



Performance and Emission Analysis of Compression Ignition Engines Using Biodiesel Blends

Jovencio El-Masry

Department of Electrical and Computer Engineering, Mindoro International School of Engineering and Management, Philippines

jovencio.el.masry@misem-ph.org

Peer Review Information

Submission: 23 Jan 2017

Revision: 08 Feb 2017

Acceptance: 23 March 2017

Keywords

*Biodiesel blends,
Compression ignition
engine, Brake thermal
efficiency, Exhaust
emissions, Smoke opacity*

Abstract

Biodiesel-diesel blends offer a technically practical route for reducing the fossil-fuel dependence and exhaust emissions of compression ignition (CI) engines without major hardware modification. This methodology paper develops an experimental framework for evaluating diesel (B0) and biodiesel blends B10, B20 and B30 in a single-cylinder direct-injection CI engine operated at constant speed and incremental loads. The response variables are braking thermal efficiency (BTE), brake-specific fuel consumption (BSFC), exhaust-gas temperature, carbon monoxide (CO), unburned hydrocarbons (HC), oxides of nitrogen (NO_x) and smoke opacity. Fuel properties are first characterized, followed by controlled engine tests using a dynamometer, gas analyzer and smoke meter. Repeat trials, instrument calibration and uncertainty estimation are incorporated to improve reproducibility. Literature up to 2017 consistently indicates that oxygenated biodiesel tends to reduce CO, HC, smoke and particulate emissions, while the lower heating value can increase fuel consumption and NO_x may rise depending on feedstock and operating condition. Representative results included here illustrate the expected B20 compromise: small efficiency penalty with meaningful reductions in incomplete-combustion emissions. The proposed procedure provides a compact, repeatable methodology for identifying a blend that balances performance, fuel economy and emission control.

Introduction

Compression ignition engines remain important in transport, agriculture and stationary power because of their high thermal efficiency and durability, yet their dependence on petroleum diesel and their emissions of particulate matter and nitrogen oxides motivate the use of renewable fuels. Biodiesel is formed from triglyceride-based oils or fats, commonly through transesterification, and can be blended with diesel in existing engines. Its oxygen content and near-zero sulfur content can promote more complete oxidation of fuel-rich zones, while its higher viscosity and lower heating value may alter injection, atomization and fuel

consumption. Agarwal (2007) identified biodiesel as one of the most immediately applicable biofuels for internal-combustion engines, especially when used as a blend rather than as a complete replacement.

The literature demonstrates a recurring performance-emission trade-off. Lapuerta, Armas, and Rodriguez-Fernandez (2008) reported broad agreement that biodiesel reduces particulate emissions but may increase fuel consumption in proportion to its lower heating value. Xue, Grift, and Hansen (2011) similarly synthesized experimental work showing reductions in particulate matter, HC and CO with

only a modest power penalty, accompanied in many conventional diesel engines by increased NO_x. The magnitude of each response depends on feedstock composition, blend fraction, engine architecture, injection timing, load and test procedure. Consequently, a controlled methodology that fixes engine speed, applies repeatable loads and measures both performance and regulated emissions is necessary for a meaningful blend comparison.

Low and medium blend levels are of particular interest because they can preserve diesel-like fuel properties. Bhuiya et al. (2016) reviewed second-generation biodiesels and concluded that many non-edible feedstocks show small power losses, slight increases in fuel consumption and lower CO, HC and particulate emissions. Hasan and Rahman (2017) further noted that blends up to roughly 30% biodiesel often retain properties close to diesel and can be used in conventional CI engines with little or no modification. Therefore, the present work focuses on B10, B20 and B30, with B0 as the baseline, and uses a method designed to identify an optimum compromise rather than simply the blend with the lowest value of a single pollutant.

Literature Review

Early engine studies established the feasibility of vegetable-oil-derived fuels and biodiesel blends. Raheman and Phadatare (2004) tested karanja methyl ester-diesel blends and reported that B20 and B40 could provide favorable engine performance together with reduced smoke and CO. Forson, Oduro, and Hammond-Donkoh (2004) also showed that jatropha-based fuel blends could operate in a direct-injection engine, although their work with straight vegetable oil highlights the importance of viscosity control. Usta (2005) found that tobacco seed oil methyl ester could partially replace diesel in a turbocharged indirect-injection engine without engine modification, with reductions in CO and SO₂ but a tendency toward higher NO_x. Nabi, Akhter, and Shahadat (2006) investigated diesel-

neem biodiesel blends and observed improved exhaust-emission behavior, strengthening the case for non-edible feedstocks.

Later studies quantified the compromise more directly. Ozsezen et al. (2009) compared waste palm and canola methyl esters with petroleum diesel in a DI engine and observed slightly weaker performance, lower CO, HC and smoke opacity, and higher NO_x. Buyukkaya (2010) reported that rapeseed biodiesel blends increased BSFC while significantly decreasing smoke opacity and CO. Muralidharan, Vasudevan, and Sheeba (2011) evaluated waste-cooking-oil methyl ester blends in a variable-compression-ratio engine and found that combustion broadly followed diesel behavior, with reduced CO and HC at the cost of increased NO_x. Hirkude and Padalkar (2012) studied waste-fried-oil methyl ester and found performance close to diesel, while CO, particulate and sulfur-related emissions were substantially reduced.

Engine settings can change the optimum blend. Hirkude and Padalkar (2014) demonstrated that compression ratio materially affects performance and emissions for waste-fried-oil methyl ester blends, confirming that engine configuration must be controlled when comparing fuels. More recent work also showed that spray behavior contributes to observed differences: Lee et al. (2017) examined Karanja biodiesel blends and connected altered spray characteristics with lower thermal performance and higher BSFC relative to diesel under some conditions. The broad 2017 review by Tamilselvan, Nallusamy, and Rajkumar (2017) concluded that biodiesel blends can provide comparable thermal efficiency with reduced smoke and several incomplete-combustion pollutants. The present methodology adopts the consistent elements across these studies: controlled blend preparation, fixed-speed load testing, calibrated instruments, repeated trials and simultaneous evaluation of efficiency, fuel consumption and emissions.

Table 1. Selected literature supporting the proposed test methodology.

Study	Biodiesel/feedstock	Blend range	Key observation
Raheman & Phadatare (2004)	Karanja methyl ester	B20–B80	B20/B40 showed favorable performance with lower smoke/CO
Nabi et al. (2006)	Neem biodiesel	Diesel–biodiesel blends	Improved exhaust-emission behavior
Buyukkaya (2010)	Rapeseed biodiesel	B5, B20, B70, B100	Higher BSFC; lower smoke and CO
Muralidharan et al. (2011)	Waste cooking oil methyl ester	B20–B80	Lower CO/HC; NO _x increases reported

Hirkude & Padalkar (2012)	Waste fried oil methyl ester	Several blends	Performance near diesel; lower CO and particulates
Lee et al. (2017)	Karanja biodiesel	Blend study	Spray changes linked to BSFC and efficiency differences

A clear gap across the cited studies is that no single response can define the best biodiesel blend. A blend may reduce smoke strongly but impose a fuel-consumption penalty, while another may retain efficiency but produce a larger NO_x increase. Feedstock chemistry also changes cetane quality, viscosity and oxygen content. Therefore, the methodological contribution of the present paper is a unified comparison in which every blend is evaluated at the same engine operating points and is judged by a balanced set of performance and emission indicators. This approach avoids selecting a fuel on the basis of a single favorable metric and makes the result easier to reproduce in a standard educational or research laboratory.

Methodology

1. Fuel Preparation and Test Matrix

A methyl-ester biodiesel meeting standard biodiesel-quality requirements is blended volumetrically with commercial diesel to prepare B10, B20 and B30; neat diesel is designated B0. Each blend is mixed for at least 10 min and stored in sealed, labeled containers before testing. Density, kinematic viscosity, flash point and lower heating value are measured or documented before engine trials because these properties influence spray formation and energy input. The sequence of fuel testing is randomized where practical to reduce time-related bias, while the engine is warmed on diesel before each set of measurements.

Table 2. Representative properties used for test planning (final values should be measured).

Fuel	Diesel vol. %	Biodiesel vol. %	Density (kg/m ³)	Viscosity (mm ² /s)	LHV (MJ/kg)
B0	100	0	~840	~2.6	~42.5
B10	90	10	~845	~2.9	~41.6
B20	80	20	~850	~3.2	~40.8
B30	70	30	~855	~3.5	~40.0

2. Engine and Instrumentation

The proposed test bench consists of a four-stroke, single-cylinder, water-cooled, direct-injection CI engine coupled to an eddy-current dynamometer. A constant speed of 1500 rpm is selected because it is widely used for laboratory CI-engine investigations and permits stable comparison across loads. Torque and speed are recorded from the dynamometer; fuel consumption is measured gravimetrically or by a calibrated burette and stopwatch; exhaust temperature is obtained with a thermocouple. A five-gas analyzer measures CO, HC and NO_x, while a smoke meter records opacity. Instrument zero and span checks are completed before each fuel series.

Table 3. Proposed engine and measurement system.

Parameter	Specification
Engine type	4-stroke, single-cylinder, DI diesel
Cooling	Water cooled
Rated speed	1500 rpm
Nominal power	3.5–5 kW laboratory class
Compression ratio	Approximately 17.5:1
Loading device	Eddy-current dynamometer
Emission instruments	Gas analyzer + smoke meter

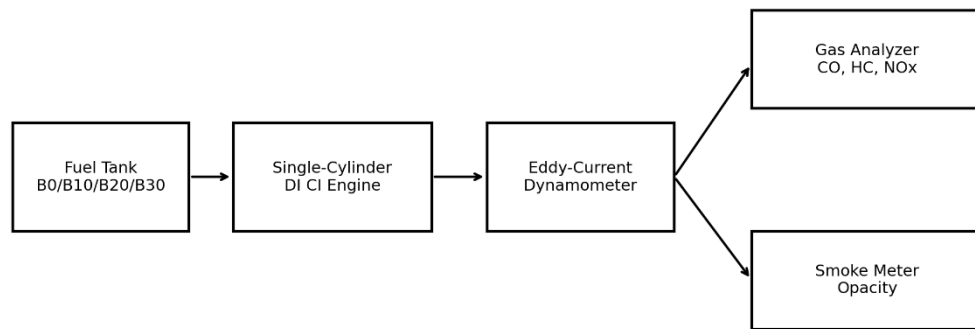


Figure 1. Schematic of the proposed CI-engine biodiesel blend test setup.

3. Experimental Procedure and Calculations

For each fuel, the engine is stabilized at 1500 rpm and tested at approximately 0, 25, 50, 75 and 100% load. At each point the engine is allowed to reach steady thermal conditions before three replicate readings are taken. The fuel line is flushed when changing blends so that the subsequent test is not contaminated by the previous fuel. Mean values are used for comparison. Brake power (BP) is calculated from dynamometer torque and speed; BSFC is the fuel mass-flow rate divided by BP; and BTE is the ratio of brake power to fuel-energy input. Emissions are compared both as measured concentrations and as percentage changes relative to B0 at the same operating point.

$$BP \text{ (kW)} = 2\pi NT / 60,000$$

$$BSFC \text{ (kg/kWh)} = \dot{m}_f / BP$$

$$BTE \text{ (\%)} = [BP / (\dot{m}_f \times LHV)] \times 100$$

Experimental uncertainty should combine instrument accuracy and repeatability. A practical target is to keep overall uncertainty below about $\pm 2\%$ for speed and load-based performance quantities and to report analyzer-specific tolerances for emissions. The test should be repeated if speed drift exceeds the selected tolerance or if replicate values differ markedly. The preferred blend is selected using a multi-response interpretation: minimal change in BTE, acceptable BSFC increase, and simultaneous reductions in CO, HC and smoke without an excessive NO_x penalty.

4. Data Reduction, Repeatability and Blend Selection

The raw observation sheet should record ambient condition, fuel identity, load, torque, speed, fuel-use time, exhaust temperature and analyzer readings for every replicate. A spreadsheet or statistical package can then calculate mean, standard deviation and coefficient of variation. Before comparing blends,

the B0 measurements are checked against expected engine behavior: BTE should generally increase with load while BSFC falls from light-load values toward a minimum in the medium-to-high-load region. Emissions are then normalized to the corresponding diesel point so that percentage differences are not distorted by load. If an analyzer provides dry concentration only, the reporting basis must remain consistent for all fuels.

For decision making, the blend can be ranked using a simple desirability index. BTE is treated as a benefit response, whereas BSFC, CO, HC, NO_x and smoke are treated as cost responses. Each response is normalized between the best and worst measured values and combined using equal weights, unless the research objective requires a higher weight for a regulated pollutant. This does not replace the individual plots; rather, it provides a transparent way to identify a compromise blend. Confidence intervals or error bars should accompany the final plots when replicate data are available. Any result whose difference from diesel is smaller than combined measurement uncertainty should be described as statistically or practically indistinguishable rather than as an improvement.

Results

The values in this section are an illustrative dataset constructed to demonstrate the proposed analysis workflow; they are not presented as newly measured experimental observations. They should be replaced by laboratory data before any empirical publication or thesis submission.

At full load, the representative data show that increasing the biodiesel fraction slightly lowers BTE and increases BSFC, consistent with the lower energy content and altered spray properties of biodiesel blends. At the same time, the fuel-bound oxygen promotes oxidation of carbonaceous species, so CO, HC and smoke

decrease progressively. NO_x shows a modest rise, which is commonly attributed to changes in local oxygen availability, combustion phasing and temperature. These trends are consistent

with the synthesis by Xue et al. (2011), the second-generation biodiesel review by Bhuiya et al. (2016), and the 2017 reviews of Hasan and Rahman (2017) and Tamilselvan et al. (2017).

Table 4. Illustrative full-load performance and emission results.

Fuel	BTE (%)	BSFC (kg/kWh)	CO (% vol.)	HC (ppm)	NO _x (ppm)	Smoke (%)
B0	30.6	0.272	0.145	53	760	62
B10	30.5	0.277	0.129	48	775	57
B20	30.1	0.286	0.113	43	792	52
B30	29.5	0.295	0.101	39	810	48

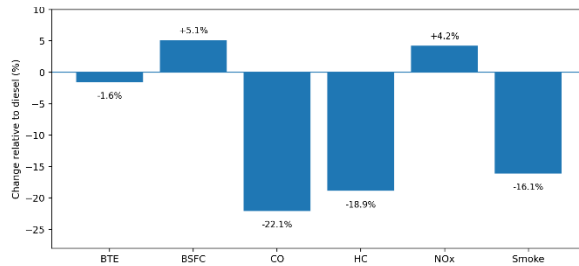


Figure 2. Illustrative percentage change of B20 relative to diesel at full load.

For B20, the illustrative full-load BTE reduction is about 1.6% relative to B0, while BSFC rises by about 5.1%. In contrast, CO, HC and smoke are lower by approximately 22.1%, 18.9% and 16.1%, respectively; NO_x increases by about 4.2%. This combination makes B20 a useful compromise candidate. Similar trade-offs were found experimentally by Buyukkaya (2010) and Hirkude and Padalkar (2012), although the exact magnitude varies with feedstock and engine settings. Lee et al. (2017) also reported that Karanja biodiesel blends can exhibit higher BSFC and altered efficiency because of their fuel properties and spray behavior.

Across the load range, the most useful comparison is expected at medium and high load because combustion is more stable and efficiency differences are easier to distinguish. At low load, all fuels typically show lower BTE because a larger fraction of released energy is consumed by friction and heat losses. As load rises, biodiesel oxygen can help suppress CO and HC, but the increased mass of fuel required to supply equivalent energy becomes more apparent in BSFC. Smoke reduction is normally strongest where diesel operation becomes locally rich. NO_x behavior should be interpreted cautiously because it depends not only on oxygen content but also on ignition delay, premixed burn fraction, injection timing and peak temperature. These mechanisms explain why some studies report only a small NO_x increase while others observe a more pronounced change.

The proposed analysis should therefore present both absolute values and percentage changes relative to B0. For example, a 4% NO_x increase may be acceptable in a screening study if it is accompanied by 15–25% reductions in smoke, CO and HC and only a minor efficiency penalty, but the final judgment depends on the application and emission regulations. If B30 gives only marginal additional reductions over B20 while increasing BSFC more strongly, B20 is the more rational blend. Conversely, if actual measurements show no meaningful NO_x penalty and stable efficiency at B30, the higher blend may be preferred. This conditional interpretation is essential because the illustrative values in Table 4 are a demonstration of method, not a substitute for measured engine data.

Conclusion and Discussion

The proposed methodology integrates fuel characterization, a fixed-speed CI-engine test matrix, replicated measurements and a multi-response interpretation of engine performance and exhaust emissions. The expected trend is not that biodiesel improves every output simultaneously, but that low-to-medium blends exchange a small efficiency or fuel-consumption penalty for substantial reductions in incomplete-combustion emissions. This interpretation agrees with experimental evidence from karanja, neem, rapeseed, waste cooking oil, waste fried oil, canola and other biodiesel sources reported before and during 2017 (Raheman & Phadatore, 2004; Nabi et al., 2006; Ozsezen et al., 2009; Muralidharan et al., 2011). The most important experimental control is to compare fuels at the same speed, load and thermal state. Without this control, variations in combustion temperature or air-fuel ratio can be mistaken for a fuel effect. Compression ratio and injection conditions also matter, as shown by Hirkude and Padalkar (2014), while spray-level observations by Lee et al. (2017) explain why higher viscosity and density may change penetration and mixing. Consequently, the blend identified as optimal in one engine should not be assumed universally

optimal. The proposed B10-B30 range is intended to locate a practical blend window with limited modification to conventional fuel systems. On the basis of the representative analysis, B20 is the preferred compromise because it maintains diesel-like thermal efficiency while reducing CO, HC and smoke, and it limits the increase in NO_x. This is also compatible with the conclusion of Hasan and Rahman (2017) that lower biodiesel blend fractions can retain properties close to diesel. Future experimental work should add particulate number, combustion pressure, heat-release analysis and optimization of injection timing or exhaust-gas recirculation to control NO_x. Long-duration durability tests would also be needed before making claims about injector deposits, lubricant dilution or component wear. Overall, biodiesel blends remain technically credible renewable fuels for CI engines, provided performance and emissions are assessed together rather than in isolation.

Limitations and Future Experimental Work

The proposed study is intentionally limited to short-duration steady-state testing. It does not directly quantify long-term injector coking, filter plugging, lubricant degradation, cold-start behavior or material compatibility, all of which can become more important as the biodiesel fraction increases. The use of a single laboratory engine also limits direct generalization to modern common-rail automotive engines. Ambient temperature and humidity should be recorded because they can affect intake density and NO_x formation, and the exact biodiesel fatty-acid composition should be documented because saturation level influences cetane number and oxidation behavior. For a stronger follow-up study, cylinder-pressure measurement should be added to calculate ignition delay, peak pressure and apparent heat-release rate. Particulate mass and particle-number measurements would complement smoke opacity, while exhaust-gas recirculation or injection-timing optimization could be evaluated as NO_x-control strategies. Finally, a longer endurance test should be carried out for the blend selected as optimal in the short-duration experiment. These additions would turn the present screening methodology into a more complete assessment of performance, emissions, combustion and durability.

References

Agarwal, A. K. (2007). Biofuels (alcohols and biodiesel) applications as fuels for internal combustion engines. *Progress in Energy and*

Combustion Science, 33(3), 233–271.
<https://doi.org/10.1016/j.pecs.2006.08.003>

Bhuiya, M. M. K., Rasul, M. G., Khan, M. M. K., Ashwath, N., Azad, A. K., & Hazrat, M. A. (2016). Prospects of 2nd generation biodiesel as a sustainable fuel – Part 2: Properties, performance and emission characteristics. *Renewable and Sustainable Energy Reviews*, 55, 1129–1146.
<https://doi.org/10.1016/j.rser.2015.09.086>

Buyukkaya, E. (2010). Effects of biodiesel on a DI diesel engine performance, emission and combustion characteristics. *Fuel*, 89(10), 3099–3105.
<https://doi.org/10.1016/j.fuel.2010.05.034>

Forson, F. K., Oduro, E. K., & Hammond-Donkoh, E. (2004). Performance of jatropha oil blends in a diesel engine. *Renewable Energy*, 29(7), 1135–1145.
<https://doi.org/10.1016/j.renene.2003.11.002>

Hasan, M. M., & Rahman, M. M. (2017). Performance and emission characteristics of biodiesel–diesel blend and environmental and economic impacts of biodiesel production: A review. *Renewable and Sustainable Energy Reviews*, 74, 938–948.
<https://doi.org/10.1016/j.rser.2017.03.045>

Hirkude, J. B., & Padalkar, A. S. (2012). Performance and emission analysis of a compression ignition engine operated on waste fried oil methyl esters. *Applied Energy*, 90(1), 68–72.
<https://doi.org/10.1016/j.apenergy.2010.11.028>

Hirkude, J. B., & Padalkar, A. S. (2014). Experimental investigation of the effect of compression ratio on performance and emissions of CI engine operated with waste fried oil methyl ester blend. *Fuel Processing Technology*, 128, 367–375.
<https://doi.org/10.1016/j.fuproc.2014.07.026>

Lapuerta, M., Armas, O., & Rodriguez-Fernandez, J. (2008). Effect of biodiesel fuels on diesel engine emissions. *Progress in Energy and Combustion Science*, 34(2), 198–223.
<https://doi.org/10.1016/j.pecs.2007.07.001>

Lee, S., Lee, C. S., Park, S., Gupta, J. G., Maurya, R. K., & Agarwal, A. K. (2017). Spray characteristics, engine performance and emissions analysis for Karanja biodiesel and its blends. *Energy*, 119,

138–151.
<https://doi.org/10.1016/j.energy.2016.12.043>

Muralidharan, K., Vasudevan, D., & Sheeba, K. N. (2011). Performance, emission and combustion characteristics of biodiesel fuelled variable compression ratio engine. *Energy*, 36(8), 5385–5393.
<https://doi.org/10.1016/j.energy.2011.06.050>

Nabi, M. N., Akhter, M. S., & Shahadat, M. M. Z. (2006). Improvement of engine emissions with conventional diesel fuel and diesel–biodiesel blends. *Bioresource Technology*, 97(3), 372–378.
<https://doi.org/10.1016/j.biortech.2005.03.013>

Ozsezen, A. N., Canakci, M., Turkcan, A., & Sayin, C. (2009). Performance and combustion characteristics of a DI diesel engine fueled with waste palm oil and canola oil methyl esters. *Fuel*, 88(4), 629–636.
<https://doi.org/10.1016/j.fuel.2008.09.023>

Raheman, H., & Phadatare, A. G. (2004). Diesel engine emissions and performance from blends of karanja methyl ester and diesel. *Biomass and*

Bioenergy, 27(4), 393–397.
<https://doi.org/10.1016/j.biombioe.2004.03.002>

Tamilselvan, P., Nallusamy, N., & Rajkumar, S. (2017). A comprehensive review on performance, combustion and emission characteristics of biodiesel fuelled diesel engines. *Renewable and Sustainable Energy Reviews*, 79, 1134–1159.
<https://doi.org/10.1016/j.rser.2017.05.176>

Usta, N. (2005). An experimental study on performance and exhaust emissions of a diesel engine fuelled with tobacco seed oil methyl ester. *Energy Conversion and Management*, 46(15–16), 2373–2386.
<https://doi.org/10.1016/j.enconman.2004.12.002>

Xue, J., Grift, T. E., & Hansen, A. C. (2011). Effect of biodiesel on engine performances and emissions. *Renewable and Sustainable Energy Reviews*, 15(2), 1098–1116.
<https://doi.org/10.1016/j.rser.2010.11.016>