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Experimental Investigations of Diesel Engine Performance Using Blends of Distilled Waste Cooking Oil Biodiesel with Diesel and Economic Feasibility of the Distilled Biodiesel

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Abstract: This paper elaborates on the production of distilled biodiesel of standard EN14214 from waste cooking oil (WCO). Its economic viability is assessed and experimental investigations of a single-cylinder, four-stroke engine using a mixture of distilled biodiesel and diesel of Euro 5 standard are described. The physical and chemical characteristics of biodiesel produced from waste cooking oil were determined. Fuel samples prepared with different percentages of biodiesel and diesel were used to run the engine. We observed the effects of increasing the percentage of biodiesel in the mixture on brake power, brake specific fuel consumption, brake thermal efficiency, and the exhaust emission from the engine. The emission species included O_2, CO, CO_2, NO_x, and SO_2. Improved engine performance and reduced emissions from the engine were noticed with blended fuels with 10% and 20% distilled WCO biodiesel mixed with 90% and 80% mineral diesel by volume, respectively. The results of this study indicate that the distilled biodiesel blends with mineral diesel can be used as an alternative fuel to run diesel engines without changing the engine design, thereby providing an alternative energy resource with reduced costs for power generation by using engine fuel. An economic assessment and sensitivity analysis were used to determine the feasibility of distilled WCO biodiesel as an alternative fuel to diesel.

Keywords: waste cooking oil; transesterification; vacuum distillation; distilled biodiesel; brake power; brake thermal efficiency; brake specific fuel consumption; economic feasibility

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1. Introduction

Available energy resources play a key role in the economic growth and future sustainability of a country. Crude oil reserves are depleting rapidly due to extensive use of petroleum products as a result of industrial growth. The increasing demand from a growing human population is leading petroleum fuels towards higher prices in terms of power generation and transport. The annual global consumption of petroleum fuels is about 15 billion tons. Countries with large populations, such as China and India, are consuming the highest amounts of aviation fuel [1].

Ecological complications are increasing due to excessive use of petroleum fuels and growing energy demand. The fluctuating prices of petroleum oil have encouraged researchers to find alternate renewable fuels that are economically feasible and suitable for burning in internal combustion engines without any change to engine designs. Researchers are looking to develop alternative fuel sources in order to avoid the various difficulties they are facing when using petroleum fuel. Biodiesel may be considered an alternative fuel to diesel for running an engine if its production is economically feasible [2].

Waste cooking oil was used as a feedstock to produce biodiesel for running a diesel engine through transesterification. The outcomes showed that the use of biodiesel resulted in better engine performance and lower pollutant emissions. The chemistry of cooking oil formed during the frying process and its impact on biodiesel quality were also investigated [3,4]. The rapid growth of populations has increased pollution and contributed to a shortage of clean energy. An engine using waste cooking oil biodiesel emits fewer toxic pollutants than petroleum diesel. Consequently, WCO biodiesel has become a strong competitor as one of the most favorable and viable sources of energy for diesel engines. The blended mixture of biodiesel and diesel can be used with zero mixing or by mixing it with an appropriate amount of mineral diesel. Therefore, waste cooking oil can be used as feedstock for biodiesel production because it is available in abundance and has a low cost [5]. Economical production of biodiesel has been accomplished using the transesterification process. Biodiesel was produced using a mild reaction between triglyceride and alcohol. Various parameters were used in the transesterification process and the ideal condition for biodiesel production was determined. Finally, waste cooking oil biodiesel and petroleum diesel were compared with respect to their physical and chemical properties [6].

Techno-economic features have been determined for biodiesel production using WCO with potassium hydroxide as a homogeneous catalyst and virgin soybean oil with cement kiln dust as a heterogeneous catalyst. Sensitivity analysis disclosed that the cost of biodiesel production is very sensitive to feedstock prices. Low-priced WCO was used as a feedstock to achieve economical production of biodiesel [7]. Waste cooking oil was used to produce a very high yield of biodiesel without any pre-treatment. Since the waste cooking oil came from different origins and had diverse issues of varying complexity, it was judged essential to establish the standard of ester content to confirm the feasibility of WCO biodiesel as an alternative fuel [8]. Colombian waste cooking oils were used for biodiesel production. A cellulose filter was used to remove 79% of the particles and, subsequently, silica gel was used at 15 °C for drying. Finally, methanol was used to esterify and transform the free fatty acid in methyl esters [9]. Biodiesels produced from cooking oils resulted in a higher production cost than petroleum diesel. Since biodiesel contains very low amounts of free fatty acid, low-priced waste cooking oil is used as feedstock for the production of biodiesel. A mathematical model was developed to study the impact of independent conditions for the experiment, and the relation between the molar ratio, catalyst content, reaction time, and temperature on the transformation of free fatty acids using a response surface methodology [10].

A blended mixture of biodiesel and diesel has been used as fuel to run a diesel generator. Analysis results for the exhaust gases indicated that the blended mixture underwent complete combustion [11]. WCO biodiesel produced using the transesterification process was used as an alternative to diesel fuel to run a direct-injection diesel engine in an experimental study. Commercially available iron oxide nanoparticles were used and their impact on the performance and emission characteristics of the engine was studied. The results showed that the brake thermal efficiency was increased marginally, while brake specific fuel consumption was reduced [12]. Another study explored the production of biodiesel from palm sludge oil and investigated its feasibility using the net present value, the internal rate of return, and the simple payback period for a small industrial business. The analysis showed that a business with the capability to produce 50–70 L of biodiesel would make the process quite feasible and profitable [13]. In another study, a broad review of the biodiesel production and their properties were explained. Alternative fuels to diesel in different generations were used in combination with diesel, and the performance and emission characteristics of diesel engines were elaborated for a clean non-toxic and eco-friendly environment. The general awareness and knowledge is that using biodiesels for different generations results in reduced emissions compared to diesel. Engine performance was decreased due to higher density, viscosity, and biodiesel cetane number whereas the heating value is lower than that of diesel. Blending a certain percentage of biodiesel with mineral diesel, and using advanced technology are the future trends in the growth of the diesel engine [14].

Changing biodiesel with diesel fuel is an active approach to decreasing fuel consumption and emissions. Biodiesel made from Lemon Peel Oil and diethyl ether is a sustainable, renewable, and ecologically suitable alternative fuel. Lemon peel oil blends reduce CO, HC, and smoke emissions. The experiments were performed with a variety of combinations for mixtures using the blends and diesel to run the engine. It was perceived that using B5 mixture, which contains 950 mL of diesel, 35 mL of lemon peel oil, and 15 mL of diethyl ether, resulted in an increase in the brake thermal efficiency of the engine in the range of 0.6% to 2% [15]. Linum Usitatissimum seed oil and Brassica Napus seed oil were used for the production of their biodiesels through the transesterification process. A triple blend of these biodiesels and diesel were tested with a single cylinder diesel engine to improve its performance and reduce CO_2 releases. The research focuses on analyzing performance and emissions of a single cylinder diesel engine at variable loads and constant speed. The results specified that the consumption of the triple blend fuel was lower than that of the diesel with the engine running at constant speed and bearing full load. It emits reduced nitrogen dioxide (NO_2) and carbon monoxide (CO) compared to those with diesel [16].

Investigations were made on the use of different blends of lotus biodiesel with diesel while n-butanol was added as an ignition improver. It was observed that the use of blended fuel D70L24B6 results in the lowest brake specific fuel consumption of a single cylinder diesel engine with a maximum heat release rate. Whereas the use of D90L8B2 fuel gives the lowest CO_2 emissions. The lowest CO and NOx emissions were obtained for L100 fuel [17].

A comparative analysis was made for the performance of a single cylinder, four stroke, diesel engine using B30 and B40 blended samples. Samples B30 and B40 were produced by blending biodiesel with high-speed diesel CN 48. The experiments were performed to determine the density and viscosity of the distilled biodiesel. The performance characteristics of a 2400 cc diesel engine were determined using samples of blended mixtures. The results showed that emissions were decreased by 3.2%, while the engine power and torque were also decreased by 1% and 1.4%, respectively [18]. The Mahua biodiesel was formed through the transesterification of Mahua oil. Blends of Mahua biodiesel with diesel were used to run the single cylinder, four stroke, CI engine. The results showed that the use of B5 and B20 blends resulted in a reduction of smoke, CO, and HC species in the exhaust emission while the engine efficiency was enhanced. Therefore B5 or B20 blends were suggested as alternative fuels to diesel for the diesel engines [19]. A review study was made on the use of WCO biodiesel blends in various proportions with mineral diesel. The comparison of physicochemical properties for WCO biodiesel and diesel determined the standard of WCO biodiesel. It was concluded that WCO biodiesel was appropriate for any diesel engine in technical, economic, environmental, and tribological aspects [20]. The effects of biodiesel blends with diesel on the performance and emission characteristics of a single cylinder diesel engine under varying load conditions were investigated. Using a 20% blend of WCO biodiesel showed slight reduction in the brake thermal efficiency and brake specific fuel consumption while the temperature of exhaust gases was increased under maximum load [21]. Biodiesel was produced using the transesterification process of jatropha, palm, algae, and waste cooking oils. Biodiesel is mixed with diesel oil in different proportions. Engine exhaust emissions were measured and compared with diesel oil using single cylinder, four stroke, diesel engine as the test engine. The results showed that CO, HC, and CO_2 emissions were found to be lower for biodiesel mixtures B10 and B20 (jatropha, algae, and palm) compared to diesel fuel, while CO_2 emissions from biodiesel blends B10 and B20 produced from waste cooking oil are higher compared to diesel fuel. NOx emissions from both biodiesel mixtures B10 and B20 were increased compared with the pure diesel fuel [22]. Experimental investigations were conducted on the performance, combustion, and emission characteristics of a single-cylinder four-stroke, direct injection diesel engine. Fish oil biodiesel and waste palm cooking oil biodiesel produced by the transesterification process were mixed in blends with mineral diesel in different proportions by volume, and the mixture was used as fuel to run a diesel engine. Various engine parameters were modified and kept constant during the experimental investigation. The results showed a close resemblance to diesel fuel when the mixture combination of 20% post mixed biodiesel and 80% diesel is used as a fuel. It also showed higher specific fuel consumption and lower thermal efficiency. The exhaust emission pollutants such as carbon monoxide, hydrocarbon, and smoke intensity were decreased whereas the oxides of nitrogen NOx were increased [23]. The research was carried out to evaluate the pooled effect of WCO biodiesel blends with diesel and exhaust gas recirculation in a twin-cylinder diesel engine using numerical and experimental techniques. WCO biodiesel obtained by transesterification process was blended with diesel and used as a fuel to test the performance, emission, combustion, and noise characteristics of a twin-cylinder diesel engine. The results showed that B20 fuel, made from 20% WCO biodiesel blended with 80% diesel was a dominant solution for improving the performance, emission (excluding NOx), combustion, and noise parameters of the test engine. The NOx emission was then controlled through exhaust gas recirculation (EGR) used with the best blended fuel at varying rates of 5%, 10%, and 15%. A combination of B20 fuel with a 10% EGR rate was selected as the most suitable fuel for significant reduction in NOx emissions showing a negligible effect on HC, CO, Smoke, and CO_2 exhaust emissions from the engine [24]. The shortcomings of biodiesel such as high viscosity and low calorific value can be controlled by the addition of CeO_2 nanoparticles-based additives to biodiesel mixtures, which increases the oxygen content and shows great potential for improvement in engine performance and emissions behavior. Toxic emissions such as NOx, CO, and HC were reduced and an increase in BTE and brake power was noticed, whereas BSFC was decreased [25]. The research work was carried out to produce biodiesel from rubber seed oil and was mixed in blends with diesel to analyze the combustion and performance characteristics of a single cylinder diesel engine along with the investigation of the exhaust emission. The addition of alumina and TiO_2 nanoparticles increases NOx emissions due to improved thermal conductivity. Both nanoparticles not only improve engine performance, but also reduce engine BSFC. Additionally, it improves the combustion process and reduces CO, HC, and smoke emissions [26].

In the present research work, distilled WCO biodiesel is produced in the purest form and used in blends with diesel to run a diesel engine. The distilled WCO biodiesel was obtained through vacuum distillation of WCO biodiesel produced by transesterification of WCO. The distilled WCO biodiesel was used in blends with diesel of Euro 5 standard to run diesel engine to investigate fuel performance, economy, and emission. The research work has been carried out by other researchers producing WCO biodiesel by the transesterification of WCO from various feedstock and testing its blends with mineral diesel for running diesel engine, thus proposing WCO biodiesel as an alternative fuel to diesel.

Current investigations focus on the production and use of distilled biodiesel for the improved performance and reduced exhaust emission of diesel engines. The physicochemical properties including the percentage amount of free fatty acid (FFA) of the mixture of WCO collected from different sources were determined. The physical and chemical properties of distilled biodiesel were also determined and compared with the EU standard to verify the quality of distilled biodiesel. The blends of distilled biodiesel and mineral diesel were used as fuels to run a diesel engine and its performance parameters including brake power, brake specific fuel consumption, and brake thermal efficiency were investigated. The percentage of distilled biodiesel was increased in the mixture and the data related to engine performance characteristics were recorded. Subsequently, the data were used to validate the usefulness of distilled biodiesel as a commercial alternative fuel for the diesel engine.

2. Production of Distilled Biodiesel

Biodiesel feedstock can be categorized as edible oils, non-edible oils, and reusable wastes oil such as waste cooking oil, WCO. Distilled biodiesel produced from WCO is free from impurities such as sulfur, metals, and oil residues. The use of distilled biodiesel fuel reduces SO_2 and CO emission which results in an increased engine life [20]. The viscosity and low volatility of WCO affect the spray pattern of the fuel. This may lead to choking of the fuel injector and sticking of the piston rings due to the carbon deposits in an incomplete combustion. Transesterification and Vacuum distillation processes were performed to overcome these problems by reducing the viscosity and improving fuel characteristics of WCO. The transformation of WCO to distilled biodiesel requires pre-treatment, transesterification, and vacuum distillation processes.

The waste cooking oil was collected from restaurants in local markets. The oil contained some solid and liquid impurities. The solid impurities were removed by settling the oil for 2 days at room temperature and filtrating with Cellulose filter, whereas liquid impurities such as water and moisture were removed by heating the filtered oil at 120 °C. Tests were performed in the laboratories of ZRS Group of Industries (Sheikhupura, Punjab, Pakistan) to determine the physicochemical properties of the WCO as shown in Table 1. Free fatty acid (FFA) contents of the WCO were found to be 3.1%. Therefore, the production of distilled biodiesel was accomplished through transesterification and distillation. If FFA was found greater than 5%, acid-catalyzed pre-esterification would also be required prior to the transesterification process.

Table 1. Physicochemical properties of waste cooking oil.

Parameters	**Results**
Color	Orange
FFA (as Oleic Acid)	3.1%
Melting Point	27.7 °C
Density @ 25 °C	915 kg/m^3
POV	20.35 m.eq/kg
Water Content	2.2%
Impurities	1.2%
Sulfur Content	67 ppm
Iodine Value (g I2/100 g)	81
Total Acid Number (mg KOH/g)	6.2.
Saponification Value (mg KOH/g)	194

The samples of waste cooking oil and distilled biodiesel are shown in Figure 1.

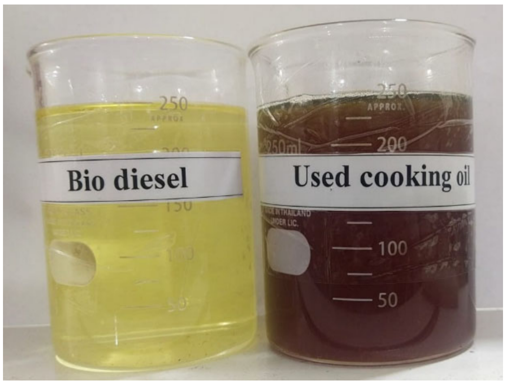

Figure 1. Waste cooking oil and distilled biodiesel.

For the transesterification process, the methanol-to-oil molar ratio of 6:1 was used with potassium hydroxide (KOH) as catalyst. At the first stage, 6 L of methanol was mixed with 20 g of KOH at an elevated temperature. Subsequently, the pre-treated WCO was added with continuous stirring for 2 h at 60 °C. The chemical reaction of the transesterification process is shown in Figure 2.

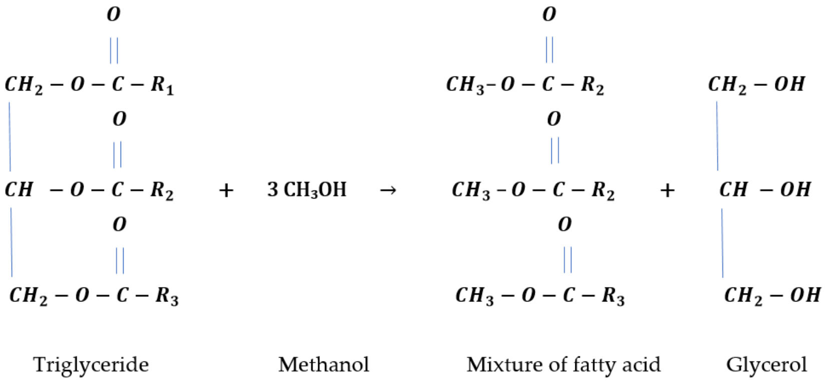

Figure 2. Transesterification of waste cooking oil.

The equation shows that a mixture of glycerol and fatty esters is produced as a result of chemical reaction between triglyceride and alcohol. The KOH is used as catalyst and stimulates the reaction. The time, temperature of reaction, catalyst, and molar ratio of the reactants affect the yield of biodiesel. The selection of catalyst is based on the nature of reactions. The reaction could be acid catalyzed and base catalyzed. The acid catalyzed is slower and require high temperature, whereas base catalyzed is less corrosive and requires lower temperature effect but it is faster and cheaper. Temperature affects the reaction rate and usually the reaction is carried out at the boiling point of methanol. The increase in temperature shows adverse effect in conversion. The transesterification process with continuous stirring requires three hours for biodiesel production whereas it requires eight hours to settle the glycerol at the bottom after the completion process as shown in Figure 3. WCO- biodiesel was separated by removing the settled glycerol at the bottom of the funnel. The transesterification process produced an 87% yield of WCO-biodiesel. The produced WCO-biodiesel contained a 97% yield of pure biodiesel and the remaining 3% were impurities (mono, di, triglyceride, gums, sulphur, nitrogen, and metallic minerals) in the biodiesel.

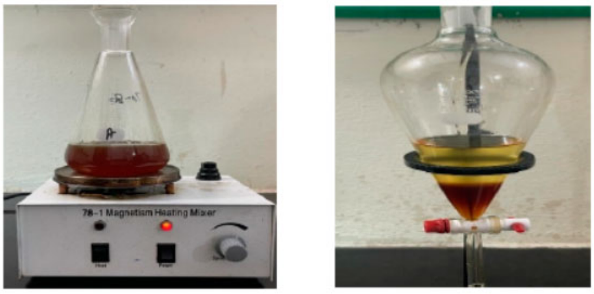

Figure 3. Transesterification of waste cooking oil.

Clean and purified distilled biodiesel, which is free from particles and impurities, was produced through vacuum distillation of WCO biodiesel acquired through the transesterification process. The vacuum distillation process reduces pressure which enables biodiesel to boil at a temperature lower than the normal boiling point temperature. This process is used when the boiling point of the liquid is greater than 150 °C. The boiling point of biodiesel is 340 to 370 °C which is challenging to achieve in given conditions. Therefore, to make pure biodiesel, vacuum distillation is used as shown in Figure 4.

Figure 4. Vacuum distillation process.

One litre of transesterified biodiesel was taken in a three-neck flask and placed on a heating mantle. Then a condenser with a flask and an adapter was connected and a vacuum was then created in the system with the help of a vacuum pump while the temperature was increased gradually. After 20 min, the biodiesel started boiling under a vacuum pressure of 1 mmHg. When the temperature reached 270 °C, the vapors moved towards the condenser. The condenser converted these vapors into a liquid state and pure biodiesel was collected in another flask. This step took almost 2 h to complete, and a 97% yield was obtained from vacuum distillation and the remaining 3% of impurities were left in the three-neck flask. The tests were performed to determine the physicochemical properties of distilled biodiesel and the values were compared with EU Biodiesel specifications showing that the distilled WCO biodiesel meets European standard EN14214. Physicochemical properties of distilled WCO biodiesel and their comparison with EU Biodiesel specifications are given in Table 2.

Table 2. Physical and chemical properties of distilled WCO biodiesel.

Property	Test Results	EU Biodiesel Specifications: EN14214	
Color	Transparent Yellow		
Ester Content % Wt	98.5%	96.5% (min)	EN 14103
Total Acid Number mg KOH/g	0.6	0.50 (max)	EN 14104
Ash Content %	0.002%	0.02% mass (max)	ISO3987
Cetane	60	51 (min)	ISO5165
CFPP °C	4	Location and season dependent	EN 116
Density @ 15 °C kg/m^3	871	860–900	ISO12185
Kinematic Viscosity @ 40 °C c St	3.9	3.5–5.0	ISO3104
Water Content mg/kg	410	500 (max)	EN ISO 12937
Oxidation Stability H: 110 °C	1.2	8 (min)	EN 14112
Sulfur Content mg/kg	18	10.0 (max)	ISO 20846
Iodine Value g I2/100 g	74	120 (max)	EN 14111
Flash Point by Open Cup °C	176	101 (min)	EN ISO 2719
Methanol Content % Wt	0.01%	0.20% (max)	EN 14110
Saponification value mg KOH/g	196	-	-
Monoglyceride % Wt	0.01%	0.70% (max)	EN 14105
Diglyceride % Wt	0%	0.20% (max)	EN 14105
Triglyceride % Wt	0%	0.20% (max)	EN 14105
Free glycerol %Wt	0.02%	0.02% (max)	EN 14105
Total glycerol % Wt	0.05%	0.25% (max)	EN 14105

3. Measurement of Distilled Biodiesel Properties

The fuel characteristics of distilled WCO-biodiesel and WCO-biodiesel were measured, and compared with those of mineral diesel. These fuel properties include calorific value, density, flash point, and kinematic viscosity. The calorific value (CV) of the distilled WCO-biodiesel sample defines its energy and its reliability as an alternative to diesel. Bomb calorimeter was used to measure the CV of the samples from WCO, WCO diesel, and distilled WCO-biodiesel. The bomb calorimeter was used for the measurement of calorific values of the samples as shown in Figure 5.

Figure 5. Bomb calorimeter for calorific values.

The results showed that CV for the distilled WCO-biodiesel was very close to CV for the diesel. The results of calorific values for diesel, WCO, WCO biodiesel, and distilled WCO-biodiesel are given in Table 3.

Table 3. Properties of biodiesel.

No	Type of Fuel	Calorific Value (Mj/kg)	Density (kg/m^3)	Flash Point Temp.°C	Kinematic Viscosity (40 °C) (cSt)
1	Diesel oil	43	850	69	3.2
2	Waste cooking oil	35	914	220	4.8
3	Transesterified WCO	40	875	169	4.14
4	Distilled WCO-biodiesel	42	871	176	3.9

Density is a prominent standard of biodiesel and provides evidence concerning fuel properties and its composition at the given temperature. The comparison of measured values of density for the distilled WCO-biodiesel and transesterified WCO indicates that the density for distilled WCO-biodiesel was comparable to the density of diesel. Hence, the distilled WCO-biodiesel and mineral diesel can be mixed to produce a uniform mixture which is quite suitable for injection into a diesel engine cylinder. The values for the density of diesel, WCO-biodiesel, and distilled WCO-biodiesel are given in Table 3.

The ignition of distilled WCO-biodiesel takes place at ignition temperature which is greater than its flash point temperature. Flash point temperature is a critical property which ensures the safe handling of diesel and biodiesel fuel in the performance of a diesel engine and is inversely related to the volatility of fuel. The standard testing method was used to determine the flash point of biodiesel. The flash point of diesel, WCO, WCO-biodiesel and distilled WCO-biodiesel are given in Table 3. The results show higher values of the flash point temperature of WCO-biodiesel and distilled WCO-biodiesel, indicating that the biodiesels are less flammable or hazardous than diesel.

Waste cooking oil is not used directly as a fuel for the engines because its kinematic viscosity is significantly high. Consequently, the viscosity of waste cooking oil was reduced through the process of transesterification. Viscosity affects the injection of fuel at a lower temperature. It is essential to have a spray pattern in the form of fine tiny droplets of fuel which is possible only with the low viscosity of the fuel. High viscosity of the fuel changes the spray pattern because the pressure of the fuel decreases with higher viscosity. The kinematic viscosity of diesel, WCO, WCO-biodiesel, and distilled WCO-biodiesel were determined at 40 °C by using a viscosity tester. The kinematic viscosities of diesel, WCO, WCO-biodiesel, and distilled WCO-biodiesel are given in Table 3. The kinematic viscosity of WCO-biodiesel was reduced significantly after the transesterification of WCO. The value of viscosity for WCO-biodiesel at 40 °C is 4.14 cSt and was further reduced to 3.9 cSt by low pressure distillation of WCO-biodiesel to produce distilled WCO-biodiesel. The viscosity diesel is 3.2 and is comparable with the viscosity of distilled WCO-biodiesel.

4. Economics of Distilled WCO-Biodiesel Production

The cost estimation for the production of distilled WCO-biodiesel was accomplished to forecast the cost-effectiveness of the biodiesel. Waste cooking oil is a cheaper feedstock material and reduces the cost of biodiesel production. The financial requirements were considered in order to findthe total cost required to launch and run the project for biodiesel production. The total project cost depends on the production targets, feedstock cost, and equipment cost etc. Fixed and operating costs of the biodiesel plant were determined. The capital cost is the cost of the equipment installed with auxiliaries, while the operating cost includes feedstock cost, utility cost, labor cost, facility cost, and overhead expenses required to produce the biodiesel at the specified rate (liter/day).

If A_0 is the inital sum today, then its growth at the end of n year with annual interest rate ir may be expressed as

$$A_n = A_0(1+ir)^n \tag{1}$$

While the present worth PW of this sum is A_0, and is given by

$$PW = A_0 = \frac{A_n}{(1+ir)^n} \tag{2}$$

Normally, the repetitive payments are made at frequent periods during the project life. An assumption is made that these payments are continuous and evenly distributed throughout the year. If the total values of all such annual payments is A, then the cash flow over a short span of time δt is $A\delta t$ while the present worth of the sum of payment over n year is given by

$$PW = \int_{t=0}^{t=n} \frac{A}{(1+ir)^t}\delta t \qquad = \frac{A}{\ln(1+ir)}\left[1 - \frac{1}{(1+ir)^n}\right] \tag{3}$$

The cost components considered for the cost estimation of per liter production of distilled WCO-biodiesel are the capital costs of the equipment C and the annual expenditure A_p which includes cost of materials, labor, and overhead. The annual benefits S_b are obtained from the sale of byproducts produced during the process. Finally, the benefits S_s are obtained from the disposal of the main equipment after the completion of the project lifetime of n years.

It is assumed that the continuous and evenly distributed payments of the annual expenditure are made throughout the year. If the sum of all these payments is A_p and the annual discount rate is ir, then its present worth in the project life is as follows:

$$PW_1 = \frac{A_p}{\ln(1+ir)}\left[1 - \frac{1}{(1+ir)^n}\right] \tag{4}$$

If the total value of all benefits received from the sale of byproduct is S_b, then its present worth with the annual discount rate of ir in the project life of n years is given as follows:

$$PW_2 = \frac{S_b}{\ln(1+ir)}\left[1 - \frac{1}{(1+ir)^n}\right] \tag{5}$$

If the reclaim worth of the equipment at the completion of the project lifetime of n years is S_s, then its present worth is given as follows:

$$PW_s = \frac{S_s}{(1+ir)^n} \tag{6}$$

The present value of project, PW_P in the project life of n years is given by:

$$PW_P = C + \frac{A_p}{\ln(1+ir)}\left[1 - \frac{1}{(1+ir)^n}\right] - \frac{S_b}{\ln(1+ir)}\left[1 - \frac{1}{(1+ir)^n}\right] - \frac{S_s}{(1+ir)^n} \tag{7}$$

The economic feasibility results of a small-scale plant in a ZRS group of industries for the production of distilled WCO-biodiesel are presented in Table 4. All the data related to the cost elements and other information such as discount rate, plant capacity, capital cost, byproducts and their sale price, and labor etc. during the plant operation have been received from the database of the plant.

Table 4. Cost of distilled WCO-biodiesel per liter.

No	Description	Quantity	Cost (USD)	Total Cost (USD)	Annual Cost (USD)
1.	Basic Information				
1a. 2a. 3a.	Capacity of the plant: 50 L/day Discount rate: 14% Project life: 10 years				
2.	Capital cost	1	500	500	=
3.	Operating costs				
3a.	Waste cooking oil	50 kg/day	0.702/kg	35.1	8421.05
3b.	Methanol cost	17.5 kg/day	0.57/kg	9.98	2395.20
3c.	Catalyst cost	1.4 kg/day	0.88/kg	1.228	294.70
3d.	HCL cost	1.75 kg/day	0.123/kg	0.215	51.60
3e.	Labor cost	2	1.32/h	21/day	5040.00
3f.	Electricity cost	30 kWh/day	0.14/kWh	4.2/day	1008.00
3g.	Facility cost	1	219.3/month	219.3/month	2631.6
3f.	Maintenance	0.01 of C. cost	500	5	5
Total Annual Payments, A_p = 3a + 3b + 3c + 3d + 3e + 3f + 3g + 6f = USD: 19845.55 $\text{PW1} = \text{USD}: 110539.71$					
4. Benefits from the sale of byproducts					
4a.	Glycerol	11.375 kg/day	0.44 /kg	5.00	1200.00
4b.	Tar	20.125 kg/day	0.53 /kg	10.67	2559.90
Annual Benefits S_b = 4a + 4b = 1200.00 + 2559.90 = USD: 3759.90 $\text{PW2} = \text{USD}: 20954.81$					
5. Benefits from the sale of equipment at the end of the project					
5a.	Salvage value	1	USD: 43.86	USD: 43.86	-
Annual Benefits S_s = 5a = USD: 43.86, PWs = USD: 60.06 $\text{PWp} = 500 + 110539.71 - 20954.81 - 60.06 = \text{USD}: 90024.84$ Cost of biodiesel per liter = $\frac{90024.84}{50 \times 240 \times 10} = \text{USD}: 0.75$					

It was discovered that if the purchase price of waste cooking oil was USD: 0.70/L, then the cost of distilled WCO-biodiesel was calculated as USD: 0.75/L with the plant running at its full capacity of 50 L per day. This shows that the production of distilled WCO-biodiesel is economically feasible as the current market price of diesel is USD: 1.09/L. The sensitivity analysis for the cost per liter of biodiesel with respect to the annual production of biodiesel in liters was carried out to observe the effect of variation in the annual production volume on the present worth of distilled WCO-biodiesel costs per liter. The results shown in Figure 6 indicate that the cost per liter of distilled biodiesel decreases with the increase in annual production volume achieving the cost of USD : 0.75 per liter for the plant running at its full capacity, producing 12,000 L of distilled biodiesel per year.

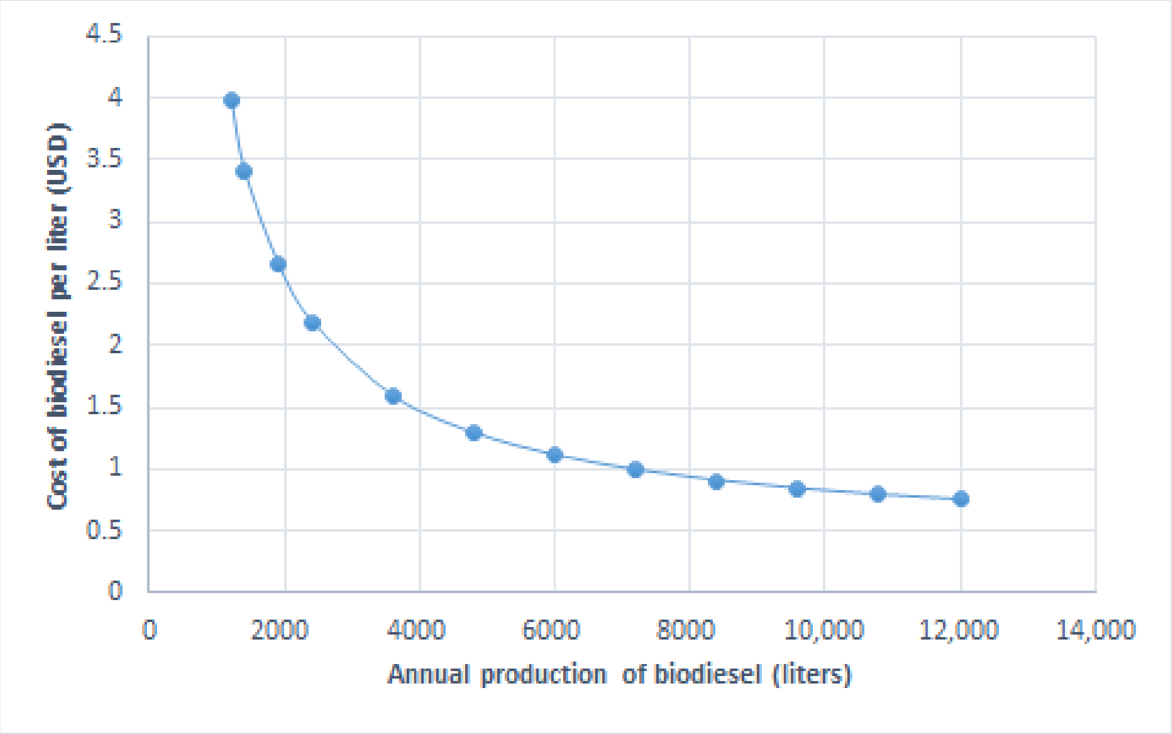

Figure 6. The sensitivity analysis for the cost per liter of distilled biodiesel to its annual production.

5. Experimental Setup for Investigations and Methodology

The engine performance characteristics were found through the experimental studies made on a single cylinder, four stroke, direct injection, air cooled diesel engine. The blends of distilled WCO-biodiesel of EN 14214 standard mixed with commercial diesel of Euro 5 standard, for different samples of fuel used to run the engine. DWB10D90, for instance, represents 10% distilled WCO-biodiesel mixed with 90% of diesel. DWB0D100 is diesel of Euro 5 standard without any mixing of biodiesel and was used as fuel for the first test on engine performance. The characteristics thus obtained provide the base-line information for the engine. Tests were repeated with different fuel samples having varying percentages of distilled biodiesel blends from 10% to 50% with diesel. The data regarding its performance were obtained for each sample. Subsequently, the base-line information was used for comparison with those from samples of the blended fuel. Arrangements for the investigation of engine performance are shown in Figure 7.

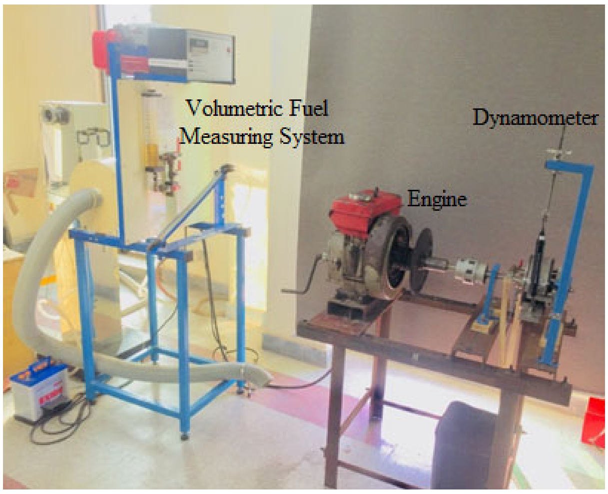

Figure 7. The setup of engine for investigations.

The experiments were conducted on diesel engine fueled with a blended mixture of distilled WCO-biodiesel and diesel to determine the brake power, brake thermal efficiency, and brake specific fuel consumption for a 10 to 50% range of biodiesel in the blended mixture. The engine was set in operation with full throttle and the fuel flow rate was determined by recording the time for a certain volume of fuel consumed by the engine measured on a graduated cylinder (5∼140 mL), whereas the speed (N) of the output shaft in rpm was measured by electronic tachometer. The braking force (F_b) was measured by a dynamometer (1∼200 N) attached at the engine output shaft and the braking torque (T) of the engine was subsequently determined. The brake power (BP) at the output shaft is given by Equation (8):

$$BP = \frac{2\pi NT}{60} \tag{8}$$

Different fuel samples having blends of distilled WCO-biodiesel with mineral diesel were used and the brake power of the engine for each fuel sample was determined and compared with the brake power of the engine running on mineral diesel as shown in Table 5. The results show that the fuels DWB10D90 and DWB20D80 generated improvements of 4.84% and 3.89%, respectively, in the engine brake power compared to that with diesel. Whereas the blended fuels DWB30D70 and DWB40D60 resulted in 2.92% and 0.93% improvements for the engine brake power, respectively. However, the use of DWB50D50 fuel caused a 6.64% reduction in the brake power of the engine.

Table 5. Engine brake power for fuels having distilled WCO-biodiesel blended with diesel.

No	Fuel	N (rpm)	Torque (N.m)	Brake Power, W
1	DWB0D100	3843	4.157	1672
2	DWB10D90	3943	4.253	1755
3	DWB20D80	3930	4.224	1737
4	DWB30D70	3920	4.194	1721
5	DWB40D60	3898	4.136	1688
6	DWB50D50	3710	4.020	1561

Break specific fuel consumption (BSFC) is calculated by Equation (9):

$$BSFC = \frac{Mass\ \text{of fuel}\ \left(\frac{\text{kg}}{\text{s}}\right) \times 3600}{\text{BP (kW)}} \tag{9}$$

BSFC values of the engine given in Table 6 were determined by running the engine with blended fuel for various proportions of diesel and distilled WCO-biodiesel and comparing them against the results for mineral diesel.

Table 6. BSFC of the engine running on blended fuels having different composition.

No	Fuel	Volume Flow Rate (L/s)	Density (kg/L)	Mass Flow Rate (kg/s)	BSFC (kg /kW.h)
1	DWB0D100	0.0002078	0.850	0.0001766	0.3803
2	DWB10D90	0.000200	0.853	0.0001706	0.3499
3	DWB20D80	0.000200	0.856	0.0001712	0.3547
4	DWB30D70	0.000238	0.859	0.0002045	0.4277
5	DWB40D60	0.000250	0.862	0.0002155	0.4597
6	DWB50D50	0.000294	0.865	0.0002544	0.5865

The results show the effect of percentage increases in distilled WCO-biodiesel in the mixture on the brake-specific fuel consumption. This shows that the BSFC increases as the percentage of distilled WCO biodiesel blend is increased from 10 percent to 50 percent in the blended fuel. This is due to the fact that when biodiesel proportion is increased in blends, the calorific value decreases, thereby increasing the flow rate of the blends for maintaining the same operating conditions in terms of power output. Furthermore, when it is compared with diesel, it is revealed that using DWB10D90 and DWB20D80 as fuels result in a 7.98% and a 6.72% reduction in the BSFC of the engine, respectively. For the fuel samples DWB30D70 and DWB40D60, there is an increase of 12.46% and 20.89% in the BSFC, respectively, whereas for DWB50D50 the BSFC increases by 54.23%.

Brake thermal efficiency (BTE) is the ratio of the brake power to energy released which has a direct relation with brake power. Different blends of distilled WCO-biodiesel and mineral diesel were used to regulate the BTE of the engine. The BTE values listed in Table 7 show the effect of percentage increases of distilled WCO-biodiesel in the blended fuel. It shows that the BTE is decreased as the percentage of distilled WCO biodiesel blend is increased from 10 percent to 50 percent in the blended fuel. This is because an increase in the proportion of biodiesel in the blends decreases BTE due to the poor atomization of the blends because of their high viscosity. Furthermore, when it was compared with diesel, it was observed that the use of DWB10D90 and DWB20D80 gave an increase of 1.97% and 1.70% in the BTE of the engine. The blended fuels DWB30D70 and DWB40D60 gave a reduction of 2.30% and 3.63% in the BTE of the engine, respectively, whereas for DWB50D50 the BTE is reduced by 7.57%.

Table 7. Brake thermal efficiency of engine using blends of distilled WCO-biodiesel and mineral diesel.

No	Fuel	Mass Flow Rate (kg/s)	Calorific Values (J/kg)	Brake Thermal Efficiency (%)
1	DWB0D100	0.0001766	43,000	22.02
2	DWB10D90	0.0001706	42,900	23.98
3	DWB20D80	0.0001712	42,800	23.71
4	DWB30D70	0.0002045	42,700	19.71
5	DWB40D60	0.0002155	42,600	18.38
6	DWB50D50	0.0002544	42,500	14.44

A SKY2000 Portable Pumping Gas Analyzer was used to measure exhaust gas emissions from the diesel engine. The experiments were carried out by inserting the probe of the gas measurement device into the exhaust pipe of the engine for measurement of emission species CO, NOx, and SO_2 in PPM and O_2 and CO_2 in %Vol soon after reaching engine running stability. The mineral diesel DWB0D100 and the blended fuels DWB10D90, DWB20D80, DWB30D70, DWB40D60, and DWB50D50 were used to run the engine. The variation of CO, NOx, O_2, CO_2, and SO_2 emission against mineral diesel and blended fuels are shown in Figures 8–12, respectively.

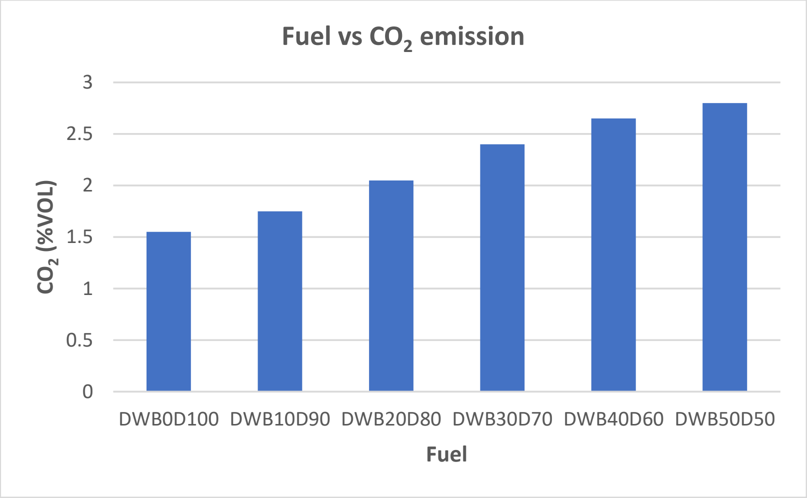

Figure 8. CO_2 emission from engine using diesel and diesel blended with distilled WCO biodiesel.

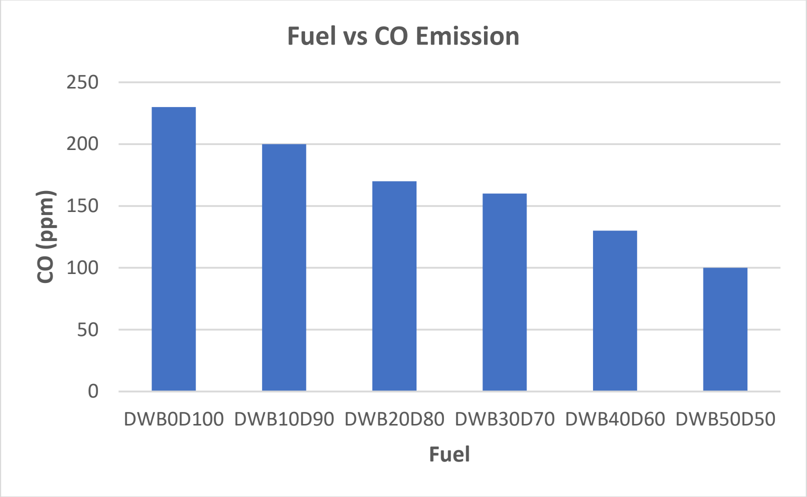

Figure 9. CO emission from engine using diesel and diesel blended with distilled WCO biodiesel.

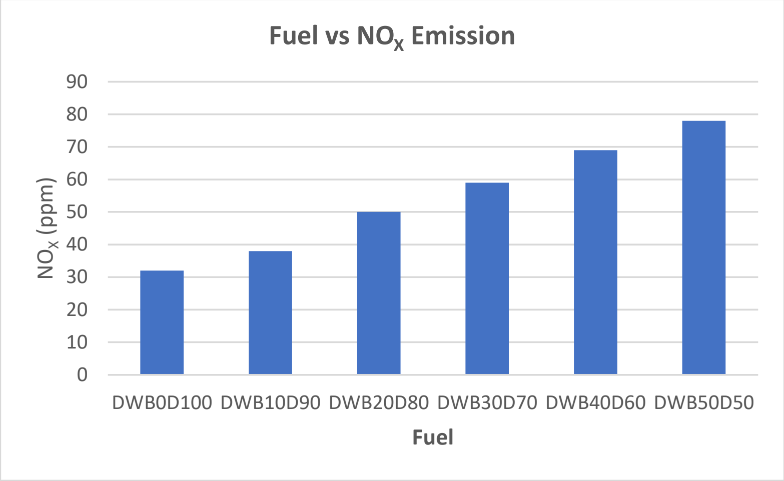

Figure 10. NO_X emission from engine using diesel and diesel blended with distilled WCO biodiesel.

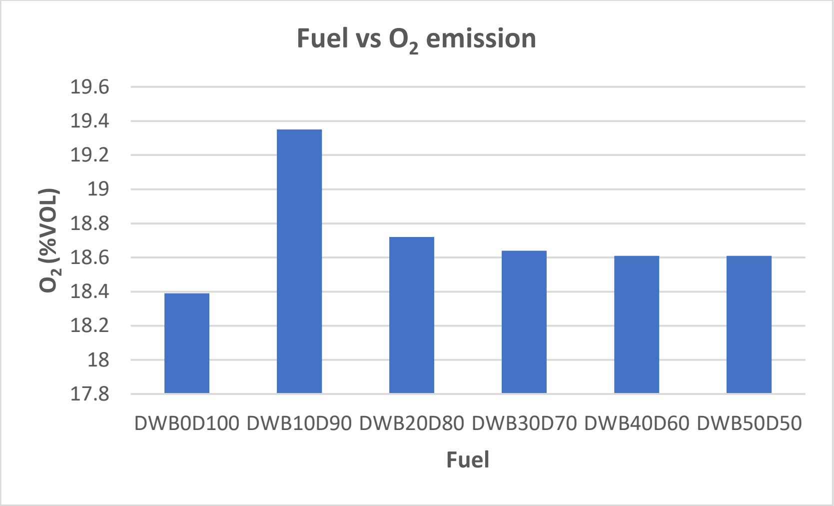

Figure 11. O_2 emission from engine using diesel and diesel blended with distilled WCO biodiesel.

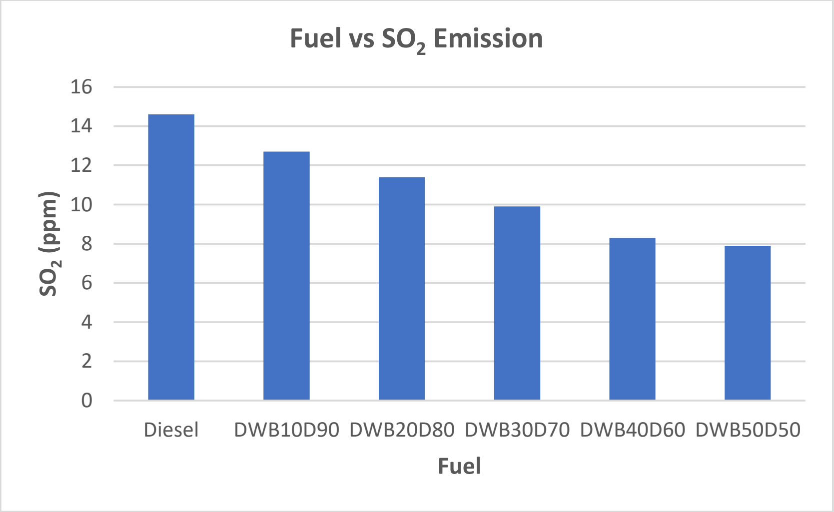

Figure 12. SO_2 emission from engine using diesel and diesel blended with distilled WCO biodiesel.

The results show that CO_2 emissions were higher for blended fuel than mineral diesel. Emission increases with a rise in the percentage of distilled WCO biodiesel blends in the blended fuel due to the higher oxygen content of biodiesel. The increasing trend of CO_2 emissions is shown in Figure 8. Carbon monoxide emission decreases with a rise in the percentage of distilled WCO biodiesel blends in the blended fuel, because of the higher oxygen content of biodiesel with more oxygen molecules which leads to better combustion, and, therefore, reduces CO species from engine emission as shown in Figure 9. NOx emission increases with a rise in the percentage of distilled WCO biodiesel blends in the blended fuel as shown in Figure 10. It is because of excessive oxygen content and higher cetane number of biodiesels compared to mineral diesel. During the combustion, the fuel-bound Sulphur is rapidly oxidized to SO_2. Since distilled WCO biodiesel contain lower Sulphur contents, so SO_2 species decreases with percentage rise of biodiesel in the blended fuel to run the engine as shown in Figure 12. The concentration of O_2 species is less with diesel fuel than that of biodiesel blend with diesel. But it decreases with percentage rise of biodiesel with diesel. Similar trends have been reported by other researchers [27].

6. Discussion and Conclusions

In this research work, possibility of the waste cooking oil biodiesel as an alternative fuel to the mineral diesel is explored. Various performance parameters of the WCO, WCO-biodiesel and distilled WCO-biodiesel are determined and compared with that of pure mineral diesel. The WCO obtained from the local market restaurants was first converted to biodiesel through transesterification process giving a biodiesel production yield of 87%. Subsequently, vacuum distillation of transesterified WCO-biodiesel resulted in 97% yield of purified distilled WCO-biodiesel.

The physical and chemical properties of the WCO and distilled WCO-biodiesel were determined. It was observed that the density of WCO which varies between 904.3 to 923.2 kg/m^3 was first reduced to 875 kg/m^3 for WCO-biodiesel produced by the transesterification process. The density of biodiesel was further reduced to 871 kg/m^3 for the distilled WCO-biodiesel whereas the density of diesel is 850 kg/m^3. The density of distilled WCO-biodiesel being very close to mineral diesel results in the formation of uniform blended mixture of distilled WCO-biodiesel and mineral diesel. The kinematic viscosity of WCO and mineral diesel are 4.8 cSt and 3.2 cSt, respectively, which were reduced 4.14 cSt for WCO-biodiesel and 3.9 cSt for distilled WCO-biodiesel. The reduced viscosity of distilled WCO-biodiesel results in less resistance to flow for blended fuel of biodiesel with diesel. The outcome is a continuous supply of blended fuel to the engine for better engine performance. The calorific value of WCO and mineral diesel are 35 MJ/kg and 43 MJ/kg, respectively. It was improved to 40 MJ/kg for WCO-biodiesel and 42 MJ/kg for distilled WCO-biodiesel. The improved calorific value of distilled WCO-biodiesel results in enhanced production of energy due to burning of blended mixture of distilled biodiesel with diesel. Consequently, there is more energy produced inside the engine cylinder and thus more power at the output shaft. Flash point temperature being inversely related to volatility of fuel ensures the safe handling of diesel and biodiesel fuel in the performance of diesel engine. The flash point of diesel, WCO, WCO-biodiesel and distilled WCO-biodiesel given in Table 3 show the higher values for the flash point temperature of WCO-biodiesel and distilled WCO-biodiesel. It was observed that the flash point temperature of WCO was 220 °C that was reduced to 169 °C for WCO-biodiesel. The flash point temperature of distilled WCO-biodiesel was 176 °C whereas the flash point temperature of diesel was 69 °C. The higher values of the flash point temperature for WCO-biodiesel and distilled WCO-biodiesel ensure the safe working of biodiesel as biodiesels are less flammable or hazardous than diesel.

The engine performance characteristics were found through the experimental studies made on a diesel engine. Tests with 100% mineral diesel fuel were performed to produce base-line information for the performance characteristics of the engine. Tests were repeated using different samples with changing percentages of distilled biodiesel blends and diesel, and a comparison was made with the base-line information.

The results show that the blended fuels DWB10D90, DWB20D80, DWB30D70, and DW40BD60 gave improvements in the engine brake power when compared with the base-line information. An increase for DWB10D90, DWB20D80 whereas the reduction was noticed in the BTE of DWB30D70 and DW40BD60 compared with the base-line information. The values of BSFC were reduced for DWB10D90 and DWB20D80 whereas an increase was noticed for DWB30D70 and DW40BD60, respectively, in comparison with the baseline information. However, DWB50D50 fuel showed a reduction in brake power, BTE and an increase in the BSFC of the engine. Therefore, the engine running on the fuels DWB10D90 and DWB20D80 showed improved performance, whereas DWB30D70, DWB40D60, and DWB50D50 fuels showed poor performance.

The variation of CO, NO_X, O_2, CO_2, and SO_2 emission against mineral diesel and blended fuels were measured using SKY2000 Portable Pumping Gas Analyzer. The result showed that CO, O_2, and SO_2 emission decreases with an increase in the percentage of distilled WCO biodiesel blends with diesel whereas CO_2 and NO_X emission increases with a rise in the percentage of biodiesel blends due to their excessive oxygen content and higher cetane number.

An economic analysis revealed that for market price of WCO at USD 0.7/L, the optimum production cost of distilled WCO-biodiesel was USD 0.75/L with the plant running at its full capacity with a production rate of 12,000 L per year, as shown in Table 4. A sensitivity analysis depicted in Figure 6, indicates that the cost per liter of biodiesel decreases with an increase in the annual production volume. This shows that the production of distilled WCO-biodiesel is economically feasible at the current diesel market price of USD 1.09/L resulting in a saving of USD 0.34/L for the portion of the distilled WCO-biodiesel fuel used in blends replacing diesel. It is concluded that DWB10D90 and DWB20D80 fuel used to run diesel engine showed improved engine performance and reduced engine exhaust emission for fuel economy, engine life and clean environment.

It is suggested for future work to use nanoparticles with distilled WCO biodiesel in order to reduce the formation of NOx by controlling the high temperatures as the use of biodiesel gave rise to the NOx emissions due to the excessive oxygen content and higher cetane number. The use of nanoparticles may result in an engine operation which can be more efficient and ecological. Investigation of the performance and emission characteristics of triple blended fuel including diesel and distilled biodiesel with nanoparticles-based additives is also included in future research plans.

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Abbreviations

WCO	Waste cooking oil
DWB	Distilled waste cooking oil biodiesel
DWB20D80	Blended fuel having 20% of distilled WCO-biodiesel and 80% of mineral diesel
BSFC	Brake specific fuel consumption
BP	Brake power
BTE	Brake thermal efficiency
CV	Calorific value
PW	Present worth
PW_1	Present worth of annual operation cost
PW_2	Present value of annual benefits received from the sale of byproducts
PW_S	Present worth of salvage value
PW_p	Present worth of project cost

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