



Performance Evaluation of a Compression Ignition Engine Fueled with Biodiesel Blends Derived from Waste Cooking Oil

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Abstract

Waste cooking oil (WCO) is a low-cost lipid feedstock that can be converted into fatty-acid methyl esters and used as a renewable substitute for petroleum diesel. The present methodology paper develops a reproducible experimental framework for evaluating the performance and exhaust-emission behavior of a compression ignition (CI) engine fueled with WCO biodiesel-diesel blends. The proposed study begins with filtration and moisture removal from collected WCO, followed by base-catalyzed transesterification, phase separation, washing, drying, fuel-property characterization, blend preparation, and engine testing. Five fuels are considered: B0, B10, B20, B30, and B100, where the numerical value denotes the volumetric percentage of WCO biodiesel. Tests are conducted on a single-cylinder, four-stroke, direct-injection diesel engine at constant speed and multiple load points. Brake thermal efficiency (BTE), brake-specific fuel consumption (BSFC), exhaust-gas temperature (EGT), carbon monoxide (CO), unburned hydrocarbons (HC), nitrogen oxides (NO_x), and smoke opacity are used as the principal response variables. Literature published up to 2016 indicates that moderate WCO biodiesel blends can maintain engine efficiency close to diesel while reducing CO, HC, and particulate-related emissions, although NO_x trends can vary with engine design, injection settings, load, and biodiesel fraction. The methodology therefore emphasizes repeat testing, fuel-property control, and statistical comparison so that the optimum blend is selected from a combined performance-emission perspective rather than from a single metric.

Introduction

Compression ignition engines remain important in transportation, agriculture, distributed power generation, and industrial applications because of their high thermal efficiency and durability. Their dependence on petroleum diesel, however, connects engine operation with fossil-resource depletion and pollutant emissions. Biodiesel is an oxygenated fuel consisting mainly of mono-alkyl esters of long-chain fatty acids and can be used in conventional diesel engines either as a neat fuel or in blends. Waste cooking oil is especially attractive because it is a discarded feedstock and

therefore avoids much of the food-versus-fuel concern associated with virgin edible oils. Converting WCO into biodiesel also provides a useful route for diverting greasy wastes from drains and disposal streams. Phan and Phan (2008) demonstrated that waste cooking oil can be converted effectively to biodiesel and highlighted the importance of pretreatment and reaction conditions for obtaining a fuel of acceptable quality.

The main technical obstacle to direct use of waste oil in a diesel engine is its high viscosity and poor

volatility. Transesterification reduces the viscosity by converting triglycerides into fatty-acid methyl esters, thereby improving atomization and combustion. Even after conversion, WCO biodiesel generally has different density, viscosity, heating value, oxygen content, and evaporation characteristics from petroleum diesel. These property differences affect injection, spray development, ignition delay, premixed combustion, diffusion burning, and ultimately engine performance and emissions. Enweremadu and Rutto (2010) concluded from a broad review that used-cooking-oil biodiesel usually gives engine performance only marginally poorer than diesel, while hydrocarbon emissions tend to decrease and NO_x may increase slightly in many engine configurations. At the same time, the review emphasized that results are not universal because fuel composition and engine operating conditions strongly influence combustion behavior.

A large part of the practical value of WCO biodiesel lies in low-to-moderate blending ratios. Utlu and Koçak (2008) reported that a waste-frying-oil methyl ester could provide torque, power, and specific fuel consumption close to conventional diesel while lowering several measured exhaust emissions in a direct-injection engine. Hirkude and Padalkar (2012) similarly found that performance parameters of WCO-based blends were close to diesel, although BSFC increased as biodiesel fraction increased because of the lower heating value of the ester fuel. Their experiments also showed substantial reductions in CO and particulate matter for the tested blends. These results support the need for a controlled study that compares multiple biodiesel fractions under identical operating conditions rather than assuming that either neat biodiesel or a single blend is universally optimum.

The objective of the present methodology is therefore to evaluate the influence of WCO biodiesel blending ratio on a CI engine using a consistent sequence of fuel preparation, property measurement, dynamometer testing, emission measurement, and statistical analysis. The proposed design focuses on B0, B10, B20, B30, and B100. B0 serves as the petroleum-diesel baseline; B10-B30 represent practical low and medium blending levels; and B100 reveals the effect of neat WCO biodiesel. The study is structured to determine whether moderate blends can retain acceptable thermal performance while improving the exhaust-emission profile. Because this paper is methodological, the Results section reports

literature-grounded benchmark trends and expected interpretation criteria rather than presenting fabricated laboratory measurements.

Literature Review

Utlu and Koçak (2008) prepared biodiesel from waste frying oil and tested it in a turbocharged, four-cylinder direct-injection diesel engine. They reported that torque, power, and specific fuel consumption were broadly comparable with No. 2 diesel, while measured CO, CO₂, NO_x, and smoke were lower under their test conditions. Their work established that a properly processed waste-oil methyl ester can function as a direct engine fuel and provided an early experimental basis for performance-emission comparison.

Enweremadu and Rutto (2010) reviewed combustion, emission, and engine-performance studies involving used cooking oil biodiesel. They observed that performance penalties were generally small, while unburned hydrocarbon emissions were usually lower than diesel. The review also showed that NO_x behavior varied across studies, which is important because it indicates that blend percentage alone cannot explain NO_x formation; injection strategy, combustion temperature, engine design, and operating condition must also be considered.

Muralidharan and Vasudevan (2011) evaluated waste-cooking-oil methyl ester blends in a variable-compression-ratio engine at 1500 rpm. Their work showed that compression ratio and blend level interact strongly with BTE, BSFC, exhaust temperature, combustion pressure, and emissions. The authors identified usable blend levels and demonstrated that engine settings must remain controlled or be included explicitly as experimental factors.

Hirkude and Padalkar (2012) tested waste-fried-oil methyl ester in a single-cylinder, four-stroke DI engine. At rated output, they reported that B50 had lower BTE and higher BSFC than diesel, while CO and particulate emissions were reduced across biodiesel blends. The study linked the BSFC increase to lower fuel heating value and showed the environmental advantage of oxygenated fuel in reducing incomplete-combustion products.

Kannan and Anand (2012) examined injection pressure and injection timing using WCO biodiesel in a DI diesel engine. An injection pressure of 280 bar with advanced timing of 25.5 degrees before top dead center improved BTE and combustion response while reducing NO and smoke in their specific configuration. The result demonstrates that fuel evaluation should

document injection settings because the apparent effect of biodiesel depends on the calibration of the engine.

Guo et al. (2012) characterized WCO biodiesel and tested biodiesel blends in two off-road engines. Their biodiesel contained roughly 10% oxygen by mass, and the emission response differed between the two engines. This engine-to-engine variability reinforces the importance of reporting hardware and operating details rather than generalizing a blend result beyond the tested platform.

Nantha Gopal et al. (2014) studied WCO methyl ester-diesel blends and reported lower CO, unburned hydrocarbon, smoke opacity, and BTE for biodiesel blends, together with higher specific energy consumption and NO_x than diesel. Their combustion traces nevertheless followed trends similar to conventional diesel, supporting the feasibility of WCO biodiesel in CI engines with appropriate blend selection.

Hirkude and Padalkar (2014) investigated compression-ratio effects using WCO methyl ester blends. Increasing compression ratio improved BTE and reduced BSFC in their test matrix, while CO and particulate matter decreased and NO_x increased. The study provides a direct methodological reason for holding compression ratio fixed when the principal factor under investigation is blend percentage.

Cheung et al. (2015) tested B0, B10, B20, B30, and B100 in a naturally aspirated DI engine at 1800 rpm over five loads. Increasing biodiesel content generally reduced HC, CO, particulate mass, and particle number but increased NO_x. Their fuel matrix is particularly relevant to the present methodology because it spans both practical blends and neat biodiesel under controlled load variation.

Sanli et al. (2015) compared methyl- and ethyl-ester biodiesels derived from waste frying oil, including 20% blends, in a DI engine. The ester fuels showed higher BSFC than petroleum diesel but lower CO and total hydrocarbon emissions, while NO_x was higher. Their results demonstrate the trade-off between fuel consumption and cleaner incomplete-combustion emissions.

Attia and Hassaneen (2016) evaluated diesel blended with WCO methyl ester at 1500 rpm and different engine loads. Their experiments identified favorable behavior for moderate blending levels: B20 produced a strong BSEC/BTE compromise, while blends in the B20-B50 region gave attractive overall environmental behavior. The study also showed that the

optimum blend depends on whether fuel economy, efficiency, or emissions receive the greatest weight.

Methodology

The methodology is designed as a controlled comparative experiment in which the independent variables are biodiesel blend ratio and engine load, while engine speed, compression ratio, injection hardware, cooling condition, and measurement procedure are held constant. A single batch of WCO biodiesel should be used for the complete test matrix to minimize batch-to-batch variation in fatty-acid composition and fuel properties. Each operating point should be repeated at least three times after thermal stabilization, and the mean value should be used for comparison.

Step 1 - Waste Cooking Oil Collection and Pretreatment

Waste cooking oil should be collected from a consistent source, such as a cafeteria or restaurant, and stored in sealed containers. The oil is first filtered through a fine mesh or filter paper to remove food particles and suspended solids. It is then heated gently to approximately 100-105 degrees C for a short period, or otherwise dried under controlled conditions, to remove residual water. Moisture and excessive free fatty acids can promote soap formation during alkali-catalyzed transesterification, so the acid value should be measured before selecting the catalyst quantity. Phan and Phan (2008) showed that WCO feedstock quality and pretreatment strongly affect conversion efficiency and final biodiesel quality.

Step 2 - Biodiesel Production by Transesterification

The dried WCO is converted to methyl ester using methanol and an alkaline catalyst such as KOH. A practical laboratory procedure is to heat the oil to approximately 55-60 degrees C, dissolve the required catalyst in methanol, add the methoxide solution to the oil, and maintain vigorous stirring for about one hour while keeping the temperature below the boiling point of methanol. After reaction, the mixture is transferred to a separating vessel and left undisturbed so that the denser glycerol phase settles. The upper biodiesel layer is decanted, washed carefully with warm distilled water until residual catalyst and soap are removed, and then dried. Final fuel should be visually clear and free from suspended water or glycerol.

Step 3 - Fuel Characterization and Blend Preparation

Before engine testing, density, kinematic viscosity, flash point, calorific value, and where available cetane index and acid value should be measured using recognized ASTM or equivalent procedures. These properties are needed to explain changes in injection and fuel

consumption. The biodiesel is then blended volumetrically with petroleum diesel to prepare B10, B20, and B30, in addition to B0 and B100. Each blend should be mixed thoroughly and stored in labeled airtight containers. Blend preparation should be completed sufficiently close to testing to minimize oxidation and contamination.

Table 1. Proposed test fuels and their role in the experimental comparison

Fuel	WCO biodiesel (vol.%)	Diesel (vol.%)	Experimental role
B0	0	100	Baseline petroleum diesel
B10	10	90	Low biodiesel blend
B20	20	80	Moderate blend; strong literature benchmark
B30	30	70	Higher practical blend
B100	100	0	Neat WCO biodiesel

Step 4 - CI Engine Test Setup

A single-cylinder, four-stroke, water-cooled, direct-injection diesel engine coupled to an eddy-current or electrical dynamometer is proposed. A constant speed of 1500 rpm is suitable because it is widely used in laboratory CI-engine studies and in earlier WCO biodiesel investigations. The engine compression ratio and original injection timing should remain fixed for all blend comparisons. Load may be applied at approximately 0%, 25%, 50%, 75%, and 100% of rated load. Fuel consumption is measured using a calibrated burette or gravimetric system; air flow is measured with an air box and manometer or mass-flow sensor; and exhaust-gas temperature is measured using a thermocouple positioned in the exhaust manifold.

Step 5 - Emission Measurement and Test Procedure

CO and HC should be measured with a calibrated exhaust-gas analyzer, NO_x with an appropriate electrochemical, chemiluminescence, or equivalent analyzer, and smoke with an opacity meter or smoke meter. Before each fuel test, the engine is warmed until coolant, lubricating-oil, and exhaust temperatures stabilize. The fuel line

is then flushed with the next blend to avoid cross-contamination. At each load, readings are recorded only after speed and exhaust temperature reach a steady state. A minimum of three replicate readings is recommended. Instrument zero and span checks should be performed according to manufacturer procedures.

Step 6 - Performance Calculations and Statistical Analysis

Brake power is obtained from measured torque and speed. BSFC is calculated as the mass flow rate of fuel divided by brake power, typically in kg/kWh. BTE is calculated from brake power divided by the fuel energy-input rate and expressed as a percentage. For each response, the mean, standard deviation, and percentage change relative to B0 should be reported. A two-factor analysis of variance may be used with blend ratio and load as the main factors. When a significant effect is found, post-hoc pairwise comparisons can be applied. An overall optimum blend can be selected by normalizing BTE, BSFC, CO, HC, NO_x, and smoke and applying transparent weighting or desirability criteria.

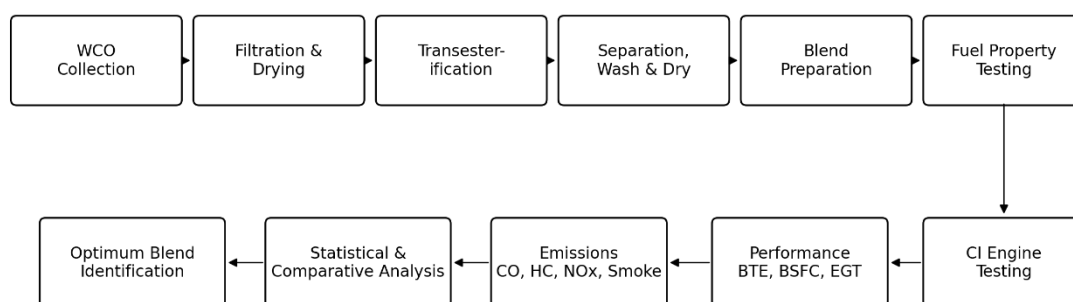


Figure 1. Proposed experimental workflow for WCO biodiesel production and CI-engine performance evaluation.

1. Algorithmic Strategy for Data Reduction

The data-processing sequence begins by validating raw measurements and removing only readings associated with documented instrument or operating faults. For each blend-load combination, replicate measurements are averaged and their standard deviations are retained. Fuel mass flow is converted to BSFC, and measured brake power together with the lower heating value is used to calculate BTE. Emission concentrations are corrected or normalized consistently if the chosen analyzer

requires such treatment. Each biodiesel result is then compared with the corresponding B0 value at the same load. Percentage change is calculated as $[(\text{Value_blend} - \text{Value_B0}) / \text{Value_B0}] \times 100$. Finally, performance and emission indicators are considered jointly. A blend should not be described as optimum merely because it gives the lowest CO if it simultaneously produces an unacceptable BSFC or NOx penalty. This multi-response logic follows the practical conclusions of Attia and Hassaneen (2016), who showed that different blending levels can be preferable depending on the performance or emission criterion considered.

Table 2. Literature-grounded benchmark trends for WCO biodiesel in CI engines (references limited to 2016 or earlier)

Study	Fuel / condition	BTE / efficiency	BSFC / energy use	CO/HC/PM or smoke	NOx trend
Utlu & Koçak (2008)	WFO biodiesel vs diesel	Comparable overall performance	SFC close to diesel	Several exhaust pollutants and smoke reduced	Lower under reported conditions
Hirkude & Padalkar (2012)	WFOME blends	B50 BTE about 6.5% lower at rated output	B50 BSFC about 6.89% higher	CO reduced 21-45%; PM reduced 23-47%	Not the principal benefit reported
Nantha Gopal et al. (2014)	WCOME blends	Lower than diesel in reported tests	Specific energy consumption higher	CO, UHC and smoke lower	Higher than diesel
Cheung et al. (2015)	B0/B10/B20/B30/B100	Not primary focus	Not primary focus	HC, CO and particulate measures reduced	Generally increased
Attia & Hassaneen (2016)	WCOME blends at 1500 rpm	B20 showed favorable efficiency behavior	Moderate blends gave competitive energy use	CO/UHC generally improved; smoke response blend-dependent	Could decrease in their tested range

Results and Discussion

Because this work defines an experimental methodology rather than reporting a newly completed engine campaign, the result statements below are benchmark expectations drawn from the cited pre-2017 literature. They should be used to judge whether measured data are physically reasonable, not as substitutes for actual measurements. The most consistent performance trend is that BTE increases with load for all fuels, while BSFC decreases as the engine moves away from very light-load operation. When biodiesel fraction is increased,

BSFC commonly rises because WCO biodiesel has a lower heating value than petroleum diesel and therefore a larger mass of fuel may be required for the same brake output. Hirkude and Padalkar (2012) quantified this penalty for B50, whereas Attia and Hassaneen (2016) found that a moderate blend could provide a particularly favorable efficiency-energy-consumption compromise. Accordingly, B10-B30 should be expected to remain closer to diesel than B100 in fuel-consumption terms.

BTE should be interpreted together with BSFC and fuel heating value. A small difference in BTE

between B0 and B20 may still be acceptable if the blend substantially reduces incomplete-combustion emissions. Nantha Gopal et al. (2014) observed a lower BTE for WCO biodiesel blends in their engine, while Kannan and Anand (2012) showed that injection pressure and timing can recover or improve thermal performance. This explains why the present design fixes injection settings: without that control, the effect attributed to biodiesel percentage could be confounded by calibration changes. If a future optimization study is desired, injection timing and pressure can be added as separate factors after the baseline blend study is complete.

For gaseous emissions, the oxygen contained within biodiesel molecules generally assists oxidation of locally rich fuel zones. Consequently, CO and HC are expected to decline as WCO biodiesel fraction increases, especially at medium and high loads. Cheung et al. (2015), Sanli et al. (2015), Nantha Gopal et al. (2014), and Hirkude and Padalkar (2012) all reported reductions in one or more incomplete-combustion or particulate-related indicators. Smoke and particulate matter frequently decrease for the same reason, although Attia and Hassaneen (2016) observed that smoke behavior can be blend-dependent. A measured increase in smoke for a specific blend therefore should not automatically be treated as an experimental error; viscosity, spray quality, injection characteristics, and combustion phasing should be examined first.

NO_x is the most variable response. Cheung et al. (2015) and Nantha Gopal et al. (2014) observed increases with biodiesel, while Attia and Hassaneen (2016) reported reductions for some WCO blend conditions. Guo et al. (2012) also found different NO_x behavior in two engines operating on the same general fuel type. These differences are technically plausible because thermal NO_x is sensitive to local flame temperature, oxygen availability, residence time, ignition delay, injection strategy, and engine calibration. For this reason, the proposed study should report NO_x separately at every load rather than relying only on a single averaged number.

From an overall performance-emission perspective, B20 is a strong candidate for detailed attention because several studies show that moderate WCO biodiesel fractions can provide a useful compromise between efficiency, fuel consumption, and pollutant reduction. Nevertheless, the methodology intentionally includes B10 and B30 because the optimum may

shift with engine hardware. B100 is retained as a boundary case that reveals the full effect of biodiesel properties but is not assumed to be the best practical fuel. The final blend selection should be based on measured multi-response performance from the specific test engine.

Conclusion and Discussion

This methodology establishes a complete experimental route for evaluating a compression ignition engine fueled with biodiesel derived from waste cooking oil. The procedure covers WCO pretreatment, alkali-catalyzed transesterification, biodiesel purification, fuel-property measurement, preparation of B0/B10/B20/B30/B100 blends, controlled engine testing, emissions measurement, performance calculations, replicate analysis, and multi-response comparison. Literature published up to 2016 consistently indicates that WCO biodiesel is technically feasible in diesel engines and that low-to-moderate blends can preserve performance close to diesel while reducing CO, HC, smoke, or particulate emissions. A recurring penalty is increased fuel consumption at higher biodiesel fractions because of lower heating value, while NO_x response is engine- and condition-dependent. Therefore, B20 should be treated as an important benchmark rather than a predetermined winner. The experimentally preferred blend should be identified from simultaneous BTE, BSFC, CO, HC, NO_x, and smoke results at matched loads. The proposed design is suitable for a laboratory methodology paper because it is reproducible, uses commonly available engine-test instrumentation, and directly connects measured fuel properties with combustion, performance, and emission outcomes.

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