Potential of Waste Cooking Oil Biodiesel as Renewable Fuel in Combustion Engines: A Review

Haseeb Yaqoob 1,2, Yew Heng Teoh 1,* , Farooq Sher 3,* , Muhammad Umer Farooq 2,* , Muhammad Ahmad Jamil 4, Zareena Kausar 5, Noor Us Sabah 5, Muhammad Faizan Shah 5, Hafiz Zia Ur Rehman 5 and Atiq Ur Rehman 5

1 School of Mechanical Engineering, Engineering Campus, Universiti Sains Malaysia, Nibong Tebal 14300, Penang, Malaysia; haseeb.yaqoob@student.usm.my
2 Department of Mechanical Engineering, Khwaja Fareed University of Engineering and Information Technology, Rahim Yar Khan 64200, Pakistan; me.noor_us_sabah2596@outlook.com (N.U.S.); faizan.shah@kfueit.edu.pk (M.F.S.)
3 School of Mechanical, Aerospace and Automotive Engineering, Faculty of Engineering, Environmental and Computing, Coventry University, Coventry CV1 5FB, UK
4 Department of Mechanical and Construction Engineering, Northumbria University, Newcastle Upon Tyne NE1 8ST, UK; muhammad2.ahmad@northumbria.ac.uk
5 Department of Mechatronics Engineering, Air University, Islamabad 44000, Pakistan; zareena.kausar@mail.au.edu.pk (Z.K.); hafizzia@mail.au.edu.pk (H.Z.U.R.); atiq.rehman@mail.au.edu.pk (A.U.R.)

* Correspondence: yewhengteoh@usm.my (Y.H.T.); Farooq.Sher@coventry.ac.uk or Farooq.Sher@gmail.com (F.S.); umer.farooq@kfueit.edu.pk (M.U.F.)

Abstract: As non-renewable conventional fossil fuel sources are depleting day by day, researchers are continually finding new ways of producing and utilizing alternative, renewable, and reliable fuels. Due to conventional technologies, the environment has been degraded seriously, which profoundly impacts life on earth. To reduce the emissions caused by running the compression ignition engines, waste cooking oil (WCO) biodiesel is one of the best alternative fuels locally available in all parts of the world. Different study results are reviewed with a clear focus on combustion, performance, and emission characteristics, and the impact on engine durability. Moreover, the environmental and economic impacts are also reviewed in this study. When determining the combustion characteristics of WCO biodiesel, the cylinder peak pressure value increases and the heat release rate and ignition delay period decreases. In performance characteristics, brake-specific fuel consumption increases while brake-specific energy consumption, brake power, and torque decrease. WCO biodiesel cuts down the emissions value by 85% due to decreased hydrocarbon, SO2, CO, and smoke emissions in the exhaust that will effectively save the environment. However, CO2 and NOx generally increase when compared to diesel. The overall economic impact of production on the utilization of this resource is also elaborated. The results show that the use of WCO biodiesel is technically, economically, environmentally, and tribologically appropriate for any diesel engine.

Keywords: renewable energy; alternative fuel; biodiesel; waste cooking oil; diesel engine; emissions

1. Introduction

Petroleum, coal, and natural gas cover the significant contribution of energy in the world [1]. However, these supplies are depleting day by day [2], and if countries continue to depend on them without changing their sources, they will quickly run out of fossil fuel reserves [3]. These typical sources are continuous sources of greenhouse gas (GHG) emissions resulting in climate change through global warming [4]. The developed world is seriously considering reducing GHG emissions, and they have already met their targets [5]. However, they estimate that the pace of emissions reduction will slow down after 2020, making it challenging to meet other targets, such as reducing the domestic emissions...
by 40% until 2030 compared to emission levels in 1990. Therefore, this should be taken seriously in all parts of the world to save the planet’s human lives and ecosystem [6]. In the developing world, diesel fuel has an essential place in the industrial economy of a country directly concerned with energy production and consumption. It is used for industrial transportation and makes agricultural and construction machinery function [7].

Moreover, the crude oil source depletion and its extraction and processing difficulties have rendered it expensive. There is a need to modify the source to something that should be renewable, reliable, economically feasible, and environmentally benign [9,10]. One source is waste cooking oil (WCO), as the cooking oil goes through the complex reactions of polymerization, oxidation, and hydrolysis when used for frying purposes. The nutritional value decreases, and some decomposition products like polymeric triglycerides and polar compounds are formed [11,12]. The standard limit for these total polar compounds is 20–25%, and above this limit the oil becomes inedible [13,14]. Wasting this resource can cause disposal problems such as soil pollution, water pollution, economic loss, and above all, human health concerns [15]. In the developing world, it is common to dispose of the used cooking oil into water bodies at a commercial level or the drainage systems at a domestic level. When toxic substances are taken underwater, they ultimately reach human bodies and cause serious health concerns. It also causes eutrophication that occurs by the presence of an oil layer on the water surface which disturbs the oxygen supply underwater and leads to suffocation of fish. At the same time, it hinders the amount of sunlight penetrating the water surface and leads to the increased growth of microorganisms that rely on oil as their food [16]. In this way, the conversion of WCO into biodiesel gives a three-win solution of pollution control, food security, and energy security [17].

Before putting it into an engine, there should be some compatibility of the physical and chemical properties with petroleum diesel. The main physical property differences that do not allow the direct use of WCO are the viscosity and the incompatible chemical property of the acid number of WCO. One way to use it directly is by preheating WCO above 100 °C along with dilution of solvents and microemulsions to reduce the viscosity and allow for use in the compression ignition engine. Another way is to blend it with petroleum diesel in different proportions [18], but this way can cause some running problems like clogging of fuel filters, coking of the injector nozzle, sticking of the piston rings with cylinder walls, contamination and gelling of lube oil, corrosion due to acidity, and increased engine wear [19,20]. Another way is the pyrolysis of WCO, which produces more bio-gasoline than biodiesel [21]. Soaps are also obtained from vegetable oils that are pyrolyzed to get HC-rich products and can be used as an alternative to diesel fuel [22]. One more way is to chemically treat WCO (residual lipids) and use the resulting biodiesel (esters of fatty acid) in the engine, which is a more sophisticated way to utilize it. First, it must be converted to biodiesel using the lower alcohol transesterification process. Biodiesel has a viscosity near standard diesel. In this way, biodiesel can be a perfect alternative to diesel [23]. The more advanced way is the co-processing of petroleum fractions with WCO as direct refinery integration [24]. WCO biodiesel chemically refers to the long-chain fatty acids of lower alkyl esters [25]. Its chemistry depends upon factors like reaction pressure, temperature, agitation rate, reaction time, catalyst, type of alcohol used, alcohol to oil ratio, moisture content, free fatty acid concentration in the raw oil, etc. [26]. Blasio et al. [27] performed an experiment on the single cylinder and revealed that the diesel/glycerol ethers blend have little impact on combustion properties or efficiencies, but the glycerol ethers’ oxygen content has major advantages in terms of NOx-PM tradeoffs and emission particles in the exhaust.

Ever-rising energy demand and environmental emissions have urged researchers to find new and novel techniques to fulfill energy demand securely and sustainably worldwide. WCO is a candidate for providing the best energy needs solution that will reduce waste management and help solve the economic crisis. It can especially be used to run a diesel engine. In the previous studies, it was difficult to find a review that comprehen-
sively covered the physiochemical properties, combustion, performance, and emission characteristics of WCO, as well as its environmental and economic impacts. This study provides a review of waste cooking oil biodiesel in CI engines from a technical perspective. The study’s layout has a comprehensive overview of the physicochemical properties, combustion characteristics, performance characteristics, and emissions characteristics. The environmental impact of the use of conventional fuels and renewables is also summarized. Finally, the economics associated with the use of biodiesel from preparation to end use are reviewed, along with the impacts caused by biodiesel on the durability of engines.

2. Physicochemical Properties

WCO is not directly used in the compression ignition (CI) engine due to the viscosity and acid number difference. However, other properties also vary from petroleum diesel. The limits defined by ASTM and European standards provide allowable values for its permissible use. Therefore, some essential physicochemical properties are first presented for comparison in Table 1.

| Property                          | ASTM D6751 | EN S90 [28] | EN 14214 [29] | Diesel | Biodiesel | Raw WCO | Reference |
|-----------------------------------|------------|-------------|---------------|--------|-----------|---------|-----------|
| Lower heating value (MJ/kg)       | -          | -           | -             | 43–47  | 36.5–38   | -       | [18]      |
| Higher heating value (MJ/kg)      | 43.00      | -           | -             | 43.286 | 37.114    | 39.99   | [18]      |
| Kinematic viscosity at 40 °C      | 1.9–6.0    | 2–4.5       | 3.5–5.0       | 1.38   | 4.92      | 32.52   | [18,30–32]|
| Density at 15 °C (kg/m³)          | -          | 820–845     | 860–900       | 816–890| 884.29    | 920.14  | [18]      |
| Cetane number                     | Min 47     | Min 51      | Min 51        | 54.50  | 45–65     | -       | [33]      |
| Flash point (°C)                  | Min 130    | Min 55      | Min 101       | 50–98  | 172       | 233     | [18,31]   |
| Pour point (°C)                   | -          | -           | -             | −37.00 | −15 to 10 | −3.00   | [18,34]   |
| Sulfur (ppm)                      | -          | Max 50      | Max. 10       | 15–500 | <10       | 20.3    | [28,35–37]|
| Carbon residue (wt%)              | -          | Max 0.3     | Max. 0.3      | -      | -         | -       | [38]      |
| Water content (mg/kg)             | Max 500    | Max 200     | Max. 500      | 36.842 | 0–500     | 491.54  | [18]      |
| Specific gravity                  | -          | -           | -             | 0.835  | 0.892     | -       | [31]      |
| Cold filter plugging point (°C)   | -          | -           | -             | −20.00 | −5 to 10  | 12.00   | [18]      |

It is noted that the biodiesel (ester) made with saturated or long-chain fatty acid gives relatively high cetane numbers and cloud point values and also clogs the nozzle, while the esters of unsaturated fatty acid give a relatively low cetane number but oxidize quickly. In general, the heat of combustion, cetane number, viscosity, and melting points of fatty acid decrease with unsaturation and increase with chain lengths [39]. Compared to diesel, WCO biodiesel has less Sulphur content, aromatic content, flash point, and biodegradability [40]. The significant findings of the physicochemical properties (e.g., cetane number, density, viscosity, calorific value, and liquid length) of waste cooking oil are discussed in Table 2.

Table 2. Physicochemical properties of waste cooking oil biodiesel blended with diesel fuel in diesel engines.

| Topic                | Findings                                                                 | References   |
|----------------------|--------------------------------------------------------------------------|--------------|
| Cetane number        | • Ignition delay time and combustion quality of the diesel are generally measured by cetane number. | [23,25]      |
|                      | • Better diesel fuel has higher cetane number values. It ensures an improved cold start and reduces white smoke formation. |             |
Table 2. Cont.

| Topic             | Findings                                                                                                                                                                                                 | References |
|-------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------|
| Viscosity         | • Due to the high viscosity of the WCO biodiesel, the diesel blends are more viscous than petroleum diesel. Therefore, up to 20% of a biodiesel blend is recommended for CI engines without modification.                   | [36,41–44] |
|                   | • Kinematic viscosity is the key to determining the fuel injection regime measured by the atomization of the fuel. The viscosity above the limit reduces the amount of atomized fuel before the combustion.               |            |
|                   | • The viscosity of WCO can also be reduced by blending it with n-propanol.                                                                                                                                 |            |
|                   | • The high viscosity of biodiesel decreases the discharge coefficient, mass flow rate, and injection velocity. To compensate for these factors, biodiesel is put at a higher injection temperature of about 60 K than petroleum diesel. |            |
|                   | • Due to high viscosity, biodiesel’s penetration depth in the cylinder increases but reduces the atomization during the injection.                                                                      |            |
| Density           | • CI engines can produce more power with more dense fuel, but the soot emission also increases for high-density fuels.                                                                                 | [41]       |
| Calorific value   | • The calorific value of WCO biodiesel is about 12% lower than diesel due to the oxygen present in its molecule, which also reduces the thermal efficiency of the biodiesel-powered engine as compared to the petroleum diesel-fueled engine. | [45]       |
| Liquid length     | • The liquid length or penetration depth of biodiesel is higher than petroleum diesel due to high viscosity.                                                                                             | [43]       |

There are many ways of process waste cooking oil (WCO), but the most appreciated treatment known for its use is transesterification. This treatment makes WCO more compatible with compression ignition engines by modifying the physicochemical properties. The most notable changes are seen in the viscous properties of the oil when it is transesterified. The kinematic viscosity at 40 °C reduces from 32.52 mm²/s for WCO to 4.915 mm²/s for WCO biodiesel. These modified properties affect the fuel’s spray characteristics, transforming the combustion characteristics when burnt in the engine.

3. Combustion Characteristics

Cylinder pressure is one of the critical factors determining engine performance as it is used to calculate how much work is transferred from burnt gases to the piston. Cylinder pressure is measured using some sophisticated displacement sensors and strain gauges [46,47]. It is measured either in terms of indicated mean effective pressure (IMEP), which is the ratio of work output and the engine swept volume or cylinder peak pressure (CPP). The IMEP leads to the assessment of the engine’s mechanical efficiency [48]. The use of biodiesel in the engine increases the cylinder peak pressure [32,33].

Ignition delay (ID) is defined as the period between the start of fuel injection to the onset of combustion, which is one of the fundamental parameters to quantify combustion. The prolonged ID period corresponds to the intensity of the premixed combustion phase’s heat release rate, as the amount of air-fuel mixture increases with time [49]. ID limits the operating and combustion range of the CI engine. A prolonged ID period can cause very high in-cylinder temperature and pressure at the end of the compression stroke. At this stage, the charge mixture combests suddenly, which can sometimes cause knocking [50]. ID is reduced for WCO biodiesel for its high cetane number as it improves the auto-ignition property and causes complete combustion of the fuel [51]. The shorter ID enhances the en-
The ID period is reduced by increasing the engine load because brake power (BP) increases with the load, increasing the combustion chamber’s heat. In this way, the charge gets ignited sooner and is observed using high proportions of WCO biodiesel in the blend [33]. Pressure increase, HRR, and overall pressure can be measured using the ignition delay values [53].

After the ignition delay period is over, the combustion process starts from the heat release rate (HRR), which changes from negative to positive with a crank angle [51]. The effect of higher HRR in the premixed combustion phase for the WCO biodiesel blends is observed in the form of high cylinder pressure [54]. Some studies also claim to reduce the HRR value for biodiesel and the subsequent blends even though the cylinder pressure rises in their case [32,33,55]. For biodiesel and blends, the increase or decrease in exhaust gas temperature (EGT) value with a reference diesel fuel has been studied by various authors. Yesilyurt et al. [18] revealed that EGT value decreases for B20 (20% biodiesel, 80% diesel fuel) compared to petroleum diesel. Yamin et al. [56] reported a decrease for 100% biodiesel (B100), and Muralidharan et al. [32] reported an increase for B40. The EGT value increases with the increase in engine load for a specific fuel, as more fuel is burnt to compensate for the extra required power. EGT value increases the WCO biodiesel amount within a range of 50% to 100% mix in the diesel as the heating value decreases [57,58]. The reason behind this reduction in EGT at higher CR is the lower calorific value and shorter ignition delay, hence the low temperature after compression stroke (peak cylinder temperature) and the performance increase by lower exhaust losses [56].

The significant findings of the combustion characteristics (i.e., cylinder pressure, ignition delay, and heat release rate) of waste cooking oil in a diesel engine are discussed in Table 3.

| Topic                | Findings                                                                                                                                                                                                 | References |
|----------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------|
| Cylinder pressure    | • At full load conditions, biodiesel blends give higher cylinder pressure values compared to petroleum diesel.                                                                                              | [32,33]    |
|                      | • The indicated MEP for blend B40 is low at high CR and high at low CR compared with the standard diesel. At CR 21, its value is 5.58 bar for B40 and 5.77 bar for diesel.                                           |            |
| Ignition delay       | • The higher proportion of biodiesel in the blends lowers the ignition delays.                                                                                                                            | [33,44]    |
|                      | • The ignition delay for biodiesel is shortened when compared to the ignition delay for petroleum biodiesel.                                                                                              |            |
| Heat release rate    | • It also shows similar trends like ignition delay. A more excellent ratio of biodiesel decreases the value of HRR.                                                                                                                                                  | [33]       |

The use of biodiesel generally delivers a rise in peak cylinder pressure compared to petroleum diesel. Another combustion property, like ignition delay, is reduced, as claimed by various authors. The heat release rate is declined generally for biodiesel and its blends compared with petroleum diesel. The EGT value depends on CR, engine load, blends proportion, heating value, and ignition delay. Therefore, different studies have published either an increase or decrease in the value of the reference fuel. The combustion properties are directly linked to the performance characteristics, such as engine torque, BP, BTE, BSFC, BSEC, and EGT.

### 4. Performance Characteristics

Due to the high viscosity of the WCO biodiesel, the blends also get more viscous than the pure diesel, which affects the fuel’s atomization during injection and disturbs the spray
characteristics. In this way, the evaporation and the burning period during expansion are prolonged, reducing the engine torque. However, this torque value increases the fuel injection pressure, which improves the fuel’s spray characteristics [18,44,59]. Spray characteristics play an important role in engine performance and exhaust emissions. According to Som et al. [43], some of the fuels may require slight design modifications to the engine, like piston bowl design, due to differences in spray and injection characteristics. Sometimes improvement of the injection or ambient conditions like density and temperature can solve the problem. The nozzle shape is also a factor that can improve the spray characteristics, as a non-circular orifice enhances the air entrance [60]. Similarly, Yu et al. [61] recommend a triangular orifice to serve this purpose. Wang et al. [62] and Agarwal et al. [63] suggest that fuel injection pressure is the best way for solving this issue as it improves the equivalence ratio and spray tip penetration and shrinks the spray cone angle and area [64]. All these improvements can enhance the engine torque output for WCO biodiesel blended fuels.

Brake power is reduced by using the biodiesel blend as compared to petroleum diesel. This is due to the small heating value of WCO biodiesel [44]. The brake power is, however, improved by increasing the fuel injection pressure [18]. BSFC is defined as the amount of fuel consumed to produce a unit output of power, which is a measure of the engine’s economic performance. Using B100, the BSFC of a diesel engine is relatively higher than using B0 fuel. The higher density and viscosity and the lower calorific value of the B100 with increasing brake mean effective pressure (BMEP) [51]. The BSFC value decreases with increasing engine load because heat loss is reduced [65]. Abed et al. [66] reveal that WCO biodiesel blends show a higher value of BSFC than pure diesel for the same power output.

Thermal efficiency is the ratio of power output and the energy produced by the injected fuel. This energy comes by taking the product of lower heating value and the mass flow rate of injected fuel [28], also called fuel conversion efficiency [51]. The BTE decreases for the biodiesel blends compared to the pure diesel, which is due to the poor atomization and combustion of the viscous and dense blended fuel [66,67]. Brake-specific energy consumption is another valuable factor for observing different heating value fuels in a CI engine. It is the product of the heating value and BSFC of the fuel [51]. For biodiesel blend B80, brake-specific energy consumption (BSEC) value decreases [55]. The significant findings of the performance characteristics (i.e., brake power, brake specific fuel consumption, brake thermal efficiency, mechanical efficiency, exhaust gas temperature, and engine torque) of waste cooking oil in a diesel engine are discussed in Table 4.

Table 4. Performance characteristics of waste cooking oil biodiesel blended with diesel fuel in diesel engines.

| Topic                        | Findings                                                                 | References |
|------------------------------|--------------------------------------------------------------------------|------------|
| Brake power                  | • At higher compression ratios (CR), the BP value decreases for higher blend proportions as the energy is converted from chemical to mechanical. At CR 21, BP for diesel and B40 is 2.12 kW and 2.07 kW, respectively.  
• Maximum BP is observed for the minor biodiesel proportion of B5 to be 7.9 kW and 5.5 kW for B100 fuel.  
• Engine power is reduced by 6, 8, and 10 kW for B20, B70, and B100 blends. | [18,32,44] |
| Brake-specific fuel consumption | • The specific fuel consumption of the B40 blend is lower than that of all other blends at the compression ratios of 20 and 21. Its value for blend B40 at the compression ratio of 21 is 0.259 kg/kWh, whereas for diesel it is 0.314 kg/kWh, which can be due to viscosity, density, or the heating value of fuels.  
• At maximum BP, brake-specific fuel consumption (BSFC) value for B100 is 0.35 kg/kWh, while 100% petroleum diesel (B0) shows 0.27 kg/kWh.  
• The BSFC value is 0.28, 0.30, and 0.31 kg/kWh for B0, B10, and B20, respectively.  
• At maximum torque and rated power, the BSFC increases up to 8.5%. | [31,32,44,51] |
Table 4. Cont.

| Topic                        | Findings                                                                                                                                                                                                 | References |
|------------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------|
| Break thermal efficiency     | • Brake thermal efficiency (BTE) is directly proportional to the compression ratio, and for diesel blends, its value can be higher than petroleum diesel.  
• BTE value for diesel, B10, and B20 at full load is 31.2%, 31.8%, and 31.6%, respectively.  
• For the compression ratio of 21, the BTE of the B40 blend comes to a maximum of 31.48%, whereas it is 26.08% for the same conditions using pure diesel. | [31,45,68] |
| Mechanical efficiency        | • In general, the ME is directly proportional to the CR for all blends. Its maximum value for B40 blend at CR 21 is 52.53% which is slightly greater than that of petroleum diesel, and for the pure diesel it is about 49.5%. | [32]       |
| Exhaust gas temperature      | • When CR is low, e.g., 18, the blends’ EGT is high compared with the standard diesel. When CR is high, e.g., 21, the EGT for the WCO biodiesel blends is lower than petroleum diesel.  
• For B40, the maximum temperature is 200.61 °C and 233.48 °C for petroleum diesel.  
• Maximum power obtained at 50–55 rpm and EGT for WCO biodiesel came out to be 552 °C, and for petroleum diesel, 585 °C, which is 5.6% lower for biodiesel than petroleum diesel. | [32,56,69,70] |
| Engine torque                | • At 1600 rpm and maximum power, B5 fuel gives about 2 Nm higher torque than petroleum diesel. For B100, B70, and B20, the torque drops about 38.7, 32, and 19.7 Nm compared to petroleum diesel, respectively. | [44]       |

The research abridgement shows that engine torque, BP, and BSEC decreases for using biodiesel and blends, and the BTE value either decreases or increases according to operating conditions such as injection pressure and spray nozzle geometry. BSFC is higher for most cases. However, a few studies claim a decrease.

5. Emission Characteristics

The amount of unburnt HC in the exhaust depends on the maxing of air and fuel within the engine cylinder [51]. The longer ignition delay can also cause high HC emission as the fuel is accumulated in the combustion chamber. The amount of HC emissions decreases for the higher proportions of the WCO biodiesel blends at all engine loads due to the higher oxygen content and higher cetane number [66]. The lower HC emission ensures that the combustion is perfect with the fuel’s good atomization [71,72]. Redfern et al. [73] performed a 60,000 km durability test on a EURO II and a EURO IV diesel engine using B10 and B8 blends. They found that total polycyclic in the EURO II engine aromatic hydrocarbons emissions was less when biodiesel was used. The EURO IV engine did not show a significant change in PAH and PCDD/F (polychlorinated dibenzo-p-dioxins and dibenzofurans) emissions.

The amount of CO in the engine emissions is directly related to the fuel’s physicochemical properties like peak temperature within the engine cylinder, air to fuel ratio, time available for the complete combustion, and the oxygen availability at high engine speed [74]. However, the higher viscosity of the WCO blends generally increases CO emission due to lower atomization in the unmodified engines [75]. At lower loads, the CO emission is even less than the diesel, but it increases at the higher loads. The decrease is due to more oxygen and less carbon in the biodiesel molecule than diesel, which helps fuel burn completely [66].
CO₂ is reported as the least harmful greenhouse gas as its life cycle can easily be regulated by growing energy crops globally. The CO₂ emission depends mainly on compression ratio and exhaust gas temperature. At lower CR, the emission content is high due to proper combustion [32]. The CO₂ amount increases for higher biodiesel proportions in diesel. Its trend rises for the engine running at higher loads due to more fuel burning at higher loads and more oxygen available in the biodiesel molecule [66]. Xue et al. [76] report about CO₂ emission that its increasing trend is for biodiesel and diesel with increasing engine load, and a similar trend has been supported by many others in the research.

Diesel emission contains harmful gases like NOₓ, the acid rain source when accumulated in the environment [50]. It is produced due to very high temperature in the premixed combustion phase, available oxygen amount, and reaction time. The NOₓ amount increases with increasing engine load no matter which fuel is being used. This is because more fuel is burnt and the rise of peak cylinder temperature is the cause of thermal/Zeldovich NOₓ synthesis. The peak cylinder temperature is directly related to the adiabatic flame temperature, which controls the NOₓ emission rate. High adiabatic flame temperature causes higher peak cylinder temperature and higher percentages of NOₓ. The biodiesel increases the cylinder temperature compared to diesel and more oxygen is contained in the biodiesel molecule, therefore the NOₓ emissions increase. In this way, biodiesel blends increase the NOₓ amount [66]. A similar concept is given by Alessandro et al. and Valente [77,78]. Reduction in the emission of oxides of nitrogen is one of the prime focuses of engine researchers. Generally, NOₓ emission increases with an increase in CR.

The smoke amount in the engine exhaust emission is due to the incomplete burning of fuel, and engines with lower smoke emission are signs of good combustion of fuel [79,80]. This occurs due to the poor atomization of the fuel. The smoke emission increases with the increase in output power due to more fuel burning inside the engine, applied to all the fuels. Particularly for diesel fuel, this increase is due to the branched and ring structure; however, the emission level decreases for the biodiesel blends due to oxygen in the biodiesel molecular structure [66,76]. Yang et al. [81] tested for durability (80,000 km) two brand new identical diesel engines fueled by B0 and B20. At 0 km, the B20 engine showed lower HC, PM, and CO emissions than the B0 engine. After 20,000 km and above, the B0 emissions were less than B20.

The significant findings of the emission characteristics (i.e., HC, CO, CO₂, NOₓ, and smoke emission) of waste cooking oil in a diesel engine are discussed in Table 5.

| Topic          | Findings                                                                                                                                                                                                 | References |
|----------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------|
| HC emissions   | - For B40, the HC emission increases with the increase in CR. For blends B20, B60, and B80, the HC emission is less than the standard diesel at high CR.                                                    | [31,32,51] |
|                | - The unburnt HC amount for B100 is found to be 0.062 g/kWh, while for B0, it is 0.081 g/kWh at minimum BP.                                                                                            |            |
|                | - The unburnt HC amount is 66, 64, and 60 ppm for B20, B10, and B0 fuels, respectively, without modifying the engine.                                                                                 |            |
| CO emissions   | - CO emission increases for higher compression ratios and B40 blend show about an equal percentage of emissions similar to diesel, while B20, B60, and B80 give less emissions than diesel.          | [31,32,44] |
|                | - At full load with no modification to the engine, the CO emission is 0.41 vol%, 0.37 vol%, and 0.32 vol% for B20, B10, and B0, respectively.                                                            |            |
|                | - The CO emissions for B5 and B100 blends are 9% less and 32% less than petroleum diesel.                                                                                                               |            |
| CO₂ emissions  | - At CR 21, the blend B40 shows less CO₂ emission.                                                                                                                                                      | [32]       |
Table 5. Cont.

| Topic            | Findings                                                                                                                                                                                                                   | References |
|------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------|
| NO\textsubscript{x} emissions | • At CR 21, the NO\textsubscript{x} emission is higher for B40 than standard diesel. For B40 it is 640 ppm, and for diesel it is 621 ppm.  
  • B100 fuel at maximum engine load produces 19.7% higher NO\textsubscript{x} than diesel.  
  • The maximum load emissions for diesel engines with no modification measure at 728, 702, and 620 ppm for B0, B10, and B20 blended fuels. | [31,32,51] |
| Smoke emission   | • For the unmodified engine, smoke emission for B0, B10, and B20 is 83.3 HSU, 78 HSU, and 70 HSU, respectively, at full load condition.  
  • Smoke emission decreases as the percentage of biodiesel increases in the blended fuel.  
  • Under all BMEP’s, B100 fuel shows less smoke emission than B0 fuel.  
  • Biodiesel smoke opacity is about 60% less than petroleum diesel. | [31,44,66,76] |

The effect of transformed physical and chemical properties is also observed on the fuel’s emission characteristics. In this regard, biodiesel and blends show a reduction in unburnt HC emissions, CO\textsubscript{2}, SO\textsubscript{2}, and smoke. CO\textsubscript{2} shows an increase because the biodiesel molecule has higher oxygen content as compared to the diesel molecule. The value of NO\textsubscript{x} emissions mainly depends on EGT, therefore the contrasting results have been published by different authors. To sum up the emission characteristics, it can be said that WCO biodiesel emissions are reduced and positively impact the environment by CO\textsubscript{2} equivalent emissions reduction. Of course, global warming will be controlled by creating legislation to make the use of biodiesel mandatory worldwide. It will also provide a way through finding an alternative, sustainable energy source.

6. Environmental Impacts

The global CO\textsubscript{2} equivalent emissions were recorded to be 35.65 billion tons in 2017, with a 2.7% increase in 2018 [82]. This amount of emissions is enough to escalate the global warming that affects melting icebergs and glaciers, weather extremes, shifting habitats, and sea-level rise [83]. It also affects marine life by increasing oxygen-consuming rates in fishes, altered emigrational patterns, and foraging in the polar seas [84]. The trees are being affected by extinction in localized species due to climate [85], and infectious diseases, especially mosquito-borne diseases like dengue, malaria, and viral encephalitis, are also influenced by the environment [86]. Figure 1 shows the emissions caused by significant sectors globally, and diesel is common in all industries [87].

GHG emissions are directly related to the world’s energy requirement for both industrial and domestic purposes [88], and it is also the primary source of emissions. Out of all the energy resources that contribute to global energy demand, the crude oil portion is the highest of all, i.e., 31% [89]. The contribution of other primary energy resources globally, including crude oil, is shown in Figure 2 [89].

In the developing world, diesel fuel has an important place in the industrial economy in countries directly concerned with energy production and consumption. The end products of crude oil include fuel gas, LPG, kerosene, gasoline, diesel, fuel oil, and naphtha. The percentages of all these products distilled from a unit mass of crude oil are shown in Figure 3 [90]. It shows that diesel is about 20% of all the end products obtained from a refinery [90]. Therefore, taking 20% of the 31% energy demand which is met by crude oil, diesel’s contribution to the global energy mix comes out to be 6.2%. In this way, diesel produces 3.2 billion tons of life cycle CO\textsubscript{2} emissions out of 35.65 billion tons of global CO\textsubscript{2} eq. emissions.

The CO\textsubscript{2} equivalent of diesel is 87 g/MJ, and that of WCO biodiesel is 13 g/MJ. This shows that WCO biodiesel causes 85% fewer emissions than diesel [91]. Utilizing WCO as biodiesel, the pollution is controlled through wastewater reduction by 79%, hazardous waste reduction by 96%, particulate matter reduction by 47%, and HC emissions by 67%.
Moreover, 3.5 renewable units of energy are extracted for the expenditure of 1 unit of energy from fossil fuel for biodiesel production [92]. This confirms that the use of biodiesel is environmentally friendly, but the production is also evidence of a clean atmosphere with energy security.

Figure 1. CO\textsubscript{2} equivalent emissions by sector [87].

Figure 2. Major contributors to global energy demand [89].
In the developing world, diesel fuel has an important place in the industrial economy in countries directly concerned with energy production and consumption. The end products of crude oil include fuel gas, LPG, kerosene, gasoline, diesel, fuel oil, and naphtha. The percentages of all these products distilled from a unit mass of crude oil are shown in Figure 3 [90]. It shows that diesel is about 20% of all the end products obtained from a refinery [90]. Therefore, taking 20% of the 31% energy demand which is met by crude oil, diesel’s contribution to the global energy mix comes out to be 6.2%. In this way, diesel produces 3.2 billion tons of life cycle CO2 emissions out of 35.65 billion tons of global CO2 eq. emissions.

7. Economic Impact

Biodiesel is produced by any fatty acid source, such as animal fats, vegetable oil, almonds, fish, etc. Out of all the fatty acid sources, the lowest cost fatty acid source is waste cooking oil [39]. The cost of production of WCO biodiesel is distributed into the feedstock, maintenance, chemicals, energy, labor, and depreciation. Each entity’s cost is given in Figure 4, which shows that the feedstock is the most significant cost [93]. The primary feedstock is collected through the wastewater bodies and food industry. The people of the world can be made aware of health issues caused by reusing cooking oil and disposing of it into sinks and garbage by targeted awareness programs. They should be educated to instead sell it to the biodiesel production facilities. In this way, an organized structure can be formulated for the collection of WCO resources.

![Figure 3. Crude oil distillation products [90].](image)

![Figure 4. Parameters effecting the biodiesel production cost [93].](image)
When the collection and purchasing of the WCO are made less and less expensive, the total production cost will be lessened significantly. The amount of this resource in the world is enough to help meet the environmental cleanliness targets quickly. The availability of WCO is tabulated in Figure 5, which shows the amount of feedstock available in different parts of the world. According to the national biodiesel board, waste cooking oil will become the second-largest feedstock for biodiesel production [94].

When this much feedstock is available worldwide, an excellent strategic structure can be built to organize the cycle of WCO collection, purchasing, biodiesel production, and supply to end users while prioritizing economic energy and a clean environment. However, the risk factors of production of WCO biodiesel must be taken into account, and proper risk management tools must be applied [101]. The WCO biodiesel does not require any engine modification [102,103]. Owing to its good lubricating properties, it does not require additional lubricants, such as diesel. It also uses local feedstock and is produced locally, so it does not require drilling, refining, and transport like petroleum diesel [40]. All these factors will save the cost and make its use economic.

On the economic side, this fuel is inexpensive due to low production cost and widespread availability of raw material, which has been wasted for years and is available equally in all parts of the world. Moreover, there is no need for massive investments in extraction and logistics such as in crude oil. It is a privilege for investors and economists to earn and provide an alternative product to the masses. The engine’s operational and maintenance costs are also reduced due to its lubricating properties that lengthen the engine life. A summary of the literature is given in Table 6.

**Table 6.** Summary of the combustion, performance, and emission parameters of a diesel engine using diesel and a waste cooking oil blend.

| Engine Specification | Test Conditions | Composition of Fuel (%) | Reference Fuel/Improver | Combustion Parameters | Performance Parameters | Emission Parameters | Reference |
|----------------------|-----------------|-------------------------|-------------------------|-----------------------|------------------------|---------------------|----------|
| 1 Cylinder           | Speed: variable | Diesel 80 WCOB 20 Others | ID:↓ EGT:↑ BSFC:↑ BP:↓ EToq:↓ CO₂↑ NOₓ↑ Smoke:↓ | Diesel              | HC:↓ CO:↓            | [18]                |          |
| 45, CI, WC           | Load: max.      | Fuel injection pressure: variable |                         |                       |                        |                     |          |
| RS: 3000 rpm         |                 |                         |                         |                       |                        |                     |          |
| Engine Specification | Test Conditions | Composition of Fuel (%) | Reference Fuel/Improver | Combustion Parameters | Performance Parameters | Emission Parameters | Reference |
|----------------------|----------------|-------------------------|-------------------------|-----------------------|------------------------|---------------------|----------|
| 4 Cylinder, 4S, CI, WC, IDI<br>Cylinders: 4S, CI, WC<br>CR: 22.3:1<br>RS: 4000 rpm<br>RP: 53.6 kW<br>MT: 155.9 Nm | constant 85% throttle position<br>Speed: variable<br>Load: variable | Diesel: 95 -<br>WCOB: 5% -<br>Others: Coconut oil | Diesel<br>EGT: ↓<br>BP: ↓ | HC: ↓<br>CO: ↓<br>CO2: ↑<br>N02: ↓<br>Smoke: ↓ | [19] |
| 4 Cylinder, 4S, CI, WC, IDI<br>Cylinders: 4S, CI, WC<br>CR: 22.3:1<br>RS: 4000 rpm<br>RP: 53.6 kW<br>MT: 155.9 Nm | constant 85% throttle position<br>Speed: variable<br>Load: variable | Diesel: 95 -<br>WCOB: 5% -<br>Others: Palm oil | Diesel<br>EGT: ↑<br>BP: ↓ | HC: ↓<br>CO: ↓<br>CO2: ↑<br>N02: ↓<br>Smoke: ↓ | [19] |
| 1 Cylinder, 4S, CI, WC, CR<br>Cylinders: 4S, CI, WC<br>CR: 18:1<br>RS: 1500 rpm<br>RP: 3.7 kW<br>MT: 275 Nm | Speed: constant<br>Load: variable (With partially stabilized zirconia coating) | Diesel: 80 -<br>WCOB: 20 -<br>Others: - | Diesel<br>BTE: ↑<br>CET: ↑<br>ID: ↑<br>BP: ↓ | HC: ↑<br>CO: ↓<br>CO2: ↓<br>N02: ↑<br>Smoke: ↓ | [31] |
| 1 Cylinder, 4S, CI, WC, CR<br>Cylinders: 4S, CI, WC<br>CR: 17:5:1<br>RS: 1600 rpm<br>RP: 5.5 kW<br>IT: 23:1 before TDC<br>Make and model: Kirloskar<br>TAF1<br>Make and model: Kirolaskar<br>TAF1<br>Cylinders: 4S, CI, WC, CR<br>CR: 17:5:1<br>RS: 1500 rpm<br>RP: 5.2 kW<br>MT: 164 kW | Speed: const.<br>Load: variable<br>Torque: variable | Diesel: 60 -<br>WCOB: 40 -<br>Others: 5 (Transes- terified fish oil biodiesel) | Diesel<br>CPP: ↑<br>ID: ↑<br>HRR: ↓<br>EGT: ↓ | ISFC: ↑<br>BP: ↓<br>BTE: ↑<br>MPP: ↓<br>ME: ↑ | HC: ↓<br>CO: ↑<br>CO2: ↑<br>N02: ↑<br>Smoke: ↓ | [32] |
| 6 Cylinder, 4S, CI, CR 17:1<br>Cylinders: 6S, CI, CR<br>CR: 17:5:1<br>RS: 2100 rpm<br>RP: 220 bars<br>MT: 819 Nm<br>RP: 164 kW<br>IT: 22° BTDC<br>Make and model: Canon<br>TAF1 | Speed: const.<br>Load: max.<br>Torque: variable | Diesel: 80 -<br>WCOB: 20 -<br>Others: 20 (Neat rapeseed oil biodiesel) | Diesel<br>CPP: ↑<br>ID: ↑<br>HRR: ↓<br>EGT: ↑<br>Torque: ↓ | ISFC: ↑<br>BP: ↓<br>BTE: ↑<br>MPP: ↓<br>ME: ↑ | HC: ↓<br>CO: ↓<br>CO2: ↓<br>N02: ↑<br>Smoke: ↓ | [44] |
| Make and model: Canon<br>1 Cylinder, 4S, CI, DI<br>Cylinders: 4S, CI, DI<br>CR: 22:1<br>RS: 1500 rpm<br>RP: 5.5 kW<br>MT: 164 kW<br>IT: 22° BTDC | CR: variable<br>A/F: variable | Diesel: 80 -<br>WCOB: 20 -<br>Others: - | Diesel<br>CPP: ↑<br>CPT: ↑<br>BTE: ↓ | CO2: ↑ | [45] |
| Make and model: Kirloskar<br>TAF1<br>1 Cylinder, 4S, CI, AC 661 cc<br>Cylinders: 4S, CI, AC<br>CR: 17:5:1<br>RS: 1500 rpm<br>RP: 4.4 kW<br>IT: 23° BTDC | Injection pressure: const. (200 bar)<br>Speed: const.<br>Load: variable<br>Torque: variable | Diesel: 0 -<br>WCOB: 100 -<br>Others: 30% EGR<br>Diesel (With 30% EGR) | Diesel<br>CPP: ↓<br>ID: ↓<br>HRR: ↓<br>EGT: ↓ | ISFC: ↑<br>BP: ↓<br>BTE: ↓<br>MPP: ↓<br>ME: ↑ | HC: ↓<br>CO: ↓<br>CO2: ↑<br>N02: ↑<br>Smoke: ↓ | [51] |
| Make and model: Tempest<br>4 Cylinder, 4S, CI, WC, DI<br>Cylinders: 4S, CI, WC<br>CR: 21:5:1<br>RS: 3600 rpm<br>RP: 4.8 kW<br>MT: 275 Nm | Speed: variable<br>Load: variable<br>Torque: variable | Diesel: 0 -<br>WCOB: 100 -<br>Others: - | Diesel<br>CPP: ↓<br>ID: ↓<br>HRR: ↓<br>EGT: ↓ | ISFC: ↑<br>BP: ↓<br>BTE: ↓<br>MPP: ↓<br>ME: ↑ | HC: ↓<br>CO: ↓<br>CO2: ↓<br>N02: ↑<br>Smoke: ↓ | [56] |
| Make and model: Rainbow–186 Diesel<br>4S, CI, AC, DI<br>Cylinders: 4S, CI, AC<br>CR: 21:5:1<br>RS: 3600 rpm<br>RP: 7.457 kW | Load: const.<br>Speed: variable | Diesel: 95 -<br>WCOB: 5 -<br>Others: - | Diesel<br>EGT: ↓<br>BP: ↓<br>MPP: ↓<br>ME: ↑ | ISFC: ↑<br>BP: ↓<br>BTE: ↓<br>MPP: ↓<br>ME: ↑ | CO: ↓<br>SO2: ↓<br>NO2: ↑<br>Smoke: ↓ | [59] |
Table 6. Cont.

| Engine Specification | Test Conditions | Composition of Fuel (%) | Reference Fuel/Improver | Combustion Parameters | Performance Parameters | Emission Parameters | Reference |
|----------------------|----------------|-------------------------|-------------------------|-----------------------|-----------------------|---------------------|-----------|
| Make and model: Rainbow–186 Diesel, 406 cc, 1 Cylinder, 4S, CI, AC, DI, CR:18:1, RS: 3600 rpm, RP: 7.457 kW | Load: const. Speed: variable | Diesel 50 WCOB 50 Others - | Diesel EGT: ↓ BSFC: ↑ BP: ↓ Torque: ↓ | CO: ↓ SO₂: ↓ NOₓ: ↓ Smoke: ↓ | [59] |
| Make and model: DEUTZ F1L511 1 Cylinder, 4S, CI, AC, CR: 17.5:1, DI, RS: 1500 rpm, RP: 5.775 kW IT: 24° BTDC | Speed: const. Load: variable | Diesel 70 WCOB 30 Others - | Diesel A/F: ↓ EGT: ↑ BSFC: ↑ BTE: ↓ | HC: ↓ CO: ↓ CO₂: ↑ NOₓ: ↑ Smoke: ↓ | [66] |
| Make and model: Kirloskar TV1 1 Cylinder, 4S, CI, WC, CR: 18:1, RS: 1500 rpm, RP: 5.2 kW IT: 25° BTDC | Load: variable | Diesel 80 WCOB 20 Others - | Diesel - BSFC: ↑ BTE: ↓ ME: ↑ - | - | [102] |
| Make and model: Kirloskar TV1 1 Cylinder, 4S, CI, WC, DI, CR: 17.5:1, RS: 1500 rpm, RP: 5.2 kW | Speed: Load: variable Injection pressure: variable | B20 80 ppm Cerium oxide (CeO₂) nanoparticles of 50 nm size | CPP: ↑ ID: ↑ HRR: ↑ EGT: ↑ MFR: ↑ BSEC: ↑ ISE: ↑ | HC: ↓ NOₓ: ↓ Smoke: ↓ | [55] |

8. Engine Durability

The use of biodiesel and waste tire pyrolysis oil increases the engine life because of its higher lubricating properties [105,106]. WCO biodiesel decreases the wear and tear of the engine which lessens the maintenance requirement [40,107]. Tribological studies show that biodiesel’s friction coefficient obtained from cottonseed oil showed a 28% smaller value than petroleum diesel, and the wear scar diameter of the same biodiesel was 47.6% smaller than petroleum diesel [108]. Bietresato et al. [109] performed an 800 h durability test on a 118 kW tractor fueled by B100 and reported that the engine had none of the problems that affect engine life when the lubricant was replaced every 100 h. According to Fazal et al. [110], engines running on biodiesel blended fuels mostly show fuel pump failure problems, coking in fuel injectors, sticky moving parts, and filter plugging. However, most of the published data shows low carbon deposition and low wear by using biodiesel blends, but a few authors also claim higher carbon deposits. Different methods are used to find the tribological performance of the circular and distorted circular bores of internal combustion engines [111].

9. Conclusions

This study covers a detailed review of the WCO biodiesel use in the CI engine with different blending proportions with petroleum diesel. The physicochemical properties comparison of diesel, biodiesel, and WCO showed whether the values come within the allowable limits by ASTM and European standards or not. This comparison was followed by the combustion, performance, and emission characteristics elucidation of biodiesel blends and reference fuel, i.e., petroleum diesel. The significant findings of the review are as follows:

- WCO is a potential source and widely available in the world for producing biodiesel through transesterification.
- The need for transesterification of WCO is due to its viscosity and acid number for direct use in engines because high viscosity disturbs the spray characteristics of fuel and a high acid number causes corrosion of the engine parts.
- In the combustion characteristics comparison of biodiesel with reference diesel, CPP increased, ID period shortened, HRR decreased, and EGT had erratic behavior.
• Similarly, the performance characteristics showed that BP, BSEC, and engine torque decrease for biodiesel. Meanwhile, BSFC increases and BTE indicates an inconsistent trend.

• Lastly, the emissions comparison revealed that HC, SO$_2$, CO, and smoke decreases, and CO$_2$ increases in the exhaust aggregate. However, NO$_x$ emissions vary inconsistently.

• Biodiesel use is economically viable due to expected availability, low processing cost, and no modification required in the CI engines’ design or structure.

• Engine life is longer for biodiesel-fueled engines because the lubricity of biodiesel is higher than petroleum diesel.

• Biodiesel reduces diesel emission values by 85%, which has a 6.2% share in the global energy mix with an emissions share of 3.2 billion tons of CO$_2$ eq. emissions.

Further work in this field has explored the inclusion of nanoparticles in biodiesel blends due to their positive effects on their physicochemical properties and emission characteristics. Better characterization is also good for enhancing combustion, performance, and emission characteristics. There is also room for improving biodiesel’s oxidative stability and the blend’s stability, especially with nanoparticle additions. Alternative fuel-related policies should be developed to commercialize the WCO-diesel blended fuel.

**Author Contributions:** Conceptualization, H.Y., M.U.F., M.A.J. and N.U.S.; methodology, H.Y. and N.U.S.; validation, H.Y. and N.U.S. formal analysis, H.Y. and N.U.S.; investigation, H.Y. and N.U.S.; resources, Y.H.T., F.S., M.A.J. and M.F.S.; data curation, H.Y. and N.U.S.; writing—original draft preparation, H.Y., N.U.S., Y.H.T. and F.S.; Funding, Validation, Writing—review and editing, F.S. and H.Y.; visualization, Z.K., A.U.R., and H.Z.U.R.; supervision, Y.H.T., F.S. and M.U.F.; project administration, M.U.F.; funding acquisition, F.S., Z.K. and M.U.F. All authors have read and agreed to the published version of the manuscript.

**Funding:** This research was funded by the Ministry of Higher Education (MOHE) of Malaysia (Fundamental Research Grant Scheme (FRGS)-203.PMEKANIK.6071444).

**Institutional Review Board Statement:** Not applicable.

**Informed Consent Statement:** Not applicable.

**Data Availability Statement:** Not applicable.

**Acknowledgments:** The authors would like to acknowledge the Khwaja Fareed University of Engineering and Information Technology, Rahim Yar Khan, and Universiti Sains Malaysia, Malaysia, for their support of this study.

**Conflicts of Interest:** The authors declare no conflict of interest.

**Nomenclature**

- 4S: Four-stroke
- AC: Air-cooled
- BMEP: Brake mean effective pressure
- BP: Brake power
- BSCO: Brake specific carbon monoxide
- BSEC: Brake specific energy consumption
- BSFC: Brake specific fuel consumption
- BTE: Brake thermal efficiency
- C: Carbon
- CI: Compression ignition
- CO: Carbon monoxide
- CO$_2$: Carbon dioxide
- CP: Cylinder pressure
CPP Cylinder peak pressure
CPT Cylinder peak temperature
CR Compression ratio
DF Diesel fuel
DI Direct injection
EGT Exhaust gas temperature
H Hydrogen
HC Hydrocarbon
HRR Heat release rate
IP Indicated power
ITE Indicated thermal efficiency
IC Internal combustion
ICE Internal combustion engine
ID Ignition delay
IDI Indirect ignition
ME Mechanical Efficiency
NA Naturally aspirated
NO<sub>x</sub> Nitrogen oxides
O Oxygen
PM Particulate matters
RP Rated power
RS Rated speed
SFC Specific fuel consumption
SO<sub>2</sub> Sulfur dioxide
TC Turbocharged
TO Torque Output
TPO Tire pyrolysis oil
WC Water-cooled
WCO Waste cooking oil

References
1. Yaqoob, H.; Teoh, Y.H.; Goraya, T.S.; Sher, F.; Jamil, M.A.; Rashid, T.; Yar, K.A. Energy evaluation and environmental impact assessment of transportation fuels in Pakistan. *Case Stud. Chem. Environ. Eng.* 2021, 3, 100081. [CrossRef]
2. Yaqoob, H.; Teoh, Y.H.; Jamil, M.A.; Gulzar, M. Potential of tire pyrolysis oil as an alternate fuel for diesel engines: A review. *J. Energy Inst.* 2021, 96, 1–17. [CrossRef]
3. Demirbas, A. Biodiesel production from vegetable oils via catalytic and non-catalytic supercritical methanol transesterification methods. *Prog. Energy Combust. Sci.* 2005, 31, 466–487. [CrossRef]
4. Norman, J.; MacLean, H.L.; Kennedy, C.A. Comparing High and Low Residential Density: Life-Cycle Analysis of Energy Use and Greenhouse Gas Emissions. *J. Urban Plan. Dev.* 2006, 132, 10–21. [CrossRef]
5. Al-Juboori, O.; Sher, F.; Hazafa, A.; Khan, M.K.; Chen, G.Z. The effect of variable operating parameters for hydrocarbon fuel formation from CO<sub>2</sub> by molten salts electrolysis. *J. CO2 Util.* 2020, 40, 101193. [CrossRef]
6. European Environment Agency, *Trends and Projections in Europe 2018*; European Environment Agency: Copenhagen, Denmark, 2018.
7. World Bank Group. *World Bank Group, Energy*; World Bank: Washington, DC, USA, 2018.
8. Zhang, Y.; Fang, Y.; Jin, B.; Zhang, Y.; Zhou, C.; Sher, F. Effect of Slot Wall Jet on Combustion Process in a 660 MW Opposed Wall Fired Pulverized Coal Boiler. *Int. J. Chem. React. Eng.* 2019, 17, 1–13. [CrossRef]
9. Yang, X.X.; Wang, Y.T.; Yang, Y.T.; Feng, E.Z.; Luo, J.; Zhang, F.; Yang, W.J.; Bao, G.R. Catalytic transesterification to biodiesel at room temperature over several solid bases. *Energy Convers. Manag.* 2018, 164, 112–121. [CrossRef]
10. Banerjee, N.; Ramakrishnan, R.; Jash, T. Biodiesel production from used vegetable oil collected from shops selling fritters in Kolkata. *Energy Procedia* 2014, 54, 161. [CrossRef]
16. El-Fadel, M.; Khoury, R. Strategies for vehicle waste-oil management: A case study. *Resour. Conserv. Recycl.* 2001, 33, 75–91. [CrossRef]

17. Zhang, H.; Wang, Q.; Mortimer, S.R. Waste cooking oil as an energy resource: Review of Chinese policies. *Renew. Sustain. Energy Rev.* 2012, 16, 5225–5231. [CrossRef]

18. Yesilyurt, M.K. The effects of the fuel injection pressure on the performance and emission characteristics of a diesel engine fuelled with waste cooking oil biodiesel-diesel blends. *Renew. Energy* 2019, 132, 649–666. [CrossRef]

19. Kalam, M.A.; Masjuki, H.H.; Jayed, M.H.; Liaquat, A.M. Emission and performance characteristics of an indirect ignition diesel engine fuelled with waste cooking oil. *Energy* 2011, 36, 397–402. [CrossRef]

20. Profito, F.; Vladescu, S.-C.; Reddyhoff, T.; Dini, D. Experimental Validation of a Mixed-Lubrication Regime Model for Textured Piston-Ring-Liner Contacts. *Mater. Perform. Charact.* 2017, 6, 112–129. [CrossRef]

21. Lima, D.G.; Soares, V.C.D.; Ribeiro, E.B.; Carvalho, D.A.; Cardoso, E.C.V.; Rassi, F.C.; Mundim, K.C.; Rubim, J.C.; Suarez, P.A.Z. Diesel-like fuel obtained by pyrolysis of vegetable oils. *J. Anal. Appl. Pyrolysis* 2004, 71, 987–996. [CrossRef]

22. Demirbaš, A. Diesel Fuel from Vegetable Oil via Transesterification and Soap Pyrolysis. *Energy Sources* 2002, 24, 835–841. [CrossRef]

23. Ramos, M.J.; Fernández, C.M.; Casas, A.; Rodriguez, L.; Pérez, Á. Influence of fatty acid composition of raw materials on biodiesel properties. *Bioreour. Technol.* 2009, 100, 261–268. [CrossRef]

24. Chrysikou, L.P.; Dagonikou, V.; Dimitriadis, A.; Bezerianni, S. Waste cooking oils exploitation targeting EU 2020 diesel fuel production: Environmental and economic benefits. *J. Clean. Prod.* 2019, 219, 566–575. [CrossRef]

25. Meher, L.C.; Vidya Sagar, D.; Naik, S.N. Technical aspects of biodiesel production by transesterification–A review. *Renew. Sustain. Energy Rev.* 2006, 10, 248–268. [CrossRef]

26. Banerjee, A.; Chakraborty, R. Parametric sensitivity in transesterification of waste cooking oil for biodiesel production-A review. *Resour. Conserv. Recycl.* 2009, 53, 490–497. [CrossRef]

27. Di Blasio, G.; Bonura, G.; Frusteri, F.; Beatrice, C.; Cannilla, C.; Viscardi, M. Experimental Characterization of Diesel Combustion Using Glycerol Derived Ethers Mixtures. *SAE Int. J. Fuels Lubr.* 2013, 6, 940–950. [CrossRef]

28. European Standards EN 590. *Automotive Fuels-Diesel-Requirements and Test Methods*; European Committee for Standardization: Europe, 2009.

29. European Standards EN 14214. *Automotive Fuels-Fatty Acid Methyl Esters (Fame) for Diesel Engines-Requirements and Test Methods*; European Committee for Standardization: Europe, 2003.

30. ASTM D445-19a. *Standard Test Method for Kinematic Viscosity of Transparent and Opaque Liquids (and Calculation of Dynamic Viscosity)*; ASTM International: West Conshohocken, PA, USA, 2019. Available online: www.astm.org (accessed on 23 April 2021).

31. Karthickeyan, V.; Balamurugan, P.; Senthil, R. Environmental effects of thermal barrier coating with waste cooking oil biodiesel-diesel blends. *Appl. Energy* 2011, 88, 3959–3968. [CrossRef]

32. Qureshi, M.W.G.; Khan, Z.M.; Hussain, M.; Ahmad, F.; Shoaih, M.; Qasim, M. Experimental evaluation of a diesel engine for combustion, performance and exhaust emissions with fuel blends derived from a mixture of fish waste oil and waste cooking oil biodiesel. *Polish J. Environ. Stud.* 2017, 26, 219–229. [CrossRef]

33. Profito, F.; Vladescu, S.-C.; Reddyhoff, T.; Dini, D. Experimental Validation of a Mixed-Lubrication Regime Model for Textured Piston-Ring-Liner Contacts. *Mater. Perform. Charact.* 2017, 6, 112–129. [CrossRef]

34. Demirbaş, A. Diesel Fuel from Vegetable Oil via Transesterification and Soap Pyrolysis. *Energy Sources* 2002, 24, 835–841. [CrossRef]

35. Qureshi, M.W.G.; Khan, Z.M.; Hussain, M.; Ahmad, F.; Shoaih, M.; Qasim, M. Experimental evaluation of a diesel engine for combustion, performance and exhaust emissions with fuel blends derived from a mixture of fish waste oil and waste cooking oil biodiesel. *Polish J. Environ. Stud.* 2017, 26, 219–229. [CrossRef]

36. Karthickeyan, V.; Balamurugan, P.; Senthil, R. Environmental effects of thermal barrier coating with waste cooking palm oil methyl ester blends in a diesel engine. *Biofuels* 2019, 10, 207–220. [CrossRef]

37. Muralidharan, K.; Vasudevan, D. Performance, emission and combustion characteristics of a variable compression ratio engine using methyl esters of waste cooking oil and diesel blends. *Appl. Energy* 2011, 88, 3959–3968. [CrossRef]

38. Muralidharan, K.; Vasudevan, D. Performance, emission and combustion characteristics of a variable compression ratio engine using methyl esters of waste cooking oil and diesel blends. *Appl. Energy* 2011, 88, 3959–3968. [CrossRef]

39. Qureshi, M.W.G.; Khan, Z.M.; Hussain, M.; Ahmad, F.; Shoaih, M.; Qasim, M. Experimental evaluation of a diesel engine for combustion, performance and exhaust emissions with fuel blends derived from a mixture of fish waste oil and waste cooking oil biodiesel. *Polish J. Environ. Stud.* 2019, 28, 2793–2803. [CrossRef]

40. Ray, S.K.; Prakash, O. Biodiesel Extracted from Waste Vegetable Oil as an Alternative Fuel for Diesel Engine: Performance Evaluation of Kirlosker 5 kW Engine. *Renew. Energy Its Innov. Technol.* 2018, 219–229. [CrossRef]

41. SVENSK Standard, SS-EN 590:2009. *Automotive Fuels-Diesel-Requirements and Test Methods*; Swedish Standards Institute: Stockholm, Sweden, 2009.

42. Valente, O.S.; Pasa, V.M.D.; Belchior, C.R.P.; Sodré, J.R. Physical-chemical properties of waste cooking oil biodiesel and castor oil biodiesel blends. *Fuel* 2011, 90, 1700–1702. [CrossRef]

43. Antolin, G.; Tiaut, F.; Briceno, Y. Optimisation of biodiesel production by sunflower oil transesterification. *Bioresour. Technol.* 2002, 83, 111–114. [CrossRef]

44. Bezerianni, S.; Dimitriadis, A.; Chrysikou, L.P. Residual lipids incorporation in a petroleum refinery. *Int. J. Glob. Warm.* 2017, 13, 473–487. [CrossRef]

45. Pinto, A.C.; Guarirobei, L.L.N.; Rezende, M.J.C.; Ribeiro, N.M.; Torres, E.A.; Lopes, W.A.; De Pereira, P.A.P.; De Andrade, J.B. Biodiesel: An overview. *J. Braz. Chem. Soc.* 2005, 16, 1313–1330. [CrossRef]

46. Mofijur, M.; Masjuki, H.H.; Kalam, M.A.; Atabani, A.E.; Shahabuddin, M.; Palash, S.M.; Hazerat, M.A. Effect of biodiesel from various feedstocks on combustion characteristics engine durability and materials compatibility: A review. *Renew. Sustain. Energy Rev.* 2013, 28, 441–455. [CrossRef]

47. Owen, K.; Coley, T. *Automotive Fuels Reference Book*, 2nd ed.; The National Academies of Sciences, Engineering, and Medicine: Washington, DC, USA, 1995; ISBN 1560915897.

48. Dhanasekaran, R.; Ganesan, S.; Rajesh Kumar, B.; Saravanan, S. Utilization of waste cooking oil in a light-duty DI diesel engine for cleaner emissions using bio-derived propanol. *Fuel* 2019, 235, 832–837. [CrossRef]

49. Som, S.; Longman, D.E.; Ramírez, A.I.; Aggarwal, S.K. A comparison of injector flow and spray characteristics of biodiesel with petrodiesel. *Fuel* 2010, 89, 4014–4024. [CrossRef]
44. Buyukkaya, E. Effects of biodiesel on a DI diesel engine performance, emission and combustion characteristics. *Fuel* 2010, 89, 3099–3105. [CrossRef]

45. Ramadhas, A.S.; Jayaraj, S.; Muraleedharan, C. Theoretical modeling and experimental studies on biodiesel-fueled engine. *Renew. Energy* 2006, 31, 1813–1826. [CrossRef]

46. Doggett, W. Measuring Internal Combustion Engine In-Cylinder Pressure with LabVIEW, Creative Technical Solutions, United States. 2020. Available online: https://www.ni.com/zh-cn/innovations/case-studies/19/measuring-internal-combustion-engine-in-cylinder-pressure-with-labview.html (accessed on 23 April 2021).

47. RAIIU, S.O.; Popa, G.N.; Alexa, V. Monitoring of the pressure inside the cylinder for an internal-combustion engine. *WSEAS Trans. CIRCUITS Syst.* 2009, 8, 105–110. [CrossRef]

48. Martyr, A.J.; Plint, M.J. *Engine Testing*, 4th ed.; Butterworth-Heinemann: Oxford, UK, 2012; p. 600.

49. Vihar, R.; Seljak, T.; Rodman Oprešnik, S.; Katrašnik, T. Combustion characteristics of tire pyrolysis oil in turbo charged compression ignition engine. *Fuel* 2015, 150, 226–235. [CrossRef]

50. Solmaz, H.; Yilmaz, E.; Yes, D. Production of waste tyre oil and experimental investigation on combustion, engine performance and exhaust emissions. *J. Energy Inst.* 2018, 1–13. [CrossRef]

51. Nanthagopal, K.; Raj, R.T.K.; Ashok, B.; Elango, T.; Saravanan, S.V. Influence of Exhaust Gas Recirculation on Combustion and Emission Characteristics of Diesel Engine Fuelled with 100% Waste Cooking Oil Methyl Ester. *Waste Biomass Valorization* 2019, 10, 2001–2014. [CrossRef]

52. Chauhan, B.S.; Kumar, N.C.H. A study on the performance and emission of a diesel engine fuelled with Jatropha biodiesel oil and its blends. *Energy* 2012, 37, 675. [CrossRef]

53. Lee, W.J.; Liu, Y.C.; Mwangi, F.K.; Chen, W.H.; Lin, S.L.; Fukushima, Y.; Liao, C.N.; Wang, L.C. Assessment of energy performance and air pollutant emissions in a diesel engine generator fueled with water-containing ethanol-biodiesel-diesel blend of fuels. *Energy* 2011, 36, 5591–5599. [CrossRef]

54. Raheman, H.; Jena, P.C.; Jadav, S.S. Performance of a diesel engine with blends of biodiesel (from a mixture of oils) and high speed diesel. *Int. J. Energy Environ. Eng.* 2013, 4, 1–9. [CrossRef]

55. Kumar, S.; Dinesha, P.; Rosen, M.A. Effect of injection pressure on the combustion, performance and emission characteristics of a biodiesel engine with cerium oxide nanoparticle additive. *Energy* 2019, 185, 1163–1173. [CrossRef]

56. Yamin, J.; Abu Mushref, A.J. Performance and mapping of direct injection diesel engine using waste cooking oil biodiesel fuel. *Adv. Mech. Eng.* 2019, 11, 1–11. [CrossRef]

57. Khiai, K.; Awad, S.; Loubar, K.; Tarabet, L.; Mahmoud, R.; Tazerout, M. Experimental investigation of Pstiscalentiscus biodiesel as a fuel for direct injection diesel engine. *Energy Convers. Manag.* 2016, 108, 392. [CrossRef]

58. Kakati, J.; Gogoi, T.K. Biodiesel production from Kutkura (MeynaspinosaRoxb. Ex.) fruit seed oil: Its characterization and engine performance evaluation with 10% and 20% blends. *Energy Convers. Manag.* 2016, 121, 152. [CrossRef]

59. Bayindir, H. Performance and emission analysis of cottonseed oil methyl ester in a diesel engine. *Renew. Energy* 2010, 35, 588–592. [CrossRef]

60. Battistoni, M.; Grimaldi, C.N. Numerical analysis of injector flow and spray characteristics from diesel injectors using fossil and biodiesel fuels. *Appl. Energy* 2012, 97, 656–666. [CrossRef]

61. Yu, S.; Yin, B.; Deng, W.; Jia, H.; Ye, Z.; Xu, B.; Xu, H. Experimental study on the performance and biodiesel spray characteristics emerging from equilateral triangular orifice under real diesel engine operation conditions. *Fuel* 2018, 224, 357–365. [CrossRef]

62. Wang, X.; Huang, Z.; Kuti, O.A.; Zhang, W.; Nishida, K. Experimental and analytical study on biodiesel and diesel spray characteristics under ultra-high injection pressure. *Int. J. Heat Fluid Flow* 2010, 31, 659–666. [CrossRef]

63. Agarwal, A.K.; Dhar, A.; Gupta, J.G.; Kim, W.I.; Choi, K.; Lee, C.S.; Park, S. Effect of fuel injection pressure and injection timing of Karanja biodiesel blends on fuel spray, engine performance, emissions and combustion characteristics. *Energy Convers. Manag.* 2015, 91, 302–314. [CrossRef]

64. Gahremani, A.R.; Saidi, M.H.; Hajinezhad, A.; Mozafari, A.A. Experimental investigation of spray characteristics of a modified bio-diesel in a direct injection combustion chamber. *Exp. Therm. Fluid Sc.* 2017, 81, 445–453. [CrossRef]

65. Heywood, J.B. *Internal Combustion Engine Fundamentals*; McGraw-Hill Inc.: New York, NY, USA, 1988.

66. Abed, K.A.; El Morsi, A.K.; Sayed, M.M.; Shaib, A.A.E.; Gad, M.S. Effect of waste cooking-oil biodiesel on performance and exhaust emissions of a diesel engine. *Egypt. J. Pet.* 2018, 27, 985–989. [CrossRef]

67. Bhaskar, K.; Nagarajan, G.; Sampath, S. Optimization of FOME (fish oil methyl esters) blend and EGR (exhaust gas recirculation) for simultaneous control of NOx and particulate matter emissions in diesel engines. *Energy* 2013, 62, 224–234. [CrossRef]

68. Devan, P.K.; Mahalakshmi, N.V. Study of the performance, emission and combustion characteristics of a diesel engine using poon oil-based fuels. *Fuel Process. Technol.* 2009, 90, 513–519. [CrossRef]

69. Hebbal, O.D.; Reddy, K.V.; Rajagopal, K. Performance characteristics of a diesel engine with decan hemp oil. *Fuel* 2006, 85, 2187–2194. [CrossRef]

70. Arul Mozhi Selvan, V.; Anand, R.B.; Udayakumar, M. Combustion characteristics of diesohol using bio diesel as an additive in a direct injection ignition engine under various compression ratios. *Energy Fuels* 2009, 23, 5413–5422. [CrossRef]

71. Usta, N. An experimental study on performance and exhaust emissions of a diesel engine fuelled with tobacco seed oil methyl ester. *Energy Convers. Manag.* 2005, 46, 2373–2386. [CrossRef]
99. Tsai, W.T.; Lin, C.C.; Yeh, C.W. An analysis of biodiesel fuel from waste edible oil in Taiwan. *Renew. Sustain. Energy Rev.* 2007, 11, 838–857. [CrossRef]

100. Yacob, M.R.; Kabir, I.; Radam, A. Households Willingness to Accept Collection and Recycling of Waste Cooking Oil for Biodiesel Input in Petaling District, Selangor, Malaysia. *Procedia Environ. Sci.* 2015, 30, 332–337. [CrossRef]

101. Hatzisymeon, M.; Kamenopoulos, S.; Tsoutsos, T. Risk assessment of the life-cycle of the Used Cooking Oil-to-biodiesel supply chain. *J. Clean. Prod.* 2019, 217, 836–843. [CrossRef]

102. Patel, M.J.; Patel, T.M.; Rathod, G.R. Performance Analysis of C.I. Engine Using Diesel and Waste Cooking Oil Blend. *IOSR J. Mech. Civ. Eng.* 2015, 12, 2320–2334. [CrossRef]

103. Gada, M.S.; El-Bazb, F.K.; Kinawyc, O.E. Performance of Diesel Engines Burning Used Cooking Oil (UCO) Biodiesel. *Int. J. Mech. Mechatronics Eng.* 2015, 15, 74–80.

104. Piloto-Rodríguez, R.; Díaz, Y.; Melo-Espinosa, E.A.; Sánchez-Borroto, Y.; Goyos, L.; Canoira, L.; Lapuerta, M. Conversion of fatty acid distillates into biodiesel: Engine performance and environmental effects. *Energy Sources Part A Recovery Util. Environ. Eff.* 2019, 42, 387–398. [CrossRef]

105. Yaqoob, H.; Teoh, Y.H.; Jamil, M.A.; Rasheed, T.; Sher, F. An Experimental Investigation on Tribological Behaviour of Tire-Derived Pyrolysis Oil Blended with Biodiesel Fuel. *Sustainability* 2020, 12, 9975. [CrossRef]

106. Yaqoob, H.; Teoh, Y.H.; Sher, F.; Jamil, M.A.; Nuhanović, M.; Razmkhah, O.; Erten, B. Tribological Behaviour and Lubricating Mechanism of Tire Pyrolysis Oil. *Coatings* 2021, 11, 386. [CrossRef]

107. Demirbaş, A. Biodiesel fuels from vegetable oils via catalytic and non-catalytic supercritical alcohol transesterifications and other methods: A survey. *Energy Convers. Manag.* 2003, 44, 2093–2109. [CrossRef]

108. Jamshaid, M.; Masjuki, H.H.; Kalam, M.A.; Zuulkifi, N.W.M.; Arslan, A.; Alwi, A.; Khuong, L.S.; Alabdulkarem, A.; Syahir, A.Z. Production optimization and tribological characteristics of cottonseed oil methyl ester. *J. Clean. Prod.* 2019, 209, 62–73. [CrossRef]

109. Bietresato, M.; Friso, D. Durability test on an agricultural tractor engine fuelled with pure biodiesel (B100). *Turkish J. Agric. For.* 2014, 38, 214–223. [CrossRef]

110. Fazal, M.A.; Haseeb, A.S.M.A.; Masjuki, H.H. Biodiesel feasibility study: An evaluation of material compatibility; Performance; emission and engine durability. *Renew. Sustain. Energy Rev.* 2011, 15, 1314–1324. [CrossRef]

111. Ma, M.T.; Sherrington, I.; Smith, E.H. Analysis of lubrication and friction for a complete piston-ring pack with an improved oil availability model part 1: Circumferentially uniform film. *Proc. Inst. Mech. Eng. Part J J. Eng. Tribol.* 1997, 211, 1–15. [CrossRef]