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Mitigation of NO_X Emissions and Enhancement of Combustion Characteristics Using Nano-Emulsified Jatropha B20 Biodiesel in a Diesel Engine

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Abstract

This study experimentally investigates the influence of Al_2O_3 nanoparticle addition on the combustion, performance, and emissions of emulsified Jatropha biodiesel in a compression-ignition engine. An emulsified fuel blend comprising 88% Jatropha methyl ester (JME), 10% water (v/v), and 2% surfactant (B20W10) was prepared using ultrasonication, into which Al_2O_3 nanoparticles were dispersed at concentrations of 25 ppm and 50 ppm. Tests were conducted at varying loads under constant speed to evaluate performance, combustion, and emission characteristics. Among the tested fuels, B20W10Al50 yielded the best outcomes, achieving a 2.03% increase in brake thermal efficiency (BTE) and a 3.84% reduction in brake specific fuel consumption (BSFC) compared to diesel, with statistical analysis confirming the significance of these improvements. Combustion analysis showed a modest increase in peak in-cylinder pressure for B20W10Al50. Emission reductions were substantial relative to diesel: unburned hydrocarbons decreased by 40%, CO by 66.7%, NOx by 22.7%, and smoke opacity by 41.7%. These findings demonstrate that nanoparticle-assisted emulsification can address the common biodiesel trade-offs between efficiency and NOx formation. The study highlights B20W10Al50 as a promising formulation for sustainable transport applications, while also noting the need for further research on long-term nanoparticle stability, injector compatibility, and durability under real-world operating conditions.

Keywords: *Biodiesel, Emulsion, Surfactant, Performance, Emission*

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I. INTRODUCTION

Research on renewable liquid fuels for compression-ignition (CI) engines has been prompted by the growing need to reduce air pollution and decarbonize transportation [1]. Because it is renewable, biodegradable, and can be used without modifications to current diesel engines, biodiesel made from non-edible feedstocks has attracted a lot of interest. Jatropha oil, specifically, is a good feedstock due to its inedibility and desirable fatty-acid profile. But typical biodiesel application comes with trade-offs: while CO, HC and particulate emissions usually drop, biodiesel tends to lower energy density and can elevate NOx emissions and change combustion properties compared to petroleum diesel. Water-in-biodiesel emulsions have appeared as a viable method for mitigating some of these negatives [2]. The atomized water phase enhances secondary atomization (micro-explosion) during droplet evaporation to create finer sprays, better fuel–air mixing and more complete combustion; consequently, HC, CO and smoke emissions can be dramatically minimized without sacrificing combustion stability. Meanwhile, the latent heat of water evaporation can decrease peak cylinder temperatures and thus suppress thermal NO_X generation. Emulsions need the right surfactants right surfactants and processing conditions (mechanical homogenization, ultrasonication) to attain an acceptable droplet size distribution and stability for engine use. Concomitant development in nanotechnology has encouraged the incorporation of nanoparticles as fuel additives to even further optimize combustion. Nanoparticles of metal oxides (e.g., Al_2O_3, TiO_2, CeO_2) in liquid fuels have been shown to enhance thermal conductivity, offer catalytic sites for oxidation, and alter spray characteristics when optimally dispersed. When nanoparticles are combined with emulsified biodiesel, synergistic interactions can occur enhanced atomization by emulsification in combination with enhanced heat transfer. Catalysis by nanoparticles can enhance combustion chemistry, modestly increase in-cylinder pressures, lower the ignition delay, and decrease unburnthydrocarbon and CO emissions. Although showing promising laboratory experiments, the literature remains short on extensive experimental studies that integrate water-in-biodiesel emulsions and nano-additives under

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various conditions, and that analyse their combined influences on combustion, performance, and regulated emissions [3].

While previous studies [4,5] investigated emulsified biodiesel with nano-oxides, they often employed higher nanoparticle concentrations and still reported NOx penalties. The present study addresses this gap by focusing on Jatropha methyl ester with low-level Al_2O_3 dosing (25–50 ppm). Using ultrasonication with a Span-80/Tween-80 surfactant system, emulsified blends were prepared and tested under controlled engine conditions. Performance (BTE, BSFC), combustion (peak pressure, heat release), and emissions were systematically evaluated. Results demonstrate that low-level nanoparticle addition can enhance efficiency while reducing NOx, establishing both the novelty and practical significance of this work.

II. Materials

A. Feedstock and Biodiesel Production

Crude Jatropha Curcas oil, obtained from a local biodiesel processing facility, was used as feedstock for biodiesel production. The free fatty acid (FFA) content of the oil was measured using acid–base titration and found to be approximately 14%. Given this FFA level, base-catalyzed transesterification was chosen, as it is suitable for oils with FFA below 15% and offers high conversion efficiency, as widely reported for Jatropha oil [6].

Biodiesel production was carried out using sodium hydroxide (NaOH) and methanol in a molar ratio of 6:1 (methanol to oil). The oil was first filtered and preheated to 60 °C, then agitated with the NaOH–methanol mixture for 90 minutes at 60 °C. The reaction mixture was allowed to settle for 12 hours to separate the top biodiesel layer from the bottom glycerol layer. The biodiesel was subsequently washed with distilled water and oven-dried at 110 °C to remove residual moisture. The conversion efficiency of the transesterification process, estimated from the biodiesel yield, was approximately 97% [7].

B. Preparation and Stability of Emulsified Biodiesel Blends

An emulsified biodiesel blend was prepared using jatropha methyl ester (JME) and diesel in a 20:80 volumetric ratio. Water was incorporated at 10% by volume along with 2% of a non-ionic surfactant mixture having a hydrophilic–lipophilic balance (HLB) value of 6.43, obtained by combining Span 80 (HLB = 4.3) and Tween 80 (HLB = 15). The emulsification process was carried out using a Hielscher UP400St ultrasonic processor (400 W, 24 kHz) for 45 minutes under continuous flow conditions to ensure uniform dispersion and steady distribution of water droplets in the fuel matrix [8]. The resulting sample was designated as B20W10.

To enhance the properties of the emulsified biodiesel, aluminum oxide (Al_2O_3) nanoparticles were dispersed into the blend at specified concentrations. The stability of the nanoparticle–emulsified biodiesel blends was evaluated through visual inspection. The prepared fuels remained homogeneous without visible sedimentation or agglomeration for approximately one week under ambient conditions, confirming sufficient short-term stability for conducting the experimental trials [9]. This ensured consistent fuel properties throughout the test duration.

C. Incorporation of Nanoparticle

Aluminium oxide (Al_2O_3) nanoparticles with an average particle diameter of 50 nm, purity > 99% were added to the B20W10 emulsion at weight percentages of 25 ppm and 50 ppm. These levels were chosen based on literature evidence that low nanoparticle dosing (<100 ppm) enhances combustion and reduces emissions without adversely affecting fuel stability or engine safety, as well as our preliminary trials, which confirmed stable dispersion at these concentrations. the fuel–nanoparticle mixtures were ultrasonicated for 15 minutes to ensure proper dispersion and prevent agglomeration [10]. The final fuels were labeled as B20W10Al25 and B20W10Al50.

D. Fuel Property Analysis

Physical properties such as density, viscosity, flash & fire point, lower heating values were measured as per ASTM standards. Table I is a summary of the properties of diesel, B20W10, B20W10Al25, and B20W10Al50 that were measured.

TABLE I. FUEL SAMPLE PROPERTIES

Properties	Diesel	B20	B20W10	B20W10Al25	B20W10Al50	Test Method (ASTM)
Density (kg/m³)	813	829	840	842	844	ASTM D4052
Viscosity at 40°C (cSt)	2.8	3.3	3.5	3.6	3.7	ASTM D445
Flash Point (°C)	52	59	63	65	66	ASTM D93
Fire Point (°C)	56	65	69	71	73	ASTM D93
Lower heating Value (kJ/kg)	42,100	40,900	38,900	38,850	38,800	ASTM D240

III. Experimental Procedure And Data Reliability

Each experimental test was performed in triplicate under identical conditions to ensure reproducibility. The variations among repeated runs were consistently within ±3%, which is well within the accuracy limits of the measurement instruments employed [12]. Accordingly, the performance and emission values presented in this study represent the mean of the repeated trials, and the observed percentage improvements can be considered reliable within the stated experimental uncertainty. All reported variations are greater than the ±3% experimental uncertainty range, confirming the reliability of the observed trends within the measurement accuracy limits.

The investigation was carried out on a 4-stroke, single-cylinder, water-cooled diesel engine equipped with a hydraulic loading system for load adjustment. The engine operated at a constant speed of 1500 rpm under different load conditions. Cylinder pressure was measured using a piezoelectric pressure transducer connected to a data acquisition system, while crank-angle positions were recorded with an optical encoder having 0.2° crank angle resolution [11]. The experimental setup is illustrated in Figure 1, and the detailed engine specifications are summarized in Table II.

TABLE II. RESEARCH ENGINE SPECIFICATIONS

Engine Specification	Value
Engine Type	4-stroke, Single-cylinder
Cooling Method	Water-cooled
Bore (mm)	87
Stroke (mm)	110
Compression Ratio	17.5:1
Rated Power (kW)	3.5
Rated Speed (rpm)	1500
Fuel Injection Type	Direct Injection (DI)
Injection Pressure (bar)	200

Fig. 1. Research Setup

Exhaust gases containing HC, CO, and NO_X were determined using AVL DI gas 444 N gas analyser and opacity of smoke was determined by a calibrated AVL 437C Smoke meter. Each sample of fuel was tested in triplicate, and the average result was taken to ensure accurate data [13].

IV. RESULTS AND DISCUSSION

Experimental testing emphasized comparing diesel, emulsified Jatropha biodiesel B20W10, and their nano-enhanced equivalents with Al_2O_3 nanoparticles (25 ppm and 50 ppm) on their performance, combustion, and emission properties. The measured parameters were BTE, BSFC, Cylinder pressure, and exhaust emissions of HC, CO, NO_X, and smoke opacity.

A. Brake Thermal Efficiency

Figure 2 shows the variation of BTE with BP for diesel, B20W10, B20W10Al25, and B20W10Al50. For all fuels, BTE increased with load due to higher in-cylinder temperatures and improved combustion efficiency [14]. Error bars representing ±3% experimental uncertainty is included at each operating point to indicate repeatability and measurement accuracy. Among them, B20W10Al50 gave the highest BTE, with a statistically validated improvement of 2.03 ± 0.3% over diesel at full load, which lies beyond the experimental uncertainty limit (±3%), confirming the reliability of the observed trend.

This gain is attributed to the combined effects of water-induced micro-explosion, which enhances atomization and fuel–air mixing, and the catalytic/thermal properties of Al_2O_3 nanoparticles that promote faster oxidation and shorter ignition delay. The oxygenated nature of JME further supports complete combustion [15]. These quantified results confirm that even low-level Al_2O_3 dosing (25–50 ppm) in emulsified biodiesel provides measurable efficiency benefits compared to diesel and earlier blends [16].

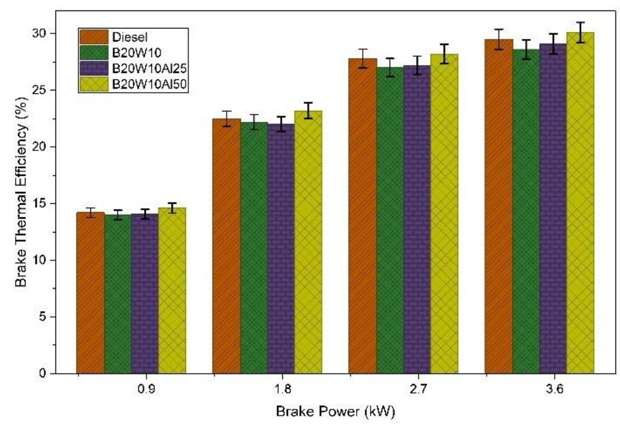

Fig. 2. BTE versus BP (±3% error bars)

B. Brake Specific Fuel Consumption

Figure 3 shows BSFC variation with BP for diesel, B20W10, B20W10Al25, and B20W10Al50. BSFC decreased with increasing load for all fuels due to improved combustion and lower relative heat losses [17]. B20W10Al50 exhibited the lowest BSFC, with a 3.84 ± 0.3% reduction compared to diesel at full load [18]. Error bars (±3%) are included to represent experimental uncertainty.

This improvement is attributed to enhanced atomization from the micro-explosion of water droplets and the catalytic and thermal effects of Al_2O_3 nanoparticles, which accelerate fuel oxidation and heat release. The inherent oxygen content in JME also supports more complete combustion, reducing the additional fuel requirement to achieve the same brake power. Combined, these mechanisms enable more efficient fuel consumption across all loading conditions [19].

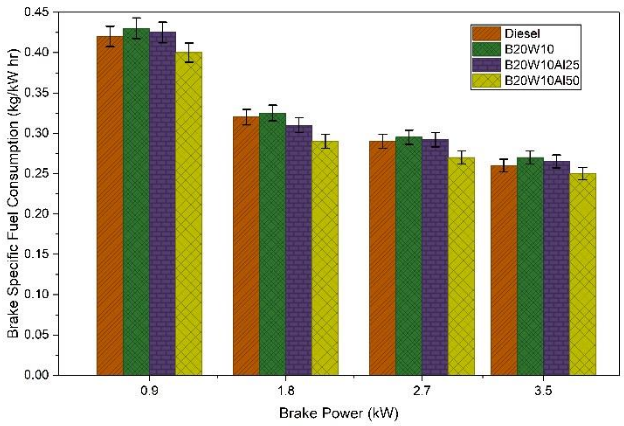

Fig. 3. BSFC Versus BP (±3% error bars)

C. Cylinder Pressure

Figure 4 illustrates crank angle and in-cylinder pressure relationship for diesel and the fuel blends of the tested emulsified biodiesel. The maximum cylinder pressure was realized at 367° crank angle for diesel and B20W10Al50, which had values of 68.89 bar and 69.89 bar, respectively. The marginal rise in maximum pressure for B20W10Al50 signifies augmented premixed combustion due to increased atomization from the micro-explosion of emulsified water droplets and the catalytic effect of Al_2O_3 nanoparticles [20-21]. These effects ensure better fuel–air mixing and quicker burning, leading to modestly higher in-cylinder pressures than those of diesel.

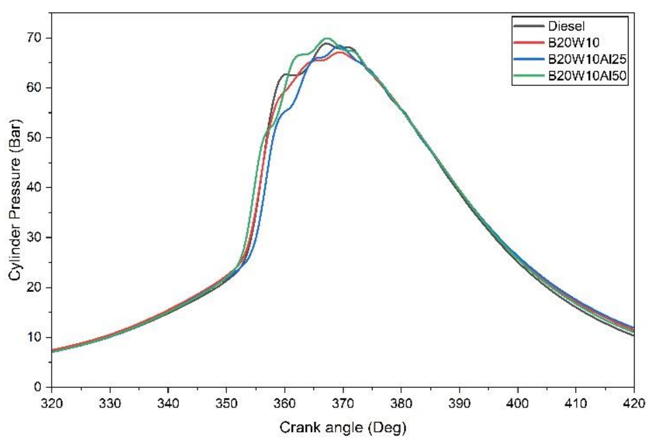

Fig. 4. Crank Angle Versus Cylinder Pressure

D. HC Emissions

Figure 5 depicts the HC emissions variation with BP for diesel and the tested blends. For the whole load range tested, the emulsified blends offered lesser HC emission than the diesel, and B20W10Al50 offered the greatest reduction among them [22]. Error bars (±3%) are included to represent experimental uncertainty. At full-load operation, B20W10Al50 had a 40% decrease in HC emissions compared to the diesel. These decreases are due to improved oxidation catalyzed by the intrinsic oxygen in biodiesel and the catalytic performance of Al_2O_3 nanoparticles, which provide more complete combustion [23]. In addition, the micro-explosion nature of the emulsified fuel enhances atomization of fuel and mixing between air and fuel, reducing the number of unburnt hydrocarbons formed [24]. The synergy of these mechanisms results in the significant reduction in HC emissions for B20W10Al50.

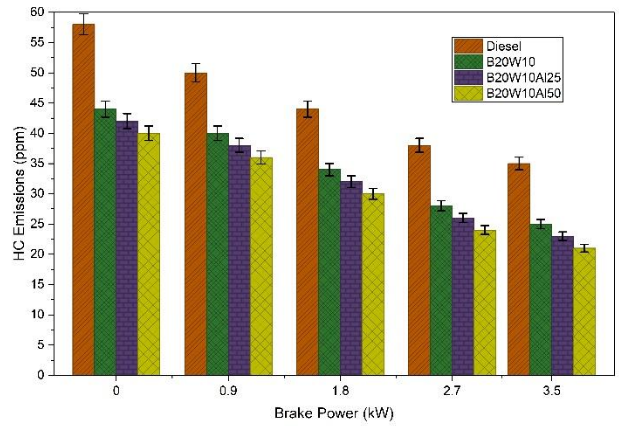

Fig. 5. HC emissions versus BP (±3% error bars)

E. NOX Emissions

Figure 6 illustrates the change of NO_X emissions with BP for diesel and the fuel blends tested. NO_X emissions for all fuels increased with load because of increased combustion temperatures and longer residence times at higher loads [25]. Among the samples tested, B20W10Al50 always exhibited lower NO_X emissions than diesel, with a peak reduction of 22.72% at full load. Error bars (±3%) are included to represent experimental uncertainty. The presence of water in the emulsified biodiesel blend contributes significantly to the NO_X reduction by means of latent heat of vaporization that depresses the peak combustion temperature [26]. Moreover, the micro-explosive behavior enhances fuel–air mixing as well as generates localized cooling regions that reduce NO_X production. The catalytic action of Al_2O_3 nanoparticles increases the combustion efficiency without necessarily increasing the in-cylinder temperatures significantly and hence sustaining minimized NO_X levels with enhanced performance [27]. This combination enables B20W10Al50 to attain both enhanced BTE and significant NO_X reduction.

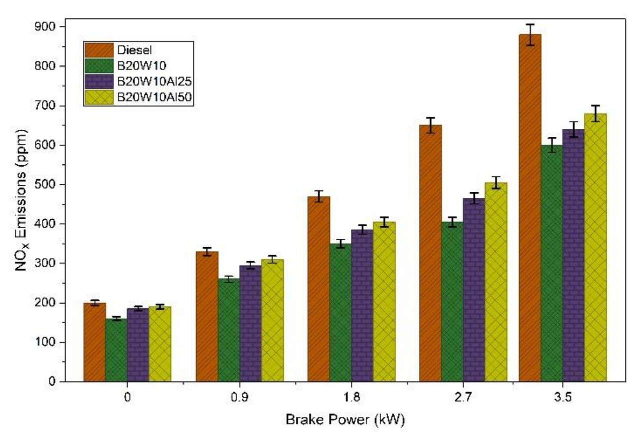

Fig. 6. NOx emissions versus BP (±3% error bars)

F. CO Emissions

Figure 7 shows the CO emission variation with BP for diesel and the fuel blends under test. CO emissions declined uniformly with load for all the fuels. This behavior is due to the enhanced combustion temperatures and higher oxidation rates at high loads, which drive the CO-to-CO_2 conversion [28]. Under all load conditions, B20W10Al50 had the minimum CO emissions with a maximum reduction of 66.67% at full load relative to diesel. Error bars (±3%) are included to represent experimental uncertainty. The reduction can be attributed to the improved atomization and fuel–air mixing due to the micro-explosion phenomenon and the oxygenated characteristics of Jatropha methyl ester that facilitate more complete oxidation of carbon species [29]. The catalytic ability of the Al_2O_3 nanoparticles further accelerates oxidation reactions, even under low local temperatures, thus reducing CO formation over the load range [30].

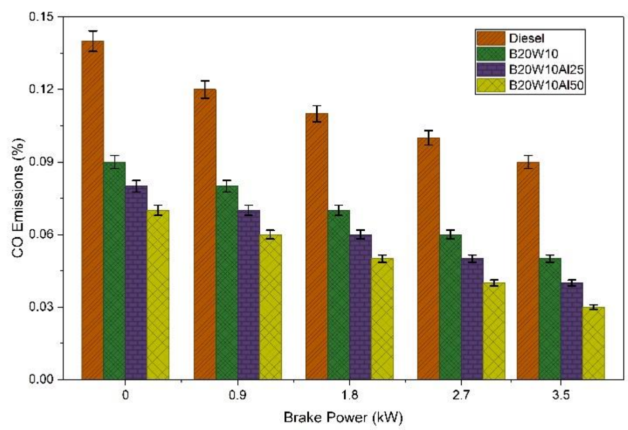

Fig. 7. CO emissions vs BP (±3% error bars)

G. Smoke Opacity

Figure 8 shows the variation of smoke opacity (FSN) with BP for diesel and the tested blends. Smoke opacity was higher with load for all the fuels because of increased fuel burning and richer mixes at higher loads that promote soot [31]. B20W10Al50, however, consistently registered the lowest smoke opacity with a maximum reduction of 41.67% at full load as compared to diesel. Error bars (±3%) are included to represent experimental uncertainty. This notable reduction is largely due to the oxygenated character of biodiesel, which supports soot oxidation, and the micro-explosion effect in emulsified fuel, enhancing secondary atomization and air–fuel interaction [32]. In addition, the Al_2O_3 nanoparticles improve oxidation kinetics and support cleaner combustion, considerably lowering soot precursors and particulate generation across the operating range [33].

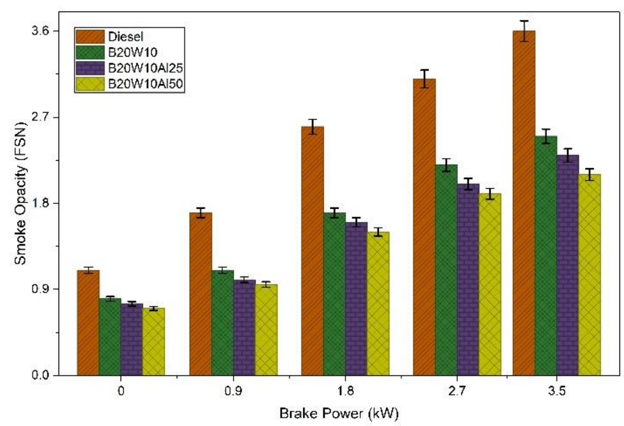

Fig. 8. Smoke opacity vs BP (±3% error bars)

V. CONCLUSIONS

An experimental investigation was conducted to evaluate the performance, combustion, and emission characteristics of water-in-Jatropha biodiesel emulsions enhanced with Al_2O_3 nanoparticles in a CI engine. Among the fuels tested, the B20W10Al50 blend exhibited the most favorable overall performance. Specifically, brake thermal efficiency improved by 2.03% and brake-specific fuel consumption decreased by 3.84% relative to diesel at full load, indicating more effective fuel-to-work energy conversion.

Combustion analysis revealed a slight increase in peak in-cylinder pressure for B20W10Al50, reflecting enhanced premixed combustion due to improved atomization and secondary breakup of fuel droplets through the micro-explosion effect. Emission measurements demonstrated substantial reductions in HC (40%), CO (66.67%), NOx (22.72%), and smoke opacity (41.67%) compared to diesel. These improvements are attributed to the synergistic effects of Al_2O_3 nanoparticles—including catalytic oxidation, improved thermal conductivity, and better fuel–air mixing—and the intrinsic oxygen content of Jatropha biodiesel. While emulsification results in increased fuel density (844 kg/m^3) and viscosity (3.7 cSt) relative to diesel (813 kg/m^3 and 2.8 cSt), the combined performance improvement and emission reduction benefits justify the proposed formulation.

Overall, the integration of Al_2O_3 nanoparticles into water-in-biodiesel emulsions provides a balanced enhancement of engine performance, combustion efficiency, and emission reduction. The study establishes B20W10Al50 as a promising, environmentally friendly, and efficient alternative fuel for CI engines, supporting sustainable and cleaner transportation applications.

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