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Effect of Neem Methyl Ester (NME) Biodiesel Blends on Combustion-Induced Vibration, Performance, and Emission Characteristics of a Variable Compression Ratio Direct-Injection Diesel Engine

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Abstract: The steady depletion of fossil-fuel reserves and increasingly stringent emission legislation have driven sustained interest in renewable, oxygenated alternatives to mineral diesel. This paper reports a systematic experimental investigation into the combustion-induced vibration, performance and emission behaviour of a single-cylinder, four-stroke, water-cooled variable compression ratio (VCR) direct-injection diesel engine fuelled with Neem Methyl Ester (NME), its diesel blends (B10, B20, B30, B40) and diesel-NME-methanol ternary blends (B1, B2). Vibration was acquired along three mutually perpendicular axes using a triaxial accelerometer, while in-cylinder pressure was captured with a piezoelectric transducer synchronised to a TDC crank encoder. Tests were conducted at 1500 rpm across compression ratios of 14, 15, 16 and 17.5, from no-load to full-load. The results show that NME consistently reduces combustion-induced vibration relative to diesel, with vertical-direction reductions of up to 42.2% at full load, alongside improved HC and CO emissions but marginally higher smoke opacity and brake specific fuel consumption. Among the blends, B10 and B1 delivered the best compromise between low vibration, low emissions and acceptable performance, supporting their use as viable near-term substitutes for diesel in unmodified compression ignition engines.

Keywords: Biodiesel; Neem Methyl Ester; combustion-induced vibration; variable compression ratio engine; brake thermal efficiency; emission characteristics.

1. Introduction

Diesel engines remain the dominant prime mover for heavy transport, agriculture and power generation because of their superior thermal efficiency and durability. However, their reliance on a depleting fossil resource and their contribution to particulate, NOx and greenhouse-gas emissions have intensified the search for renewable, oxygenated substitutes. Biodiesel, produced from vegetable oils, waste cooking oils and non-edible feedstocks through transesterification, has emerged as the most technically mature alternative because it is biodegradable, largely sulphur-free and compatible with existing compression-ignition (CI) engine architecture without major hardware modification.

Beyond the well-studied performance and emission trade-offs of biodiesel-diesel blends, combustion-induced vibration is increasingly recognised as a low-cost, non-intrusive diagnostic of in-cylinder combustion quality. Because vibration signatures are directly excited by the rate of cylinder pressure rise, they offer a route to monitor combustion phasing, injection timing and fuel-related knock without invasive pressure instrumentation. Despite this potential, comparatively few studies have examined vibration behaviour of biodiesel-fuelled engines along three mutually perpendicular directions and across a range of compression ratios simultaneously with performance and emission characterisation — the gap this study addresses using Neem Methyl Ester (NME), a non-edible, tropical-region feedstock with limited prior vibration characterisation.

This paper is organised as follows. Section 2 reviews prior work on biodiesel combustion, performance, emission and vibration characteristics. Section 3 states the research gap and objectives. Section 4 details the fuel preparation and experimental methodology. Section 5 presents and discusses the results for vibration, combustion, performance and emissions. Section 6 concludes the study and outlines future scope.

2. Literature Review

A broad body of work has examined biodiesel combustion, performance and emission behaviour in compression-ignition engines, and a smaller but growing subset has linked these characteristics to engine vibration. Table 1 summarises representative studies relevant to the present investigation.

Table 1. Summary of representative prior studies on biodiesel combustion, performance and vibration.

Study (Year)	Fuel / Focus	Key Finding
Alptekin (2017)	Biodiesel + oxygenated additives, common-rail diesel	Higher BSFC with ethanol/solketal-biodiesel blends vs. neat diesel; comparable peak pressure
Nour et al. (2017)	Ethanol port injection, single-cylinder diesel	AHRR increased with ethanol injection; NOx and smoke reduced by up to 88% and 30%
Babji & Rao (2017)	Waste oil biodiesel, IDI engine vibration	Vibration used as indirect combustion/performance diagnostic
Haozhong & Teng (2016)	Pine oil-diesel blends with EGR	Smoke reduced but NOx increased with pine-oil addition; EGR dominates NOx trend
Sarangan et al. (2016)	Sunflower ME + diethyl ether additive	BTE improved 11.9–20.9%; NOx reduced 261–469 ppm at full load
Karagoz (2016)	Dual-fuel diesel-CNG, common-rail retrofit	NOx and smoke reduced at low gas-energy fraction; CO increased at 15% CNG
How & Masjuki (2014)	Coconut biodiesel blends B10-B50	52.4% smoke reduction at B50, 0.86 MPa; 13.7% RMS vibration reduction
Kondaveeti & Rao (2013)	Chicken-fat biodiesel (CFBD)	CFBD performance/combustion close to diesel; vibration dominated by fuel and axis
Rakopoulos et al. (2012)	HSDI single-cylinder diesel, biodiesel blends	Fume emission and efficiency characterised across blend ratios
Taghizadeh-Alisaraei et al. (2012)	Biodiesel-petrodiesel vibration analysis	Vibration signatures correlate with combustion phasing

Collectively, these studies establish that (i) biodiesel and its blends generally reduce CO, HC and smoke emissions relative to diesel at the cost of a modest NOx and BSFC penalty; (ii) oxygenated additives such as ethanol, methanol and diethyl ether can further improve combustion completeness; and (iii) vibration analysis is an emerging but underutilised diagnostic for combustion quality in biodiesel-fuelled engines, particularly across multiple axes and compression ratios.

3. Research Gap and Objectives

While vibration-based fault diagnosis (misalignment, bearing defects, looseness) is well established, few studies isolate the effect of compression ratio and load on combustion-induced vibration for biofuels and their blends along three mutually perpendicular directions. This study addresses that gap using NME and its blends (B10-B40, B1, B2), benchmarked against standard diesel.

The specific objectives are to:

- Examine the performance, emission and combustion behaviour of a diesel engine using oxygenated (NME) fuel.
- Quantify the influence of neem-oil-derived biodiesel as a fuel additive on engine combustion and emissions.
- Characterize combustion, performance and emission behaviour at compression ratios up to 17.5, benchmarked against diesel.
- Evaluate performance from no-load to full-load across the tested compression ratios.
- Compare engine vibration between NME/blends and diesel along vertical, lateral and longitudinal directions.

4. Materials and Methods

4.1 Fuel Preparation

NME was produced from raw neem seed oil by a three-stage transesterification process: (i) acid treatment, reducing the free fatty acid content to approximately 1% using methanol and H_2SO_4 at 50-60°C; (ii) base treatment, using a sodium methoxide solution (methanol + NaOH) at 50-60°C for 1.5 h followed by 24 h settling to separate glycerine; and (iii) water washing with phosphoric acid to remove residual glycerine and soap, followed by heating to 100°C to remove moisture. Blends B10, B20, B30 and B40 were prepared by volumetric mixing of NME with diesel (10-40% NME). Ternary blends B1 (50% diesel, 45% NME, 5% methanol) and B2 (50% diesel, 40% NME, 10% methanol) were also prepared. Fuel properties, measured per ASTM standards, are summarised in Tables 2 and 3.

Table 2. Properties of diesel, NME and methanol.

Property	Method	Diesel	NME	Methanol
Calorific value (kJ/kg)	ASTM D 240	42500	38500	19674
Kinematic viscosity @ 40°C (cSt)	ASTM D 445	2.4	4.4	0.59

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Property	Method	Diesel	NME	Methanol
Density (kg/m³)	ASTM D 4052	835.6	875.8	790
Flash point (°C)	ASTM D 93	56	183	11

Table 3. Properties of blended fuels B10-B40, B1 and B2.

Property	B10	B20	B30	B40	B1	B2
Calorific value (kJ/kg)	42100	41700	41300	40900	39725	38950
Kinematic viscosity @ 40°C (cSt)	2.75	2.96	3.10	3.36	3.21	3.02
Density (kg/m³)	841	846	851	856	850	847

4.2 Experimental Setup

Tests were performed on a single-cylinder, four-stroke, water-cooled, variable compression ratio (VCR) direct-injection diesel engine coupled to an eddy-current dynamometer, operated at a constant speed of 1500 rpm across compression ratios of 14, 15, 16 and 17.5, from no-load (0 kW) to full-load (3.5 kW). In-cylinder pressure was measured with a piezoelectric transducer (1 mV/PSI, range 5000 PSI) mounted on the cylinder head and synchronised with a TDC crank-angle encoder; pressure-crank angle data for 100 consecutive cycles were logged via a USB-6210 data acquisition module for heat-release-rate computation using the first law of thermodynamics. Engine vibration was measured with a PCB triaxial accelerometer bonded to the cylinder head, sampled at 51.2 kHz for 12.5 consecutive combustion cycles via an NI-9234 module. Exhaust gases (CO, HC, CO_2, NO, O_2) were measured with an AVL DiGas 444 five-gas analyser, and smoke opacity with an AVL 437C smoke meter (Hartridge Smoke Units).

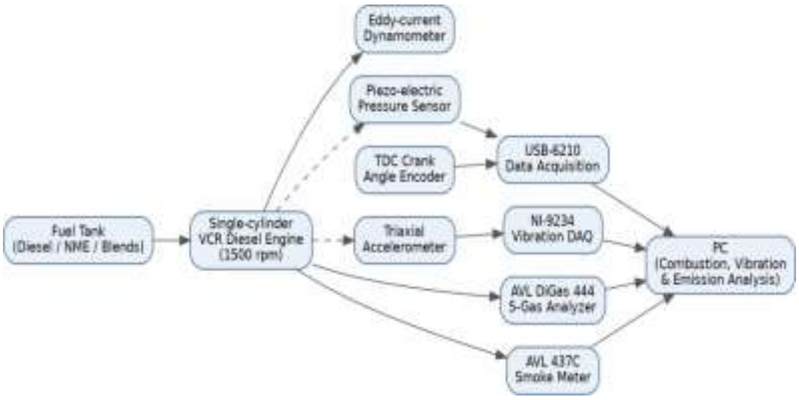

Figure 1. Schematic layout of the experimental engine test rig and instrumentation.

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5. Results and Discussion

5.1 Combustion-Induced Vibration

Time-domain vibration signals for both diesel and NME show a dominant peak near 25 Hz across all compression ratios, with markedly higher amplitude in the lateral and longitudinal directions at low frequency compared to the vertical direction, attributable to unbalanced forces from reciprocating and rotating components. At the combustion-dominated high-frequency zone (2000-3000 Hz), NME consistently produced lower peak vibration than diesel in the vertical direction. Figure 2 presents the percentage reduction in vertical-direction combustion-induced vibration when the engine is switched from diesel to NME, at no-load and full-load, across the four tested compression ratios.

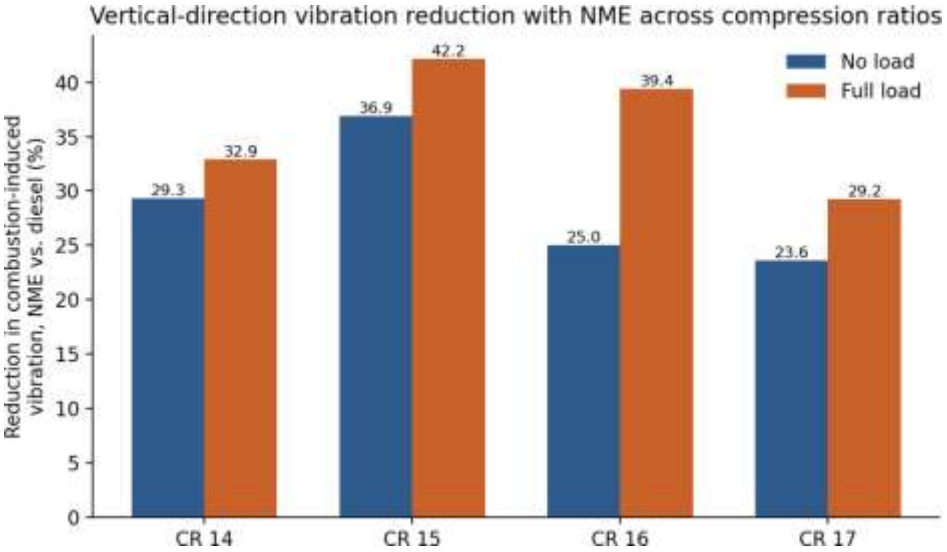

Figure 2. Reduction in vertical-direction combustion-induced vibration (NME vs. diesel) across compression ratios.

The largest full-load reduction (42.2%) occurs at CR 15, while the smallest (29.2%) occurs at CR 17. In the lateral direction, full-load reductions of 27.1-46.3% were observed across CR 14-17, and in the longitudinal direction reductions of 5.6-14.5% were recorded, confirming that the vertical direction is the most sensitive and most consistently favourable axis for detecting the NME-related reduction in combustion severity. Among the blends, B10 produced the largest full-load vibration reduction relative to diesel (38.5% and 35.4% at the first and second dominant peak frequencies), while B20 performed best at no-load.

5.2 In-Cylinder Combustion Characteristics

Peak cylinder pressure increased with compression ratio for both fuels, reaching its maximum at CR 17.5. The percentage rise in peak pressure from no-load to full-load was largest at CR 14 (71.5% for diesel, 72.3% for NME) and smallest at CR 17 (49.8% for NME, 44.6% for diesel), indicating a diminishing marginal sensitivity to load as compression ratio increases. At CR 17, the peak net heat release rate (NHRR) reached 44.4 J/deg for NME and 35.2 J/deg for diesel — approximately 20.7% lower for NME than for diesel across all loads and compression ratios, consistent with NME's lower calorific value and higher viscosity delaying and moderating premixed combustion. The rate of pressure rise (RPR) was correspondingly higher for diesel than NME; at full load and CR 17, peak RPR values of 4.46 J/deg (NME) and 3.6 J/deg (diesel) were recorded, a difference of 23.8%.

5.3 Performance Characteristics

Brake thermal efficiency (BTE) increased with load for all fuels at all compression ratios, peaking at CR 16 with 31.17% for diesel and 30.57% for NME — a modest 0.6-percentage-point penalty consistent with NME's slightly lower energy density. Brake specific fuel consumption (BSFC) was higher for NME than diesel at all compression ratios (7.1-32.3% higher, depending on CR and load), attributable to NME's lower calorific value and higher viscosity requiring greater fuel mass for equivalent power output. Among the blends, B10 exhibited the lowest BSFC at all loads, while B40 achieved a slightly higher BTE than diesel (by 3.8% and 1.2% at 75% and 100% load respectively) owing to improved combustion phasing at higher biodiesel fractions. Figure 3 compares BTE across the tested fuels at CR 16, full load.

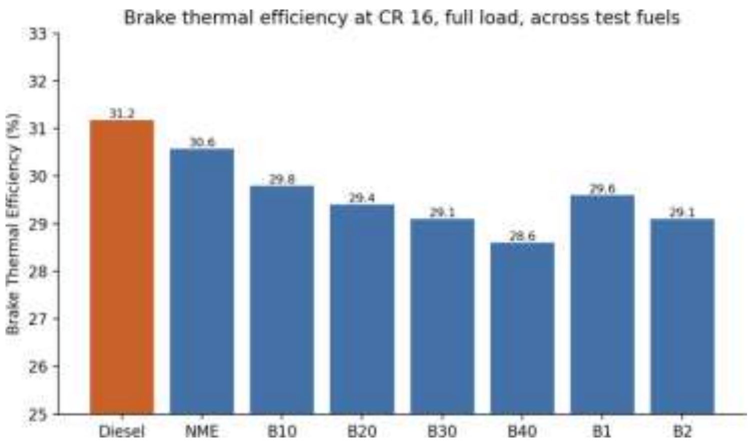

Figure 3. Brake thermal efficiency at CR 16, full load, for diesel, NME and biodiesel blends.

5.4 Emission Characteristics

CO and HC emissions decreased with load for both diesel and NME at all compression ratios, reflecting more complete combustion at higher in-cylinder temperatures. At full load, HC emissions for NME were lower than diesel by 60% at CR 14, and by 87.5-100% at CR 15-17 — the most pronounced improvement of any measured parameter. Figure 4 illustrates this trend.

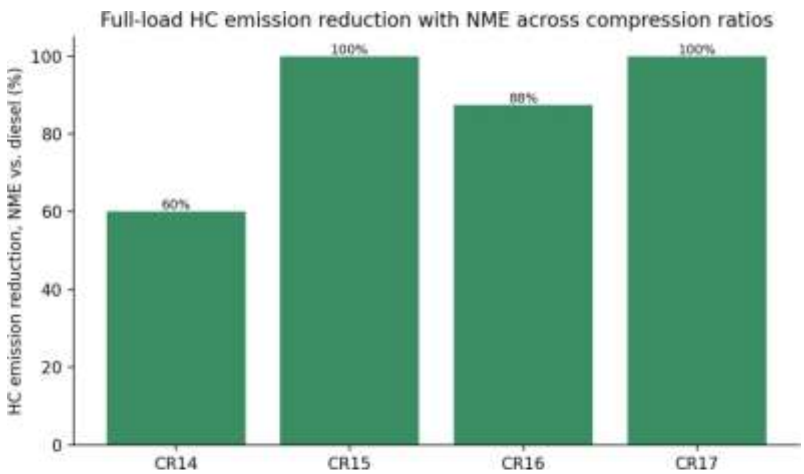

Figure 4. Full-load HC emission reduction for NME relative to diesel across compression ratios.

CO_2 emission rose initially with load before declining at higher loads for both fuels, while NOx emissions were lower for NME than diesel at lower compression ratios. Smoke density, however, was consistently higher for NME than diesel across all compression ratios, and increased with load — an expected trade-off linked to NME's higher viscosity and consequent spray/atomisation quality. Among the blends, B10 achieved the lowest smoke density, 34.9-74.3% lower than diesel across the load range, and the lowest CO emissions (66.7% lower than diesel at 25% load). B20 and B10 produced the lowest NOx emissions among all fuels tested, while B40 exhibited comparatively higher CO_2 emission than the other blends.

5.5 Discussion

Taken together, the results indicate a consistent trade-off pattern: NME and its blends reduce combustion-induced vibration, CO, HC and (at low CR) NOx relative to diesel, at the cost of higher BSFC and higher smoke opacity. The reduction in vibration correlates with the lower NHRR and RPR observed for NME, supporting the hypothesis that combustion-induced vibration is primarily excited by the rate of pressure rise during the premixed combustion phase rather than by peak pressure magnitude alone. Among all fuels and blends tested, B10 and B1 offer the most balanced profile — competitive BTE, the lowest BSFC among the NME blends, and substantial reductions in smoke, CO and vibration — making them the most promising near-term substitutes for diesel in existing, unmodified CI engines.

6. Conclusion

- NME consistently reduces combustion-induced vibration relative to diesel in the vertical direction, with full-load reductions ranging from 29.2% (CR 17) to 42.2% (CR 15).
- Peak NHRR is approximately 20.7% lower and peak RPR approximately 23.8% lower for NME than diesel at CR 17, explaining the observed vibration reduction.
- BTE is marginally lower for NME than diesel (30.57% vs. 31.17% at CR 16), while BSFC is 7-32% higher for NME depending on operating condition.
- HC emissions for NME are dramatically lower than diesel at full load (60-100% reduction across CR 14-17); CO and NOx are also generally lower, but smoke density is consistently higher for NME.
- Among the blends studied, B10 and B1 provide the best overall balance of low vibration, low emissions and acceptable performance, and are recommended as promising near-term diesel substitutes.

These findings support the use of NME and its low-percentage blends (B10, B1) as viable, low-vibration, low-emission alternative fuels for existing compression-ignition diesel engines without hardware modification, while confirming that smoke opacity and fuel consumption remain the principal trade-offs requiring further mitigation.

6.1 Future Scope

- Extending vibration characterisation to other non-edible biodiesel feedstocks and their blends.
- Systematically varying methanol content (0-30% by volume) and testing alternative alcohols (ethanol, propanol, butanol) in ternary blends.
- Applying time-frequency (wavelet, waterfall) vibration analysis for finer combustion-phase resolution.
- Using vibration signatures for early detection of engine knock in biodiesel-fuelled engines.

References

[1] K. Agarwal, L. M. Das, "Bio-diesel development and characterization for use as a fuel in CI engines," ASME Transactions, vol. 123, pp. 440-447, 2001.

[2] Ü. Ağbulut, M. Karagoz, S. Sarıdemir, A. Öztürk, "Impact of various metal-oxide based nanoparticles and biodiesel blends on the combustion, performance, emission, vibration and noise characteristics of a CI engine," Fuel, vol. 270, 117521, 2020.

[3] Ü. Ağbulut, S. Sarıdemir, S. Albayrak, "Experimental investigation of combustion, performance and emission characteristics of a diesel engine fuelled with diesel-biodiesel-alcohol blends," Journal of the Brazilian Society of Mechanical Sciences and Engineering, vol. 41, 2019.

[4] Taghizadeh-Alisaraei, B. Ghobadian, T. Tavakoli-Hashjin, S. S. Mohtasebi, "Vibration analysis of a diesel engine using biodiesel and petrodiesel fuel blends," Fuel, vol. 102, pp. 414-422, 2012.

[5] N. Ozsezen, M. Canakci, "Determination of performance and combustion characteristics of a diesel engine fueled with canola and waste palm oil methyl esters," Energy Conversion and Management, vol. 52, pp. 108-116, 2011.

[6] E. Alptekin, "Emission, injection and combustion characteristics of biodiesel and oxygenated fuel blends in a common rail diesel engine," Energy, vol. 119, pp. 44-52, 2017.

[7] Datta, S. Palit, B. K. Mandal, "An experimental study on the performance and emission characteristics of a CI engine fuelled with Jatropha biodiesel and its blends with diesel," Journal of Mechanical Science and Technology, vol. 28, pp. 1961-1966, 2014.

[8] ASTM International, ASTM D6751-07b, Standard Specification for Biodiesel Fuel Blend Stock (B100) for Middle Distillate Fuels, West Conshohocken, PA, 2008.

[9] K. Agarwal, "Biofuels (alcohols and biodiesel) applications as fuels for internal combustion engines," Progress in Energy and Combustion Science, vol. 33, pp. 233-271, 2007.

[10] P. Babji, B. Rao, A. Kolakoti, "Combustion estimation by cylinder vibration analysis on a supercharged IDI diesel engine — a comparative study with a new fuel as total replacement," International Journal of Recent Trends in Engineering & Research, vol. 3, pp. 110-116, 2017.

[11] S. Chauhan, N. Kumar, H. M. Cho, "Performance and emission studies on an agriculture engine on neat Jatropha oil," Journal of Mechanical Science and Technology, vol. 24, no. 2, pp. 529-535, 2010.

[12] V. A. Bueno, J. A. Velasquez, L. F. Milanez, "A new engine indicating measurement procedure for combustion heat release analysis," Applied Thermal Engineering, vol. 29, pp. 1657-1675, 2009.

[13] Wang, Y. Zhang, Z. Zhong, "Fault diagnosis for diesel valve trains based on time-frequency images," Mechanical Systems and Signal Processing, vol. 22, pp. 1981-1993, 2008.

[14] Çalık, "Determination of vibration characteristics of a compression ignition engine operated by hydrogen enriched diesel and biodiesel fuels," Fuel, vol. 230, 2018.

[15] M. Canakci, "Combustion characteristics of a turbocharged DI compression ignition engine fueled with petroleum diesel fuels and biodiesel," Bioresource Technology, vol. 98, pp. 1167-1175, 2007.

[16] K. Celebi, E. Uludamar, M. Ozcanli, "Evaluation of fuel consumption and vibration characteristic of a compression ignition engine fuelled with high viscosity biodiesel and hydrogen addition," International Journal of Hydrogen Energy, vol. 42, 2017.

[17] S. Chauhan, N. Kumar, H. M. Cho, "A study on the performance and emission of a diesel engine fueled with Jatropha biodiesel oil and its blends," Energy, vol. 37, pp. 616-622, 2012.

[18] K. Cheikh, S. Awad, K. Loubar, A. Liazid, M. Tazerout, "Experimental assessment of performance and emissions maps for biodiesel fueled compression ignition engine," Applied Energy, vol. 161, pp. 320-329, 2016.