



Performance and Emission Characteristics of Diesel Engines Using Biodiesel Blends

Nozomi Zuberiwala

Department of Electrical and Computer Engineering, Mauritius Institute of Marine Engineering, Mauritius
nozomi.zuberiwala@mime-mu.edu

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Abstract

Biodiesel-diesel blends provide a practical pathway for reducing dependence on petroleum diesel while retaining compatibility with conventional compression-ignition engines. This methodology paper proposes a controlled experimental framework for evaluating engine performance and regulated exhaust emissions with B0, B10, B20, and B30 fuels. The design combines fuel-property characterization, a constant-speed single-cylinder diesel-engine test, staged loading, exhaust-gas measurement, and calculation of brake thermal efficiency (BTE) and brake-specific fuel consumption (BSFC). The principal emissions considered are carbon monoxide (CO), unburned hydrocarbons (HC), nitrogen oxides (NO_x), and smoke opacity. The methodology is grounded in published work available up to 2019 and therefore treats the numerical outcomes presented in the Results section as literature-supported benchmark expectations rather than original measured data. Prior studies consistently indicate that low-to-moderate biodiesel fractions can reduce CO, HC, and smoke because of the oxygenated nature of biodiesel, although BSFC may rise because biodiesel generally has a lower heating value and NO_x may increase under some operating conditions. The proposed protocol is intended to enable reproducible comparison of blend ratio and engine load and to identify a practical compromise between efficiency, fuel consumption, and emissions, with B20 serving as a particularly important reference blend.

Introduction

Compression-ignition engines are widely used in transport, agriculture, distributed power generation, and industrial applications because of their high thermal efficiency, durability, and favorable part-load fuel economy. Their continued reliance on petroleum diesel, however, links these advantages to fossil-resource depletion and to emissions of particulate matter, carbon monoxide, hydrocarbons, nitrogen oxides, and greenhouse gases. The search for renewable fuels that can be introduced with limited engine modification has therefore been a persistent research priority. Biodiesel is attractive in this context because it is

biodegradable, contains little or no sulfur, has inherent oxygen content, and can be produced from vegetable oils, animal fats, and waste-derived lipids. Early engine studies demonstrated that transesterified vegetable oils could be used successfully in compression-ignition engines and that moderate biodiesel blending could improve smoke behavior without demanding major hardware changes (Agarwal & Das, 2001).

Biodiesel is composed mainly of fatty-acid alkyl esters. In comparison with petroleum diesel, it normally exhibits higher density and viscosity, higher flash point, and lower lower-heating

value. These differences influence atomization, spray penetration, ignition, heat release, and fuel consumption. Agarwal (2007) reviewed biofuel applications in internal-combustion engines and concluded that biodiesel can substantially reduce unburned hydrocarbon, carbon monoxide, and particulate emissions, while the effect on nitrogen oxides is more complex. Experimental work on soybean-derived biodiesel also found a small increase in BSFC and a slight decrease in BTE, together with pronounced reductions in CO and smoke at high load and a modest increase in NO_x (Qi et al., 2010). These trade-offs explain why blend ratio must be treated as an experimental variable rather than assuming that a larger renewable fraction is always superior.

The feedstock used to produce biodiesel also affects density, viscosity, cetane quality, oxidation stability, and cold-flow properties. Mofijur et al. (2013) emphasized that fuel properties and material compatibility vary across edible, non-edible, animal-fat, and waste-oil feedstocks, and that such variation can influence combustion and durability. For practical engine studies, low and medium blend levels are especially relevant because they can generally be used in existing engines with few changes. Hasan and Rahman (2017) summarized a large body of biodiesel-diesel research and reported that blends containing up to about 30% biodiesel often retain properties close enough to diesel for conventional CI-engine operation, while commonly decreasing HC, CO, and particulate emissions.

The present paper therefore develops a reproducible methodology for comparing diesel with B10, B20, and B30 blends under controlled engine loading. The focus is not the chemistry of a single feedstock, but the experimental logic required to determine whether a blend offers an acceptable compromise among brake thermal efficiency, specific fuel consumption, and exhaust emissions. Because the paper is methodology-oriented, it also specifies calibration, repeat testing, data reduction, uncertainty control, and benchmark criteria. The central research question is: how does increasing biodiesel fraction from 0% to 30% affect the performance and emission characteristics of a small direct-injection diesel engine across its operating load range?

Literature Review

The literature up to 2019 shows a broad consensus that biodiesel can be used in conventional diesel engines, but it also identifies a recurring performance-emission trade-off.

Tamilselvan et al. (2017) reviewed combustion, performance, and emissions across many biodiesel feedstocks and noted that the oxygenated nature of biodiesel tends to improve oxidation of fuel-rich zones, thereby lowering smoke, CO, and HC. At the same time, higher viscosity and lower energy content can increase the mass of fuel required to produce a given brake output. This pattern is consistent with the soybean-biodiesel experiments of Qi et al. (2010), which reported higher BSFC and slightly lower BTE than diesel under comparable operating conditions.

Feedstock-specific studies support the same general trend while showing that the optimum blend is not universal. Das et al. (2018) experimentally evaluated diesel-castor-oil biodiesel blends and compared fuel properties, combustion, performance, and emissions. Their work reinforced the need to characterize viscosity, surface tension, heating value, and other fuel properties before interpreting engine data. Sivaramakrishnan (2018), using Karanja biodiesel blends in a variable-compression-ratio engine, found that B25 at a compression ratio of 18 achieved a BTE of 30.46% and a BSFC of 0.28 kg/kWh compared with 0.29 kg/kWh for diesel. Hydrocarbon emissions were also lower for biodiesel blends. These findings demonstrate that operating variables such as compression ratio can change the apparent ranking of fuels.

Injection strategy is another important control variable. How et al. (2018) studied B20 and B50 with different injection timing and split-injection schemes and showed that late start of injection together with multiple injections could suppress NO_x and smoke simultaneously. Their results are especially relevant because the frequently reported NO_x increase with biodiesel is not an unavoidable fuel property; it can be moderated through combustion control. Similarly, Ansari et al. (2018) optimized blend ratio, injection timing, and injection pressure for polanga biodiesel and found that engine response is strongly influenced by the interaction of fuel composition and injection settings. Their study reported high BTE for a B30 condition and demonstrated the usefulness of structured multi-factor experimentation.

By 2019, work on emulsified diesel-biodiesel systems and additives had further expanded the range of emission-control strategies. Kapadia et al. (2019) reviewed emulsion stability and the influence of water and additives on combustion and emissions, reporting that B20 frequently provides a useful performance compromise and that appropriately prepared emulsions can

reduce harmful exhaust constituents. Taken together, the reviewed studies justify a baseline methodology in which blend fraction and load are varied first under fixed engine settings. More advanced factors such as compression ratio, injection timing, injection pressure, exhaust-gas recirculation, or additives can then be incorporated in a second-stage optimization study.

Methodology

The proposed investigation follows a controlled comparative experimental design. Petroleum diesel (B0) is treated as the baseline, and three biodiesel blends are evaluated: B10 (10% biodiesel by volume), B20 (20%), and B30 (30%). The study keeps engine speed and injection settings constant so that the effects of fuel blend and brake load can be isolated. Each test point is repeated at least three times after the engine reaches stable operating temperature. Mean values are used for comparison, and any run with abnormal speed fluctuation, unstable

exhaust temperature, or analyzer fault is discarded and repeated.

1. Fuel Preparation and Characterization

Biodiesel should be produced by transesterification of a selected oil feedstock or obtained as standards-compliant fuel. Before engine testing, the biodiesel and diesel are filtered and stored in clean, sealed containers. Blends are prepared volumetrically using calibrated glassware or a mass-based equivalent corrected for density. The mixture is agitated until visually homogeneous and is allowed to stand to check for phase separation. Density, kinematic viscosity, flash point, and lower heating value are measured or documented for each fuel. These measurements are important because the higher viscosity and lower heating value typical of biodiesel can affect atomization and fuel consumption (Mofijur et al., 2013; Das et al., 2018).

Table 1. Proposed engine test conditions and measured responses

Item	Proposed condition	Purpose / response
Fuel blends	B0, B10, B20, B30	Effect of biodiesel fraction
Engine	Single-cylinder, 4-stroke, DI, water-cooled	Controlled CI-engine platform
Rated condition	≈4–5 kW; 1500 rpm	Representative laboratory diesel engine
Load points	0, 25, 50, 75, 100%	Load-response characterization
Replicates	Minimum 3 per test point	Repeatability and mean estimation
Performance	Fuel rate, brake power, BTE, BSFC	Efficiency and fuel-economy comparison
Emissions	CO, HC, NO _x , smoke opacity	Regulated/pollutant comparison

2. Engine Test Rig and Instrumentation

A single-cylinder, four-stroke, direct-injection, water-cooled diesel engine coupled to an eddy-current or electrical dynamometer is suitable for this experiment. A rated speed of 1500 rpm and power near 4–5 kW provide a common laboratory-scale configuration comparable with previously published biodiesel studies (Sivaramakrishnan, 2018). Fuel consumption is measured with a calibrated burette or gravimetric fuel-flow system. Brake torque is obtained from the dynamometer load cell, and brake power is calculated from torque and rotational speed. Exhaust gas temperature is measured with a thermocouple. CO and HC are measured using an exhaust-gas analyzer, NO_x using an electrochemical or chemiluminescence channel as available, and smoke opacity using a smoke meter. All analyzers are zeroed and spanned according to the manufacturer's procedure before a test series.

3. Experimental Procedure

1. Start the engine on B0, allow cooling-water and lubricant temperatures to stabilize, and set the target speed at 1500 rpm.
2. Record baseline observations at no load, then increase load sequentially to 25%, 50%, 75%, and 100% of rated load. At each point, wait for stable speed, exhaust temperature, and gas-analyzer readings before logging data.
3. Measure fuel consumption, torque, speed, exhaust temperature, CO, HC, NO_x, and smoke opacity. Repeat each point at least three times.
4. After completing B0, flush the fuel line and repeat the same load sequence for B10, B20, and B30. Keep injection timing, injection pressure, cooling-water flow, and ambient measurement procedure unchanged.

5. Calculate BTE and BSFC for each run, average the replicates, and compare each blend with diesel at the same load.

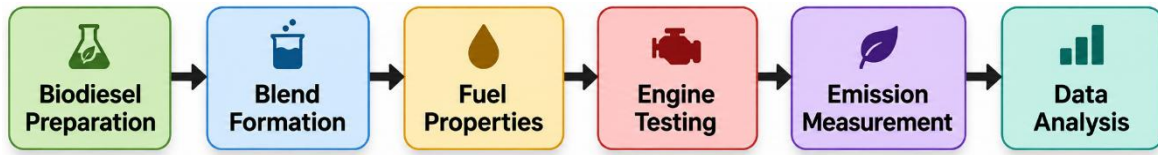


Figure 1. Proposed workflow for evaluating performance and emissions of biodiesel-diesel blends.

4. Performance Calculations

The principal performance quantities are calculated from the measured engine variables. Brake power is obtained from torque and rotational speed using $BP = 2\pi NT/60$, where N is rotational speed in revolutions per second and T is torque in $N\cdot m$. Brake-specific fuel consumption is $BSFC = \dot{m}_f/BP$, normally reported in kg/kWh after unit conversion. Brake thermal efficiency is $BTE = BP/(\dot{m}_f \times LHV) \times 100$, where LHV is the lower heating value of the test fuel. For each pollutant, the percentage change relative to diesel at the same load can be reported as $\Delta E = [(E_{blend} - E_{B0})/E_{B0}] \times 100$. These calculations permit a matched comparison even when the energy content and density of the blends differ.

5. Data Reduction and Statistical Treatment

For emissions, the primary analysis compares absolute measured values at matched loads and percentage change relative to B0. Mean, standard deviation, and coefficient of variation are reported for replicate runs. A two-factor analysis of variance may be used with blend fraction and load as factors; statistical significance can be assessed at $p < 0.05$. Main-effect plots are useful for visualizing whether load and blend fraction act independently, while an interaction plot helps identify whether the influence of biodiesel becomes stronger at high load. If a later optimization stage is desired, response-surface or Taguchi approaches can be adopted, as

demonstrated in prior biodiesel-engine studies (Ansari et al., 2018).

6. Quality Control and Uncertainty

Instrument calibration and repeatability are essential because the differences between low-percentage biodiesel blends and diesel can be small. Speed should be maintained within a narrow tolerance, fuel temperature should be recorded, and the same load-increment sequence should be used for every fuel. The exhaust analyzer should be checked for zero drift between fuels. Uncertainty in brake power is obtained from torque and speed uncertainties, while BSFC uncertainty includes fuel-flow and brake-power components. The method should report uncertainty bars when presenting numerical results. This requirement prevents small apparent changes from being interpreted as physically meaningful when they fall inside the measurement uncertainty.

Results

As this is a methodology paper rather than a report of newly completed engine tests, the results below are literature-supported benchmark expectations that can be used to validate the proposed experiment. They indicate the direction and approximate magnitude of behavior that a correctly conducted B0-B30 test series is likely to reproduce. They must not be presented as original measurements unless the described experiment is actually performed.

Table 2. Literature-supported benchmark outcomes relevant to the proposed methodology

Reference / condition	Performance benchmark	Emission benchmark	Methodological implication
Agarwal & Das (2001), B20	B20 gave the best performance among tested blends; peak thermal efficiency increased about 2.5%.	Substantial smoke-opacity reduction.	B20 is a key comparison blend.
Qi et al. (2010), biodiesel blends	Minor BSFC increase and BTE decrease versus diesel.	CO and smoke decreased at high load; NOx slightly increased.	Measure performance and emissions together.

Sivaramakrishnan (2018), B25, CR 18	BTE 30.46%; BSFC 0.28 kg/kWh vs 0.29 for diesel.	HC and CO lower for favorable blend conditions.	Engine settings can shift the optimum blend.
How et al. (2018), B20/B50	Performance depends on injection strategy.	Late SOI + triple injection produced NO _x below 100 ppm in tested conditions and reduced smoke.	Injection timing should be fixed in baseline tests.
Ansari et al. (2018), polanga blends	B30 reached high BTE under optimized timing/pressure.	UHC decreased for some blends; NO _x tended to rise with biodiesel fraction.	Second-stage optimization is justified.

The first expected performance trend is a small increase in BSFC as biodiesel fraction increases. Biodiesel generally contains less chemical energy per unit mass than diesel, so a larger mass flow is required to produce the same brake power. Qi et al. (2010) observed this tendency experimentally, and broader reviews reached the same conclusion (Hasan & Rahman, 2017; Tamilselvan et al., 2017). The effect should be most visible at medium and high load, where the fuel-flow measurement is more stable. BTE may remain close to diesel for low blends and can occasionally improve under favorable combustion conditions, as shown by the B20 and B25 findings of Agarwal and Das (2001) and Sivaramakrishnan (2018). Therefore, a practical optimum should be selected on the basis of both BTE and BSFC rather than either variable alone.

For emissions, CO, HC, and smoke are expected to decrease as the biodiesel fraction increases from B0 to B20 or B30, particularly at higher load. The chemically bound oxygen in biodiesel promotes oxidation in locally rich zones and reduces soot formation. The literature summarized by Agarwal (2007), Hasan and Rahman (2017), and Tamilselvan et al. (2017) supports this pattern. NO_x is less predictable: many conventional engine tests report a slight increase with biodiesel, while injection retarding, split injection, exhaust-gas recirculation, or other combustion-control strategies can reverse the trend. How et al. (2018) demonstrated that injection strategy can substantially lower NO_x for biodiesel blends.

On the basis of these benchmarks, B20 is expected to provide the most balanced first-stage result for an unmodified engine: renewable fuel substitution is meaningful, CO/HC/smoke benefits are usually measurable, and the penalty in BSFC is generally modest. B30 may provide additional smoke and HC reduction but can impose a larger fuel-consumption penalty or NO_x increase depending on feedstock properties and engine settings. The experimental data should therefore be interpreted as a multi-response

problem rather than selecting a blend from a single performance indicator.

Discussion

The proposed method is intentionally simple enough to reproduce in a standard internal-combustion-engine laboratory while remaining rigorous enough to separate fuel-blend effects from uncontrolled operating changes. Its main strength is the matched-load comparison: each biodiesel blend is compared with B0 at the same speed, load, and injection settings. This design directly addresses the central limitation in cross-study comparisons, where differences in engine geometry, compression ratio, injection equipment, feedstock, and instrumentation can be as important as the biodiesel percentage itself. The methodology also requires fuel-property measurement, because viscosity and heating value provide a physical explanation for changes in atomization and BSFC (Das et al., 2018).

The literature shows why B20 is a logical baseline blend for further development. It has repeatedly produced acceptable engine performance with lower smoke and incomplete-combustion emissions, and it can be used without major engine modification in many applications (Agarwal & Das, 2001; Kapadia et al., 2019). Nevertheless, the optimum is engine-specific. Sivaramakrishnan (2018) showed that a B25 blend could outperform diesel at a favorable compression ratio, while Ansari et al. (2018) demonstrated that injection timing and pressure can change the relative performance of polanga biodiesel blends. Thus, once the B0-B30 baseline is complete, the next research stage should optimize one or two engine-control variables around the most promising blend.

The most important limitation of a small laboratory study is external validity. A single-cylinder constant-speed engine does not fully represent turbocharged automotive engines, transient drive cycles, cold starting, after-treatment systems, or long-term durability. In

addition, biodiesel composition changes with feedstock and production route. For these reasons, the methodology should be viewed as a screening framework. If the results confirm the expected reduction in CO, HC, and smoke without an unacceptable BSFC or NO_x penalty, subsequent work should include transient testing, long-duration operation, injector deposits, lubricant dilution, and material compatibility, issues highlighted in the review by Mofijur et al. (2013).

Interpretation of Load and Blend Interactions

Load should be interpreted as a second experimental factor rather than only a sequence of operating points. At low load, the small injected fuel quantity and lower combustion temperature can increase the relative influence of measurement scatter and incomplete oxidation. At medium and high load, combustion temperatures and fuel flow become larger, making the effects of biodiesel oxygen content on CO, HC, and smoke easier to resolve. For this reason, a blend that appears neutral at 25% load may show a clear emission advantage at 75–100% load. Conversely, NO_x can become more sensitive at high load because thermal formation mechanisms depend strongly on local temperature and oxygen availability. Reporting blend-by-load interaction plots therefore provides more information than presenting only overall averages.

Reproducibility and Reporting Requirements

A publishable study should report sufficient detail for another laboratory to repeat the work. At minimum, the final report should identify the biodiesel feedstock, blend preparation method, measured fuel properties, engine model and geometry, rated power, compression ratio, injection timing and pressure, dynamometer type, analyzer model, calibration procedure, ambient conditions, replicate count, and measurement uncertainty. Raw readings should be retained so that BTE and BSFC calculations can be independently checked. Graphs should show B0 and all biodiesel blends at the same load points, and tables should distinguish measured data from values adopted from the literature. This reporting discipline is particularly important in biodiesel research because apparently conflicting results often arise from differences in feedstock chemistry or engine settings rather than from experimental error.

Conclusion

A structured methodology has been developed for evaluating the performance and emission

characteristics of diesel engines using biodiesel blends up to B30. The protocol compares B0, B10, B20, and B30 at identical engine speed and staged load while measuring fuel consumption, brake output, CO, HC, NO_x, and smoke. BTE and BSFC provide the principal performance indicators, and replicate testing with calibration and uncertainty reporting improves reliability. Literature available up to 2019 indicates that low-to-moderate biodiesel blends usually lower CO, HC, and smoke, while BSFC tends to increase slightly because of lower fuel heating value. NO_x may increase under conventional injection settings, but this response is sensitive to injection timing and combustion strategy. Evidence from the reviewed studies suggests that B20 is an appropriate reference blend for an unmodified diesel engine, although B25-B30 can become preferable when operating parameters are optimized. The proposed methodology therefore supports two sequential decisions: first, identify the best blend under fixed baseline engine settings; second, optimize engine parameters around that blend. The numerical values in this paper are benchmark values taken from published literature and should be replaced by measured values when the experiment is executed.

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