ISSN NO. 2456-3129

IJEPAS

International Journal of Engineering, Pure and Applied Sciences,
Vol. 10, No.4, Dec 2025

MULTI-OBJECTIVE OPTIMIZATION OF BIODIESEL FUEL PROPERTIES FOR IMPROVED THERMAL EFFICIENCY AND REDUCED CARBON EMISSIONS

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ABSTRACT
The increasing demand for sustainable energy sources and the need to mitigate greenhouse gas emissions have intensified research into alternative fuels for compression ignition engines. Biodiesel has emerged as a promising renewable substitute for conventional petroleum diesel because of its biodegradability, renewable origin, lower sulphur content and favourable combustion characteristics. However, variations in biodiesel fuel properties, including viscosity, density, cetane number, calorific value, flash point and oxygen content, significantly influence engine performance, combustion behaviour and exhaust emissions. The present study examines the application of multi-objective optimisation techniques for improving biodiesel fuel properties to achieve higher thermal efficiency and reduced carbon emissions. The research develops a conceptual optimisation framework integrating fuel composition, production parameters and engine operating conditions. Important fuel characteristics are considered as decision variables, while brake thermal efficiency, brake-specific fuel consumption and carbon-related emissions are treated as performance objectives. Multi-objective optimisation methods, particularly the Non-dominated Sorting Genetic Algorithm II (NSGA-II), are discussed for identifying optimal combinations of biodiesel properties and operating parameters. The framework also incorporates the principles of the Pareto optimality approach to evaluate competing performance indicators. The analysis indicates that biodiesel blends containing appropriate proportions of fatty acid methyl esters can provide a favourable balance between combustion efficiency and emission reduction. Particular attention is given to the influence of viscosity, oxygen content and heating value on fuel atomisation, combustion completeness and engine efficiency. The study proposes an integrated decision-making framework that can support the development of efficient biodiesel formulations for sustainable transportation and industrial energy applications. It also highlights the need for experimental validation under different engine loads, speeds and environmental conditions.

Keywords: Biodiesel, Multi-objective optimisation, Thermal efficiency, Carbon emissions, NSGA-II, Fuel properties, Renewable energy, Combustion performance, Sustainable transportation.

INTRODUCTION

The continuous growth of industrialisation, transportation activities and global energy consumption has increased dependence on fossil fuels. Petroleum-based diesel remains an important energy source for heavy-duty transportation, agricultural machinery, electricity generation and industrial operations. However, the extensive utilisation of conventional diesel contributes to atmospheric pollution, greenhouse gas emissions and the depletion of non-renewable energy resources. Carbon dioxide (CO_2), particulate matter, nitrogen oxides (NOx) and other combustion-related pollutants have become significant environmental concerns. Consequently, the development of renewable and environmentally sustainable alternatives to petroleum diesel has become a major research priority.

Biodiesel is recognised as a renewable liquid fuel produced primarily through the transesterification of vegetable oils, animal fats and waste cooking oils. It consists of fatty acid alkyl esters, commonly fatty acid methyl esters (FAME), which can be utilised in compression ignition engines either in pure form or through blending with conventional diesel. Its renewable origin, relatively high oxygen content, biodegradability and potential for reducing lifecycle greenhouse gas emissions make it an attractive alternative fuel.

Despite these advantages, biodiesel exhibits certain physicochemical characteristics that influence engine performance. Higher viscosity, lower calorific value and differences in density compared with petroleum diesel can affect fuel injection, spray formation, atomisation and combustion. These characteristics may result in increased fuel consumption or variations in thermal efficiency. Furthermore, although biodiesel can reduce certain emissions, its influence on NOx emissions, carbon monoxide and particulate matter depends on feedstock composition, blend ratio, engine technology and operating conditions.

The performance of biodiesel cannot therefore be evaluated through a single fuel property or emission

parameter. A fuel formulation that provides higher thermal efficiency may not necessarily produce the lowest emissions. Similarly, reducing fuel viscosity or increasing oxygen content may improve particular combustion characteristics while creating trade-offs in other performance indicators. This complex relationship establishes the need for a systematic optimisation approach.

Multi-objective optimisation provides an effective mathematical framework for addressing these competing requirements. Unlike conventional optimisation, which focuses on a single performance indicator, multi-objective optimisation simultaneously considers several objectives and identifies a range of non-dominated solutions. These solutions are commonly represented through a Pareto front, which provides alternative combinations of fuel properties and engine operating parameters.

The present research examines how multi-objective optimisation can be applied to biodiesel fuel formulation to improve thermal efficiency while reducing carbon-related emissions. Particular emphasis is placed on the integration of fuel-property optimisation, combustion performance and evolutionary computational techniques.

REVIEW OF LITERATURE

Research on biodiesel has developed considerably over recent decades, particularly in relation to alternative feedstocks, fuel processing, engine performance and environmental sustainability. Existing investigations demonstrate that biodiesel characteristics are strongly influenced by feedstock composition and production conditions.

Demirbas (2009) discussed the significance of biodiesel as an alternative renewable transportation fuel and highlighted its potential contribution to energy security and environmental sustainability. The study identified feedstock availability, production cost and fuel characteristics as important considerations influencing the wider adoption of biodiesel.

Knothe (2005) examined the relationship between biodiesel composition and fuel properties. The research demonstrated that fatty acid composition influences important characteristics such as cetane number, viscosity, oxidative stability and cold-flow behaviour. The findings suggest that selecting appropriate feedstocks is essential for producing biodiesel with desirable combustion characteristics.

Agarwal (2007) investigated the development and utilisation of biodiesel in internal combustion engines. The research discussed the influence of fuel properties on engine performance and emissions and identified the importance of fuel quality in determining combustion behaviour.

Lapuerta et al. (2008) reviewed the influence of biodiesel on diesel engine emissions. Their findings indicated that biodiesel generally offers favourable reductions in particulate matter, carbon monoxide and unburned hydrocarbons, although NOx emissions may increase under certain operating conditions.

Atadashi et al. (2012) examined biodiesel purification and production technologies, emphasising the importance of controlling production parameters to obtain fuel that meets established quality specifications. The study highlighted the role of process optimisation in improving biodiesel quality and commercial viability.

Sharma et al. (2008) reviewed biodiesel production from non-edible oils and discussed the potential of alternative feedstocks for sustainable fuel development. Their work is relevant to optimisation because feedstock composition directly influences the resulting fuel characteristics.

Although previous studies have examined individual fuel properties, production techniques and engine emissions, the simultaneous optimisation of multiple fuel characteristics and engine performance indicators remains an important research area. A comprehensive framework should integrate fuel formulation, production conditions and engine operating parameters rather than treating them as independent variables.

RESEARCH METHODOLOGY

Research Design

The study adopts a computational and analytical research framework for evaluating the relationship between biodiesel fuel properties and engine performance. The proposed methodology integrates three major stages: fuel-property characterisation, engine-performance evaluation and multi-objective optimisation.

The first stage involves identifying relevant biodiesel properties and establishing suitable operating ranges based on recognised fuel-quality standards. The second stage considers the influence of these properties on engine performance and exhaust emissions. The third stage applies evolutionary optimisation to identify fuel formulations that provide an appropriate balance between thermal efficiency and environmental performance. For empirical implementation, the framework can be supported by laboratory experiments involving biodiesel blends and a compression ignition engine.

Selection of Biodiesel Fuel Properties

The optimisation process considers the following physicochemical properties:

Fuel property	Symbol	Significance
Kinematic viscosity	V	Influences fuel atomisation and injection
Density	D	Affects injected fuel mass and spray characteristics
Cetane number	CN	Influences ignition quality
Calorific value	CV	Determines energy available during combustion
Oxygen content	O	Influences oxidation and combustion characteristics
Flash point	FP	Indicates fuel handling and storage safety
Biodiesel blend ratio	B	Determines biodiesel concentration in diesel blends

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The selected properties are interdependent. For example, increasing the proportion of certain saturated fatty acid esters may improve cetane number and oxidative stability but can adversely affect cold-flow properties. Similarly, higher oxygen content can support more complete combustion, although its influence depends on injection and combustion conditions.

Engine Performance Parameters

The following parameters are selected for evaluating engine performance:

- Brake thermal efficiency (BTE).
- Brake-specific fuel consumption (BSFC).
- Exhaust carbon dioxide (CO_2).
- Carbon monoxide (CO).
- Unburned hydrocarbons (HC).
- Nitrogen oxides (NOx).

Brake thermal efficiency indicates the proportion of fuel energy converted into useful brake power. BSFC represents the fuel mass required to produce a unit of brake power over a specified period. Both parameters provide essential information about the energy-conversion performance of biodiesel.

Experimental Data Collection

A suitable experimental investigation may be conducted using a single-cylinder or multi-cylinder compression ignition engine equipped with appropriate fuel measurement and exhaust gas analysis systems.
Different biodiesel blends, such as B10, B20, B30 and B40, may be evaluated under controlled engine operating conditions. The experimental programme should include multiple engine loads and speeds to capture variations in combustion behaviour.
The following instruments may be employed:

- Engine dynamometer for brake power measurement.
- Fuel consumption measurement system.
- Exhaust gas analyser for CO, CO_2 and HC.
- NOx analyser for nitrogen oxide measurement.
- Temperature sensors for exhaust and engine operating conditions.
- Laboratory equipment for determining viscosity, density, calorific value and cetane number.

The fuel characteristics should be measured according to relevant ASTM or EN standards. Repeated measurements should be conducted to improve reliability and reduce experimental uncertainty.

Multi-Objective Optimisation Model

Multi-objective optimisation is formulated to identify suitable fuel-property combinations that simultaneously maximise thermal efficiency and minimise fuel consumption and emissions.

The general mathematical representation is:
Optimise $F(X) = [f_1(X), f_2(X), ..., f_n(X)]$
Subject to: $g_i(X) \leq 0$; $h_j(X) = 0$
where X represents the decision-variable vector, $f_i(X)$ represents the objective functions, $g_i(X)$ represents inequality constraints and $h_j(X)$ represents equality constraints.
The decision-variable vector may be expressed as X = [V, D, CN, CV, O, B, L, S], where L represents engine load and S represents engine speed.
Objective 1: Maximisation of brake thermal efficiency
$\max f_1(X) = BTE(X)$
$BTE = [BP \times 3600 / (\dot{m}f \times CV)] \times 100$
where BP is brake power (kW), $\dot{m}f$ is fuel mass consumption (kg/h), and CV is calorific value (kJ/kg).
Objective 2: Minimisation of brake-specific fuel consumption
$\min f_2(X) = BSFC(X)$; $BSFC = \dot{m}f / BP$
Objective 3: Minimisation of carbon dioxide emissions
$\min f_3(X) = CO_2(X)$
Objective 4: Minimisation of carbon monoxide emissions
$\min f_4(X) = CO(X)$
These objectives are evaluated simultaneously rather than independently.
A critical distinction is necessary between exhaust CO_2 concentration, mass emissions and lifecycle greenhouse gas emissions. Exhaust CO_2 measurements alone cannot establish the overall carbon advantage of biodiesel because the carbon released during combustion must be considered alongside feedstock cultivation, processing, transportation and land-use effects.

Application of Non-Dominated Sorting Genetic Algorithm II (NSGA-II)

The Non-dominated Sorting Genetic Algorithm II (NSGA-II) is selected as the principal optimisation technique because of its ability to solve complex multi-objective problems involving nonlinear relationships and competing performance indicators. The algorithm is particularly suitable for biodiesel optimisation because fuel properties influence combustion efficiency and emissions through interconnected mechanisms.

1. Population initialisation: A population of potential biodiesel formulations is generated within predefined fuel-property constraints.
2. Objective evaluation: Each solution is evaluated according to thermal efficiency, fuel consumption and emission performance.
3. Non-dominated sorting: Candidate solutions are classified into different Pareto fronts according to their dominance relationships.
4. Crowding distance calculation: Diversity among solutions is maintained to avoid concentrating the search in a limited region.

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5. Selection and reproduction: Parent solutions are selected using rank and crowding distance.
6. Crossover and mutation: New candidate solutions are generated to explore alternative fuel formulations.
7. Termination: The algorithm continues until the specified number of generations or convergence criterion is achieved.

The principal advantage of this method is that it does not require the researcher to assign arbitrary weights to all objectives at the beginning of the optimisation process. Instead, it generates a collection of non-dominated alternatives from which the most appropriate solution can be selected according to engineering and environmental priorities.

Constraints and Fuel Quality Requirements

The optimisation model must incorporate practical constraints to ensure that the resulting biodiesel formulation remains suitable for engine operation. Fuel properties cannot be optimised without considering accepted quality specifications and operational safety.

- Kinematic viscosity must remain within the applicable fuel-quality specification.
- Density must be appropriate for the fuel injection system.
- Cetane number must satisfy the relevant minimum requirement.
- Flash point must meet storage and handling safety requirements.
- Fuel stability must be sufficient to maintain acceptable storage characteristics.
- Biodiesel blends must remain compatible with engine materials and fuel delivery systems.
- Emissions must be evaluated under comparable engine operating conditions.

ASTM D6751 and EN 14214 provide recognised specifications for biodiesel quality. Their requirements should be considered when defining the feasible optimisation region.

PRACTICAL APPLICATIONS OF THE PROPOSED FRAMEWORK

Transportation Sector

Heavy-duty vehicles, buses, agricultural tractors and commercial transportation fleets can benefit from biodiesel blends that provide appropriate fuel characteristics and engine compatibility. Optimised fuel formulations may contribute to improved fuel economy and reduced dependence on petroleum diesel.

Agricultural Machinery

Agricultural machinery frequently operates under variable engine loads and environmental conditions. The optimisation of biodiesel properties can help identify formulations appropriate for tractors, irrigation pumps and other diesel-powered agricultural equipment.

Industrial Power Generation

Diesel generators are extensively used in industrial establishments and remote locations. Biodiesel optimisation can support the development of renewable fuel alternatives for stationary electricity generation.

Sustainable Energy Planning

The proposed framework can assist policymakers, energy researchers and fuel manufacturers in evaluating alternative feedstocks and identifying technically and environmentally suitable biodiesel formulations.

Limitations and Future Research Directions

Although the proposed optimisation framework provides a systematic approach to biodiesel formulation, certain limitations require consideration.

First, fuel properties vary according to feedstock composition and biodiesel production conditions. Consequently, optimisation models developed for one feedstock may not be directly applicable to another.

Second, engine performance is influenced by several interacting variables, including injection pressure, compression ratio, engine load, speed and ambient temperature. A model that does not incorporate these parameters may produce limited or misleading optimisation outcomes.

Third, the relationship between fuel properties and exhaust emissions is nonlinear. Therefore, accurate experimental data are required to develop reliable predictive models. Machine learning techniques, including artificial neural networks, random forests and gradient boosting, could be integrated with evolutionary optimisation to improve predictive accuracy.

Fourth, carbon emission reduction must be evaluated using appropriate system boundaries. Direct exhaust measurements and lifecycle greenhouse gas assessments provide different forms of environmental information and should not be treated as interchangeable.

Future research should investigate the following areas:

1. Experimental validation of NSGA-II-generated biodiesel formulations using standardised engine testing procedures.
2. Integration of artificial neural networks with multi-objective evolutionary algorithms.
3. Investigation of biodiesel derived from non-edible oils, waste cooking oils and microalgae.
4. Evaluation of long-term engine durability, lubricant degradation and fuel-system compatibility.
5. Development of optimisation models incorporating engine load, speed and injection pressure.
6. Integration of lifecycle assessment with engine-performance optimisation.

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7. Comparative evaluation of NSGA-II, multi-objective PSO and other advanced metaheuristic algorithms.

The integration of computational intelligence with experimental fuel characterisation may provide a more reliable foundation for developing next-generation biodiesel formulations.

RESULTS AND DISCUSSION

Influence of Fuel Viscosity on Thermal Efficiency

Kinematic viscosity is one of the most influential characteristics affecting biodiesel combustion. It determines the resistance of the fuel to flow and influences injection characteristics, spray penetration and atomisation. Biodiesel generally exhibits higher viscosity than conventional diesel because of its molecular structure.

Higher viscosity can produce larger fuel droplets and less effective atomisation, potentially resulting in incomplete combustion and increased fuel consumption. These effects may be particularly significant in engines designed specifically for petroleum diesel.

Optimisation of viscosity is therefore necessary to achieve improved combustion characteristics. Appropriate transesterification, blending and feedstock selection can help produce biodiesel with viscosity characteristics suitable for compression ignition engines. However, reducing viscosity beyond an appropriate range is not necessarily beneficial. The objective should be to identify a technically suitable viscosity range that supports stable injection and combustion rather than simply minimising viscosity.

Role of Calorific Value in Fuel Consumption

Calorific value represents the amount of energy released during the complete combustion of a unit mass of fuel. Biodiesel generally has a lower heating value than conventional diesel because of its oxygen-containing molecular structure.

Consequently, a larger quantity of biodiesel may be required to produce equivalent engine output under certain operating conditions. This characteristic can contribute to increased BSFC.

The optimisation framework therefore considers calorific value as an important decision variable. A suitable biodiesel formulation should provide an appropriate balance between oxygen content, molecular composition and energy density. The relationship between calorific value and thermal efficiency is not necessarily linear. Actual engine efficiency also depends on combustion quality, ignition delay, heat losses and injection characteristics.

Influence of Cetane Number on Combustion Characteristics

Cetane number is an indicator of diesel fuel ignition quality. Fuels with higher cetane numbers generally exhibit shorter ignition delays under comparable operating conditions.

Biodiesel often possesses favourable cetane characteristics, although the actual value depends on its fatty acid composition. Higher proportions of saturated fatty acid esters generally contribute to higher cetane numbers, whereas greater unsaturation may reduce cetane quality.

An appropriate cetane number can improve combustion stability and influence the timing of heat release. Nevertheless, excessively modifying fuel composition to maximise cetane number may negatively affect cold-flow characteristics and other fuel properties. Consequently, cetane number should be treated as a constrained optimisation variable rather than an isolated maximisation objective.

Contribution of Oxygen Content to Carbon Emission Reduction

One of the distinguishing characteristics of biodiesel is its chemically bound oxygen content. This oxygen can support oxidation reactions during combustion and may contribute to reductions in incomplete combustion products.

The presence of oxygen in biodiesel can improve local oxidation in fuel-rich regions, potentially reducing carbon monoxide, unburned hydrocarbons and particulate matter. However, the relationship between oxygen content and emissions is influenced by fuel injection pressure, combustion chamber geometry, engine temperature, air-to-fuel ratio, engine load, ignition delay and combustion duration.

An increase in oxygen content does not automatically guarantee a proportional reduction in all emissions. NOx emissions, in particular, may increase under some operating conditions because of changes in combustion temperature and oxygen availability.

Effect of Biodiesel Blend Ratio

The blend ratio determines the proportion of biodiesel mixed with conventional diesel. Different blend proportions produce different combinations of fuel properties and combustion characteristics. B20 is frequently investigated because it offers a practical compromise between biodiesel utilisation and conventional diesel compatibility. Nevertheless, the optimum blend ratio cannot be established universally. Engine design, feedstock composition, fuel specifications and operating conditions must be considered.

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Parameter	B10	B20	B30	B40
Biodiesel concentration	Low	Moderate	Higher	High
Oxygen contribution	Low	Moderate	Higher	High
Calorific value	Near diesel	Slightly lower	Lower	Relatively lower
Viscosity	Near diesel	Slightly higher	Higher	Relatively higher
Renewable fuel contribution	Low	Moderate	Higher	High
Potential carbon benefit	Limited	Moderate	Higher potential	Higher potential

Relationship Between Thermal Efficiency and Emissions

Thermal efficiency and exhaust emissions represent interconnected but sometimes competing performance indicators. Improving combustion completeness may increase thermal efficiency while reducing CO and HC emissions. However, changes in combustion temperature and timing can influence NOx formation.
Similarly, reducing fuel consumption may lower the amount of fuel required to generate a specific power output, but the resulting carbon emissions depend on the carbon content of the fuel and combustion characteristics.
The proposed multi-objective framework evaluates these relationships simultaneously. Instead of assuming that one biodiesel blend is optimal for every application, the method identifies alternative solutions suitable for different operating requirements.

Pareto Optimality and Decision-Making

A Pareto-optimal solution is one for which no objective can be improved without worsening at least one other objective, assuming all constraints are satisfied.
For example, one biodiesel formulation may provide comparatively high thermal efficiency but slightly higher CO_2 emissions. Another formulation may produce lower emissions but require marginally greater fuel consumption. Both solutions may be Pareto-optimal because neither dominates the other across all objectives.
The Pareto front enables decision-makers to identify the most appropriate fuel formulation according to operational priorities. For heavy-duty transportation, fuel economy and engine reliability may receive greater emphasis, whereas stationary power-generation applications may prioritise emission reduction.
A final solution can be selected using a multi-criteria decision-making technique such as TOPSIS (Technique for Order Preference by Similarity to Ideal Solution). This approach ranks the Pareto-optimal alternatives according to their relative distance from an ideal solution.

Potential Contribution to Energy Efficiency

The proposed optimisation framework can contribute to improved energy efficiency by identifying appropriate combinations of fuel viscosity, calorific value, cetane number and biodiesel concentration. These characteristics influence the fuel injection process, ignition delay and combustion duration.
An appropriately formulated biodiesel blend may support more effective fuel-air mixing and combustion stability. Improved combustion can increase the proportion of fuel energy converted into useful mechanical work, thereby improving brake thermal efficiency. However, the actual efficiency improvement will depend on engine design, injection technology, operating temperature and load conditions. Therefore, the optimisation results should be validated through controlled engine experiments.

Implications for Carbon Emission Reduction

Carbon emission reduction is an important consideration in developing renewable transportation fuels. Biodiesel derived from sustainable feedstocks can contribute to lower lifecycle greenhouse gas emissions compared with petroleum diesel, although the magnitude of the reduction depends on production methods and feedstock sources.
The proposed optimisation framework distinguishes between direct exhaust emissions and lifecycle greenhouse gas emissions. This distinction is essential because biodiesel combustion releases CO_2, even though some of the carbon may originate from recently absorbed atmospheric carbon during feedstock growth.
The environmental assessment should therefore incorporate feedstock cultivation and harvesting; oil extraction and biodiesel production; methanol and catalyst consumption; fuel transportation and distribution; direct engine exhaust emissions; land-use changes and associated emissions; and by-product utilisation and allocation methods.
A lifecycle assessment based on ISO 14040 and ISO 14044 can provide a more comprehensive evaluation of the environmental performance of optimised biodiesel formulations.

CONCLUSION

Multi-objective optimisation offers a systematic approach to improving biodiesel fuel characteristics while addressing the competing requirements of engine thermal efficiency, fuel consumption and exhaust emission reduction. The present study proposes an integrated optimisation framework that considers viscosity, density, cetane number, calorific value, oxygen content and biodiesel blend ratio as important decision variables.
The analysis demonstrates that biodiesel performance depends on the combined influence of physicochemical characteristics and engine operating conditions. Fuel viscosity influences atomisation and injection behaviour, calorific value affects energy availability, cetane number influences ignition quality, and chemically bound oxygen contributes to combustion characteristics. These relationships establish the need

for simultaneous evaluation rather than isolated optimisation of individual fuel properties.

The proposed application of NSGA-II provides a suitable computational mechanism for identifying Pareto-optimal biodiesel formulations. By considering brake thermal efficiency, brake-specific fuel consumption, CO_2 and CO emissions as competing objectives, the framework can generate alternative fuel-property combinations for different engine applications. TOPSIS or other multi-criteria decision-making methods may subsequently be used to select an appropriate compromise solution.

A significant contribution of the proposed framework is its integration of fuel-property optimisation with environmental evaluation. The distinction between direct exhaust emissions and lifecycle greenhouse gas emissions provides a more comprehensive basis for assessing biodiesel sustainability.

The framework requires experimental validation using standardised fuel-characterisation procedures, controlled engine testing and reliable emission measurement systems. Future integration with machine learning and lifecycle assessment techniques could further strengthen its predictive capability. The proposed methodology provides a foundation for developing technically suitable, energy-efficient and environmentally responsible biodiesel formulations for sustainable transportation and industrial energy applications.

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