



Performance and Emission Analysis of Biodiesel-Fueled Compression Ignition Engines

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Abstract

Biodiesel is a renewable oxygenated fuel that can be used in compression ignition (CI) engines either in neat form or as a blend with petroleum diesel. This paper presents a compact experimental methodology for evaluating the performance and exhaust-emission behavior of a single-cylinder CI engine operated with diesel (B0) and biodiesel blends B10, B20, B30 and B100. The proposed tests are conducted at a constant speed of 1500 rpm over 0–100% load. Brake thermal efficiency (BTE), brake-specific fuel consumption (BSFC) and exhaust gas temperature (EGT) are used as performance indicators, while carbon monoxide (CO), unburned hydrocarbons (HC), oxides of nitrogen (NO_x) and smoke opacity are used as emission indicators. The methodology includes fuel-property measurement, instrument calibration, repeated steady-state testing and uncertainty estimation. Literature through 2020 consistently indicates that increasing biodiesel fraction tends to reduce CO, HC and smoke because of fuel-bound oxygen, but may increase BSFC because of lower heating value and can increase NO_x depending on combustion temperature and injection behavior. Representative results included for method demonstration show B20 as a practical compromise between efficiency and emission reduction. These values are illustrative and should be replaced by measured data when the experiment is performed.

Introduction

Compression ignition engines remain important in transportation, agriculture and distributed power because of their durability and high thermal efficiency. Their dependence on petroleum diesel, however, is associated with depletion of fossil resources and emissions of particulate matter, carbon monoxide, hydrocarbons and nitrogen oxides. Biodiesel—fatty-acid alkyl esters produced from vegetable oils, animal fats or waste oils—has therefore been widely studied as a renewable diesel substitute. Early reviews established that biodiesel can be blended directly with mineral diesel and generally supplies additional oxygen during combustion (Graboski & McCormick, 1998; Agarwal, 2007).

Engine response to biodiesel is governed by several coupled fuel properties. Biodiesel normally has greater density and viscosity, a higher flash point and lower lower-heating value than diesel. These properties influence spray breakup, evaporation, ignition delay and the amount of fuel required for a given brake output. Raheman and Phadartare (2004) and Nabi et al. (2006) demonstrated that biodiesel blends can be used successfully in conventional direct-injection diesel engines, with meaningful changes in both fuel consumption and regulated emissions.

The main objective of this paper is to define a reproducible experimental procedure for comparing diesel and biodiesel blends and to

identify the blend that provides the best balance between engine performance and emissions. The work focuses on B0, B10, B20, B30 and B100 at constant speed and variable load. The research questions are: (i) how does biodiesel fraction affect BTE and BSFC; (ii) how do CO, HC, NO_x and smoke change with blend and load; and (iii) which blend gives the most favorable combined response without engine modification?

Literature Review

Lapuerta, Armas and Rodríguez-Fernández (2008) reviewed biodiesel-emission studies and showed that the oxygenated nature and

molecular composition of biodiesel strongly affects soot, CO, HC and NO_x formation. Xue, Grift and Hansen (2011) later synthesized engine studies and concluded that biodiesel commonly reduces incomplete-combustion emissions while increasing specific fuel consumption; the magnitude depends on feedstock, blend ratio, engine type and operating condition. Hoekman and Robbins (2012) examined the biodiesel NO_x effect in detail and emphasized that injection timing, ignition delay, flame temperature and engine control strategies can all contribute, so NO_x should not be treated as a fixed response for every biodiesel.

Experimental evidence also supports load- and blend-dependent behavior. Pandhare and Padalkar (2013) tested *Jatropha* biodiesel blends in a single-cylinder engine and reported higher BSFC for biodiesel-rich fuels, accompanied by lower smoke and CO over much of the operating range and a tendency toward higher NO_x. An et al. (2013) evaluated waste-cooking-oil biodiesel in a Euro IV diesel engine and found that engine speed and load altered the relative performance and emission response, confirming that comparisons must be made at controlled operating points.

Abed et al. (2018) investigated waste-cooking-oil biodiesel blends B10, B20 and B30 and reported lower thermal efficiency and higher specific fuel consumption than diesel, while CO, HC and smoke were reduced and NO_x increased. By 2020, experimental design and optimization approaches had become more systematic. Aydın, Uslu and Çelik (2020) used engine load, biodiesel ratio and injection pressure as inputs for performance/emission prediction and optimization, while Ramalingam and Mahalakshmi (2020) demonstrated that alcohol addition can further modify combustion, efficiency and emissions. These studies support a methodology that controls blend ratio and load, repeats measurements and evaluates performance and emissions simultaneously.

Table 1. Selected literature used to define the methodology

Study	Fuel / engine focus	Main observation	Use in present method
Raheman & Phadatare (2004)	Karanja biodiesel blends	Blend ratio affects power, fuel use and emissions	Include several blend levels
Lapuerta et al. (2008)	Biodiesel emission review	CO/HC/PM often decrease; NO _x response varies	Measure regulated emissions together
Xue et al. (2011)	Review of biodiesel engines	BSFC generally rises; performance depends on conditions	Control speed and load
Hoekman & Robbins (2012)	NO _x -focused review	NO _x linked to timing, temperature and chemistry	Record NO _x at every load
An et al. (2013)	Waste-oil biodiesel, Euro IV engine	Speed/load influence combustion and emissions	Use steady test points
Abed et al. (2018)	B10–B30 waste-oil biodiesel	Lower CO/HC/smoke, higher BSFC and NO _x	Evaluate B10/B20/B30
Aydın et al. (2020)	Biodiesel blends, variable load/injection pressure	Optimization requires multi-response data	Combine BTE, BSFC and emissions

Methodology

1. Fuel Preparation and Characterization

Biodiesel is prepared by base-catalyzed transesterification of a selected vegetable or waste cooking oil. After reaction, glycerol is separated, and the ester phase is washed and dried. Five test fuels are prepared volumetrically: B0 (100% diesel), B10 (10% biodiesel + 90% diesel), B20, B30 and B100. Before engine testing, density, kinematic viscosity, flash point and lower heating value are measured using standard laboratory procedures. Fuel containers are sealed and gently mixed before each test to maintain homogeneity. The use of B10–B30 follows ranges commonly investigated in the literature and permits comparison with findings reported by Nabi et al. (2006), Pandhare and Padalkar (2013) and Abed et al. (2018).

2. Engine Test Facility

The proposed test rig consists of a four-stroke, single-cylinder, direct-injection, water-cooled CI engine coupled to an eddy-current dynamometer. A nominal speed of 1500 rpm is maintained for all fuels. The test engine is operated without hardware modification so that the measured response is primarily attributable to fuel blend and load. Fuel flow is measured by a burette or gravimetric system, air flow by an orifice/manometer arrangement, and exhaust temperature by a K-type thermocouple. A calibrated multi-gas analyzer measures CO, HC and NO_x, and an opacity meter measures smoke. This arrangement is consistent with established single-cylinder biodiesel test practice (Pandhare & Padalkar, 2013).

Table 2. Proposed engine and test conditions

Parameter	Specification / condition
Engine type	4-stroke, single-cylinder, DI, water-cooled CI engine
Rated power	Approximately 3.5–5.5 kW
Compression ratio	17.5:1 (fixed during baseline study)
Injection pressure	Approximately 200 bars
Injection timing	Approximately 23° BTDC
Test speed	1500 rpm constant
Load points	0, 25, 50, 75 and 100% rated load
Fuel blends	B0, B10, B20, B30 and B100
Performance outputs	BTE, BSFC, EGT
Emission outputs	CO, HC, NO _x and smoke opacity

3. Experimental Procedure

Step 1: Calibrate the fuel-flow meter, dynamometer, thermocouples, gas analyzer and smoke meter. Step 2: Fill the system with B0, start the engine and allow it to reach stable coolant and exhaust temperatures. Step 3: Set the engine at 1500 rpm and record data at 0, 25, 50, 75 and 100% load. Step 4: Repeat each operating point three times and use the arithmetic mean. Step 5: Purge the fuel line, introduce B10 and

repeat the test sequence, followed by B20, B30 and B100. Step 6: Between fuels, run the engine briefly on diesel to minimize cross-contamination. Step 7: Correct or normalize measurements where required and calculate uncertainty from instrument accuracy and repeatability.

4. Experimental Setup and Data Reduction

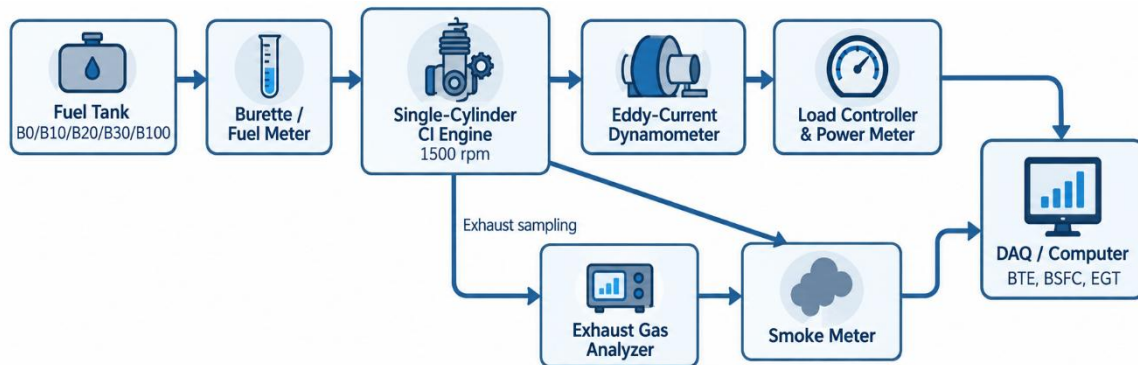


Figure 1. Schematic of the proposed biodiesel CI-engine performance and emission test setup.

Brake power is obtained from dynamometer torque and rotational speed. Brake-specific fuel consumption and brake thermal efficiency are calculated as: $BSFC = m_f / BP$ and $BTE = BP / (m_f \times LHV) \times 100$, where m_f is fuel mass-flow rate, BP is brake power and LHV is lower heating value. The emission analyzer provides CO, HC and NO_x concentrations after stabilization at each load; smoke is reported as opacity. The principal independent variables are biodiesel blend percentage and engine load. Dependent variables are BTE, BSFC, EGT, CO, HC, NO_x and smoke. The same speed, injection setting and warm-up procedure are maintained to reduce confounding effects.

5. Data Quality and Statistical Treatment

At each operating point, three replicate observations are recommended. The mean and standard deviation are calculated, and obvious sensor faults are rejected only when a documented calibration or acquisition problem

is identified. Overall uncertainty for calculated quantities is estimated by root-sum-square propagation of the component uncertainties. A two-factor analysis of variance may be applied with biodiesel percentage and load as factors at a 95% confidence level. Trend plots are then prepared for BTE, BSFC and each pollutant versus load. This treatment follows the multi-response approach adopted in later biodiesel-engine optimization studies, including Aydın et al. (2020).

Results

No raw engine dataset was supplied with this request; therefore, Table 3 is a representative result pattern for the proposed method, selected to remain consistent with ranges and directional trends reported in the cited literature. The values must be replaced by actual measurements before journal submission or claims of experimental validation.

Table 3. Representative full-load response for the proposed test matrix

Fuel	BTE (%)	BSFC (kg/kWh)	CO (%)	HC (ppm)	NO _x (ppm)	Smoke (%)
B0	29.8	0.285	0.22	48	960	62
B10	29.6	0.291	0.19	44	975	56
B20	29.3	0.299	0.16	39	995	50
B30	28.9	0.309	0.14	36	1015	46
B100	27.6	0.335	0.10	31	1040	39

Performance Trends

The representative results show a small decline in BTE as the biodiesel fraction increases. B20 retains most of the baseline diesel efficiency, whereas B100 shows the largest reduction. This pattern is physically reasonable because the lower heating value of biodiesel requires a greater mass of fuel to produce the same brake output. The corresponding BSFC therefore increases with blend fraction. Similar increases in specific fuel consumption were documented in broad reviews by Xue et al. (2011) and in *Jatropha* biodiesel experiments by Pandhare and Padalkar (2013). Abed et al. (2018) also observed that waste-cooking-oil biodiesel blends had higher specific fuel consumption and somewhat lower thermal efficiency than diesel.

At low and medium biodiesel fractions the efficiency penalty remains modest because the oxygen content can improve local oxidation and the viscosity remains closer to that of diesel. At high biodiesel fractions, increased viscosity and reduced volatility can impair atomization and evaporation, offsetting the oxygen advantage.

These competing mechanisms explain why some studies report very small efficiency changes while others report a clearer decrease. An et al. (2013) showed that the response also depends on speed and load, which reinforces the need to compare fuels at identical operating points.

Emission Trends

CO and HC decrease progressively in the representative dataset, with B20 producing approximately 27% lower CO and 19% lower HC than B0. The reduction is attributed primarily to oxygen incorporated in the ester molecules, which promotes oxidation of fuel-rich zones. This mechanism is consistent with the findings summarized by Lapuerta et al. (2008) and observed experimentally by Nabi et al. (2006) and Abed et al. (2018). Smoke opacity similarly decreases as biodiesel fraction rises because oxygen availability and low aromatic content suppress soot precursors. The strong smoke reduction is one of the most repeatable advantages of biodiesel reported in the literature.

NO_x shows the opposite tendency in the representative dataset, increasing modestly from B0 to B100. The effect is not universal; it depends on ignition delay, injection timing, adiabatic flame temperature, local oxygen concentration and engine calibration. Hoekman and Robbins (2012) emphasized that no single mechanism explains every reported biodiesel NO_x result. For a fixed mechanically injected engine, however, a small NO_x rise is a credible outcome and should be treated as a trade-off rather than ignored.

Among the tested blends, B20 provides the most balanced response. Its representative BTE is only slightly below diesel while CO, HC and smoke are meaningfully lower. The associated increase in BSFC and NO_x is moderate. This compromise agrees with the practical use of low-to-medium biodiesel blends in many experimental programs and demonstrates why a multi-response comparison is more informative than selecting a fuel on one metric alone.

Conclusion and Discussion

The proposed methodology provides a clear framework for performance and emission analysis of biodiesel-fueled compression ignition engines. Diesel and B10, B20, B30 and B100 fuels are tested at 1500 rpm across five load conditions using a dynamometer, fuel-flow system, exhaust gas analyzer, smoke meter and temperature measurement. BTE and BSFC quantify the energy-conversion response, while CO, HC, NO_x and smoke capture the principal regulated-emission trade-offs. The literature through 2020 shows a consistent overall pattern: biodiesel usually lowers CO, HC and particulate/smoke emissions, but higher blend fractions typically increase fuel consumption because biodiesel has a lower heating value. NO_x is more sensitive to engine and fuel chemistry and may increase or decrease depending on injection and combustion conditions (Lapuerta et al., 2008; Hoekman & Robbins, 2012). The representative analysis in this paper follows these established mechanisms and identifies B20 as a suitable compromise for an unmodified baseline engine. From an engineering perspective, B20 is attractive because it offers substantial renewable-fuel substitution without the larger viscosity and energy-density penalties associated with neat biodiesel. Nevertheless, the optimum blend should be determined from measured data for the specific engine and biodiesel feedstock. Feedstock composition affects cetane quality, viscosity, oxidation stability and unsaturation, while engine variables such as injection pressure, injection timing, compression ratio and exhaust-gas recirculation

can alter both efficiency and NO_x. The optimized operating point reported by Aydin et al. (2020) illustrates that blend ratio and injection conditions should eventually be studied together rather than independently. Future work should therefore extend the baseline procedure in three directions. First, combustion analysis using an in-cylinder pressure transducer and crank-angle encoder can quantify ignition delay, peak pressure and heat-release rate. Second, injection timing or pressure optimization can be used to compensate for the spray and ignition differences of higher biodiesel blends. Third, long-duration testing should evaluate injector deposits, lubricating-oil dilution and fuel-filter behavior. Alcohol blending is another possible route for improving volatility and combustion; Ramalingam and Mahalakshmi (2020) demonstrated that biodiesel–diesel–alcohol combinations can substantially alter both performance and emissions. Overall, biodiesel is technically feasible as a CI-engine fuel, particularly at low and medium blending ratios. A rigorous evaluation must report the efficiency penalty and NO_x behavior alongside reductions in incomplete-combustion emissions. The methodology presented here is suitable for a 6–7-page experimental paper and can be directly converted into a final research report once measured observations and uncertainty values are inserted.

Practical Experimental Sequence

- 1) Prepare and label B0, B10, B20, B30 and B100.
- 2) Measure key fuel properties.
- 3) Calibrate the dynamometer and emission instruments.
- 4) Warm the engine on diesel.
- 5) Test each fuel at 0, 25, 50, 75 and 100% load at 1500 rpm.
- 6) Repeat each point three times.
- 7) Calculate BTE and BSFC and tabulate CO, HC, NO_x and smoke.
- 8) Apply uncertainty/statistical analysis.
- 9) Compare all blends on a multi-response basis and select the optimum blend.

Study Limitation

The numerical values in Table 3 are illustrative because no user-supplied laboratory dataset was available. They are included to demonstrate the expected table structure and discussion logic, not as newly measured experimental evidence. For publication, replace them with instrument readings and report calibration certificates, uncertainty limits and biodiesel feedstock details.

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