SUSTAINABLE FUELS

Experimental Evaluation of Alternative Biodiesel Fuels for Energy Efficiency, Emission Characteristics and Sustainable Engineering Applications

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Abstract

The increasing demand for sustainable energy resources and the need to mitigate environmental pollution have encouraged the investigation of renewable and alternative fuels for diesel-powered engineering applications. This study presents a comparative experimental investigation of four vegetable-oil-derived biodiesels, namely rice bran oil methyl ester (RME), polanga oil methyl ester (PME), karanja oil methyl ester (KME) and uppage oil methyl ester (UME), in a single-cylinder, four-stroke, direct-injection diesel engine. High-speed diesel (HD) was used as the reference fuel. The investigation evaluated brake thermal efficiency (BTE), brake-specific energy consumption (BSEC), carbon monoxide (CO), unburned hydrocarbons (HC), oxides of nitrogen (NOx), smoke opacity, in-cylinder pressure and heat-release rate (HRR). At 80% of full load, PME exhibited the highest BTE among the biodiesels (25.41%) and the lowest BSEC (approximately 14.2 MJ kW^{-1} h^{-1}). It also showed comparatively favourable CO, HC and smoke results, while NOx emissions were higher than those of HD. The results indicate that the relative suitability of biodiesel depends on the balance between energy performance and emission characteristics. The findings are relevant to the assessment of alternative fuels for diesel-powered engineering equipment. Potential implications for construction and infrastructure equipment are discussed from an application perspective; however, the present experiments were conducted on a laboratory engine, and no field trials, life-cycle assessment or direct ambient-air-quality measurements were performed. The study therefore provides an experimental basis for further interdisciplinary research connecting engine performance, emission mitigation and sustainable engineering applications.

Keywords: biodiesel; renewable fuels; engine performance; combustion; exhaust emissions; environmental sustainability; engineering applications

1 Introduction

Growing energy demand, concerns about the depletion of fossil-fuel resources and the environmental impacts associated with conventional fuels have motivated research into renewable alternatives for compression-ignition engines. Vegetable oils, animal fats, alcohols, biogas, hydrogen and other renewable or low-carbon energy carriers have been investigated as potential alternatives to petroleum-derived diesel. Vegetable oils are of interest because they originate from biological resources and can be converted into liquid fuels that may be used in existing compression-ignition engine technologies.

The use of vegetable oils in compression-ignition engines has a long history. Direct use of unprocessed vegetable oils is generally constrained by their comparatively high viscosity, which can

affect fuel injection, atomisation and combustion. These effects may contribute to injector deposits, carbon formation and increased unburned-hydrocarbon emissions. Transesterification converts triglycerides into fatty-acid alkyl esters and reduces viscosity, producing biodiesel with fuel properties more suitable for engine applications.

Biodiesel is renewable and biodegradable and typically contains chemically bound oxygen. Previous engine studies have reported reductions in carbon monoxide, unburned hydrocarbons and particulate or smoke emissions in some operating conditions. However, the effects on NOx emissions, fuel consumption and thermal efficiency vary with feedstock, fuel properties, blend ratio, engine design and operating conditions [1–15].

The environmental significance of diesel emissions extends beyond engine operation. Diesel-powered equipment is used in transportation, construction, earthmoving, road building and infrastructure maintenance. Accordingly, improvements in fuel-related emission characteristics may be relevant to efforts to reduce the environmental burden of engineering operations. Nevertheless, engine-out emission measurements alone do not establish the overall life-cycle environmental performance of a fuel; feedstock production, processing, transport and land-use effects also need to be considered.

Although several biodiesel feedstocks have been studied individually, a comparative evaluation of rice bran, polanga, karanja and uppage oil methyl esters under a common engine configuration provides a basis for assessing their relative behaviour. The present study compares their fuel properties, engine performance, exhaust emissions and combustion characteristics against high-speed diesel. The wider relevance to sustainable engineering applications is considered without claiming field performance or life-cycle benefits that were not measured.

1.1 Objectives of the study

- To compare the reported physical properties of RME, PME, KME and UME with those of high-speed diesel.
- To experimentally evaluate engine performance in terms of BTE and BSEC under different load conditions.
- To compare CO, HC, NOx and smoke emissions for the test fuels.
- To examine combustion behaviour using in-cylinder pressure and heat-release-rate characteristics.
- To discuss the potential relevance of the measured engine and emission characteristics to cleaner energy use in diesel-powered engineering equipment.

2 Materials and methods

2.1 Test fuels and fuel properties

The test fuels comprised neat rice bran oil methyl ester (RME), polanga oil methyl ester (PME), karanja oil methyl ester (KME) and uppage oil methyl ester (UME). High-speed diesel (HD) was used as the reference fuel. The physical-property values reported in the supplied experimental manuscript are reproduced in Table 1. The original record does not provide test standards, measurement uncertainty or replicate data for these properties; these details should be added if available.

Table 1. Reported physical properties of the test fuels.

Properties	HD	RME	PME	UME	KME
Density at STP (kg/m^3)	840	875	870	860	881
LCV (MJ/kg)	43.12	38.47	39.98	36.97	37.98
Kinematic Viscosity (centistokes)	2.5	4.9	4.4	5.2	4.3
Cetane Number	48	56	55	54	51

2.2 Engine test facility

Experiments were conducted using a Kirloskar, single-cylinder, four-stroke, direct-injection diesel engine coupled to an eddy-current dynamometer. The engine specifications reported in the source manuscript are presented in Table 2 and Figure 1shows the schematic representation of the engine test facility. The test facility included instrumentation for measuring engine load and speed, fuel consumption, airflow, in-cylinder pressure and crank angle. Exhaust emissions were measured using an exhaust-gas analyser, and smoke was measured using a Hartridge smoke meter.

Table 2. Test engine specification.

Make & Type	Kirloskar – Single cylinder four stroke DI Diesel Engine
Injector opening pressure (bar)	200
Injection timing	23^0 bTDC
Rated power (kW)	5.2 (7 hp)
Rated Speed (rpm)	1500
Bore (mm)	87.5
Stroke (mm)	110
Compression ratio	17.5:1

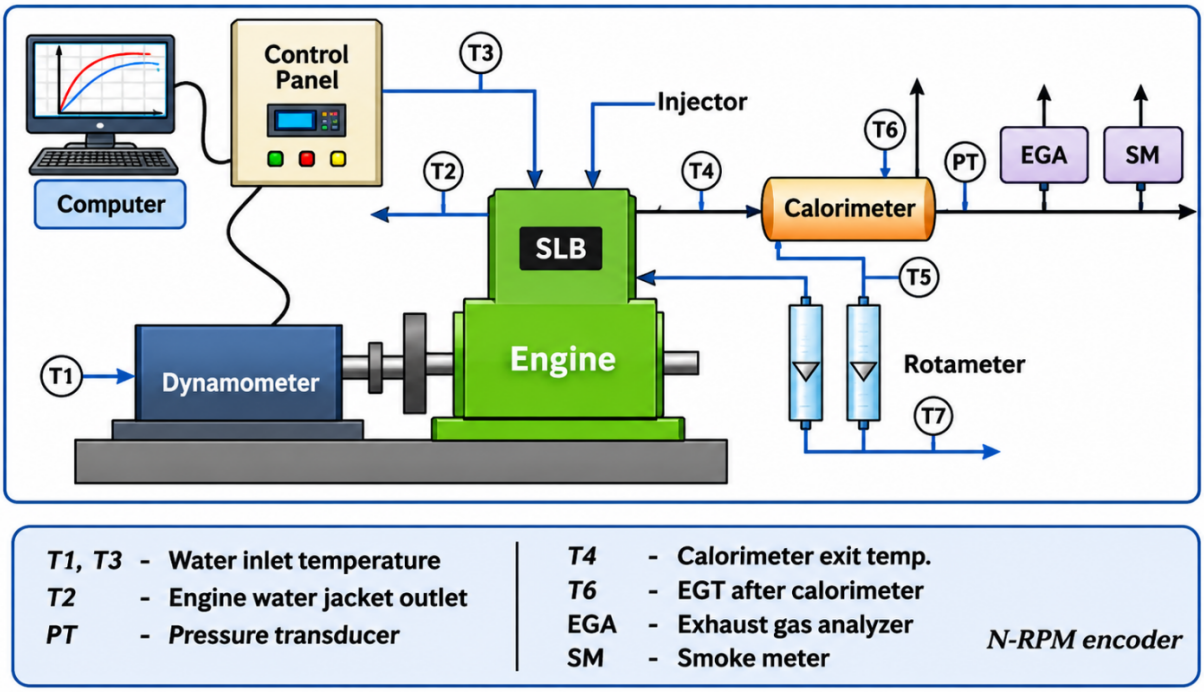


Figure 1. Engine test facility.

2.3 Experimental procedure and evaluated parameters

The engine was operated on each test fuel after the system had reached steady-state conditions. Load was applied using the eddy-current dynamometer. Engine speed, fuel-consumption rate and airflow rate were recorded to determine brake power and the corresponding performance parameters. BTE and BSEC were evaluated from the measured operating data and fuel energy input. CO, HC and NOx emissions were measured using the exhaust-gas analyser, and smoke opacity was measured using the Hartridge smoke meter. In-cylinder pressure was recorded as a function of crank angle for combustion analysis.

The performance and emission parameters considered were BTE, BSEC, CO, HC, NOx and smoke opacity. Combustion behaviour was assessed using peak cylinder pressure (PCP) and HRR. The reported comparisons place particular emphasis on the results at 80% of full load.

3 Results and discussion

3.1 Brake thermal efficiency

BTE increased with engine load for all test fuels, with the maximum reported value occurring at 80% of full load (Figure 2). At this operating point, the reported BTE values were 30.25% for HD, 25.30% for RME, 25.41% for PME, 24.67% for UME and 24.30% for KME. PME therefore exhibited the highest BTE among the tested biodiesels, although its value was approximately 16.0% lower than that of HD when expressed relative to the HD value. The lower heating value and higher viscosity of the methyl esters may contribute to the observed difference; however, the individual contributions of these properties were not isolated in the reported experiments.

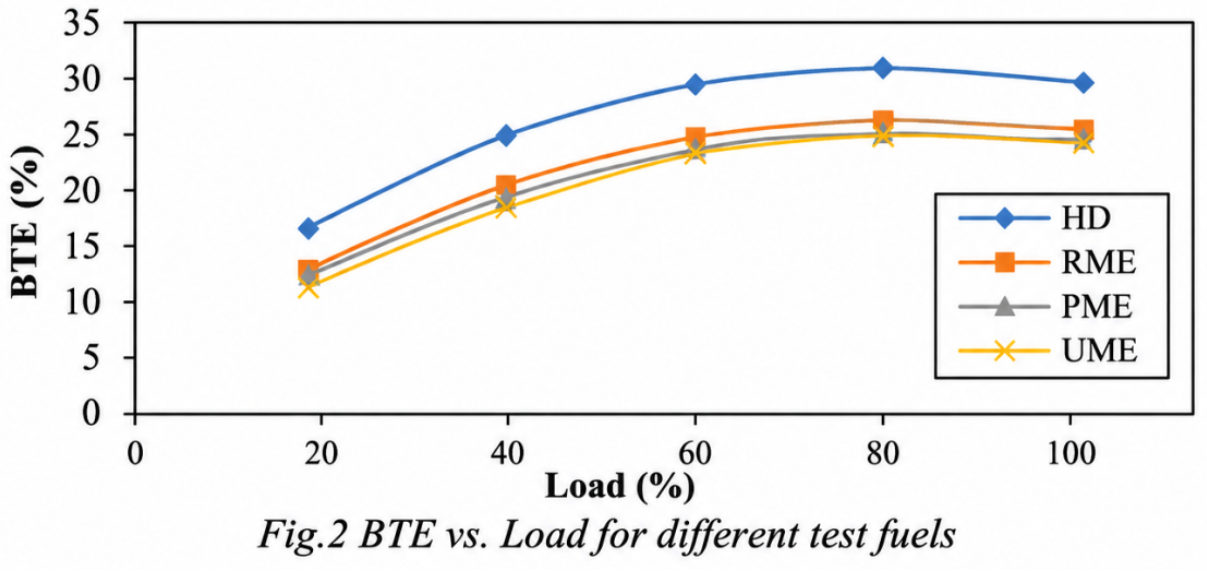


Figure 2. BTE vs. load for different test fuels.

3.2 Brake-specific energy consumption

BSEC decreased as engine load increased for all test fuels (Figure 3). At 80% of full load, the reported BSEC values were 11.9 MJ kW^{-1} h^{-1} for HD, 14.3 MJ kW^{-1} h^{-1} for RME, 14.2 MJ kW^{-1} h^{-1} for PME, 14.59 MJ kW^{-1} h^{-1} for UME and 14.8 MJ kW^{-1} h^{-1} for KME. PME recorded the lowest BSEC among the biodiesels. The higher BSEC of the methyl esters relative to HD is consistent with their lower calorific values and may also reflect differences in fuel-injection and combustion behaviour.

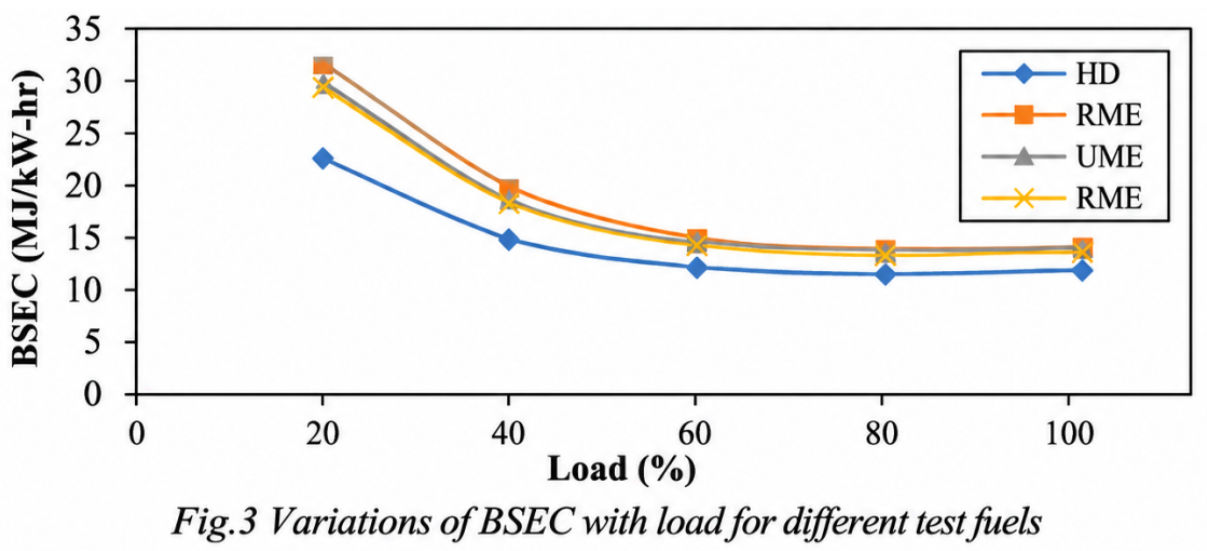


Figure 3. Variations of BSEC with load for different test fuels.

3.3 Carbon monoxide emissions

Figure 4 presents the variation of CO emissions with engine load. The source manuscript reports a mean CO concentration of 0.05% by volume for PME, described as the lowest mean value among the tested fuels. At 80% load, the reported CO concentrations were 0.10% for RME, 0.07% for PME, 0.06% for UME and 0.08% for KME. The corresponding HD value is not stated clearly in the source text, although reductions of 30%, 33%, 27% and 18% are reported for RME, PME, UME and KME, re-

spectively, relative to HD. The lower CO emissions observed with biodiesel may be associated with the oxygen content of the fuel, which can support oxidation in locally fuel-rich regions.

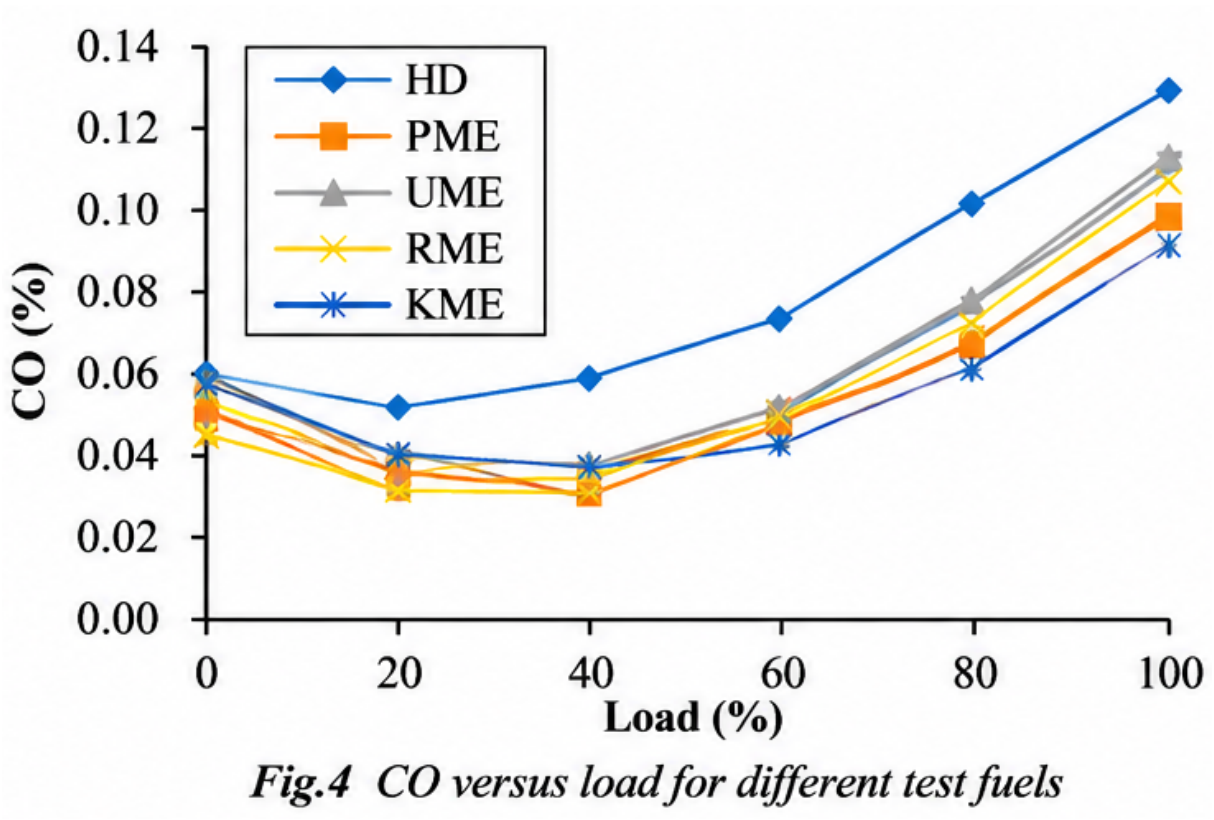


Figure 4. CO versus load for different test fuels.

3.4 Unburned hydrocarbon emissions

Figure 5 shows HC emissions for the test fuels at different engine loads. The reported mean HC emissions were 30.33 ppm for HD, 23.16 ppm for RME, 23.5 ppm for PME, 25.5 ppm for UME and 24.3 ppm for KME. At 80% of full load, the reported values were 40 ppm for HD, 28 ppm for PME, 29 ppm for RME, 32 ppm for UME and 27 ppm for KME. These results indicate lower HC emissions for all four biodiesels than for HD at the stated operating point. The reduction may be related to the oxygenated nature of biodiesel, although spray, mixing and in-cylinder temperature effects may also influence HC formation.

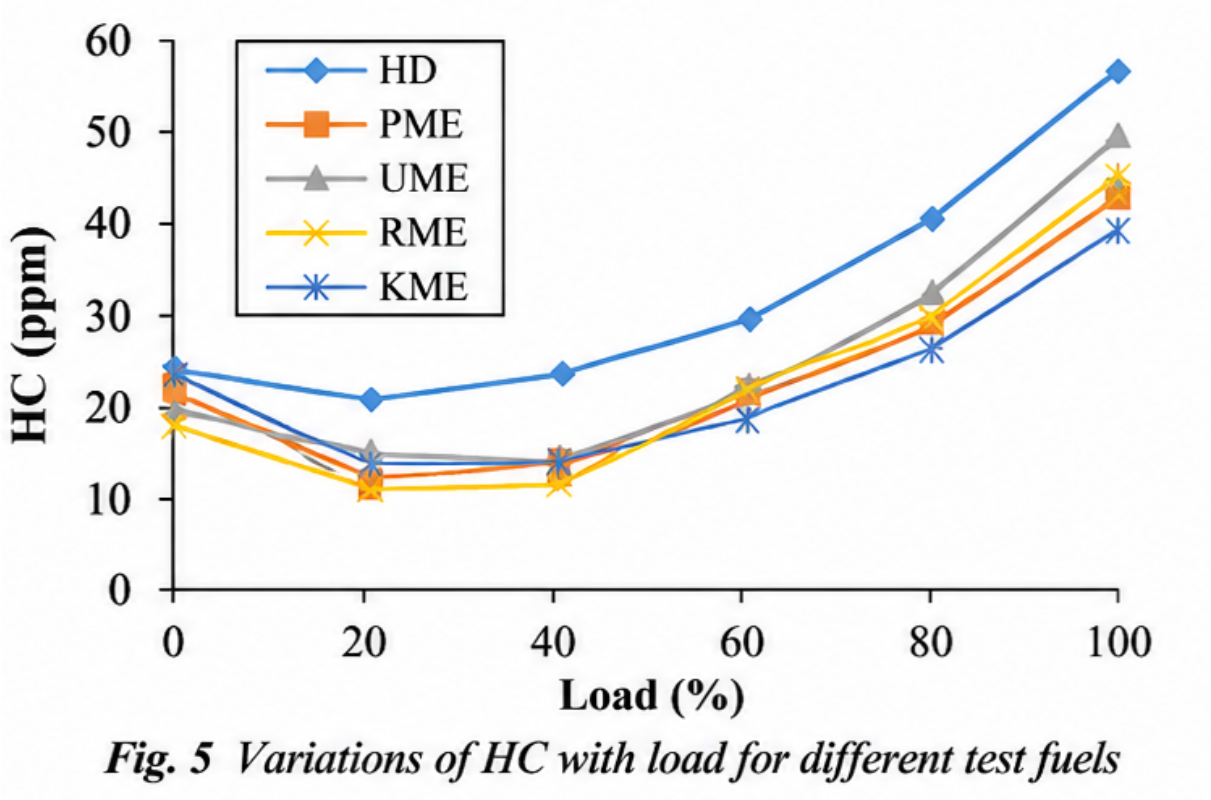


Figure 5. Variations of HC with load for different test fuels.

3.5 Oxides of nitrogen emissions

The variation of NOx emissions with engine load is shown in Figure 6. The mean NOx emissions were reported to increase by 8.7% for PME, 8.41% for RME, 13.44% for UME and 12.37% for KME relative to HD. At 80% of full load, the reported concentrations were 1080 ppm for HD, 1121 ppm for PME, 1139 ppm for RME, 1146 ppm for UME and 1165 ppm for KME. Thus, NOx emissions were higher for all biodiesels than for HD at this operating point. The increase may be associated with changes in combustion temperature and oxygen availability during combustion. The increase calculated from the 80%-load values for PME is approximately 3.8%, which differs from the reported mean increase of 8.7%; the two values refer to different comparison bases and should be clearly distinguished.

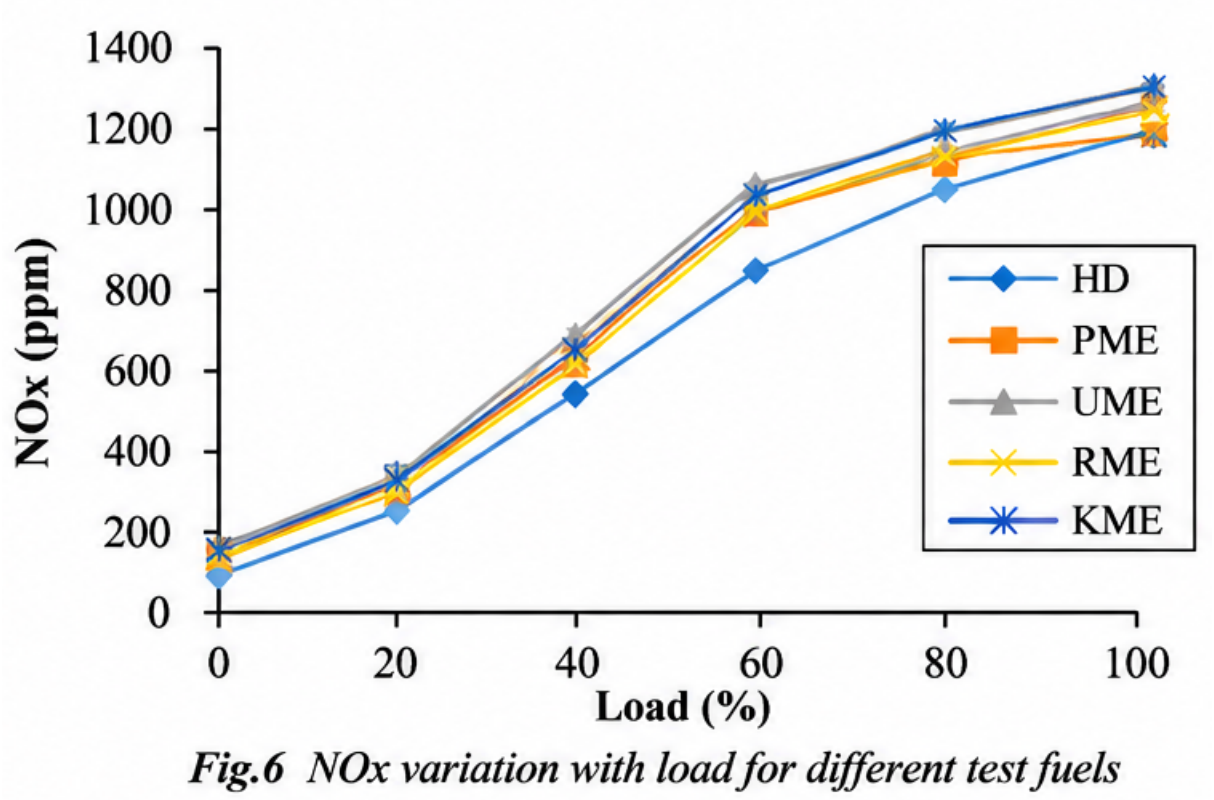


Figure 6. NOx variation with load for different test fuels.

3.6 Smoke opacity

Figure 7 presents smoke readings as a function of engine load. The reported average smoke reductions relative to HD were 32.28% for PME, 30.94% for RME, 25.11% for UME and 23.31% for KME. At 80% of full load, smoke readings were 46 HSU for HD, 34 HSU for PME, 35 HSU for RME, 37 HSU for UME and 33 HSU for KME. The lower smoke levels observed with biodiesels may be associated with fuel-bound oxygen and differences in fuel composition that favour soot oxidation. At 80% load, KME had the lowest absolute smoke reading, whereas PME had the largest reported average reduction; these are different comparison measures.

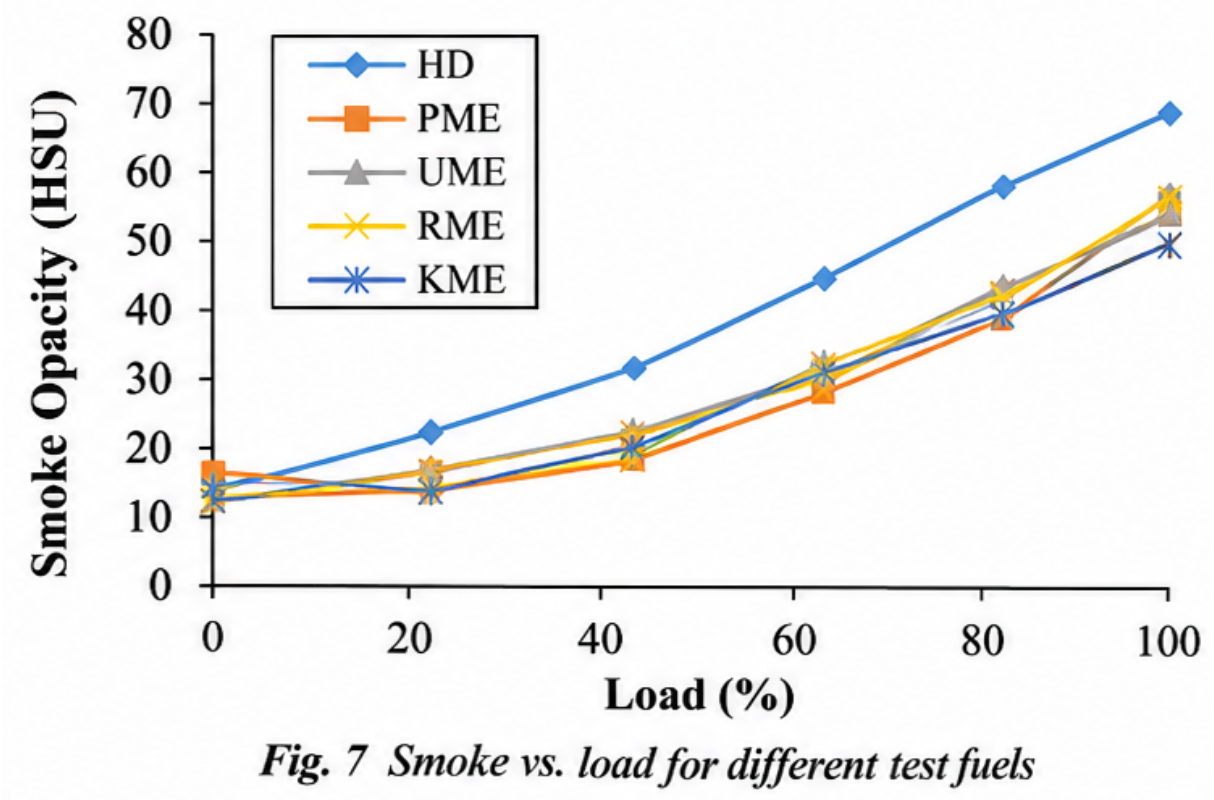


Figure 7. Smoke vs. load for different test fuels.

3.7 Combustion characteristics

The combustion analysis considered heat-release rate and in-cylinder pressure as functions of crank angle. Figure 8 represents the variation of maximum heat release rate with different load conditions for all test fuels. Figure 9 indicated that there is a negative heat release rate for all test fuels and it is due to vaporization of heat required during ignition period. The source reports a negative heat-release-rate region during the ignition period and attributes it to the energy absorbed during fuel vaporisation. At 80% of full load, the reported peak HRR values were 64.8 J/°CA for PME, 63.4 J/°CA for RME, 67.79 J/°CA for KME, 66.64 J/°CA for UME and 79.01 J/°CA for HD. PME therefore exhibited a lower peak HRR than HD. The source attributes the behaviour of PME, in part, to its comparatively low viscosity and high cetane number among the methyl esters, which may promote fuel atomisation and mixture formation.

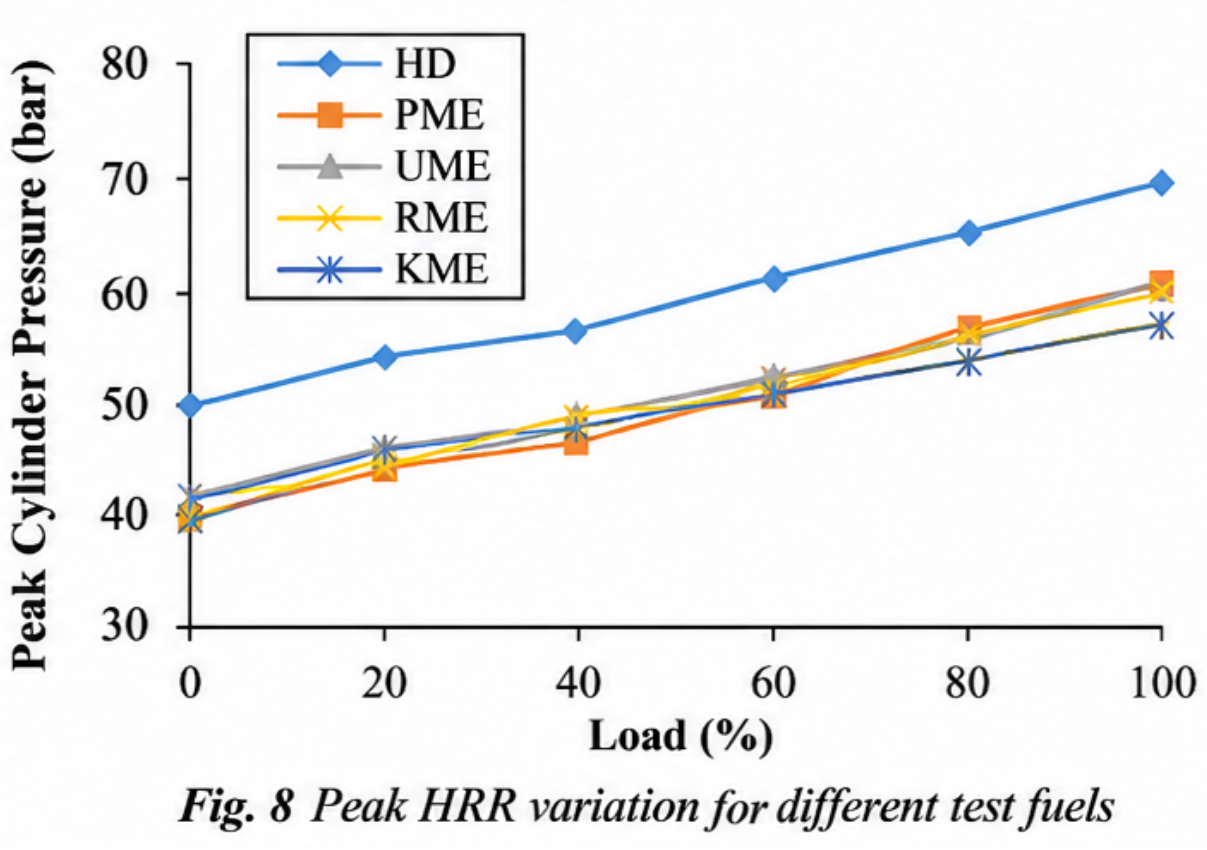


Figure 8. Peak HRR variation for different test fuels.

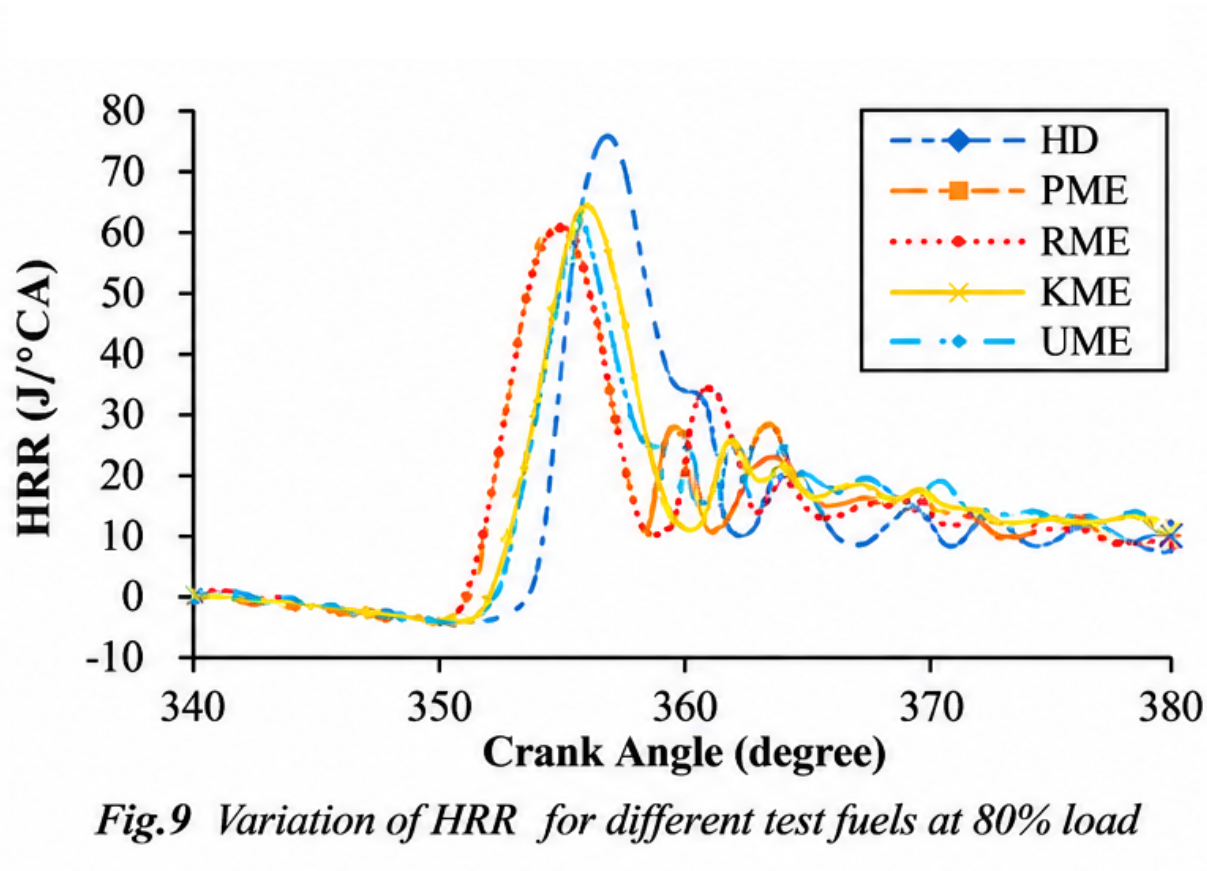


Figure 9. Variation of HRR for different test fuels at 80% load.

From Figure 10, it can be concluded that peak cylinder pressure increased with load for all test fuels. At 80% of full load, the conclusion section reports a PME peak cylinder pressure of approximately 56.7 bar, which was 12.46% lower than the HD value. The original document also refers to pressure traces over 240°–480° crank angle, as evident from Figure 11. The underlying pressure and HRR plots are required to support a more detailed interpretation of ignition delay, premixed combustion and diffusion-controlled combustion.

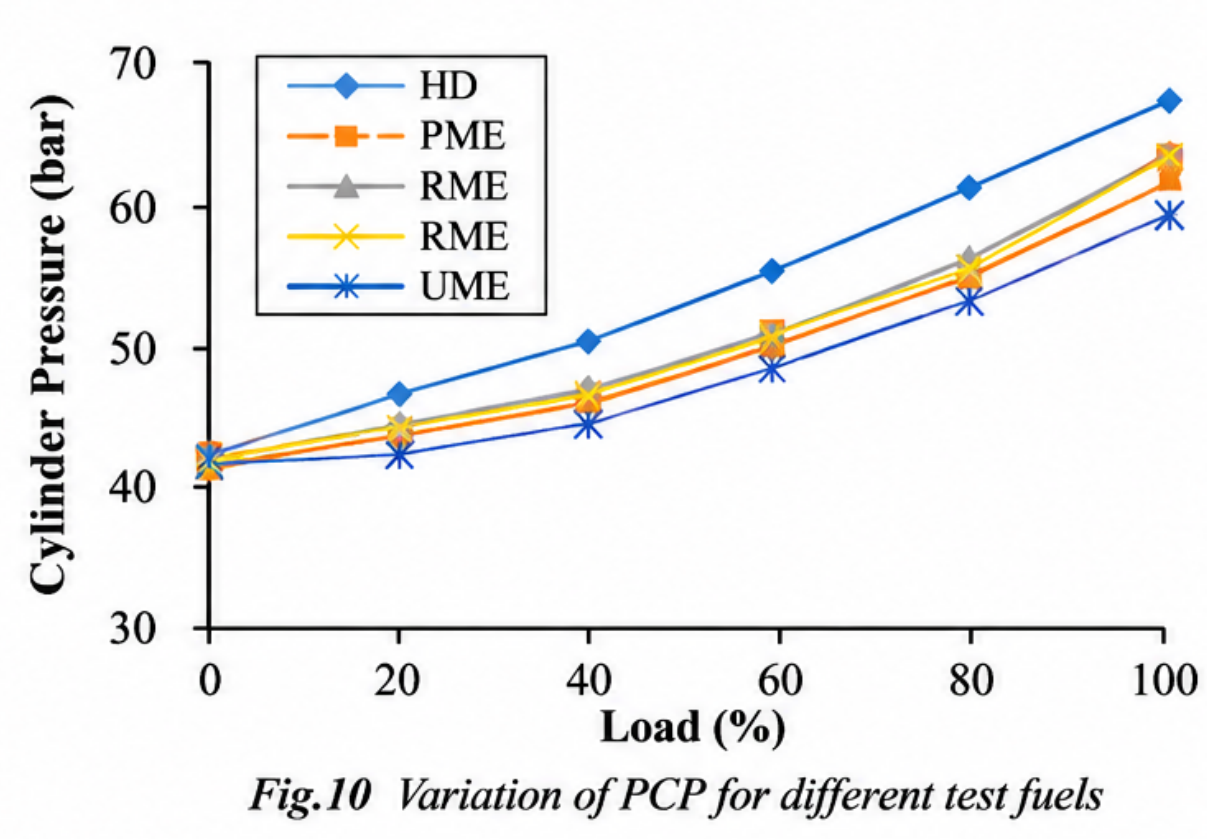


Figure 10. Variation of PCP for different test fuels.

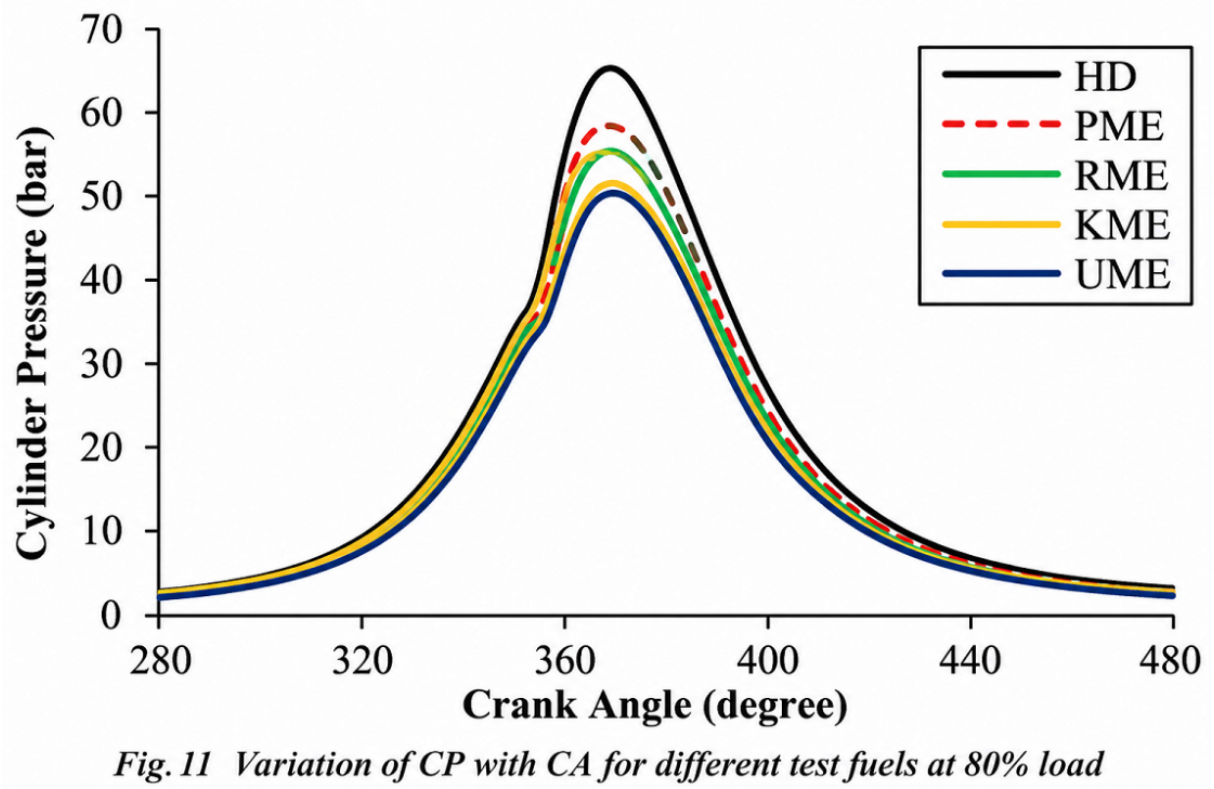


Figure 11. Variation of CP with CA for different test fuels at 80% load.

3.8 Environmental implications and sustainable engineering applications

3.8.1 Implications of measured exhaust emissions

The measured CO, HC, NOx and smoke characteristics provide an engine-level basis for discussing the potential environmental implications of the tested fuels. Lower CO and HC concentrations and lower smoke readings, where observed relative to HD, indicate favourable changes in selected engine-out emission indicators under the investigated operating conditions. Conversely, the higher NOx concentrations reported for the biodiesels demonstrate that emission outcomes involve trade-offs and that improvements in one pollutant do not necessarily imply reductions in all pollutants.

These results should be interpreted as exhaust measurements from the tested engine and operating conditions. They do not directly quantify ambient air-quality improvement, population exposure, particulate mass, greenhouse-gas emissions or total environmental impact. Such conclusions would require additional measurements and/or a defined environmental assessment methodology.

3.8.2 Potential relevance to construction and infrastructure equipment

Diesel engines are widely used in equipment associated with construction and infrastructure development, including earth-moving machinery, road rollers, compactors, generators and material-transport vehicles. The present engine-level comparison may therefore inform future investigations of alternative biodiesel fuels for such applications. In particular, the observed differences in BTE, BSEC and exhaust emissions can help identify fuel candidates for further evaluation.

The present study did not test the fuels in excavators, road rollers, concrete mixers, generators or other construction equipment. It also did not evaluate duty cycles, transient loads, durability, maintenance requirements, fuel-system compatibility or field emissions. Accordingly, the application

to construction and infrastructure machinery is prospective and requires validation through engine-specific and field-based studies.

3.8.3 Renewable feedstocks and sustainable resource utilization

The four methyl esters investigated originate from different biological oil resources. Their comparative evaluation is relevant to research on diversifying biodiesel feedstocks and expanding the range of renewable liquid fuels available for compression-ignition applications. The use of rice bran oil and other non-conventional vegetable-oil resources may also be considered in the broader context of resource utilization. However, the present study does not provide feedstock availability, land-use, cultivation, processing-energy, production-cost or supply-chain data. It is therefore not possible to quantify resource sustainability or establish the overall environmental superiority of any one feedstock from the engine tests alone.

3.8.4 Further assessment required for environmental and infrastructure claims

A complete assessment of the environmental suitability of these fuels would require a life-cycle perspective covering feedstock sourcing, oil extraction, transesterification, chemical inputs, energy consumption, transport and fuel combustion. A well-to-wheel or cradle-to-grave life-cycle assessment could quantify greenhouse-gas emissions and other environmental impact categories using transparent system boundaries and verified inventory data. In addition, field trials in representative construction equipment would be needed to evaluate operational performance, durability and real-world emissions.

4 Conclusions

A comparative experimental investigation was conducted using neat RME, PME, KME and UME in a single-cylinder, four-stroke, direct-injection diesel engine, with HD as the reference fuel. Based on the reported results, the following conclusions are drawn:

- Among the four biodiesels, PME provided the highest BTE at 80% of full load (25.41%), although this remained below the HD value (30.25%).
- PME recorded a BSEC of approximately 14.2 MJ kW^{-1} h^{-1} at 80% load, compared with 11.9 MJ kW^{-1} h^{-1} for HD.
- At 80% load, the reported PME emissions were 0.07% by volume CO, 28 ppm HC, 1121 ppm NOx and 34 HSU smoke. The reported CO, HC and smoke values were lower than those for HD, whereas NOx was higher.
- The peak HRR reported for PME was 64.8 J/°CA, compared with 79.01 J/°CA for HD. The PME peak cylinder pressure was reported as approximately 56.7 bar.
- Considering the combined performance, emission and combustion observations, PME showed the most favourable overall behaviour among the four biodiesels under the investigated conditions. This conclusion is limited to the fuels, engine configuration and operating conditions studied.
- The emission results provide an engine-level basis for considering the potential relevance of biodiesel in cleaner diesel-powered engineering operations. Application to construction and infrastructure equipment remains prospective and requires equipment-specific validation.
- No life-cycle assessment, carbon-footprint calculation, ambient-air-quality assessment or field trial was undertaken. Consequently, the overall environmental benefit and sustainability of the tested fuels cannot be quantified from the present dataset.

5 Limitations and future work

The study is limited to a single-cylinder laboratory diesel engine and the operating conditions reported. The supplied manuscript does not include sufficient information on repeatability, measurement uncertainty, instrument calibration or complete raw datasets to independently verify all reported comparisons. Certain CO values and percentage reductions, as well as some figure legends and captions, require reconciliation with original laboratory records.

Future work should include replicated measurements and uncertainty analysis; fuel-property characterization using recognized standards; tests in representative construction and infrastructure equipment; assessment of transient operating conditions and durability; measurement of particulate mass and additional regulated pollutants where feasible; and a life-cycle assessment based on verified feedstock, production, transport and use-phase inventories. A techno-economic assessment would also be useful in evaluating practical deployment.

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