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Comparative Analysis of Jatropha and Waste Cooking Oil Biodiesel Blends: Fuel Properties, Engine Performance, and Emissions

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Abstract: - This study evaluates the fuel properties, engine performance and emission characteristics of biodiesel-diesel blends prepared from Jatropha oil and waste cooking oil (WCO). Three biodiesel feedstock combinations were considered: J50W50, J70W30 and J60W40, where the notation represents the volume percentage of Jatropha biodiesel and WCO biodiesel in the biodiesel fraction. Four biodiesel-diesel blends, B20, B40, B60 and B80, were tested in a single-cylinder, four-stroke, direct-injection diesel engine at 1500 rpm and a fixed-load operating point corresponding to approximately 72% of the rated engine power. Fuel properties, brake power (BP), brake specific fuel consumption (BSFC), brake thermal efficiency (BTE) and exhaust emissions (CO_2, CO, HC and NO_x) were measured and compared with diesel operation. The results show that biodiesel blends produced lower brake power and higher BSFC than diesel under the selected operating condition, while HC emissions were generally lower. CO and NO_x trends were blend-dependent. However, the measured viscosity, density and calorific-value data for several high-biodiesel blends fall outside the expected ranges reported for biodiesel fuels and standards; therefore, the fuel-property results are treated as preliminary values requiring instrument calibration verification and repeated measurements. The revised analysis avoids using these questionable fuel-property values to draw strong combustion correlations and identifies J70W30-B60 CO_2 as an outlier requiring re-measurement. The study highlights the potential of Jatropha-WCO biodiesel blends while emphasizing the need for rigorous fuel-property validation before final performance-emission correlations are published.

Keywords: *Biodiesel; Jatropha oil; Waste cooking oil; Binary biodiesel blend; Transesterification; CI engine; Emissions; Uncertainty analysis.*

1. Introduction

1.1. Background

The depletion of petroleum resources and increasing concern over exhaust emissions have encouraged the use of renewable oxygenated fuels in compression-ignition (CI) engines. Biodiesel, commonly produced from vegetable oils, non-edible oils, animal fats and waste cooking oil, is biodegradable and can be used in diesel engines as a neat fuel or in blends with petroleum diesel. Transesterification reduces the high viscosity of raw oils and produces fatty-acid methyl esters suitable for fuel applications [1-6].

Jatropha oil is an attractive non-edible feedstock, while waste cooking oil (WCO) is a low-cost waste-derived feedstock that can reduce disposal problems and overall biodiesel production cost. Binary biodiesel blending, in which methyl esters from two feedstocks are mixed before blending with diesel, can balance fuel properties and combustion behaviour. Recent studies on Jatropha-WCO and other WCO-based blends show that engine performance and emissions depend strongly on biodiesel fraction, feedstock composition, injection parameters and engine load [7-10].

1.2. Problem statement and objectives

Although Jatropha biodiesel and WCO biodiesel have been studied separately, comparatively fewer studies report binary Jatropha-WCO biodiesel blends at multiple biodiesel-diesel blend levels under the same engine operating condition. This work evaluates J50W50, J70W30 and J60W40 biodiesel combinations at B20, B40, B60 and B80 blend levels. The objectives are to: (i) measure fuel properties including flash point, fire point, kinematic viscosity, density, specific gravity and calorific value; (ii) evaluate BP, BSFC and BTE at a fixed operating condition; (iii) measure CO_2, CO, HC and NO_x emissions; and (iv) compare the results with standard/literature ranges and identify any data requiring revalidation.

1.3. Literature basis for expected trends

Published literature generally reports that increasing biodiesel fraction increases fuel density and viscosity while reducing the lower heating value relative to petroleum diesel. These trends usually increase BSFC and may reduce BTE at high biodiesel fractions, although oxygen content can reduce HC and CO under some conditions. Ibrahim et al. [7] specifically investigated Jatropha-WCO biodiesel blends and reported that blend response depends on output power and biodiesel composition. Recent WCO studies also show that CO, HC, CO_2 and NO_x do not always vary in the same direction, especially when additives, injection pressure or load are changed [8-10]. Therefore, strong claims of universal emission reduction are avoided in the present revision.

2. Materials and Methods

2.1. Feedstocks, nomenclature and biodiesel preparation

Jatropha oil and filtered waste cooking oil were used as feedstocks. Waste cooking oil was filtered to remove food particles and suspended impurities before processing. The biodiesel feedstock combinations were denoted as J50W50, J70W30 and J60W40, where J and W represent Jatropha biodiesel and WCO biodiesel, respectively. For example, J70W30-B60 denotes a fuel containing 60% biodiesel and 40% diesel, where the biodiesel portion consists of 70% Jatropha biodiesel and 30% WCO biodiesel by volume.

A two-stage process was used because high free fatty acid (FFA) content can reduce conversion efficiency during direct base-catalysed transesterification. In the first stage, acid esterification was carried out at 60 °C using concentrated H_2SO_4 at 1% w/w of oil and anhydrous methanol at a 6:1 methanol-to-oil molar ratio. The mixture was stirred for 2 h, settled in a separating funnel, and washed to remove residual acid and methanol. In the second stage, base-catalysed transesterification was performed at 60 °C using NaOH at 0.5% w/w of oil and anhydrous methanol at the same 6:1 molar ratio. The reaction mixture was stirred for 1 h, settled for glycerol separation, washed repeatedly with warm water until approximately neutral wash-water pH (about 6.8-7.2), and dried at 100 °C for 1 h to remove residual water.

2.2. Blend preparation

Four biodiesel-diesel blends were prepared for each feedstock combination: B20, B40, B60 and B80. B20 contains 20% biodiesel and 80% diesel by volume, whereas B80 contains 80% biodiesel and 20% diesel. Before testing, each blend was mixed until visually homogeneous and stored in sealed containers to minimize moisture absorption.

2.3. Fuel-property testing and calibration verification

Flash point was measured using a Pensky-Martens closed-cup apparatus according to ASTM D93. Kinematic viscosity should be reported at 40 °C using a calibrated capillary viscometer consistent with ASTM D445. Density and specific gravity should be corrected to the reference temperature of 15 °C using a hydrometer method consistent with ASTM D1298 or a digital density meter method consistent with ASTM D4052. Calorific value was measured using a bomb calorimeter consistent with ASTM D240. The present manuscript retains the original measured fuel-property values, but the values are explicitly flagged for revalidation because several high-biodiesel blends fall below expected biodiesel/diesel-blend viscosity and density ranges and show calorific values closer to diesel than expected for B80 fuels.

The viscometer constant, bath temperature, hydrometer/density-meter correction, bomb-calorimeter calibration with benzoic acid, thermometer calibration and sample moisture control should be verified. At least three repeat measurements are recommended for each fuel-property parameter. In the present figures, error bars show instrument-level uncertainty.

2.4. Engine performance and emission testing

The engine tests were conducted using a single-cylinder, four-stroke, water-cooled, direct-injection Kirloskar diesel engine coupled to an eddy-current dynamometer. The engine had a bore and stroke of 80 mm x 110 mm, rated power of 3.75 kW, compression ratio of 17.5:1 and rated speed of 1500 rpm. The injection pressure range was 160-220 bar and injection timing was 25 deg bTDC. The tests were conducted at a fixed operating point near 2.7 kW for diesel, corresponding to approximately 72% of rated power. This mid-high load was selected to avoid instability at low load and thermal overload near rated full load while providing stable emission readings. The dynamometer load was adjusted to maintain the selected load, and the engine governor/fuel-rack setting maintained the speed at 1500 rpm for all fuels.

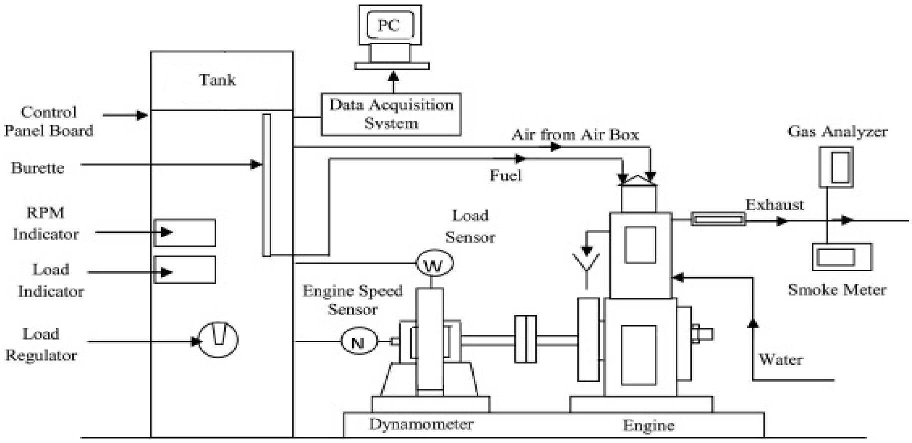

Figure 1: Schematic diagram of the experimental engine test setup

Brake power was calculated from the dynamometer load and engine speed. BSFC was calculated from measured fuel consumption rate divided by brake power. BTE was calculated as the ratio of brake power output to the chemical energy input of the fuel. Exhaust emissions were measured using an ECO GAS-4 gas analyser. CO_2 and CO were measured using non-dispersive infrared sensing, HC using flame-ionisation detection and NO_x using chemiluminescence/electrochemical detection depending on analyser configuration. The gas analyser should be zeroed and span-calibrated before each set of tests. The number of test repetitions and standard deviations must be reported when repeat data are available.

3. Results and Discussion

3.1. Fuel properties and critical plausibility check

Tables 1-3 show the measured fuel properties. A diesel reference row has been added for direct comparison. The numerical values are retained from the experimental dataset, but the interpretation has been revised because the measured viscosity and density of several biodiesel-rich blends are lower than expected for biodiesel-diesel blends. For B100 biodiesel, standards and literature commonly report viscosity and density ranges higher than those of diesel; therefore, the low B80 values in the present dataset indicate possible unit, temperature-correction or calibration errors.

Table 1. Fuel properties of Jatropha 50% + WCO 50% blends with diesel reference.

Fuel	Flash point (°C)	Fire point (°C)	Viscosity (cSt at 40 °C)	Density (kg/m^3 at 15 °C)	Specific gravity	Calorific value (kJ/kg)

B20	61	85	1.98	792	0.792	43500
B40	69	84	2.01	801	0.801	42346
B60	74	88	2.12	814	0.814	42345
B80	94	115	2.42	828	0.828	42250
Diesel reference	56	64	2.90	850	0.850	42000

Table 2. Fuel properties of Jatropha 70% + WCO 30% blends with diesel reference.

Fuel	**Flash point (°C)**	**Fire point (°C)**	**Viscosity (cSt at 40 °C)**	**Density (kg/m³ at 15 °C)**	**Specific gravity**	**Calorific value (kJ/kg)**
B20	60	79	1.63	794	0.794	43410
B40	74	84	1.82	823	0.823	42312
B60	78	88	1.92	819	0.819	42310
B80	94	108	2.16	816	0.816	42150
Diesel reference	56	64	2.90	850	0.850	42000

Table 3. Fuel properties of Jatropha 60% + WCO 40% blends with diesel reference.

Fuel	**Flash point (°C)**	**Fire point (°C)**	**Viscosity (cSt at 40 °C)**	**Density (kg/m³ at 15 °C)**	**Specific gravity**	**Calorific value (kJ/kg)**
B20	60	82	1.95	795	0.795	43450
B40	80	98	2.10	823	0.823	42340
B60	81	100	2.15	803	0.803	42220
B80	92	104	2.21	818	0.818	42110
Diesel reference	56	64	2.90	850	0.850	42000

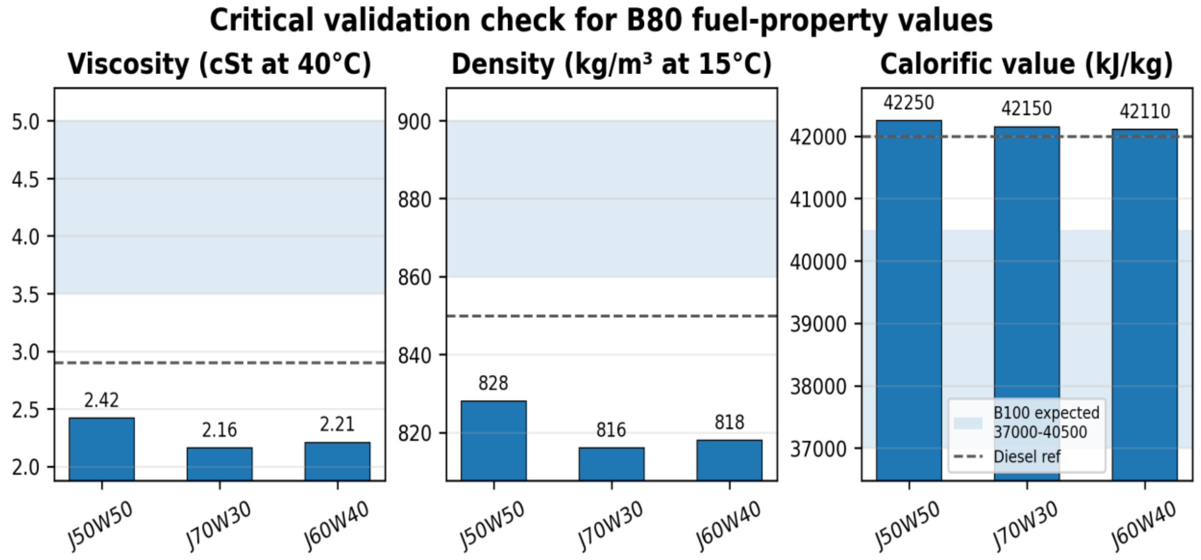

Figure 2. Critical validation check for B80 fuel-property values. Shaded bands indicate broad expected B100 biodiesel ranges; the low measured viscosity and density values remain flagged for re-measurement.

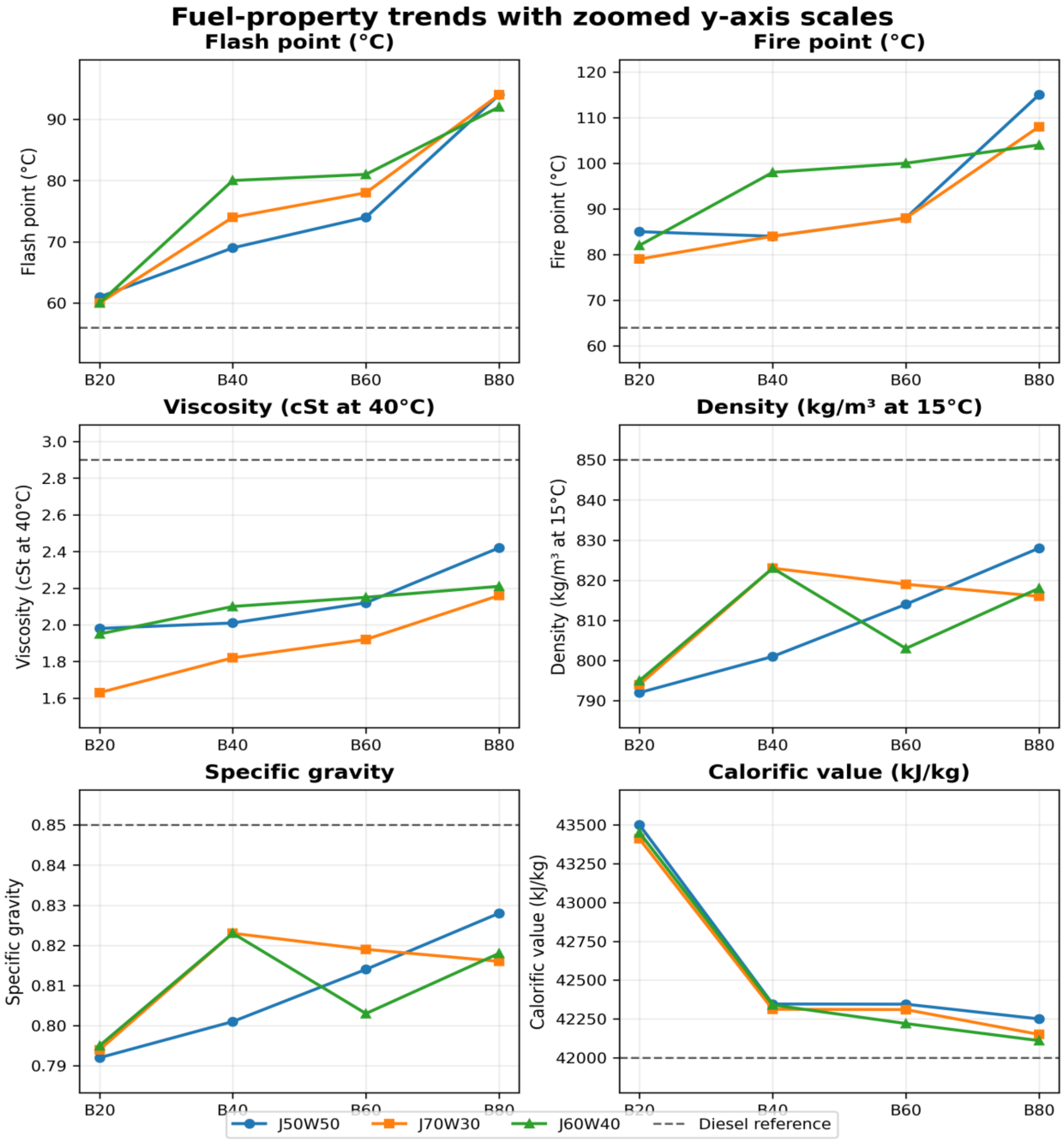

Figure 3. Fuel-property trends redrawn with separate zoomed y-axis scales to make blend-to-blend variation visible. Diesel reference lines are included for direct comparison.

The fuel-property data should not be used to draw strong mechanistic links with engine performance until the measurement issue is resolved. Specifically, B80 blends would normally be expected to have higher viscosity and density than B20 blends and a lower calorific value than diesel. The present B80 calorific values remain close to diesel, while viscosity and density remain unusually low. Possible causes include reporting viscosity at a temperature other than 40 °C, uncorrected hydrometer readings, calibration drift, residual alcohol contamination, sample-water contamination, or unit conversion errors. These possibilities should be examined using fresh samples and calibrated instruments.

3.2. Engine performance

Table 4. Performance parameters of Jatropha 50% + WCO 50% blends at 1500 rpm and fixed load.

Fuel	BP (kW)	BSFC (kg/kW-h)	BTE (%)
B20	2.664	0.598	13.229
B40	2.643	0.646	12.219
B60	2.630	0.639	12.394
B80	2.605	0.681	11.696
Diesel reference	2.713	0.470	16.805

Table 5. Performance parameters of Jatropha 70% + WCO 30% blends at 1500 rpm and fixed load.

Fuel	BP (kW)	BSFC (kg/kW-h)	BTE (%)
B20	2.570	0.583	13.855
B40	2.576	0.635	15.553
B60	2.612	0.658	12.181
B80	2.598	0.680	11.831
Diesel reference	2.713	0.470	16.805

Table 6. Performance parameters of Jatropha 60% + WCO 40% blends at 1500 rpm and fixed load.

Fuel	BP (kW)	BSFC (kg/kW-h)	BTE (%)
B20	2.570	0.583	13.855
B40	2.576	0.635	14.553
B60	2.612	0.658	12.181
B80	2.548	0.680	13.821
Diesel reference	2.713	0.470	16.805

Diesel produced the highest BP and lowest BSFC under the selected test condition. The biodiesel blends generally showed slightly lower BP and higher BSFC than diesel. This behaviour is consistent with many biodiesel studies, where higher density, viscosity and lower heating value can increase fuel consumption for a given brake output. However, because the present fuel-property measurements require revalidation, the performance trends are discussed directly from measured engine output rather than from the questionable fuel-property values.

The identical BP and BSFC values reported for J70W30-B20 and J60W40-B20, and the similarity of some rows in Tables 5 and 6, should be checked against the original log sheets. If the values are confirmed, the manuscript should state that the differences between those blends were within instrument resolution at the selected operating condition.

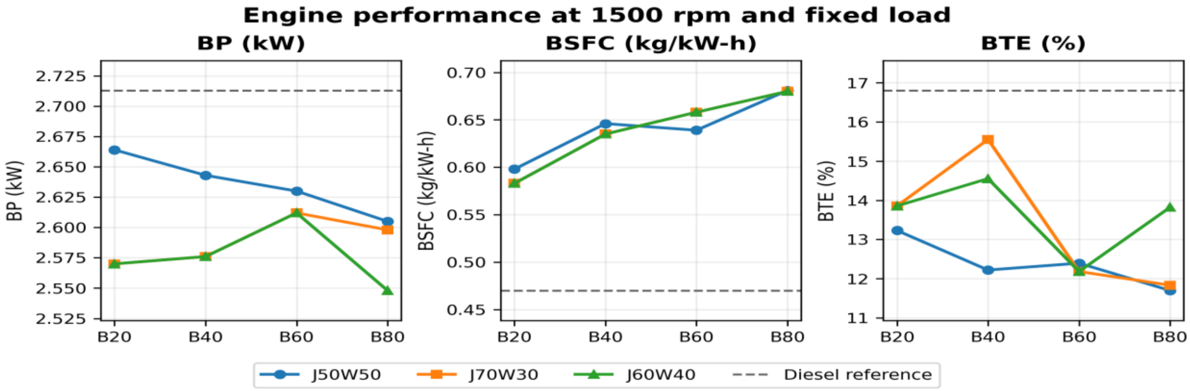

Figure 4. Engine performance of Jatropha-WCO biodiesel blends at the fixed test point, redrawn using separate scaled panels so BP, BSFC and BTE.

3.3. Emission characteristics

Table 7. Emission parameters of Jatropha 50% + WCO 50% blends at 1500 rpm and fixed load.

Fuel	CO_2 (%)	CO (%)	HC (ppm)	NO_x (ppm)
B20	7.3	0.75	65	536
B40	7.4	1.01	63	525
B60	7.5	0.64	61	569
B80	7.3	0.76	74	542
Diesel reference	7.0	0.69	89	527

Table 8. Emission parameters of Jatropha 70% + WCO 30% blends at 1500 rpm and fixed load.

Fuel	CO_2 (%)	CO (%)	HC (ppm)	NO_x (ppm)
B20	7.4	1.20	75	504
B40	6.7	0.92	63	436
B60	4.3	0.67	37	330
B80	6.5	1.08	64	405
Diesel reference	7.0	0.69	89	527

Table 9. Emission parameters of Jatropha 60% + WCO 40% blends at 1500 rpm and fixed load.

Fuel	CO_2 (%)	CO (%)	HC (ppm)	NO_x (ppm)
B20	7.3	0.75	65	536
B40	7.4	1.01	63	525
B60	7.5	0.64	61	569
B80	6.9	0.71	67	508
Diesel reference	7.0	0.69	89	527

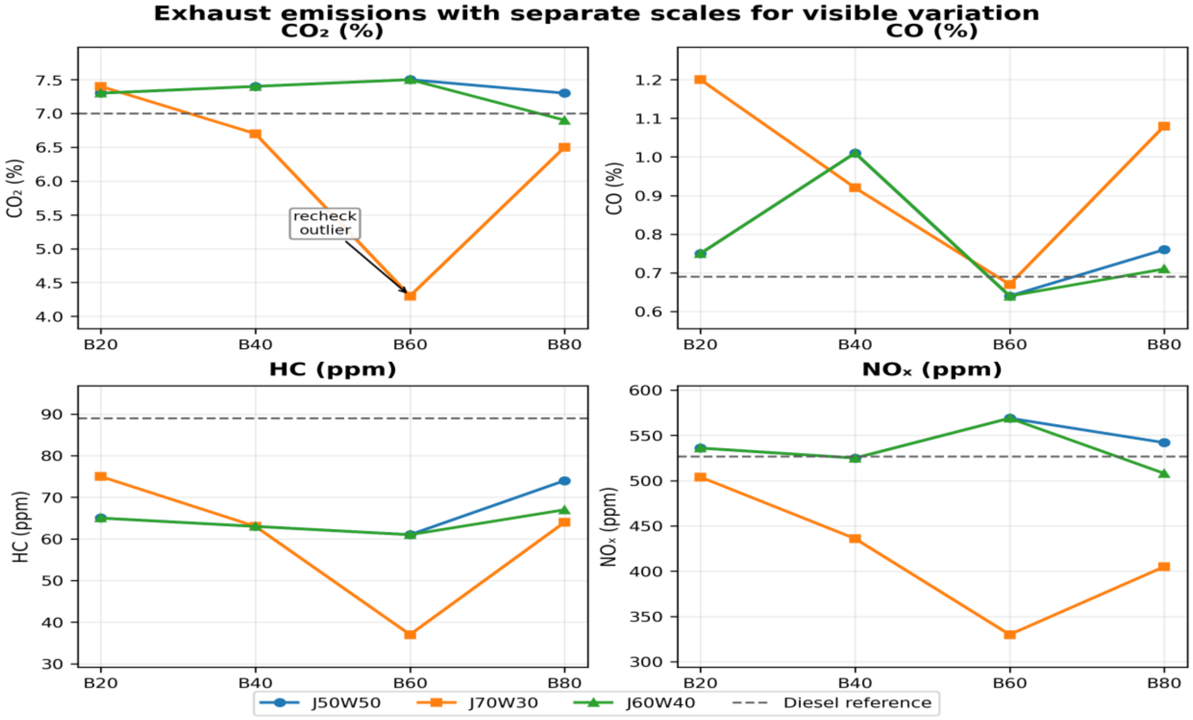

Figure 5. Exhaust emissions of Jatropha-WCO biodiesel blends, redrawn with separate scales for CO_2, CO, HC and NO_x. The J70W30-B60 CO_2.

HC emissions were generally lower for biodiesel blends than for diesel, which may be associated with the oxygenated nature of biodiesel promoting oxidation of unburned hydrocarbons. CO values were not consistently lower than diesel; several blends showed higher CO, indicating possible incomplete combustion, mixture preparation effects or operating-point sensitivity. NO_x behaviour was also blend-dependent. Therefore, the revised manuscript avoids the unsupported claim that all emissions were significantly reduced.

The J70W30-B60 blend shows a CO_2 value of 4.3%, which is more than 35% lower than diesel despite comparable brake power. This result is unusual because a similar brake output generally requires comparable fuel carbon input unless the mixture is much leaner or the emission measurement is affected by dilution, analyser calibration or sampling error. The simultaneous decrease in NO_x to 330 ppm further indicates that this point should be re-measured. Until repeat data confirm the value, J70W30-B60 CO_2 is interpreted as a potential outlier and not used as the basis for a strong environmental claim.

3.4. Comparison with published journal trends and standards

The present results were compared with earlier biodiesel studies and fuel standards to check whether the observed trends are reasonable. In general, biodiesel blends are expected to have higher viscosity and density and lower calorific value than diesel. Because of this, many studies report higher BSFC and a slight reduction in engine performance when the biodiesel percentage increases.

In this study, diesel gave the highest brake power and the lowest BSFC, while most Jatropha–WCO biodiesel blends showed slightly lower brake power and higher fuel consumption. This trend is in line with previous biodiesel engine studies. The HC emissions were lower for most biodiesel blends, mainly because biodiesel contains oxygen, which helps in better combustion. However, CO and NO_x did not follow a fixed trend and changed with blend ratio and feedstock composition.

Some fuel-property values, especially for higher biodiesel blends, were not fully matching the expected trend. The viscosity, density and calorific value results should therefore be checked again with calibrated instruments and repeated trials. The low CO_2 value observed for J70W30-B60 also needs confirmation before making any strong claim. Overall, the results agree with published trends for performance and HC emissions, but further validation is required for more reliable interpretation

Table 10. Literature/standard comparison.

Parameter	Published journal/standard trend	Present data	Revision made
Jatropha-WCO binary biodiesel blends	Ibrahim et al. [7] reported Jatropha-WCO biodiesel blends and found best performance/emission balance at lower biodiesel fractions; DOI: 10.1177/09544062231181809.	The present work uses higher B20-B80 blend levels and shows higher BSFC than diesel at the fixed point.	Discussion now compares trends cautiously and avoids broad emission-reduction claims.
Biodiesel-rich fuel viscosity and density	ASTM D6751 covers B100 biodiesel blendstock properties and EN-type biodiesel specifications commonly place B100 viscosity/density above diesel ranges [11].	Measured B80 viscosity (2.16-2.42 cSt) and density (816-828 kg/m³) are unexpectedly low.	Fuel-property results are flagged as preliminary and requiring recalibration/repetition.
Calorific value	Biodiesel heating value is normally lower than diesel due to oxygen content; ASTM D240 defines heat-of-combustion measurement [12].	B80 values remain close to diesel, which is inconsistent with expected high-biodiesel behaviour.	Calorific-value interpretation was corrected and no longer supports strong conclusions.

Performance trends	El-Shafay et al. [9] reported that binary WCO/Jatropha or related hybrid blends often increase SFC and reduce thermal efficiency relative to diesel; DOI: 10.1016/j.csite.2025.106688.	Most blends show lower BP/higher BSFC than diesel, consistent with this direction.	Performance discussion was retained but decoupled from questionable fuel-property correlations.
WCO biodiesel emission trade-offs	Recent WCO biodiesel studies report emission trade-offs rather than universal reductions [8,10].	HC decreases generally, but CO and NO_x vary; J70W30-B60 CO_2 is anomalously low.	Abstract and conclusion now state that emissions are blend-dependent and that the outlier must be re-measured.
Uncertainty and repeatability	Publication-quality engine studies normally report repetitions, standard deviations or error bars.	Original dataset provides single values only.	A repeatability/uncertainty subsection and provisional instrument-level error bars were added; final SDs must be inserted after repeated tests.

4. Conclusion

The present study examined Jatropha–waste cooking oil biodiesel blends in a single-cylinder diesel engine at 1500 rpm and about 72% load. From the results, it can be observed that diesel gave the best brake power and the lowest fuel consumption. Most biodiesel blends showed slightly lower brake power and higher BSFC than diesel.

Among the emission results, HC was reduced for most biodiesel blends, which may be due to the oxygen content present in biodiesel. However, CO and NO_x did not show a regular trend, and their values changed with blend percentage and feedstock ratio. This shows that the emission behaviour of Jatropha–WCO biodiesel blends depends on the blend composition.

Some fuel-property values, especially for higher biodiesel blends, did not fully match the expected biodiesel trend. Therefore, viscosity, density and calorific value should be checked again using calibrated instruments and repeated tests. The low CO_2 value recorded for J70W30-B60 also needs confirmation before making a strong conclusion.

Overall, Jatropha and waste cooking oil biodiesel blends can be considered as possible alternative fuels for diesel engines, mainly for reducing HC emissions. However, further testing with repeat readings and proper uncertainty analysis is required before final performance and emission conclusions are made.

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