li et al. [44] showed that addition of pentanol to biodiesel/diesel improved emissions and performance especially at low/medium loads. A ternary blend containing diesel (40%), biodiesel (30%) and pentanol (30%) delivered good combustion, performance and emissions. Imdadul et al. [45] obtained optimum emissions and performance with 15–20% addition of npentanol with Calophyllum biodiesel/diesel blends in a DI diesel engine. All test fuels have been used to operate the injector tip shown in Figure 3. EDS analyzes the deposits' surfaces elementally, and the deposits themselves may be seen with a scanning electron microscope (SEM) with the magnification set to 25 times. Figure 3 also shows the oxygen (O) content of the top layer, which is 16.14% for DF fuel. DF95WCO5 and DF65WCO20Pe15 contained top layers with 37.81% and 3.18% of oxygen, respectively. In each of these places, there is 32.54%, 56.17%, and 27.58% of carbon. Because the droplets in the higher viscosity gasoline take longer to evaporate, it ignites more slowly than the lower viscosity fuel. Consequently, there may be a tendency for the rate of deposit formation to rise [46]. Even yet, DF95WCO5 encounters the same issue. In DF95WCO5, iron (Fe) (0.87%) is the basic metal that is present in higher concentration along with negligible levels of other metals.

Deposit deposition surrounding the injector tip had no effect on the nozzle holes in baseline DF testing. After a few additional elements (O), the main components present in the sediments were carbon (C) and oxygen (O). Hydrocarbons have the ability to decompose into smaller elements like carbon and hydrogen, or they can condense or polymerize into bigger aromatic hydrocarbons (PAHs), which can subsequently form carbonaceous deposits. Because of produced deposition, metal components were visible in the spectrum. A wide range of engine components may come into direct contact with fuel and engine oil. These include the filter, fuel tank, fuel line, fuel injector housing, exhaust system, and cylinder liner. Dynamic components that may also come into contact include the piston, piston rings, inlet and exhaust valve, plunger for the fuel pumps and filters, connecting rod, etc. Engine components may accumulate Al, Cr, Cu, Fe, Zn, Pb, and other elements as a result of tribo-corrosion, wear, and corrosion. These metal fragments are destroyed by gasoline and lubricant. Considering that motor oil lubricates the high-pressure pump. Deposits on a DF95WCO5-powered injector tip are seen in Figure 3. The elemental analysis of the deposited EDS is also displayed. As can be observed in Figure 3b, thick, overlapping deposits are accumulating around the exit and tip of the injector nozzle hole as its diameter decreases. More nozzle apertures appear to be totally blocked by the same deposits.

Lubricating Oil Analysis

IC engines depend on engine lubricant. It is a complicated blend of hydrocarbons made up of additional additives and basic oils. Lubricants serve as a variety of purposes, such as detergents, dispersants, anti-oxidants, viscosity modifiers, and more, to minimize wear and friction on an engine's sliding and rotating components and to maintain their cleanliness [40, 41, 47–49]. During the DF, DF95WCO5, and DF65WCO20Pe15 endurance tests. To evaluate the effect on the engine oil, lubricating oil samples were taken after 20 hours of operation. The results are listed below.

Viscosity

Engine lubricants must have a certain viscosity. In contrast to low viscosity, which signals dilution, high viscosity indicates oxidation or contamination [46]. At 40°C and 100°C, we took measurements of the viscosity. Motor oil's temperature was thought to be equivalent to the viscosity at 100°C [50]. The endurance test revealed that the DF and DF65WCO20Pe15fueled engines had reduced oil viscosity at 40 and 100°C (Figures 3a and b). This likely resulted from gasoline diluting crankcase oil, which decreased the viscosity of the lubricant. The viscosity of the engine lubricating fluid dropped higher in the DF65WCO20Pe15 engine endurance test than it did in the DF exam. Because of the endurance test's reduced engine oil viscosity, engine wear and life may be limited [51]. In accordance with ASTM D 6751, a biofuel exhibits a viscosity of between 1.9 and 4.9 cSt at 40°C, which is the minimum required to be utilized in a diesel engine. The research's specifications were satisfied by every blend and kind of biodiesel [52]. DF95WCO5blend that has not burnt and has found its way into the crankcase over time has been reported to have the effect of decreasing the viscosity of the lubricating oil, increasing the thickness of the lubrication layer, and increasing component wear. In order to increase the fuel droplet diameter and enable more fuel to reach the combustion chamber, a greater fuel viscosity causes the fuel spray cone angle to decrease. Furthermore, poor oil performance, durability issues, and catalyst poisoning are just a few of the issues that can arise from excessive engine oil dilution. Based on the aforementioned data, Figures 4 and 5 show that the lubricating oil viscosity of engines powered by DF95WCO5 decreased more than that of engines powered by DF and DF65WCO20Pe15.

Density

Understanding wear metal contamination and fuel dilution requires measurements of engine oil density from long-term endurance tests. Higher moisture content, dilution of gasoline, and addition of wear particles result in denser

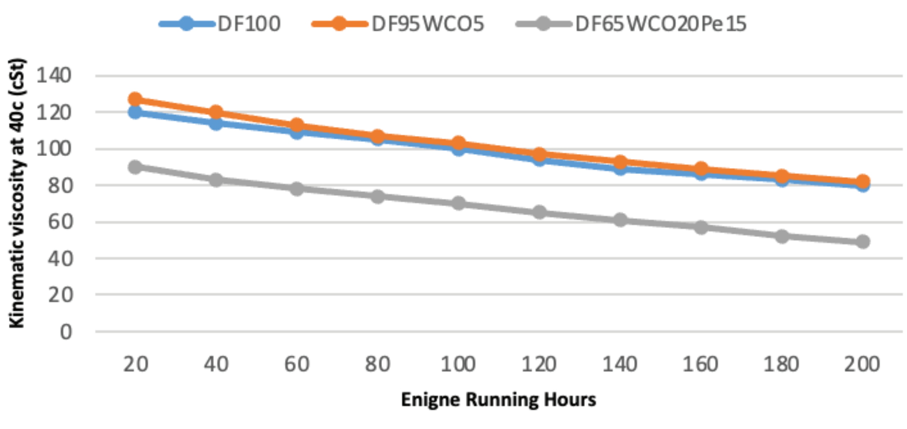

Figure 4. Kinematic viscosities of DF100, DF95WCO5 and DF65WCO20Pe15 at 40°C.

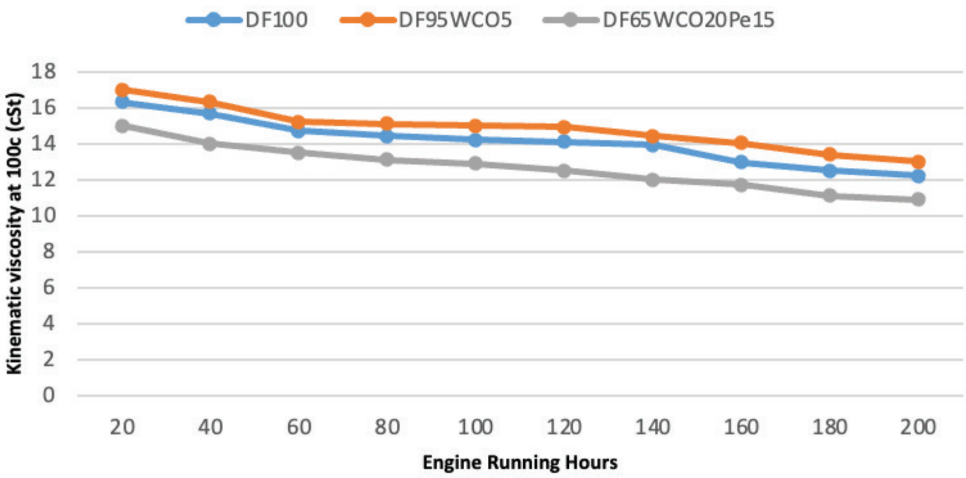

Figure 5. Kinematic viscosities of DF100, DF95WCO5 and DF65WCO20Pe15 at 100^{o}C.

used engine oil [53]. As seen in Figure 6. There is a tendency for the density of engine oil to grow with more use. Engine component wear is accelerating in addition to fuel dilution commencing. Therefore, compared to an engine operating with a DF65WCO20Pe15 and DF mix, the combined action of these components has a greater influence on the rate at which the density of the engine oil increases. Notably, over the first 20 hours of use.

Debris Analysis

It is useful to measure the number of wear particles in old engine oil to monitor its condition and decide when to change it. Preventive engine maintenance has additional benefits [54]. Viscosity and sediment level rise as a result of the two samples' high iron content, which is consistent with findings from the author's study published in [12, 44, 55-57] regarding the physicochemical examination of the identical used motor oil samples. Engine analysis wear and debris were assessed with an Atomic Absorption Spectrophotometer (AAS) fitted with hollow cathode lamps for each element. Iron (Fe), copper (Cu), and nickel (Ni) were dissolved in standard solutions.

Iron (Fe)

As shown in Figure 7, DF fuel and DF95WC05 have a greater iron growth rate. The most important discovery was that the lubricating oil of mix fuel-powered engines (DF65WC020Pe15, DF95WCO5) had less iron than that of diesel engines. Figure 5 shows that engines running on diesel have less iron wear than engines running on mix fuels. When compared to DF, the binary blend DF95WC05 and the ternary mix DF65WC020Pe15 exhibited the greatest iron contents.

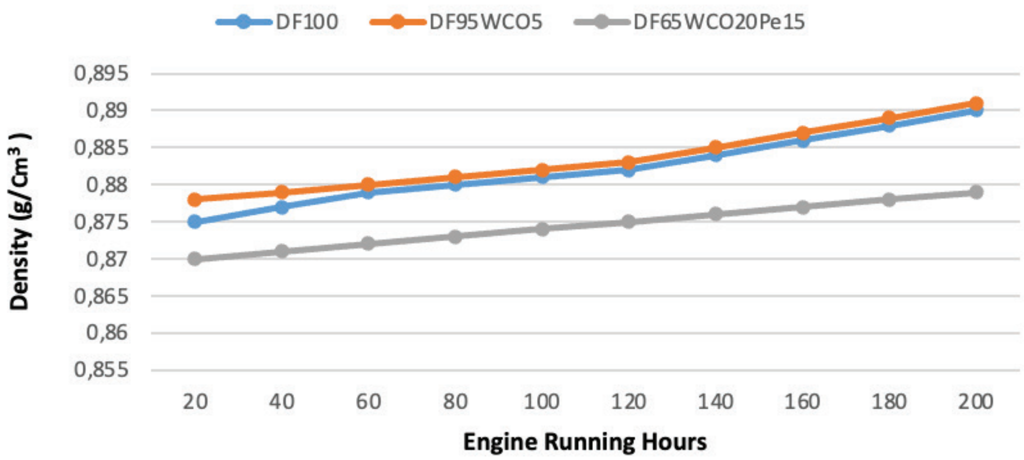

Figure 6. Oil density evaluation on different hours DF100, DF95WCO5 and DF65WCO20Pe15.

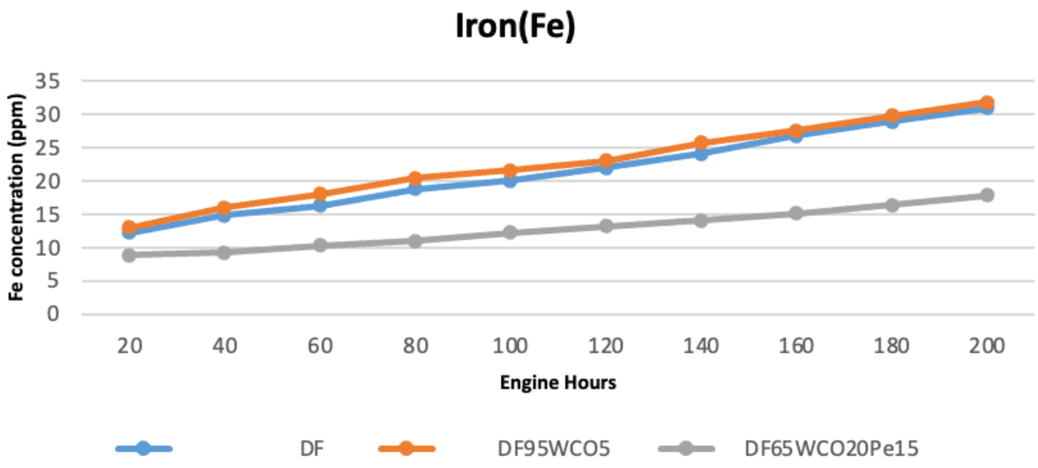

Figure 7. Fe Concentration in lubricating oil of DF100, DF95WCO5 and DF65WCO20Pe15.

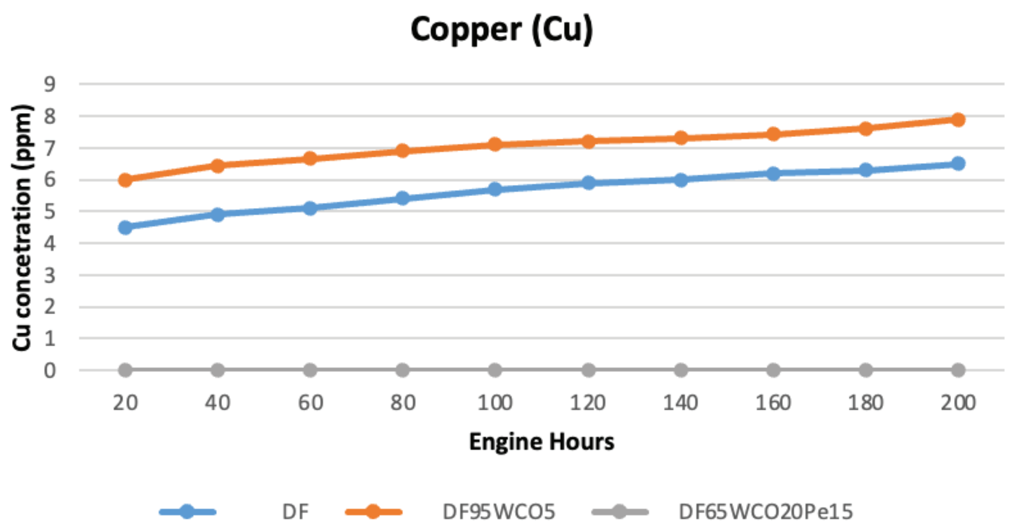

Figure 8. Cu Concentration in lubricating oil of DF100, DF95WCO5 and DF65WCO20Pe15.

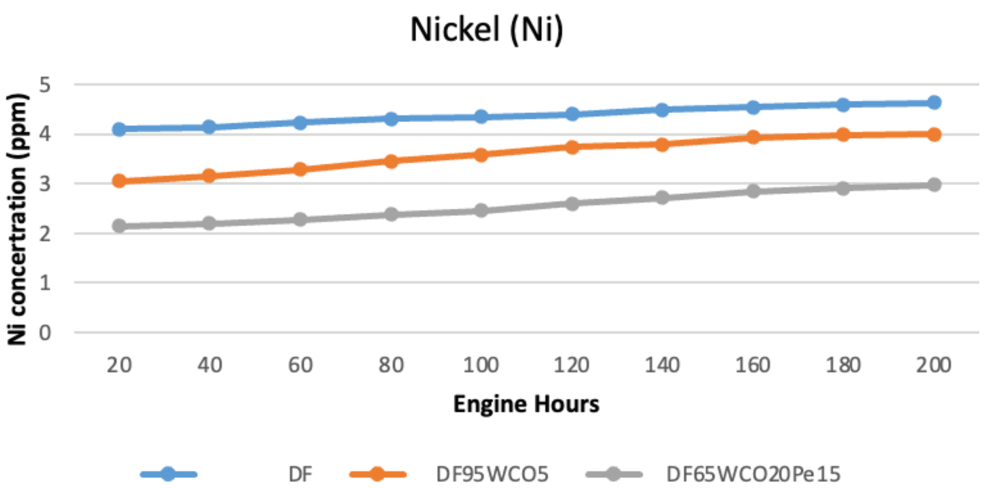

Figure 9. Ni Concentration in lubricating oil of DF100, DF95WCO5 and DF65WCO20Pe15.

Copper (Cu)

Figure 8 displayed the concentration of copper in pure diesel and its binary and ternary blends, such as DF95WC05 and DF65WC020Pe15 powered engines, after 20 hours of lubricating oil consumption. The graphic showed how binary mixes may be used to boost copper content. When n-pentanol is added as a ternary mix, the engine impacts are minimal in comparison to diesel fuel. The diesel engine's copper wear was decreased in ternary mix. The binaries with the greatest copper content were DF95WC05 and DF. The machine determined that ternary mixtures DF65WC020Pe15 were non-detective due to their extremely low concentration.

Nickel (Ni)

The results, which show that nickel metal is the main concentration in the lubricating oil, are shown in Figure 9 as predicted. As seen by the graph, the amount of nickel element is only slightly determined to be at its lowest level when an engine is running on a ternary combination of diesel fuel and DF60WCO20Pe15. Still, it turned out that diesel fuel was not as good as binary mix in this instance (DF95WCO5).

CONCLUSION

This research focused on the effects of waste cooking oil blends and DF as the baseline fuel on injector deposits, engine wear, and lubricating oil during 200 hours on each fuel. However, the percentages of blends varied for the conduct of long-term endurance test for safe operations and waste cooking oil was utilized." Based on an investigative inquiry, the following conclusions were made:

1. Deposits were found in injectors operating on all test fuels, including DF, DF95WCO5, and DF65WCO20Pe15. DF65WCO20Pe15 was demonstrated to be better than both injectors, although DF95WCO5 was determined to be dirtier than DF.
2. SEM and EDS analysis after the 200-hour endurance test showed that injector deposits with DF65WCO20Pe15 were substantially less than those with DF95WCO5. There were isolated carbon deposits discovered. The proportion of carbon layer on injector surfaces for DF, DF95WCO5, and DF65WCO20Pe15 is 32.54%, 56.17%, and 27.58%, respectively. In all test fuels, injector tip deposits did not affect the nozzle holes. Consequently, the engine operated by DF95WCO5 shows thicker, overlapping deposits at the injection hole exit and smaller injector nozzle hole sizes. Carbon concentrations increased across the whole deposited layer.
3. Injector deposits can produce detrimental alterations to the intended spray patterns, including altered spray angles, extended spray penetration distances, asymmetric spray envelopes, and bigger spray droplet diameters. They can also lower the injector fuel flow rate. Injector fouling can result in poor combustion and emissions since optimized spray is crucial to the preparation of the fuel/air mixture. Severe injector deposit issues can make an engine to drive and make misfires more common. It is also suggested that injector fouling leads to an increase in emissions.
4. When using DF and two mix fuels in the engine, the lubricating oil's viscosity is reduced during the course of the engine's operation at 40 and 100°C. The drop in DF95WCO5, however, was greater than that of DF.

NOMENCLATURE

AAS	Atomic Absorption spectrophotometer
C	Carbon
Cu	Copper
CI	Compression ignition
DF	Diesel fuel
DI	Direct injection
DF95-WCO5	Diesel fuel 95% + Waste cooking oil 5%
DF65-WCO20-Pe15	Diesel fuel 65% + Waste cooking oil 20% + n-pentanol 15%
EDS	Energy dispersive X-ray spectroscopy
Fe	Iron
IID	Internal injector deposits
IC	Internal combustion
Ni	Nickel
O	Oxygen
Pb	Lead
PPM	Parts per million
SEM	Scanning electron microscopy
WCO	Waste cooking oil

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AUTHORSHIP CONTRIBUTIONS

Faheem Ahmed Solangi: Conceptualization, Methodology, Validation, Formal analysis, Investigation, writing- original draft, Writing- review & editing, Visualization. **Liaquat Ali Memon:** Conceptualization, Formal analysis, Investigation, writing- original draft, Supervision, Project administration, Visualization. **Saleem Raza Samo:** Investigation, Writing- review & editing. **Muhammad Ramzan Luhur:** Conceptualization, Resources, Supervision, Project administration, Writing- review & editing, Visualization. **Umair Ahmed Rajput:**Writing- review & editing, Visualization. **Ali Murtaza Ansari:**Writing- review & editing.

DATA AVAILABILITY STATEMENT

The authors confirm that the data that supports the findings of this study are available within the article. Raw data that support the finding of this study are available from the corresponding author, upon reasonable request.

CONFLICT OF INTEREST

The authors declared there is no conflict of interest.

ETHICS

There are no ethical issues with the publication of this manuscript.

REFERENCES

[1] Gowda PB, Chandrashekar R, Kumar SM. Comparative analysis of carbon particle emissions from exhaust of an IC engine using HSD and blends of HSD and Honge/Jatropha biodiesel. J Therm Eng 2023;9:1070–1077. [CrossRef]

[2] Manigandan S, et al. Emission and injection characteristics of corn biodiesel blends in a diesel engine. Fuel 2019;235:723–735. [CrossRef]

[3] Yilmaz N, Atmanli A, Vigil FM. Quaternary blends of diesel, biodiesel, higher alcohols and vegetable oil in a compression ignition engine. Fuel 2018;212:462–469. [CrossRef]

[4] Hidayat JA, Sugiarto B. Review on effect biodiesel blend on the growth of deposit in combustion chamber. AIP Conf Proc 2020;2230:050002. [CrossRef]

[5] Chakraborty A, Bardhan S, Das S, Roy S, Chowdhury BR. Bio-diesel production as a promising approach of industrial wastewater bio-refinery. In: Shah MP, ed. Biorefinery for Water and Wastewater Treatment. Cham: Springer; 2023. pp. 109–136. [CrossRef]

[6] Suryantoro MT, Sugiarto B, Mulyadi F. Growth and characterization of deposits in the combustion chamber of a diesel engine fueled with B50 and Indonesian biodiesel fuel (IBF). Biofuel Res J 2016;3:521–527. [CrossRef]

[7] Jain NL, Soni SL, Poonia MP, Sharma D, Srivastava AK, Jain H. A durability study of a compression ignition engine operating with Thumba (Citrullus colocynthis) vegetable oil. Energy 2019;176:8992–9004. [CrossRef]

[8] Capuano D, et al. Direct use of waste vegetable oil in internal combustion engines. Renew Sustain Energy Rev 2017;69:759–770. [CrossRef]

[9] Boopathi D, Thiyagarajan S, Geo VE, Madhankumar S, Gheith R. Effect of geraniol on performance, emission and combustion characteristics of CI engine fueled with gutter oil obtained from different sources. Energy 2018;157:391–401. [CrossRef]

[10] Chand SM, Prakash JO, Rohit K. Impact of biodiesel blends on performance, emissions and waste heat recovery of diesel engine driven cogeneration system. J Therm Eng 2024;10:680–696. [CrossRef]

[11] Jikol F, Akop MZ, Arifin YM, Salim MA, Herawan SG. Deposits formation, emissions, and mechanical performance of diesel engine fuelled with biodiesel: a review. Int J Nanoelectron Mater 2022;15:125–145.

[12] Krishnamoorthy V, Dhanasekaran R, Rana D, Saravanan S, Kumar BR. A comparative assessment of ternary blends of three bio-alcohols with waste cooking oil and diesel for optimum emissions and performance in a CI engine using response surface methodology. Energy Convers Manag 2018;156:337–357. [CrossRef]

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

[14] Sabudak T, Yildiz M. Biodiesel production from waste frying oils and its quality control. Waste Manag 2010;30:799–803. [CrossRef]

[15] Sekharraj K, Balu P, Ravisankar R, Saravanan AM. An experimental assessment of performance and emission analysis on a green microalgae biodiesel DI engine with Bi2O3 nanoparticles. J Therm Eng 2021;10:904–910. [CrossRef]

[16] Doppalapudi AT, Azad AK, Khan MMK. Advanced strategies to reduce harmful nitrogen-oxide emissions from biodiesel fueled engine. Renew Sustain Energy Rev 2023;174:113123. [CrossRef]

[17] Pandian B. An experimental study on performance, emissions, and combustion characteristics of a CI engine running on Citrullus colocynthis biodiesel blends. J Therm Eng 2024;10:954–960. [CrossRef]

[18] Senthil Kumar M, Jaikumar M. A comprehensive study on performance, emission and combustion behavior of a compression ignition engine fueled with WCO (waste cooking oil) emulsion as fuel. J Energy Inst 2014;87:263–271. [CrossRef]

[19] Kalam MA, Masjuki HH, Jayed MH, Liaquat AM. Emission and performance characteristics of an indirect ignition diesel engine fueled with waste cooking oil. Energy 2011;36:397–402. [CrossRef]

[20] Agarwal D, Kumar L, Agarwal AK. Performance evaluation of a vegetable oil fueled compression ignition engine. Renew Energy 2008;33:1147–1156. [CrossRef]

[21] Bari S, Yu CW, Lim TH. Filter clogging and power loss issues while running a diesel engine with waste cooking oil. Proc Inst Mech Eng Part D J Automob Eng 2002;216:993–1001. [CrossRef]

[22] Pugazhvadivu M, Jeyachandran K. Investigations on the performance and exhaust emissions of a diesel engine using preheated waste frying oil as fuel. Renew Energy 2005;30:2189–2202. [CrossRef]

[23] Diaz-Felix W, Riley MR, Zimmt W, Kazz M. Pretreatment of yellow grease for efficient production of fatty acid methyl esters. Biomass Bioenergy 2009;33:558–563. [CrossRef]

[24] Atmanli A, Yüksel B, İleri E. 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 2013;109:503–511. [CrossRef]
[25] Sharon H, Jai Shiva Ram P, Fernando KJ, Murali S, Muthusamy R. Fueling a stationary direct injection diesel engine with diesel-used palm oil–butanol blends – an experimental study. Energy Convers Manag 2013;73:95–105. [CrossRef]
[26] Lujaji F, Kristóf L, Bereczky A, Mbarawa M. Experimental investigation of fuel properties, engine performance, combustion and emissions of blends containing croton oil, butanol, and diesel on a CI engine. Fuel 2011;90:505–510. [CrossRef]
[27] Atmanli A, İleri E, Yüksel B. Experimental investigation of engine performance and exhaust emissions of a diesel engine fueled with diesel–n-butanol–vegetable oil blends. Energy Convers Manag 2014;81:312–321. [CrossRef]
[28] Atmanli A, İleri E, Yüksel B. 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 2015;88:209–220. [CrossRef]
[29] Atmanli A, İleri E, Yüksel B, Yilmaz N. Extensive analyses of diesel–vegetable oil–n-butanol ternary blends in a diesel engine. Appl Energy 2015;145:155–162. [CrossRef]
[30] Atmanli A. 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 2016;172:209–217. [CrossRef]
[31] Atmanli A. Comparative analyses of diesel–waste oil biodiesel and propanol, n-butanol or 1-pentanol blends in a diesel engine. Fuel 2016;176:209–215. [CrossRef]
[32] Lingfa P, Das B. Energy analysis of karanja oil as a supplementary fuel for compression ignition engine. J Urban Environ Eng 2015;9:97–101. [CrossRef]
[33] Maleki B, Kalanakoppal Venkatesh Y, Ashraf Talesh SS, Esmaeili H, Mohan S, Balakrishna GR. A novel biomass derived activated carbon mediated AC@ZnO/NiO bifunctional nanocatalyst. Chem Eng J 2023;467:143399. [CrossRef]
[34] Maleki B, Ashraf Talesh SS. Optimization of ZnO incorporation to αFe2O3 nanoparticles as an efficient catalyst for biodiesel production in a sonoreactor: application on the CI engine. Renew Energy 2022;182:43–59. [CrossRef]
[35] Rajak U, Panchal M, Nashine P, Verma TN, Kumar R, Pugazhendhi A. Sustainability evaluation of green microalgae biofuel production and reducing the engine emissions in a common rail direct engine. Fuel 2023;350:128687. [CrossRef]
[36] Rajpoot AS, Choudhary T, Chelladurai H, Rajak U, Sahu M. Comparison of the effect of CeO2 and CuO2 nanoparticles on performance and emission of a diesel engine fueled with Neochloris oleoabundans algae biodiesel. Mater Today Proc 2023;102:59–64. [CrossRef]
[37] Li J, Yu W, Yang W. Evaluating performance and emissions of a CI engine fueled with n-octanol/diesel and n-butanol/diesel blends under different injection strategies. Fuel 2021;284:119085. [CrossRef]
[38] Sinha S, Agarwal AK. Experimental investigation of the effect of biodiesel utilization on lubricating oil degradation and wear of a transportation CIDI engine. Proc Inst Mech Eng Part D J Automob Eng 2010;224:85–97. [CrossRef]
[39] Proc K, Barnitt R, Hayes RR, McCormick R, Ha L, Fang H. 100,000-mile evaluation of transit buses operated on biodiesel blends (B20). SAE Technical Paper 2006-01-3253. [CrossRef]
[40] Shu G, Dong L, Liang X. A review of experimental studies on deposits in the combustion chambers of internal combustion engines. Int J Eng Res 2012;13:357–369. [CrossRef]
[41] Leedham A, Caprotti R, Graupner O, Klaua T. Impact of fuel additives on diesel injector deposits. SAE Technical Paper 2004-01-2935. [CrossRef]
[42] Hoang AT, Tran QV, Al-Tawaha ARMS, Pham VV, Nguyen XP. Comparative analysis on performance and emission characteristics of an in-Vietnam popular 4-stroke motorcycle engine running on bio-gasoline and mineral gasoline. Renew Energy Focus 2019;28:47–55. [CrossRef]
[43] Konkol I, Cebula J, Świerczek L, Sopa J, Cenian A. Characterization of deposits formed in gas engines fuelled by coal mine methane. Materials 2023;16:2517. [CrossRef]
[44] Li L, Wang J, Wang Z, Xiao J. Combustion and emission characteristics of diesel engine fueled with diesel/biodiesel/pentanol fuel blends. Fuel 2015;156:211–218. [CrossRef]
[45] Imdadul HK, Masjuki HH, Kalam MA, Zulkifli NWM, Alabdulkarem A, Rashed MM, et al. Higher alcohol–biodiesel–diesel blends: an approach for improving the performance, emission, and combustion of a light-duty diesel engine. Energy Convers Manag 2016;111:174–185. [CrossRef]
[46] Yusmady MA. Diesel and bio-diesel fuel deposits on a hot wall surface [dissertation]. Japan: GUNMA University; 2009.
[47] Basinger M, Reding T, Rodriguez-Sanchez FS, Lackner KS, Modi V. Durability testing of modified compression ignition engines fueled with straight plant oil. Energy 2010;35:3204–3220. [CrossRef]
[48] Leung DYC, Wu X, Leung MKH. A review on biodiesel production using catalyzed transesterification. Appl Energy 2010;87:1083–1095. [CrossRef]

[49] Ansari AM, Memon LA, Ghannam MT, Selim MYE. Impact of biodiesel blended fuel with nanoparticles on performance and noise emission in compression ignition engine. Int J Thermofluids 2023;19:100390. [CrossRef]

[50] Zhang W, Yuan W, Zhang X, Coronado M. Predicting the dynamic and kinematic viscosities of biodiesel–diesel blends using mid- and near-infrared spectroscopy. Appl Energy 2012;98:122–127. [CrossRef]

[51] Mohamed Arifin Y, Furuhata T, Saito M, Arai M. Diesel and bio-diesel fuel deposits on a hot surface. JSAE Trans 2008;39:207–213.

[52] Guan L, Feng XL, Xiong G, Xie JA. Application of dielectric spectroscopy for engine lubricating oil degradation monitoring. Sens Actuators A Phys 2011;168:22–29. [CrossRef]

[53] Maleque MA, Masjuki HH, Haseeb ASMA. Effect of mechanical factors on tribological properties of palm oil methyl ester blended lubricant. Wear 2000;239:117–125. [CrossRef]

[54] Reksowardojo IK, Bui HN, Sok R, Kilgour AJ, Brodjonegoro TP, Soerawidjaja TH, et al. The effect of biodiesel fuel rubber (Hevea brasiliensis) seed oil on a direct injection (DI) diesel engine. ASEAN Eng J 2011;1:65–81. [CrossRef]

[55] Wander PR, Altafini CR, Colombo AL, Perera SC. Durability studies of mono-cylinder compression ignition engines operating with diesel, soy and castor oil methyl esters. Energy 2011;36:3917–3923. [CrossRef]

[56] Lugo-Méndez H, Sánchez-Domínguez M, Sales-Cruz M, Olivares-Hernández R, Lugo-Leyte R, Torres-Aldaco A. Synthesis of biodiesel from coconut oil and characterization of its blends. Fuel 2021;295:120595. [CrossRef]

[57] Agarwal AK, Dhar A. Karanja oil utilization in a direct-injection engine by preheating. Part 2: Experimental investigations of engine durability and lubricating oil properties. Proc Inst Mech Eng Part D J Automob Eng 2010;224:85–97. [CrossRef]