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Original citation & hyperlink:
Yaqoob, H., Teoh, Y.H., Sher, F., Farooq, M.U., Jamil, M.A., Kausar, Z., Sabah, N.U., Shah, M.F., Rehman, H.Z.U. and Rehman, A.U., 2021. Potential of Waste Cooking Oil Biodiesel as Renewable Fuel in Combustion Engines: A Review. *Energies*, *14*(9), 2565.
https://dx.doi.org/10.3390/en14092565

DOI 10.3390/en14092565
ISSN 1996-1073

Publisher: MDPI

energies

MDPI

Review

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Citation: Yaqoob, H.; Teoh, Y.H.; Sher, F.; Farooq, M.U.; Jamil, M.A.; Kausar, Z.; Sabah, N.U.; Shah, M.F.; Rehman, H.Z.U.; Rehman, A.U. Potential of Waste Cooking Oil Biodiesel as Renewable Fuel in Combustion Engines: A Review. *Energies* **2021**, *14*, 2565. https://doi.org/10.3390/en14092565

Academic Editor: Diego Luna

Received: 30 March 2021
Accepted: 20 April 2021
Published: 29 April 2021

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, SO_2, CO, and smoke emissions in the exhaust that will effectively save the environment. However, CO_2 and NO_x 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]. The problem is the source from which it is derived, i.e., fossil fuel reserves, which cause environmental pollution and seriously degrade the environment [8].

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 comprehensively 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.

Table 1. Physicochemical properties of different fuels.

Property	ASTM D6751	EN 590 [28]	EN 14214 [29]	Diesel	Biodiesel	Raw WCO	Reference
Lower heating value (MJ/kg)	-	-	-	43–47	36.5–38	-	
Higher heating value (MJ/kg)	43.00	-	-	43.286	37.114	39.99	[18]
Kinematic viscosity at 40 °C (mm^2/s)	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/m^3)	-	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. • Better diesel fuel has higher cetane number values. It ensures an improved cold start and reduces white smoke formation.	[23,25]

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. • 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.	[36,41–44]
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 mm^2/s for WCO to 4.915 mm^2/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 combusts 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 engine's fuel consumption characteristics due to higher oxygen content in WCO biodiesel [52]. 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.

Table 3. Combustion characteristics of waste cooking oil biodiesel blended with diesel fuel in diesel engines.

Topic	Findings	References
Cylinder pressure	• At full load conditions, biodiesel blends give higher cylinder pressure values compared to petroleum diesel. • 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.	[32,33]
Ignition delay	• The higher proportion of biodiesel in the blends lowers the ignition delays. • The ignition delay for biodiesel is shortened when compared to the ignition delay for petroleum biodiesel.	[33,44]
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].

CO_2 is reported as the least harmful greenhouse gas as its life cycle can easily be regulated by growing energy crops globally. The CO_2 emission depends mainly on compression ratio and exhaust gas temperature. At lower CR, the emission content is high due to proper combustion [32]. The CO_2 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 CO_2 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 NO_x, 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 NO_x 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 NO_x synthesis. The peak cylinder temperature is directly related to the adiabatic flame temperature, which controls the NO_x emission rate. High adiabatic flame temperature causes higher peak cylinder temperature and higher percentages of NO_x. The biodiesel increases the cylinder temperature compared to diesel and more oxygen is contained in the biodiesel molecule, therefore the No_x emissions increase. In this way, biodiesel blends increase the NO_x 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, NO_x 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, CO_2, NO_x, and smoke emission) of waste cooking oil in a diesel engine are discussed in Table 5.

Table 5. Emission characteristics of waste cooking oil biodiesel blended with diesel fuel in diesel engines.

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. • 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.	[31,32,51]
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. • 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.	[31,32,44]
CO_2 emissions	• At CR 21, the blend B40 shows less CO_2 emission.	[32]

Table 5. *Cont.*

Topic	Findings	References
NO_x emissions	• At CR 21, the NO_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_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, SO_2, and smoke. CO_2 shows an increase because the biodiesel molecule has higher oxygen content as compared to the diesel molecule. The value of NO_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_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_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_2 emissions out of 35.65 billion tons of global CO_2 eq. emissions.

The CO_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.

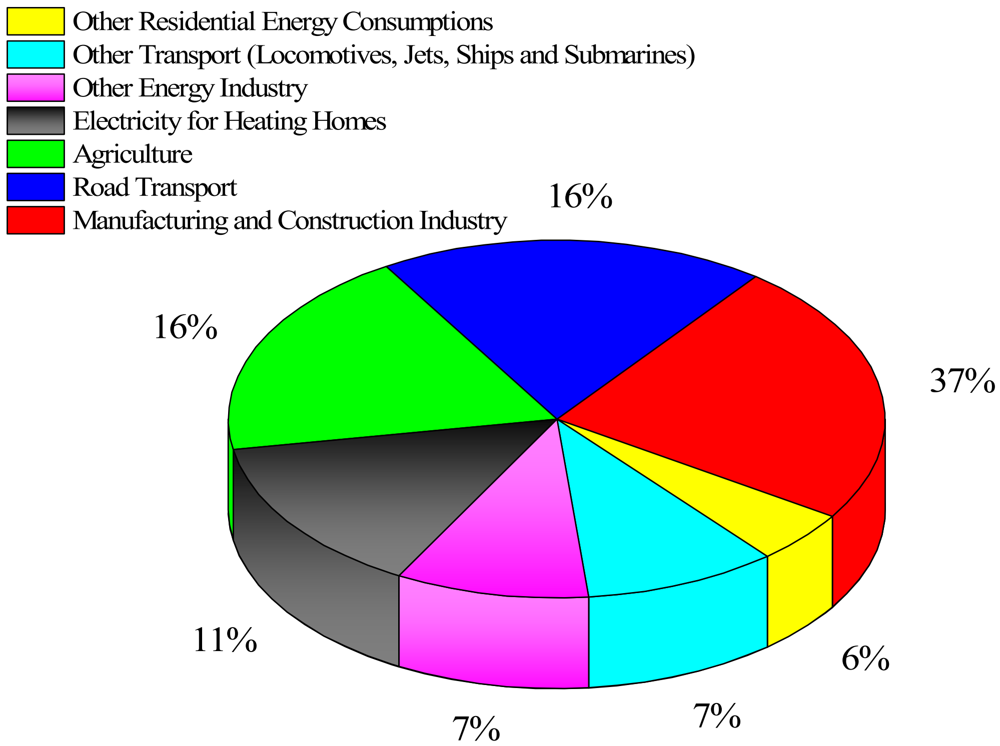

Figure 1. CO_2 equivalent emissions by sector [87].

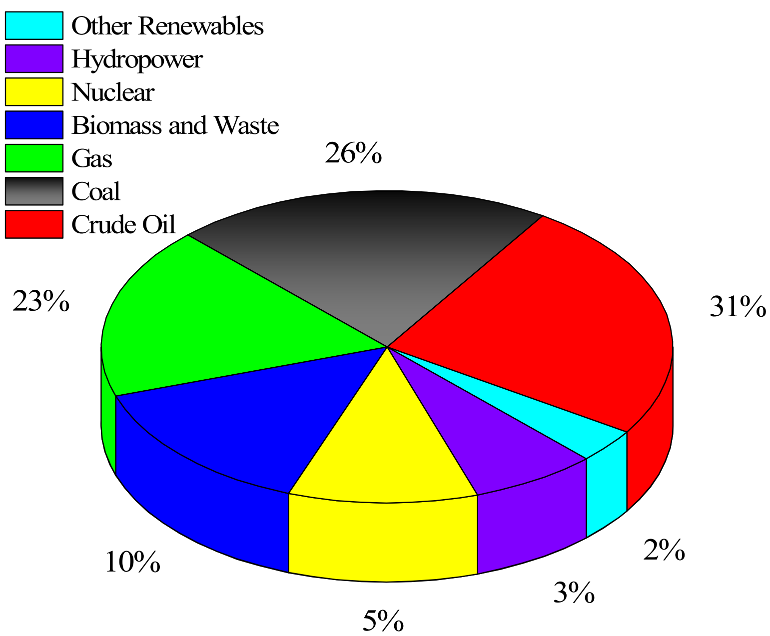

Figure 2. Major contributors to global energy demand [89].

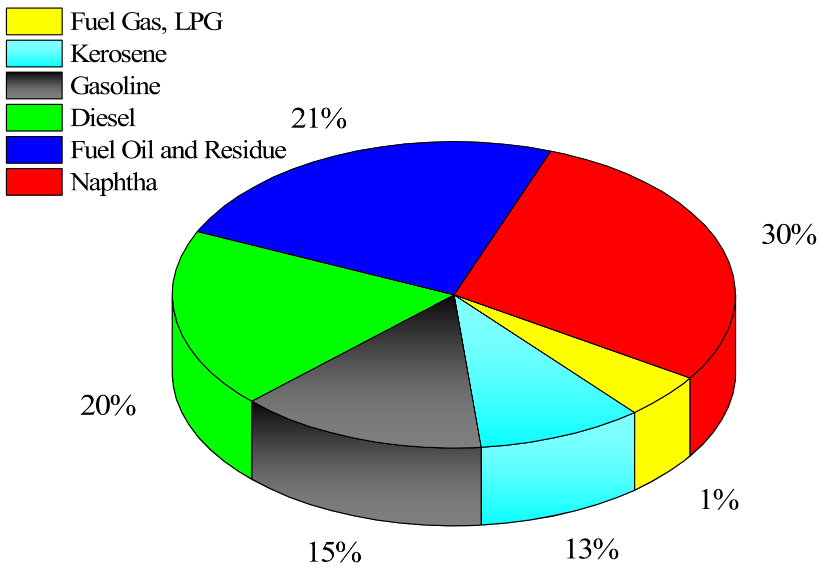

Figure 3. Crude oil distillation products [90].

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.

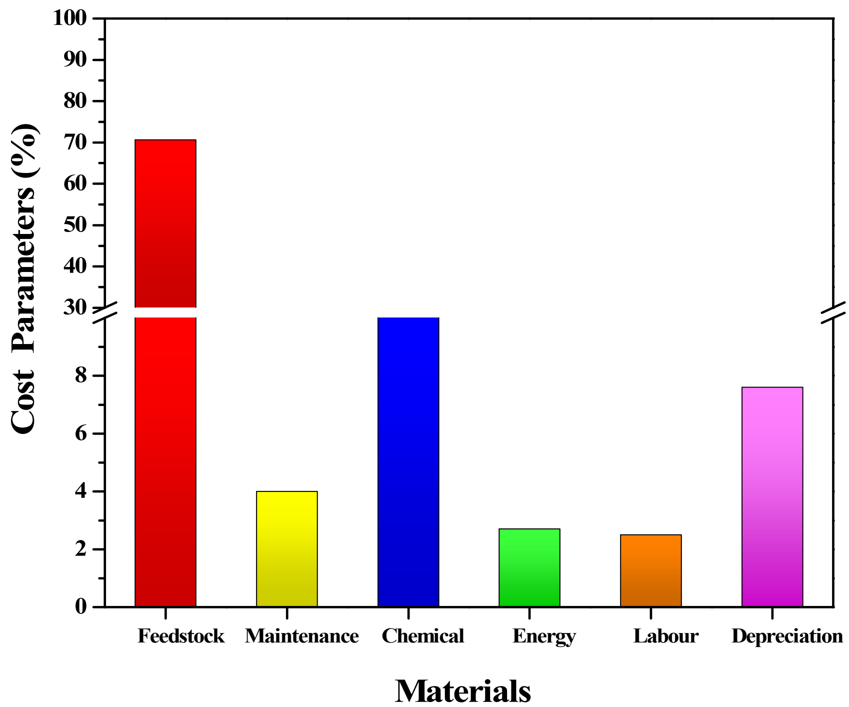

Figure 4. Parameters effecting the biodiesel production cost [93].

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].

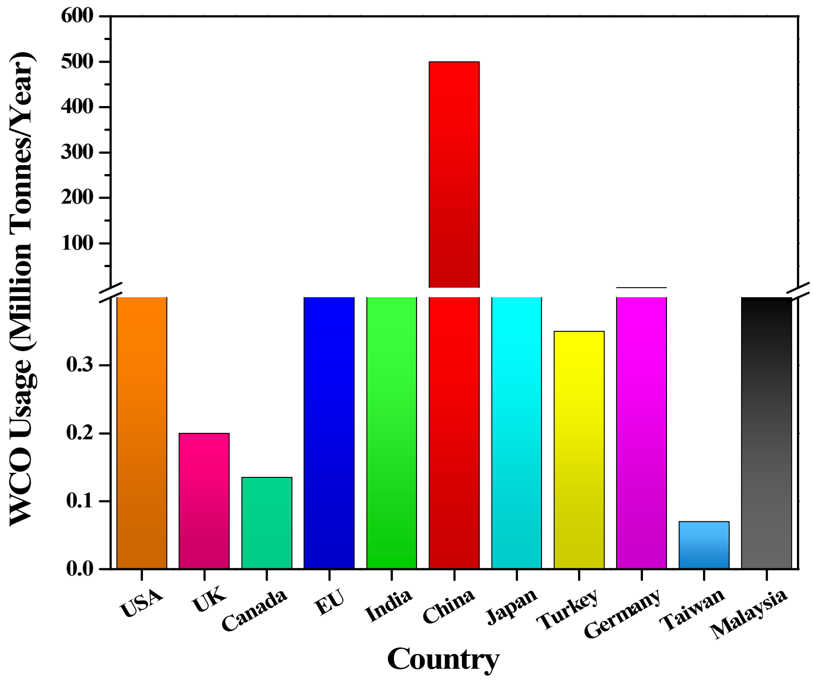

Figure 5. Amount of WCO in different regions of the world [17,39,95–100].

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
		Diesel	WCOB	Others					
1 Cylinder 4S, CI, WC RS: 3000 rpm	Speed: variable Load: max. Fuel injection pressure: variable	80	20	-	Diesel	ID:↓ EGT: ↑	BSFC: ↑ BP: ↓ BTE: - ETorq: ↓	HC: ↓ CO: ↓ CO_2: ↑ NO_x: ↑ Smoke: ↓	[18]

Table 6. *Cont.*

Engine Specification	Test Conditions	Composition of Fuel (%)			Reference Fuel/Improver	Combustion Parameters	Performance Parameters	Emission Parameters	Reference
		Diesel	WCOB	Others					
4 Cylinder, 4S, CI, WC, IDI CR: 22.3:1 RS: 4000 rpm RP 53.6kW MT: 155.9 Nm	constant 85% throttle position Speed: variable Load: variable	95	-	5% Coconut oil	Diesel	EGT: ↓	BP: ↓	HC: ↓ CO: ↓ CO_2: ↑ NO_x: ↓ Smoke: ↓ O_2: ↓	[19]
4 Cylinder, 4S, CI, WC, IDI CR: 22.3:1 RS: 4000 rpm RP 53.6kW MT: 155.9 Nm	constant 85% throttle position Speed: variable Load: variable	95	-	5% Palm oil	Diesel	EGT: ↑	BP: ↓	HC: ↓ CO: ↓ CO_2: ↑ NO_x: ↑ Smoke: ↓ O_2: ↑	[19]
1 Cylinder, 4S, CI, WC, CR 18:1, DI, IP: 210 bar	Speed: constant Load: variable (With partially stabilized zirconia coating)	80	20	-	Diesel	-	BSFC: ↑ BTE: ↑	HC: ↓ CO: ↓ NO_x: ↓ Smoke: ↓	[31]
1 Cylinder, 4S, CI, WC, DI, CR: 5:1–22:1, RS: 1500 rpm, RP: 3.7 kW	Speed: constant Load: 50% CR: variable	60	40	-	Diesel	CPP: ↑ ID: ↑ HRR: ↓ EGT: ↓	BSFC: ↓ BP: ↓ BTE: ↑ MEP: ↓ ME: ↑	HC: ↑ CO: ↑ CO_2: ↓ NO_x: ↑	[32]
1 Cylinder, 4S, CI, WC, DI, CR 17.5:1, RS: 1600 rpm, RP: 5.5 kW IT: 23° before TDC Make and model: Kirolaskar TAF-1	Speed: const. Load: variable	90	5	5 (Transes-terified fish oil biodiesel)	Diesel	CPP: ↑ ID: ↓ HRR: ↓ EGT: ↑	BSFC: ↑ BTE: -↓	HC: ↓ CO: - NO_x: ↑ Smoke: ↓	[33]
Make and model: Kirlosker TV1 Cylinder, 4S, CI, 661 cc, DI, CR: 17.5:1, RS: 1500 rpm, RP: 5.2 kW	Speed: const. Load: variable	80	20	-	Diesel	A/F: ↑	BSFC: ↓ BTE: ↑	-	[34]
6 Cylinder, 4S, CI, CR 17:1, DI, Turbocharged RS: 2100 rpm, IP: 220 bars MT: 819 Nm RP: 164 kW IT: 22° BTDC	Speed: const. Load: max. Torque: variable	80	-	20 (Neat rapeseed oil biodiesel)	Diesel	CPP: ↓ ID: ↓ HRR: ↓ EGT: ↑	BSFC: ↑ BP: ↓ BTE: ↑ Torque: ↓	HC: ↓ CO: ↓ NO_x: ↑ Smoke: ↓	[44]
Make and model: Canon 1 Cylinder, 4S, CI, DI, RS: 1500 rpm, RP: 5.5 kW	CR: variable A/F: variable	80	20	-	Diesel	CPP: ↑ CPT: ↑	BTE: ↓	CO_2: ↑	[45]
Make and model: Kirloskar TAF1 1 Cylinder, 4S, CI, AC, 661 cc, CR: 17.5:1, DI, RS: 1500 rpm, RP: 4.4 kW IT: 23° BTDC	Injection pressure: const. (200 bar) Speed: const.	0	100	30% EGR	Diesel (With 30% EGR)	CPP: ↓ ID: ↓ HRR: -	BSFC: ↑ BTE: ↓ ME: ↑	HC: ↓ CO: ↓ CO_2: ↑ NO_x: ↓ Smoke: ↓	[51]
Make and model: Tempest 4 Cylinder, 4S, CI, WC, DI, 1500 cc CR: 21.5:1, RS: 3600 rpm, RP –kW	Speed: variable Load: variable	0	100	-	Diesel	CPP: - CPT: ↓ ID: ↓ HRR: ↓ EGT: ↓	BSFC: ↑ BP: ↓ BTE: ↓ Torque: ↓	-	[56]
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	95	5	-	Diesel	EGT: ↓	BSFC: ↑ BP: ↓ Torque: ↑	CO: ↓ SO_2: ↓ NO_x: ↑ Smoke: -	[59]

Table 6. *Cont.*

Engine Specification	Test Conditions	Composition of Fuel (%)			Reference Fuel/Improver	Combustion Parameters	Performance Parameters	Emission Parameters	Reference
		Diesel	WCOB	Others					
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	50	50	-	Diesel	EGT: ↓	BSFC: ↑ BP: ↓ Torque: ↓	CO: ↓ SO_2: ↓ NO_x: ↓ 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	70	30	-	Diesel	A/F: ↓ EGT: ↑	BSFC: ↑ BTE: ↓	HC: ↓ CO: ↓ CO_2: ↑ NO_x: ↑ Smoke: ↓	[66]
Make and model: Kirloskar 1 Cylinder, 4S, CI, WC, CR: 18:1, RS: 1500 rpm, RP: 5.2 kW IT: 25° BTDC	Load: variable	80	20	-	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	20	80	80 ppm Cerium oxide (CeO2) nanoparticles of 50 nm size	B20	CPP: ↑ ID: ↓ HRR: ↑ EGT: ↑ MFB: ↑	BTE: ↑ BSEC: ↓	HC: ↓ NO_x: ↓ 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
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_x	Nitrogen oxides
O	Oxygen
PM	Particulate matters
RP	Rated power
RS	Rated speed
SFC	Specific fuel consumption
SO_2	Sulfur dioxide
TC	Turbocharged
TO	Torque Output
TPO	Tire pyrolysis oil
WC	Water-cooled
WCO	Waste cooking oil

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