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Performance Evaluation of a CI Engine Using Binary, Ternary, and Quaternary Bio-Diesel Fuel Blends

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Abstract

The present study utilizes dual biodiesel-alcohol blends to evaluate the engine performance. Five test fuels were prepared on a volume basis with different constituting percentages, each consisting of 70 % pure diesel (D70), a binary blend of biodiesel: B1 (WCO30), a ternary blend of biodiesel: B2 (WCO15 and WCCO15) and three quaternary blends: B3 (WCO10, WCCO15, Bu5), B4 (WCO15, WCCO10, Bu5) and B5 (WCO10, WCCO10, Bu10). The biodiesel is made from used cooking oil. The effects of each blend on engine performance were examined by performing the engine test on a single-cylinder, four-stroke, water-cooled Kirloskar compression ignition (CI) engine at various engine speeds and loads. The indicated power (IP), brake power (BP), friction power (FP), fuel consumption (FC), and mechanical efficiency (%) were evaluated, and the experimental results show that the performance is best for B3 when run with 75 % of the maximum load capacity of the engine. The study thus justifies that to lower the density and viscosity of biodiesel fuel, adding alcohol can be acknowledged as a valuable application to boost the engine's brake thermal efficiency (BTE). This also lowers the emissions of oxides of nitrogen (NOx), carbon monoxide (CO), and hydrocarbons (HC).

Keywords: Biodiesel; Alcohols; *n*-Butanol; Waste cooking oil; Brake specific fuel Consumption; Transesterification; Brake thermal efficiency.

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1. Introduction

Conventional fuels are less favorable due to their hazardous nature, as they can potentially cause environmental degradation by releasing harmful gases into the atmosphere. However, fossil fuels such as petrol, oil, coal, and natural gas play a pivotal role, and studies suggest that around 80 % of the world's energy needs are supplied by fossil fuels [1]. Thus, they have also been reduced continuously due to extensive usage, leading to their complete eradication in the near future. Additionally, emissions from the burning of fossil fuels increase global warming and air pollution [2-5]. Consequently, there is an urgent need to identify alternative fuels to meet global energy demands for sustainable development. The introduction of alternative fuels in the form of bioenergy fuels can be

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blended with fossil diesel. One such promising biofuel is biodiesel, but its usage is constrained by poor low-temperature flow characteristics and high viscosity. In this context, alcohol is a potential additive for diesel-biodiesel (DB) blends due to its abundance, ease of production, and environmental benefits. As most industrial units run diesel-powered machinery, they are to be powered by clean and renewable alternative fuels. Biodiesel as a renewable fuel resource has become increasingly important because of the depletion of fossil fuels, and the economic and sustainability issues related to its production have been discussed [6]. However, other potential biodiesel alternatives, such as microalgae, fat-oils-grease (FOG), different solid wastes, and other non-edible raw materials, are considered promising alternatives. Reviews on biodiesel blends offered valuable insights into using biodiesel as a renewable, clean-burning diesel replacement in existing diesel engines without modification [7]. Such reviews discussed the appropriate blending ratios for biodiesel and also the recommended percentage of organic blends, avoiding issues with water and cetane content.

Biodiesel, as an alternative, shares many characteristics with conventional diesel fuel. As a result, biodiesel has gained a lot of importance as a substitute for fossil fuels. It is being studied extensively to remove the negative environmental effects of petroleum-fueled diesel engines and the concerns of depleting petroleum reserves [8]. Recent patents and research studies have discussed biodiesel production from various bio-resources and illustrated the primary steps of producing biodiesel through oil extraction from the feedstock and its conversion into biodiesel (trans-esterification) [9]. Many studies in the literature discuss various sources of biodiesel production. However, not all the production techniques are equally viable, and the production cost was higher as the raw material cost for the biodiesel preparation accounted for almost 80 % of the total biodiesel production cost [10]. Studies on alternate fuels for vehicular operation have been more emphasized in the last few decades due to the various disadvantages of the available fossil fuels. Vehicles running on fossil fuels are highly polluting, with 75 % of diesel engines found to emit opacity higher than the national emission limit value and 60 % of SI engines emitting CO and HC concentrations higher than such recommended values [11]. Another study observed that biodiesel from Parsley seed oil could be a suitable alternative fuel for diesel engines, promoting a green environment [12]. Performance investigation of a single-cylinder four-stroke CI engine using three types of biodiesel (palm, jatropha, and cottonseed) showed that the biodiesel blends have slightly higher BTE than diesel, with the best blend being J30 (Jatropha 30 %) [13]. However, the P10 (palm 10 %) blend provides higher performance and lower emissions and could be used as a supplemental fuel blended with diesel.

Studies are thus particularly aimed at locating a less expensive raw material. In this situation, waste cooking oil (WCO) was found to be one of the suitable alternatives to vegetable oils in the preparation of biodiesel. The use of WCO cut down on the preparation cost, providing an effective way to utilize waste oil [14]. Biodiesel production from waste cooking oil (WCO) as a raw material was found to be an effective alternative to fossil fuels due to its renewability, biodegradability, and non-toxicity [15]. Thus, biodiesel has several advantages over petroleum diesel, including a higher cetane number, a lower ash percentage, a lower carbon residue, and improved engine ignition and emission performance. Moreover, WCO is abundant globally, making it a cost-effective source of biodiesel. However, WCO requires pre-treatment steps to remove impurities before transesterification.

The large number of WCOs available can be used as raw material to be converted into a useful fuel that could largely meet the demand for biodiesel worldwide [16]. According to some reports, the WCOs can be effectively turned into biodiesel at very high yields per kilogram, and the synthesis of biodiesel from WCOs enables savings of 96 % of fossil energy and 21 % of crude oil [17]. Though it is economical to opt for the use of WCOs as the starting material in the preparation of biodiesel, WCOs mostly contain water and free fatty acids (FFA), which make them unsuitable for homogenous alkaline transesterification catalysis. The typical alkaline catalysts tend to undergo a saponification reaction in the presence of water, which is not desirable as this might lead to choking of the combustion chamber and injector nozzles, gumming, and sticking of the engine's piston rings. Also, a high FFA content led to poor biodiesel yield quality and quantity. To get rid of this, esterification is performed before transesterification, which again adds to the additional cost of more chemicals to be used, especially the cost of excess alcohol. Biodiesel produced from waste cooking oil using calcium oxide nano-catalyst yields the highest conversion rate of 96 % under optimized experimental conditions [18]. The produced biodiesel was then tested according to ASTM D6571 standards and offered economic, environmental, and waste management benefits.

Certain drawbacks associated with engine operation based on pure biodiesel include filter and pipeline clogging due to its high viscosity, engine pump failure, weakening of fuel system seals, injector choking, and piston sticking [19-23].

Besides, the energy density and lower heating values (LHV) of WCO-derived biodiesel (39–40 MJ/kg) are low, and the flash and fire points are higher than diesel. The cetane number of biodiesel (up to 70) is normally higher than that of diesel (up to 55); however, biodiesel alone cannot be effectively used as engine fuel [21]. Thus, biodiesel, in general, is to be blended with diesel and employed for practical applications.

The physical and chemical properties of oil derived from Camelina sativa L. seeds were investigated [24] to ascertain its suitability as a major feedstock for the production of biofuels. This study found that the derived oil has good physicochemical properties in terms of a high oil yield percentage (36.66 %) and a low acid value (5.39 mg KOH/g) and could be considered an ideal raw material for biodiesel synthesis. The production of biodiesel from Kutkura fruit seed oil was studied, and it was found that the Free Fatty Acid (FFA) content in the Kutkura fruit seed oil was 3.1 % [25]. Furthermore, it was found that the biodiesel derived from waste cooking refined oil (R-oil) is more viscous, and research has been carried out on other waste cooking oils. One such alternative is waste-cooking coconut oil (C-oil), which has excellent properties and performs better than the usual R-oil-derived biodiesel. In another study [26], waste coconut oil was used for biodiesel preparation. Five samples (pure diesel, B10, B20, B30, and B50) were tested for engine performance, and all samples' BTE and brake-specific fuel consumption (BSFC) values were obtained. The engine test results showed that the optimum blends were B10 and B20, and from the emission test, it was found that emissions were reduced significantly with the use of the waste coconut oil biodiesel fuel blends. Thus, from the several studies, it is evident that the above approach has certain limitations that led researchers and scientists to look for a better solution, and the inclusion of alcohol in biodiesel-diesel blends has been found to be significant. A number of alcohols have been studied, and the similarity in the chemical properties of biodiesel and alcohol with pure diesel makes them suitable for diesel engines. Moreover, the oxygen content in biodiesel and alcohol is high, thus ensuring complete combustion of the fuel and reducing the release of harmful emissions from the engines. The viability of employing heavy alcohol and safflower biodiesel as blended fuel for a test diesel engine was assessed [27]. Safflower biodiesel fuel was blended with 20 % volumetric amounts of propanol, pentanol, butanol, and octanol. The major findings include an increase in fuel consumption due to a decrease in lower thermal performance caused by alcohol inclusion and a significant increase in engine BTE with the use of heavy alcohol.

Most of these researches are on using lower alcohols like methanol and ethanol, and there are a few studies on higher alcohols. The study [28] assessed the fuel qualities, engine performance, and emission characteristics of diesel, biodiesel, and their blends with butanol. The blends were B20D70Bu10, B20D60Bu20, B20D80 and B100. It was observed that the addition of alcohol to diesel and biodiesel fuel reduces torque value; the average torque and power values reduced when the butanol ratio was increased to 20%; with more butanol added, the average specific fuel consumption rose. Further, changes in alcohol content affect CO and CO_2 emissions.

The study of high-carbon alcohols like butanol has recently gained interest in the field of diesel engines. The addition of oxygenated substances such as ethanol or methanol, propanol, butanol, etc., to enhance the quality of blends of traditional diesel and biodiesel is suggested [29,30]. Due to its higher heating value (HHV), lower heat of vaporization, longer stability, and improved solubility with diesel fossil fuels without corrosion, n-butanol, however, appeared to be a better choice amongst all these alcohols for use in CI engines. Table 1 lists the physical and chemical characteristics of diesel fuel, ethanol, and n-butanol fuel. Butanol is a renewable fuel made from biomass.

Table 1. Properties of diesel fuel, n-butanol, and ethanol.

Fuel properties	Diesel fuel	n-butanol (C_4H_9OH)	Ethanol (C_2H_5OH)
Density at 20 °C (kg/m^3)	837	810	788
Cetane number	50	~25	~8
Lower calorific value (MJ/kg)	43	33.1	26.8
Kinematic viscosity at 40 °C (mm^2/s)	2.6	3.6	1.2
Boiling point	180-360	118	78
Latent heat of evaporation (kJ/kg)	250	585	840
Oxygen (% wt)	0	21.6	34.8
Stoichiometric air-fuel ratio	15	11.2	9
Molecular weight	170	74	46

The main straight-chain molecule that is produced when butanol is produced from biomass is n-butanol. The present work uses n-butanol. Three quaternary blends with WCO, WCCO, and Bu as B3: (WCO10, WCCO15, Bu5); B4: (WCO15, WCCO10, Bu5); and B5: (WCO10, WCCO10, Bu10), a binary blend of biodiesel with WCO as B1: (WCO30) and a ternary blend of biodiesel with WCO and WCCO as B2: (WCO15 and WCCO15) — were prepared as test fuels on a volume basis with each test fuel blend containing in common 70 % of fossil diesel (D70). Hence, five test fuel blends were prepared. As per the available literature, several studies have been carried out on the use of alcohol as a possible constituent of DB blends. However, most of these researches are on the usage of lower alcohols like methanol and ethanol, and there are few studies on higher alcohols. High-carbon alcohols such as butanol have recently attracted significant research interest in the field of diesel engines due to their higher mixing stability, higher energy density, lower water retention, and higher cetane number compared to low-carbon alcohols. Biodiesel production from edible oil is not encouraged due to the conflict between fuel and food. n-Butanol can be prepared comparatively more easily than other alcohols like pentanol and hexanol [31]. Thus, n-butanol is used as a constituent in the current work from the category of alcohols.

2. Materials and Methods

The biodiesel (R and C) was made from waste cooking oil, which was initially collected and filtered to separate food residues from the oil, followed by water removal by heating. The base transesterification process was then employed to produce biodiesel. NaOH and Methanol were used as a catalyst in biodiesel production. Oil reacts with the methoxide, forming biodiesel and glycerol as a by-product. The mixture was allowed to cool and settle, and methanol was recovered by heating the oil to 70 °C. This is followed by multiple washings with water till the solution is neutral, along with the complete removal of glycerol. The remaining oil was heated to remove any traces of water.

The biodiesel was then blended with pure diesel to create various blends. Butanol was then added to make the final blends as desired. The blends' fundamental physical and chemical characteristics were identified. The different blends' density, kinematic viscosity, calorific values, flashpoint, and fire-point were measured. The blends were subsequently utilized for engine testing and performance analysis with a 1-cylinder, 4-stroke CI engine. The proportions used to make the test blends are listed in Table 2.

Table 2. The proportion of constituents in preparation of biodiesel blends.

Blend	Proportion (% by volume)			
	Pure diesel (D)	Biodiesel from WCO (R)	Biodiesel from WCCO (C)	Butanol (Bu)
Blend 1 (B1)	70	30	0	0
Blend 2 (B2)	70	15	15	0
Blend 3 (B3)	70	10	15	5

Blend (B4)	4	70	15	10	5
Blend (B5)	5	70	10	10	10

Stability tests of the butanol blend are performed to find out the blend's solubility. For the test, a sample of the most optimal blend with butanol as a constituent and another sample wherein we replaced butanol with methanol was prepared. The two blend samples were then left undisturbed, and a clear demarcation was observed, as seen in Fig. 1, between the layer of methanol and the rest of the sample (second sample). In contrast, the first one (with butanol) was stable even after 2 weeks of the test. It is thus evident that butanol blends are more stable in terms of the solubility of the blends.

Fig. 1. Stability test: Sample 1 (D70WCO10WCCO15Bu5) and Sample 2 (D70WCO10WCCO15Me5).

2.1. ***Transesterification***

Here, triglycerides react with an alcohol in the presence of a catalyst to form a mixture of free fatty acid ester and glycerol. This mixture is then allowed to settle in a fractional separator, which finally yields biodiesel. Biodiesel can be produced either by base-catalyzed transesterification, acid-catalyzed transesterification, or by a two-step acid-base esterification. Due to the reversibility of the reaction, excess alcohol is used to move the equilibrium to the product side. The biodiesel preparation process is shown as a flow chart in Fig. 2 below.

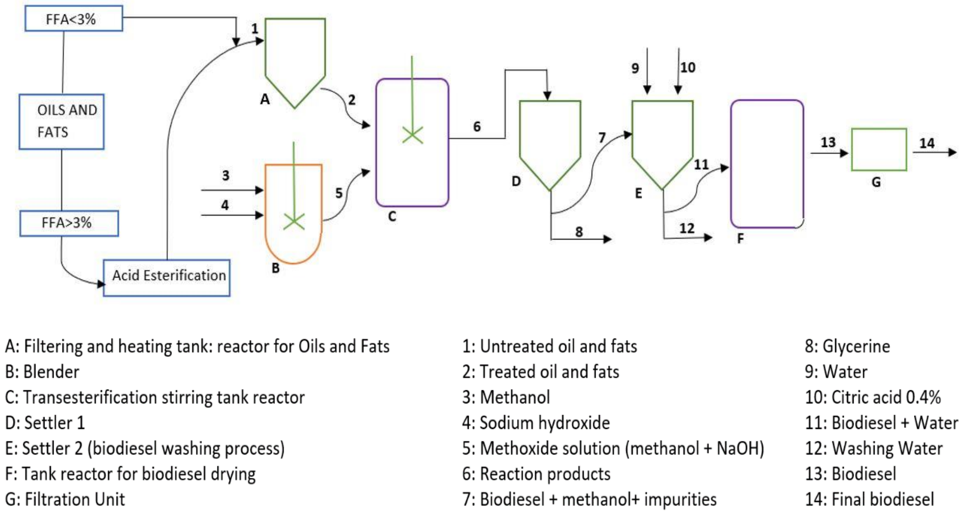


Fig. 2. Flow process chart for biodiesel preparation.

3. Experimental Setup and Test Procedure

In this study, the performance of a 3.5 kW, 1500 rpm, water-cooled, single-cylinder, four-stroke, variable compression ratio (VCR) CI engine was analyzed, which was coupled to an eddy current dynamometer. The engine system enables to change of the compression ratio without stopping the engine with the help of the tilting cylinder block assembly. The schematic diagram of the experimental engine setup and location of various temperature and pressure sensors are shown in Fig. 3. Whereas, Fig. 4 illustrates the front view of the experimental facility. A summary of the engine setup specifications is given in Table 3, and a description of the related equipment is given in Table 4. In all experimental evaluations, steady-state conditions were assumed for engine operation. In the experiment, the signals recorded by several sensors (piezo sensor, crank angle sensor, load sensor, thermocouple, differential pressure transducer) were sent to the engine software (Apex Innovations Pvt. Ltd., India) [32] through a data acquisition device. The data acquisition system recorded the various engine operating parameters, such as air, water, and fuel flow rates, loads, water inlet and outlet temperatures, and exhaust gas temperatures. The engine performance is then evaluated by measuring braking power, indicated power, frictional power, BTE, and heat losses owing to exhaust, cooling water, and unaccounted losses.

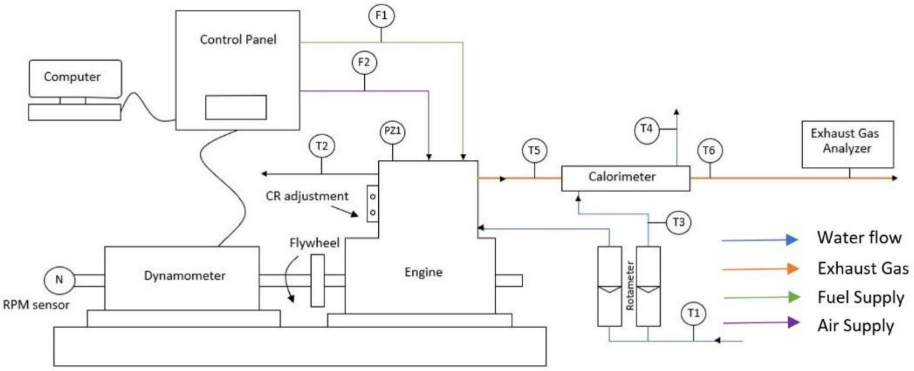


Fig. 3. Schematic of the experimental setup.

Table 3. Engine specification. (Source: Apex Innovations Pvt. Ltd., Sangli, Maharashtra).

Sl No.	Parameters	Technical Specification
1.	Make and model	Kirloskar
2.	Type	Single cylinder, 4 S, water-cooled
3.	Bore and stroke	87.5 mm × 110 mm
4.	Rated brake power	3.5 kW
5.	Speed range	1200–1800 RPM
6.	Compression ratio range	12 to 18:1
7.	Connecting rod length	234 mm
8.	Swept volume	661 cc

Fig. 4. Engine setup (front-view).

Table 4. Equipment description

Equipment	Description
Dynamometer	Type eddy current, water-cooled with the loading unit
Propeller Shaft	Make Hindustan hardy, With universal joints.
Air Box	M S fabricated with orifice meter and manometer.
Fuel tank	Capacity 15 lit with glass fuel metering column
Calorimeter	Type pipe in pipe
Piezo sensor	Make PCB USA, Combustion: Range 350 bar, Diesel line: Range 350 bar with low noise cable.
Crank angle sensor	Make Kubler Germany, Resolution 1 Deg, speed 5500 rpm with TDC pulse.
Data acquisition device	Make NI Instrument USA, NI USB-6210, 16-bit, 250kS/s
Temperature sensor	Make Radix, Type RTD, PT100, and Thermocouple, Type K
Temperature transmitter	Make ABUSTEK USA, Type 2 wire, Input RTD /Thermocouple, Output 4–20 mA
Load Sensor	Make VPG Sensotronics, Load cell, Type strain gauge, range 0–50 Kg
Fuel flow transmitter	Make Yokogawa Japan, DP Transmitter, Range 0–500 mmWC
Air flow transmitter	Make Wika Germany, Pressure transmitter, Range (–) 250 mmWC
Software	“Enginesoft” Engine performance analysis software
Rotameter	Make Eureka, Engine cooling 40-400Lph; Calorimeter 25–250 Lph
Pump	Make Kirloskar, Type Monoblock

4. Results and Observations

4.1. *Measured properties of biodiesel blends*

At constant temperature, the kinematic viscosity and density of the blends fluctuate from blend B1 to blend B5. The addition of butanol and biodiesel from WCCO reduces the density and kinematic viscosity of the blends. Therefore, blend 3 and blend 5 give a minimum value of density and kinematic viscosity as they contain the maximum amount of (butanol + biodiesel from WCCO). As given in Table 5, the calorific value of blend 3 is the maximum, whereas that of blend 5 has a minimum value. This may be due to the maximum amount of biodiesel from WCCO in blend 3, which has a high calorific value. However, butanol has a low calorific value, and hence blend 5 may have the minimum calorific value as it contains a high amount of butanol.

The measurement results also revealed that when the proportion of butanol in a blend rises, the flashpoint and fire point temperatures decrease. Butanol, being volatile, provides sufficient fuel-bound oxygen, which, along with its high evaporative qualities, promotes the mixing rate of the air and fuel vapors as well as the combustion of the blends.

Table 5. Properties of biodiesel blends.

Fuel blend	Kinematic viscosity (cSt)	Density (kg/m^3)	Temperature (^{o}C)	Calorific value (kJ/kg)	Flash point (^{o}C)	Fire point (^{o}C)
B1	2.400	833.7	40	42032.46	63	68
B2	2.384	831.1	40	41626.62	60	64
B3	2.112	824.9	40	42074.30	50	58

B4	2.137	828.6	40	41754.23	38	40
B5	2.041	824.9	40	40143.39	41	47

4.2. *Engine test results*

The engine performance with different blends was evaluated in terms of BP, IP, BSFC, and BTE at different engine loading conditions.

4.2.1. *BP vs. load*

The brake power generated by the engine using pure diesel and different biodiesel blends B1-B5 under different load conditions from 25 % to 100 % is illustrated in Table 6. As the load increases, the brake power produced by the engine also increases for diesel fuel and for all the blends. At 25 % load, maximum BP is obtained for the B2 blend. At 50 % load, it is for B1. The trend has resulted from the energy value of the fuels.

Table 6. Estimation of BP using diesel and biodiesel blends with percentage load variation.

Load	Diesel (kW)	B1 (kW)	B2 (kW)	B3 (kW)	B4 (kW)	B5 (kW)
25% (3kg)	0.91	0.94	0.97	0.93	0.93	0.91
50% (6kg)	1.78	1.82	1.79	1.78	1.78	1.79
75% (9kg)	2.63	2.61	2.62	2.71	2.63	2.62
100% (12kg)	3.46	3.46	3.49	3.49	3.51	3.5

4.2.2. *IP vs. load*

The indicated power generated by the engine under different load conditions is illustrated in Table 7. With an increase in load, the indicated power of the engine also increases for all blends, but it is at its maximum for B3 at all loads. This is due to the higher energy value of B3 compared to other blends. At a constant load, the IP values first increase from pure diesel to blend B3 as the load increases up to 75 % of full load and then reduces or remains constant for blends: B4 and B5. However, at full load, a similar trend in IP variation is observed only from blend B1 to B5, with pure diesel being an exception. Such variations may be a result of variations in the energy value of the fuels.

Table 7. Estimation of IP using diesel and biodiesel blends with percentage load variation.

Load	Diesel (kW)	B1 (kW)	B2 (kW)	B3 (kW)	B4 (kW)	B5 (kW)
25% (3kg)	3.38	3.84	4.1	4.22	4.14	4.08
50% (6kg)	4.13	4.37	4.43	4.8	4.51	4.52
75% (9kg)	4.72	4.81	4.83	5.25	4.93	4.93
100% (12kg)	5.46	5.26	5.44	5.63	5.4	5.36

4.2.3. *BSFC vs. load*

The variation of BSFC with respect to load is presented in Table 8. The BSFC was found to decrease with an increase in load for the diesel and all blends. This may be due to the relatively higher percentage increase in brake power with the load as compared to the increase in fuel consumption. From Table 8, it is seen that the BSFCs at full engine load are the lowest.

Table 8. Load vs. BSFC.

Load	Diesel (Kg/kWh)	B1 (Kg/kWh)	B2 (Kg/kWh)	B3 (Kg/kWh)	B4 (Kg/kWh)	B5 (Kg/kWh)
25% (3kg)	0.77	0.79	0.81	0.86	0.89	0.92
50% (6kg)	0.49	0.48	0.51	0.53	0.54	0.55
75% (9kg)	0.41	0.4	0.41	0.41	0.43	0.43
100%(12kg)	0.38	0.35	0.36	0.36	0.37	0.37

4.2.4. *BTE vs. load*

The BTE of the diesel engine obtained for different blends of biodiesel, butanol, and diesel is shown in Table 9 as a function of load. From Table 9, it is observed that the BTE, in general, reduces with the increasing concentration of biodiesel and alcohol in the blends. As seen from Table 9, the BTE of the engine while using diesel fuel, as well as any blend, increases as the engine load is increased. However, the BTE fluctuates among the blends at a given engine load depending on the nature of the blend. Apart from full load operating conditions, the highest BTE occurs at 75 % load using the B1 blend, while B4 gives the lowest efficiency. This may be due to a higher fuel flow rate, as shown in Fig. 5., to overcome higher frictional power losses.

Table 9. Load vs. BTE.

Load	Diesel (%)	B1 (%)	B2 (%)	B3 (%)	B4 (%)	B5 (%)
25 % (3 kg)	10.52	10.87	10.53	9.94	9.74	9.79
50 % (6 kg)	16.38	17.77	16.73	16.11	16.02	16.31
75 % (9 kg)	19.68	21.38	21.09	20.79	20.22	20.90
100 % (12 kg)	21.41	24.30	24.10	23.47	23.17	24.30

As the engine load increases, there is a corresponding increase in the fuel flow rate for diesel, and all blends B1 to B5. The present study measures the engine's fuel consumption using a hydrostatic head. The fuel flow transmitters measure hydrostatic head in fuel measuring units (Model FF0012, Apex Innovation, Make: Apex Innovations) consisting of glass burettes. The fuel flow rate is calculated based on the difference between two signals within one minute. From Fig. 5, it is observed that the highest consumption of fuel occurs for blend B5 followed by blend B3 at full load. At a given load, the fuel rate fluctuated from diesel to blend B5, except in the case when the load is 3/4th of the full load, where the fuel consumption is held constant.

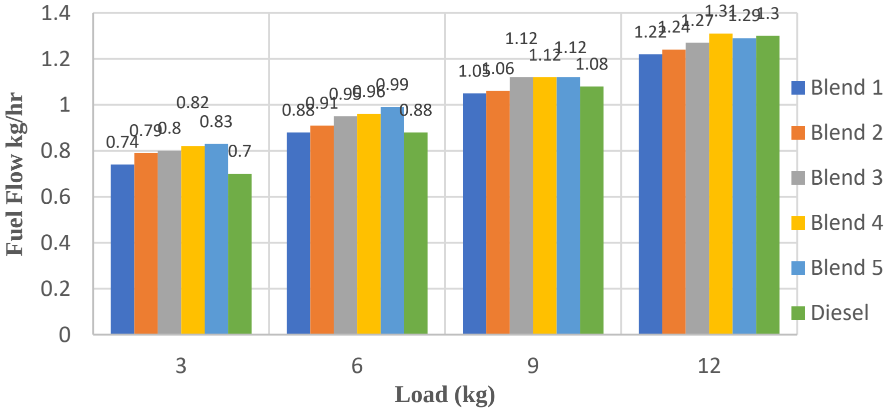
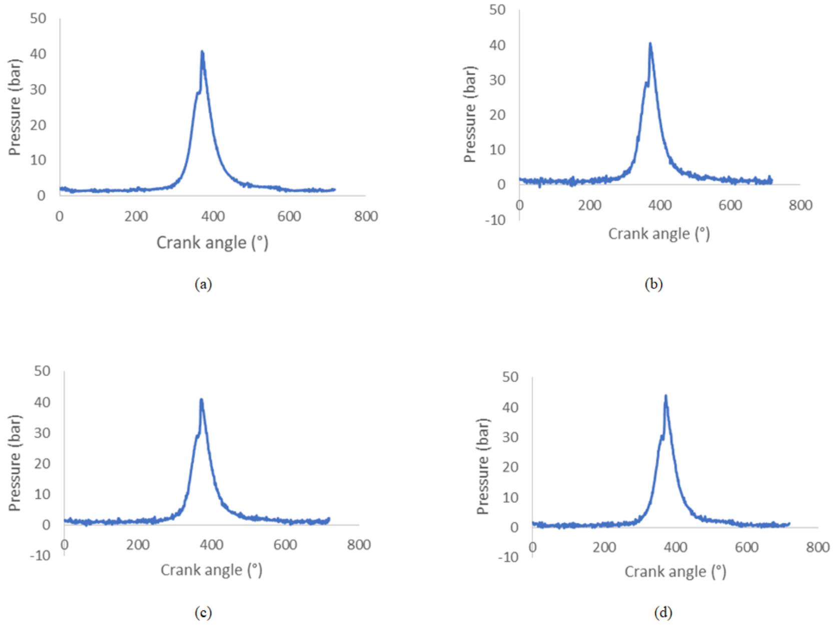
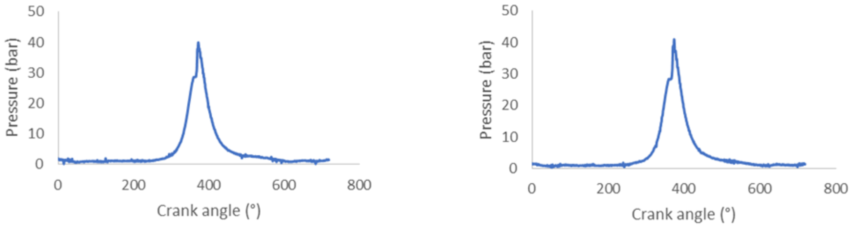


Fig. 5. Load vs. fuel flow rate.

At a given load, the maximum engine pressure using diesel and the blends B1 to B5 occurred at nearly close crank angles. Further from Figs. 6 (a) – 6(f), it is seen that the maximum engine pressure fluctuation among the fuel blend is not significantly high. However, it is observed that the peak pressure of blend 3 with 43.99 bars is found to be maximum at 75 % of the full load. The peak pressure is influenced by the amount of fuel consumed in uncontrolled combustion, which depends on the fuel injected's delay period and sprays envelope. A longer ignition delay may lead to more fuel accumulation and higher peak pressure. This is due to the higher calorific value and lower density of B3 as compared to other blends. The crank angles at which peak pressure occurred were 373°, 373°, 371°, 373°, 372°, and 374° for diesel, B1, B2, B3, B4 and B5, respectively.





(e) (f)

Fig. 6. Pressure vs. crank angle for (a) Diesel, (b) B1, (c) B2, (d) B3, (e) B4, and (f) B5.

4. Conclusion

Resources like waste cooking oil and other bio-wastes can be employed cost-effectively as the primary raw materials for the preparation of biodiesel to supplement diesel fuel consumption. Further, biodiesel usage can be increased by adding certain additives, with alcohol being an excellent choice. In this study, the performance of a single-cylinder, four-stroke diesel engine is evaluated when the engine is run with the five different prepared test fuel blends. The experimental findings are summarized as follows:

- The addition of the extra constituents, viz., butanol and C-oil (biodiesel from WCCO), proved beneficial when the engine ran at 75 % of its maximum load capacity. With Bu and C-oil addition, the engine's overall performance was equivalent to DB blends, despite a modest fall in engine power and torque values. This is because, in most practical cases, an engine performs better when it is run at an optimum load condition.
- At a given temperature, the B1 blend possesses the highest values of flash and fire point, density, and kinematic viscosity, whereas blend B5 has the least values, while the maximum calorific value occurs for blend B3.
- The engine test run shows that the choice of biodiesel blends for maximum engine BP varies with load and occurs for different blends at different loads. However, the engine IP is independent of the choice of blend and has maximum value for the blend B3 at all loads.
- Similarly, the maximum BSFC is found to be independent of the choice of blend and has the maximum value for the blend B5 at all loads.
- The maximum brake thermal efficiency occurs in the case of blend B1 under all loads except the half-full load, where B2 blend provides the highest value. This appears due to the absence of butanol in blends B1 and B2.
- Lastly, blend B5 has the highest fuel flow rate because the fraction of butanol has been doubled compared to blends B3 and B4.

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References

1. D. Huang, H. Zhou, and L. Lin, Egy Procedia **16**, 1874 (2012). d https://doi.org/10.1016/j.egypro.2012.01.287
2. A. K. Agarwal, Prog. Egy and Comb Sci. **33**, 233 (2007). https://doi.org/10.1016/j.pecs.2006.08.003
3. A. Zhou and E. Thomson, Appl. Egy. **86**, S11 (2009). https://doi.org/10.1016/j.apenergy.2009.04.028
4. E. C. Quaye, Ren. Egy. **9**, 1029 (1996). https://doi.org/10.1016/0960-1481(96)88455-2
5. S. V. R. K. Prabhakar and M. Elder, Appl. Egy. **86**, 30 (2009). https://doi.org/10.1016/j.apenergy.2009.04.026
6. T. Mizik, Clean Tech. **3**, 19 (2021). https://doi.org/10.3390/cleantechnol3010002
7. R. Kamaraj, Y. K. S. S. Rao, and B. Balakrishna, Env. Sci. Pollu. Res. **29**, 43770 (2022). https://doi.org/10.1007/s11356-021-13316-8
8. V. Perumal and M. Ilangkumaran, Energy **129**, 228 (2017). https://doi.org/10.1016/j.energy.2017.04.120
9. M. C. Ncibi and M. Sillanpää, Rec. Pat. Chem. Engg. **6**, 184 (2013). https://doi.org/10.2174/22113347079991402211646O9
10. S. K. Narwal and R. Gupta, Biotechnol. Lett. **35**, 479 (2013). https://doi.org/10.1007/s10529-012-1116-z
11. M. M. Rana, M. H. Khan, M. A. K. Azad, S. Rahman, and S. A. Kabir, J. Sci. Res. **12**, 15 (2020). https://doi.org/10.3329/jsr.v12i1.41501
12. S. O. Bitire and T. C. Jen, Mat. Ren. Sus. Energy **11**, 143 (2022). https://doi.org/10.1007/s40243-022-00213-4
13. A. Chaudhary, S. H. Panchal, A. Surana, M. Sreekanth, S. Ismail, and M. Feroskhan, J. Therm. Anal. Cal. **147**, 2455 (2022). https://doi.org/10.1007/s10973-021-10642-4
14. J. Yan, X. Zheng, and S. Li, Biores. Tech. **151**, 43 (2014). https://doi.org/10.1016/j.biortech.2013.10.037
15. M. U. H. Suzihaque, H. Alwi, U. K. Ibrahim, S. Adullah, and N. Haron, Mat. Today Proc. **63**, S490 (2022). https://doi.org/10.1016/j.matpr.2022.04.527
16. C. Lopresto, S. Naccarato, L. Albo, M. De Paola, S. Chakraborty, and S. Curcio, Ecotox. Environ. Saf. **121**, 229 (2015). https://doi.org/10.1016/j.ecoenv.2015.03.028
17. M. C. Bobadilla, R. L. Lorza, R. E. García, F. S. Gómez, and E. P. V. González, Energies **10**, 130 (2017). https://doi.org/10.3390/en10010130
18. T. A. Degfie, T. T. Mamo, and Y. S. Mekonnen, Sci. Rep. **9,** 18982 (2019). https://doi.org/10.1038/s41598-019-55403-4
19. A. Monyem, M. Canakci, and J. H. Van Gerpen, Appl. Eng. Agri. **16**, 373 (2000). https://doi.org/10.13031/2013.5213
20. A. T. Hoang, J. Marine Eng. Tech. **20**, 229 ((2021). https://doi.org/10.1080/20464177.2018.1532734
21. G. Dwivedi and M. P. Sharma, Int. J. Ren. Energy Res. **3**, 827 (2013).
22. S. B. Lee, K. H. Han, J. D. Lee, and I .K. Hong, J. Ind. Eng. Chem. **16**, 1006 (2010). https://doi.org/10.1016/j.jiec.2010.09.015
23. O. Özener, L. Yüksek, A. T. Ergenç, and M. Özkan, Fuel **115**, 875 (2014).

https://doi.org/10.1016/j.fuel.2012.10.081
24. R. K. Pathak, M. Mohsin, and S. K. Mehta, J. Sci. Res. **13**, 589 (2021). https://doi.org/10.3329/jsr.v13i2.49783
25. J. Kakati and T. K. Gogoi, Energy Conv. Mgmt. **121**, 152 (2016)**.** https://doi.org/10.1016/j.enconman.2016.05.019
26. T. K. Gogoi and D. C. Baruah, Appl. Egy. **88**, 2713 (2011). https://doi.org/10.1016/j.apenergy.2011.02.023
27. H. A. Abhishek, N. Kumar, and G. Irfan. Int. J. Mech. Eng. Tech. **8**, 184 (2017).
28. M. Z. IŞIK, App. Therm. Eng. **184**, ID 116142 (2021). https://doi.org/10.1016/j.applthermaleng.2020.116142
29. Q. Ma, Q. Zhang, J. Liang, and C. Yang, Energy Report **7**, 1016 (2021). https://doi.org/10.1016/j.egyr.2021.02.027
30. M. A. Akar, Adv. Mech. Eng. **8** (2016). https://doi.org/10.1177/1687814016632677
31. I. Erol, A. Alpaslan, and N. Yilmaz, J. Egy. Inst. **89**, 586 (2016). https://doi.org/10.1016/j.joei.2015.06.004
32. L. Haifeng, X. Wang, Z. Zheng, J. Gu, H. Wang, and Y. Mingfa, Energy **74**, 741 (2014). https://doi.org/10.1016/j.energy.2014.07.041