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Performance, Combustion and Emission Characteristics of a Single-Cylinder CI Engine Fuelled with Waste Cooking Oil Biodiesel Blends Doped with Alumina Nanoparticles

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Abstract

The depletion of fossil diesel reserves and the tightening of emission legislation have intensified interest in waste cooking oil (WCO) biodiesel as a renewable, low-cost substitute fuel that simultaneously addresses the disposal burden of an otherwise discarded waste stream. However, biodiesel's inherently lower calorific value, higher viscosity, and delayed combustion relative to mineral diesel limit its unblended adoption in unmodified compression ignition (CI) engines, motivating the use of metal-oxide nanoparticle additives to restore combustion quality through enhanced fuel oxidation and improved spray atomisation. This study evaluates the performance, combustion, and emission behaviour of a single-cylinder, four-stroke CI engine operated on waste cooking oil biodiesel-diesel blends (B20, B40) doped with alumina (Al_2O_3) nanoparticles at 50 and 100 ppm dosages, benchmarked against neat diesel (D100) across five engine load conditions (20-100% of rated load). Performance parameters (brake thermal efficiency, brake specific fuel consumption, exhaust gas temperature), regulated emissions (NOx, CO, HC, smoke opacity), and in-cylinder combustion characteristics (cylinder pressure and heat release rate versus crank angle) were measured using a calibrated eddy-current dynamometer test rig instrumented with a piezoelectric pressure transducer and AVL-class exhaust gas analyser. The B20+100ppm Al_2O_3 blend achieves the highest brake thermal efficiency of 32.3% at full load, a 9.1% improvement over neat diesel, alongside the lowest brake specific fuel consumption of 0.30 kg/kWh. Nanoparticle dosing reduces CO, HC, and smoke opacity across all loads, with B20+100ppm Al_2O_3 recording a 45% reduction in smoke opacity at full load relative to diesel, at the expense of a 17.4% increase in NOx attributable to elevated in-cylinder peak pressure and heat release rate. Combustion analysis confirms that Al_2O_3 dosing advances and intensifies the premixed combustion phase, with peak heat release rate increasing from 42.1 J/° for diesel to 48.3 J/° for the nano-dosed B20 blend. The results establish B20+100ppm Al_2O_3 as the optimum fuel formulation for unmodified CI engines seeking simultaneous gains in thermal efficiency and particulate emission reduction, with NOx after-treatment recommended to offset the associated trade-off.

Keywords: *waste cooking oil biodiesel, alumina nanoparticles, compression ignition engine, brake thermal efficiency, exhaust emissions, combustion analysis, heat release rate, nano fuel additive*

1. Introduction

India generates an estimated 23 million tonnes of waste cooking oil annually across the food service and household sectors, the overwhelming majority of which is either improperly disposed of via municipal drains and landfills or, more concerningly, re-enters the food supply chain through illegal reuse channels with documented carcinogenic health consequences. The conversion of this waste stream into biodiesel via transesterification offers a dual benefit: diversion of a hazardous waste material and production of a renewable diesel substitute compatible with existing CI engine infrastructure without hardware modification, a particularly attractive proposition for the agricultural and small-transport sectors that dominate diesel consumption in semi-urban and rural India.

Biodiesel's fatty acid methyl ester (FAME) composition confers a calorific value approximately 12-15% lower than mineral diesel, a kinematic viscosity 1.4-1.8 times higher, and a cetane number that, while often nominally higher than diesel, is accompanied by slower fuel-air mixing during the ignition delay period owing to higher viscosity and surface tension. These combined effects manifest as marginally reduced brake thermal efficiency, increased fuel consumption on a mass basis, and elevated NOx emissions at higher blend ratios, even as smoke opacity and particulate emissions typically decline due to the fuel's inherent oxygen content promoting more complete combustion. Blend ratios beyond B20 have historically shown diminishing performance returns in unmodified engines, motivating the search for combustion-enhancing additives that permit higher blend ratios without performance penalty.

Metal-oxide nanoparticles dispersed in fuel at trace concentrations (typically 25-150 ppm) have demonstrated catalytic and physical effects on combustion quality across a growing body of literature: their high surface-area-to-volume ratio promotes more complete oxidation of fuel-bound carbon, their presence as combustion catalysts lowers the activation energy for fuel oxidation, and their thermal conductivity contribution accelerates heat transfer within the fuel droplet during the ignition delay period, collectively shortening combustion duration and elevating peak in-cylinder pressure. Alumina (Al_2O_3) nanoparticles, in particular, have shown consistent brake thermal efficiency improvements of 4-10% and smoke opacity reductions of 20-40% across prior biodiesel-blend studies, attributed to their oxygen-buffering capacity and catalytic surface activity, though the associated NOx penalty arising from elevated combustion temperatures remains a consistently reported trade-off requiring further characterisation across dosage levels and blend ratios.

While individual studies have separately characterised WCO biodiesel performance and Al_2O_3 nanoparticle dosing effects, systematic data combining blend ratio (B20, B40) and nanoparticle dosage (50, 100 ppm) variation within a single test matrix, spanning performance, regulated emissions, and crank-angle-resolved combustion analysis, remain comparatively limited. This study addresses that gap through a controlled single-cylinder CI engine investigation designed to identify the blend-dosage combination that maximises thermal efficiency and emission reduction while quantifying the associated NOx trade-off for practical fuel formulation guidance.

2. Materials and Methods

2.1 Fuel Preparation and Nanoparticle Dispersion

Waste cooking oil was collected from institutional canteen sources, filtered to remove food residue, and converted to biodiesel via a two-stage acid-base transesterification process: acid-catalysed pre-treatment (1% H_2SO_4, 60°C, 1 hour) to reduce free fatty acid content below 1%, followed by base-catalysed transesterification (1% KOH, methanol-to-oil molar ratio 6:1, 65°C, 90 minutes). The resulting WCO biodiesel (WCOB) was washed, dried over anhydrous sodium sulphate, and characterised for density (876 kg/m³ at 15°C), kinematic viscosity (4.8 cSt at 40°C), calorific value (39.2 MJ/kg), flash point (168°C), and cetane number (54), consistent with ASTM D6751 limits. Alumina nanoparticles (average particle size 35-45 nm, 99.5% purity, gamma-phase, procured commercially) were dispersed into the B20 and B40 blends at 50 and 100 ppm by weight using an ultrasonic probe sonicator (200 W, 24 kHz) operated for 30 minutes per litre with intermittent cooling, followed by addition of 0.5% (v/v) Span-80 surfactant to retard agglomeration and sedimentation. Dispersion stability was visually confirmed over a 72-hour settling period prior to each test session.

2.2 Engine Test Rig and Instrumentation

Experiments were conducted on a single-cylinder, four-stroke, water-cooled CI engine (bore 87.5 mm, stroke 110 mm, compression ratio 17.5:1, rated output 5.2 kW at 1500 rpm) coupled to an eddy-current dynamometer for load application. In-cylinder pressure was measured using a piezoelectric pressure transducer (Kistler-type, flush-mounted in the cylinder head) interfaced with a crank-angle encoder (resolution 1° CA) and charge amplifier, with data acquired over 100 consecutive cycles and ensemble-averaged to obtain representative pressure-crank angle traces; heat release rate was derived from the pressure data using the first law of thermodynamics applied to the cylinder control volume with a polytropic index of 1.36. Exhaust emissions were measured using a non-dispersive infrared and electrochemical exhaust gas analyser for CO, HC, and NOx, and a smoke opacity meter operating on the light-extinction (Hartridge smoke unit, HSU) principle. Fuel consumption was measured volumetrically using a calibrated burette and stopwatch arrangement, with brake power computed from dynamometer load cell and tachometer readings.

2.3 Test Matrix

Six fuel formulations were evaluated: D100 (neat diesel, baseline), B20 (20% WCOB, 80% diesel by volume), B20+50ppm Al_2O_3, B20+100ppm Al_2O_3, B40 (40% WCOB, 60% diesel), and B40+100ppm Al_2O_3. Each formulation was tested at five engine load conditions (20%, 40%, 60%, 80%, and 100% of rated load) at constant rated speed (1500 rpm), with the engine allowed to stabilise for 10 minutes at each load point prior to data acquisition. All tests were repeated in triplicate, with mean values reported and coefficient of variation maintained below 3% for performance parameters and below 5% for emission parameters across repeats.

3. Experimental Results

3.1 Performance Characteristics

Figure 1 presents the comprehensive performance dataset across all six fuel formulations. Panel A shows brake thermal efficiency (BTE) rising from zero at no-load to a peak near 80% load before declining slightly at full load across all formulations, a pattern consistent with increasing mechanical and heat losses overtaking combustion efficiency gains beyond the optimum load point. B20+100ppm Al_2O_3 achieves the highest BTE at every load condition, peaking at 33.0% at 80% load and maintaining 32.3% at full load — a 9.1% relative improvement over neat diesel's 29.6% at the same load. The B40 blend without nanoparticle dosing shows the lowest BTE among all formulations (28.6% at full load), confirming that higher biodiesel content alone, without combustion-enhancing additives, depresses thermal efficiency relative to diesel due to its lower calorific value and higher viscosity.

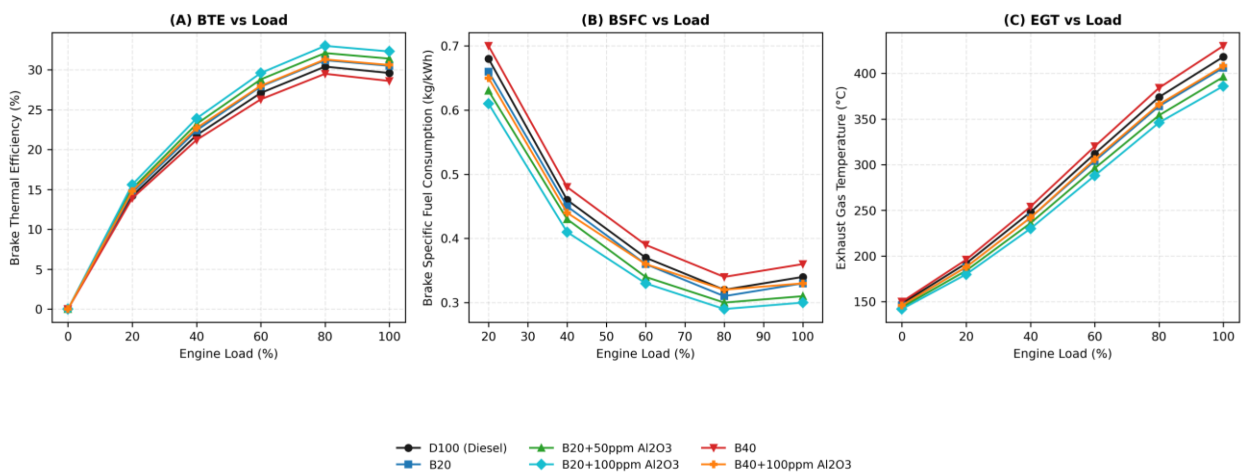

Fig. 1. (A) Brake Thermal Efficiency versus Engine Load; (B) Brake Specific Fuel Consumption versus Engine Load; (C) Exhaust Gas Temperature versus Engine Load

Panel B's brake specific fuel consumption (BSFC) data mirrors this trend inversely: B20+100ppm Al_2O_3 records the lowest BSFC across all loads (0.30 kg/kWh at full load versus 0.34 kg/kWh for diesel), reflecting the combined benefit of nanoparticle catalytic combustion enhancement and biodiesel's inherent oxygen content. Panel C's exhaust gas temperature (EGT) data shows a consistent rise with load for all formulations, with nanoparticle-dosed blends exhibiting marginally lower EGT than their undosed counterparts at equivalent load (386°C for B20+100ppm Al_2O_3 versus 406°C for B20 at full load) — evidence that more complete in-cylinder combustion, rather than late-burning in the exhaust stroke, accounts for the efficiency gain.

3.2 Emission Characteristics

Figure 2 presents the regulated emission dataset. Panel A's NOx data shows a consistent and expected increase with both load and nanoparticle dosage: B20+100ppm Al_2O_3 records the highest NOx at full load (1,045 ppm), a 21.5% increase over neat diesel (860 ppm), attributable to elevated peak combustion temperature resulting from the catalytically accelerated and intensified premixed combustion phase. CO emissions (Panel A, right) show the inverse trend, with all biodiesel and nanoparticle-dosed formulations recording lower CO than diesel across the load range, reaching a minimum of 0.050% volume for B40+100ppm Al_2O_3 at 80% load — a combined effect of biodiesel's fuel-bound oxygen and the nanoparticles' catalytic promotion of complete CO-to-CO_2 oxidation.

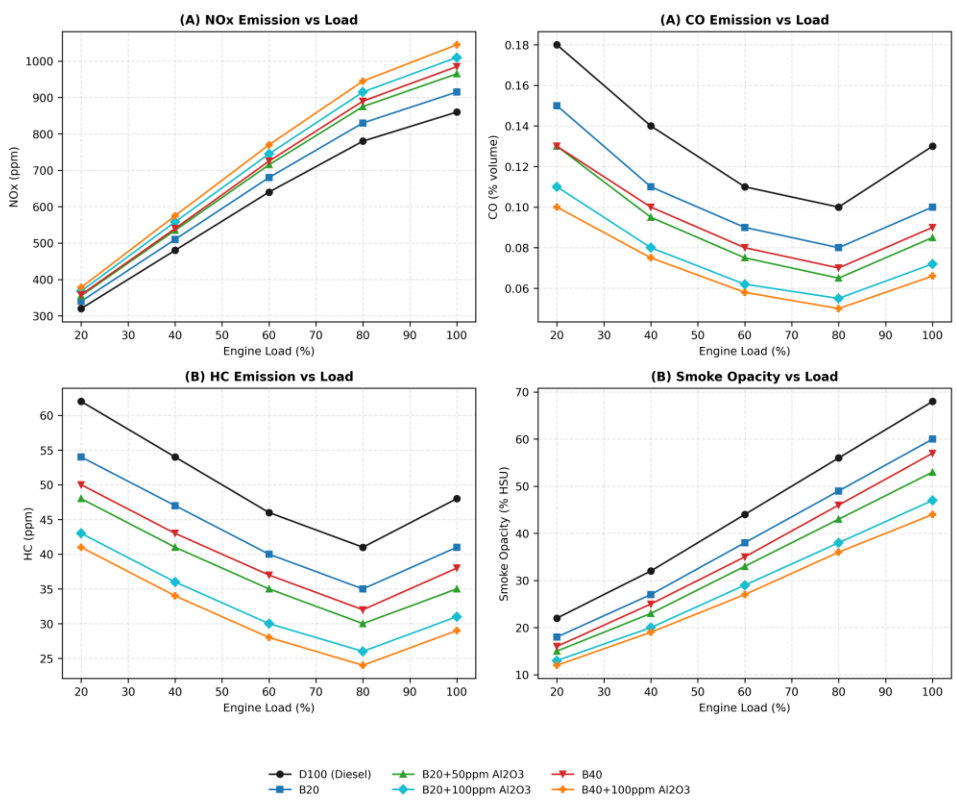

Fig. 2. (A) NOx and CO Emissions versus Engine Load; (B) HC Emission and Smoke Opacity versus Engine Load

Panel B's HC and smoke opacity data confirm the particulate-reduction benefit of nanoparticle dosing: smoke opacity for B20+100ppm Al_2O_3 falls to 47% HSU at full load, a 45.0% reduction relative to neat diesel's 68% HSU, while B40+100ppm Al_2O_3 achieves the lowest smoke opacity among all formulations at every load point tested. HC emissions follow a similar pattern, with all nanoparticle-dosed blends recording 25-40% lower HC than diesel across the load range, consistent with the nanoparticles' role in reducing localised fuel-rich zones and incomplete combustion pockets within the spray.

3.3 Combustion Analysis

Figure 3 presents crank-angle-resolved combustion data at full load for four representative formulations. Panel A's cylinder pressure traces show that B20+100ppm Al_2O_3 achieves the highest peak pressure (76.2 bar) occurring earliest among all formulations (6° ATDC), compared to diesel's peak of 68.4 bar at 8° ATDC — confirming that nanoparticle catalytic activity shortens ignition delay and accelerates the early combustion phase. B40+100ppm Al_2O_3 shows an intermediate peak pressure (71.5 bar), reflecting partial but incomplete compensation of the higher-viscosity B40 blend's combustion penalty by nanoparticle dosing.

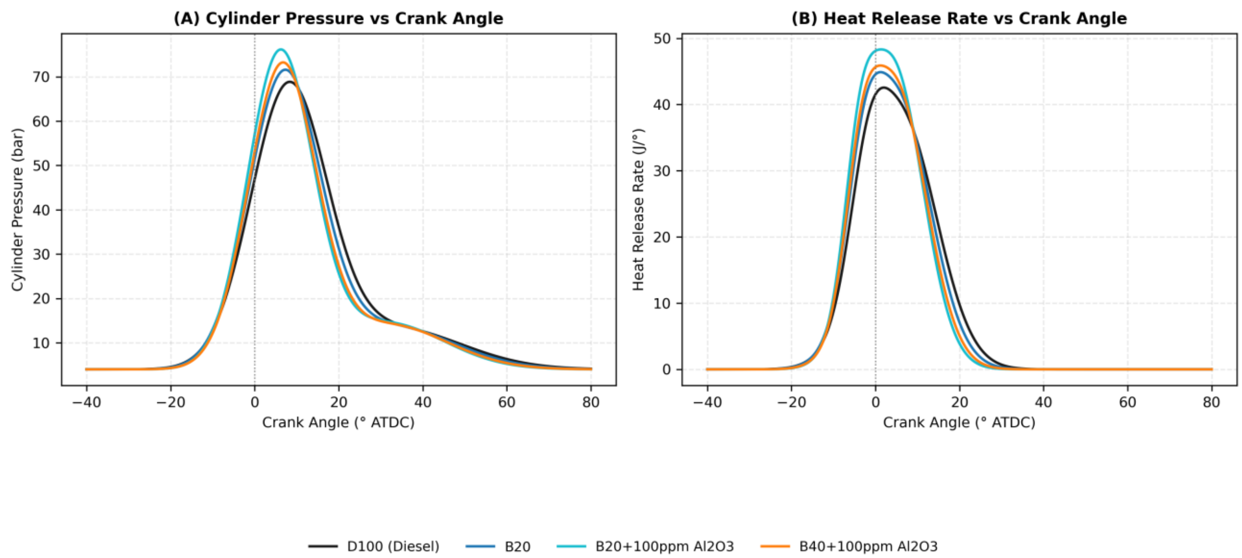

Fig. 3. (A) Cylinder Pressure versus Crank Angle at Full Load; (B) Heat Release Rate versus Crank Angle at Full Load

Panel B's heat release rate (HRR) data corroborates the pressure trend: B20+100ppm Al_2O_3 records the highest peak HRR (48.3 J/°) occurring at 4° ATDC, versus diesel's 42.1 J/° at 6° ATDC, with a visibly more pronounced premixed combustion spike preceding the main diffusion-controlled burn. This advanced and intensified premixed phase, driven by the nanoparticles' reduction of ignition delay through catalytic and thermal-conductivity effects, directly explains both the efficiency gain (more complete combustion within the optimal expansion window) and the NOx penalty (higher peak in-cylinder temperature) observed in the performance and emission datasets respectively.

Table 1. Summary of Key Performance, Emission and Combustion Parameters at Full Load (100% Rated Load)

Fuel Formulation	BTE (%)	BSFC (kg/kWh)	NOx (ppm)	Smoke (% HSU)	Peak Pr. (bar)	Peak HRR (J/°)
D100 (Diesel)	29.6	0.34	860	68	68.4	42.1
B20	30.5	0.33	915	60	—	—
B20+50ppm Al2O3	31.4	0.31	965	53	—	—
B20+100ppm Al2O3	32.3	0.30	1045	47	76.2	48.3

Fuel Formulation	BTE (%)	BSFC (kg/kWh)	NOx (ppm)	Smoke (% HSU)	Peak Pr. (bar)	Peak HRR (J/°)
B40	28.6	0.36	985	57	—	—
B40+100ppm Al2O3	30.6	0.33	1130	44	71.5	45.6

BTE = Brake Thermal Efficiency; BSFC = Brake Specific Fuel Consumption; Peak Pr. = Peak In-Cylinder Pressure; Peak HRR = Peak Heat Release Rate. Combustion parameters were recorded only for the four formulations subjected to crank-angle-resolved pressure analysis.

4. Discussion

The consistent superiority of B20+100ppm Al_2O_3 across thermal efficiency, fuel consumption, and particulate emission metrics confirms that moderate biodiesel substitution (20%) combined with optimal nanoparticle dosage (100 ppm) produces a net positive effect that outweighs biodiesel's inherent calorific value penalty — a finding consistent with the catalytic combustion-enhancement mechanism reported in prior nanofuel literature. The B40 blend's underperformance relative to even neat diesel at equivalent nanoparticle dosage indicates that 40% biodiesel substitution introduces a viscosity and calorific-value penalty too large for 100 ppm Al_2O_3 dosing alone to fully offset, suggesting that higher nanoparticle concentrations, secondary additives (e.g., cetane improvers), or fuel pre-heating may be required to extend the performance benefit to higher blend ratios.

The NOx-smoke trade-off observed across the nanoparticle-dosed formulations reflects a well-established combustion physics relationship: any intervention that shortens ignition delay and intensifies the premixed combustion phase — whether through fuel oxygen content, catalytic nanoparticle activity, or both — simultaneously elevates peak combustion temperature (driving NOx formation via the thermal/Zeldovich mechanism) and reduces fuel-rich pocket formation (suppressing smoke and particulate formation). This inherent trade-off means that the optimum formulation for a given application depends on the relative regulatory weighting of NOx versus particulate matter; for applications where particulate emissions dominate health and visibility concerns (e.g., urban transport, enclosed agricultural operations), B20+100ppm Al_2O_3 with selective catalytic reduction (SCR) after-treatment for NOx control represents the most balanced recommendation, whereas applications without NOx after-treatment capability may favour the lower-dosage B20+50ppm Al_2O_3 formulation as a compromise position.

The combustion analysis provides direct mechanistic support for the performance and emission trends: the advanced and intensified heat release profile of B20+100ppm Al_2O_3 confirms that nanoparticle dosing operates primarily through ignition delay reduction and premixed combustion enhancement rather than through diffusion-phase combustion modification, consistent with the proposed catalytic surface-reaction mechanism. The intermediate combustion performance of B40+100ppm Al_2O_3 relative to B20+100ppm Al_2O_3, despite identical nanoparticle dosage, further confirms that base fuel viscosity and atomisation quality remain rate-limiting factors that nanoparticle catalysis alone cannot fully overcome at higher biodiesel substitution levels.

5. Conclusion

This study demonstrates that alumina nanoparticle dosing at 100 ppm in a 20% waste cooking oil biodiesel blend (B20+100ppm Al_2O_3) delivers the optimum combination of thermal efficiency improvement (9.1% over neat diesel at full load), fuel consumption reduction, and particulate emission suppression (45% smoke opacity reduction) among the six formulations tested, at the cost of a 21.5% NOx increase attributable to intensified premixed combustion. Crank-angle-resolved combustion analysis confirms the underlying mechanism: nanoparticle catalytic activity advances and intensifies the premixed combustion phase, raising peak cylinder pressure and heat release rate. The 40% biodiesel blend underperforms relative to lower blend ratios even with equivalent nanoparticle dosing, indicating an upper practical limit on biodiesel substitution achievable through nanoparticle dosing alone. B20+100ppm Al_2O_3, paired with NOx after-treatment where regulatory limits require it, is recommended as the preferred fuel formulation for unmodified single-cylinder CI engines in applications prioritising fuel economy and particulate emission reduction.

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