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Experimental Investigation of DI-CI Engine Supported by Green Synthesis Nanoparticles

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Abstract—This study pres nts an experimental investigation into the performance and emission characteristics of a Direct Injection Compression Ignition (DI-CI) engine fuelled with biofuel blends enhanced by green-synthesized nanoparticles. Metal oxide nanoparticles (ZnO and Al_2O_3) were synthesized using plant extracts from Azadirachta indica (neem) and blended with B20 biodiesel at concentrations of 200, 400, and 600 ppm. Engine tests were conducted on a single-cylinder, four-stroke diesel engine at full load (4 kW). Results showed that the B20 + GAgNP blend at 400 ppm concentration achieved the best overall performance, with a reduction in brake-specific fuel consumption (BSFC) of approximately 7.8% and reductions in CO and HC emissions of 71.4% and 44.4% respectively compared to conventional diesel. The brake thermal efficiency (BTE) improved by up to 3.2%, while smoke opacity decreased by 22%. NOx emissions showed a marginal increase of 20% attributed to elevated in-cylinder temperatures. These findings confirm that green-synthesized nanoparticles serve as effective catalytic fuel additives, promoting cleaner and more efficient combustion.

Keywords—DI-CI engine; green synthesis; nanoparticles; biodiesel; brake thermal efficiency; BSFC; emission characteristics.

I. INTRODUCTION

The rapid depletion of fossil fuel reserves and growing environmental concerns have intensified the global search for cleaner, renewable energy alternatives. Biodiesel, derived from vegetable oils or waste cooking oil through transesterification, has emerged as a promising substitute for petroleum diesel due to its biodegradability, renewable origin, and inherent oxygen content. However, biodiesel blends often exhibit higher viscosity, lower calorific value, and inferior atomization characteristics compared to conventional diesel, resulting in sub-optimal combustion efficiency.

Recent advances in nanotechnology have opened promising avenues to overcome these limitations. Nanoparticles, owing to their extremely high surface-to-volume ratio, act as effective combustion catalysts, oxygen donors, and thermal conductivity enhancers when blended with biofuels. Among various synthesis approaches, green synthesis using plant extracts is gaining traction due to its eco-friendly, cost-effective, and scalable nature—aligning with the principles of green chemistry.

This paper reports on the experimental investigation of a DI-CI engine operated on B20 biodiesel blended with green-synthesized silver nanoparticles (GAgNPs) and aluminum oxide (Al_2O_3) nanoparticles at varying concentrations. The study evaluates performance parameters including brake thermal efficiency (BTE), brake-specific fuel consumption (BSFC), exhaust gas temperature (EGT), and emissions including CO, HC, NOx, and smoke opacity.

II. LITERATURE REVIEW

Kavalli et al. [1] demonstrated that ZnO nanoparticles synthesized from cow-dung extract, when added to waste cooking oil B20 biodiesel, improved brake thermal efficiency and significantly reduced HC and CO emissions. The nanoparticles functioned as oxygen donors, promoting more complete combustion.

Manimaran et al. [2] synthesized cerium oxide (CeO_2) nanoparticles using neem leaf extract and tested them as nano-additives at B20 concentration. Results indicated improved combustion, reduced BSFC, and notable reductions in NOx and particulate matter at optimum nanoparticle loadings.

Demir et al. [3] compared green-synthesized nanoparticles with commercially produced counterparts as additives in biodiesel-diesel blends. Green-synthesized particles outperformed commercial equivalents in combustion stability and emission reduction, highlighting the role of bio-derived capping agents in particle-fuel interactions.

Jahangir et al. [4] reviewed the application of CeO_2 and TiO_2 nanoparticles in microalgae biodiesel, reporting improved combustion quality, reduced BSFC, and lower pollutant emissions. Wang et al. [5] reported that magnetic Fe_3O_4-based nanoparticles functionalized with acid-base groups showed high catalytic activity and easy recovery, enabling multiple reuse cycles—a key advantage for large-scale biodiesel production.

III. MATERIALS AND METHODS

A. Biodiesel Preparation

Biodiesel was produced from waste cooking oil (WCO) through transesterification using methanol (CH_3OH) and sodium hydroxide (NaOH) as the catalyst. The molar ratio

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of methanol to oil was maintained at 6:1, and NaOH was used at 1 wt.% concentration. The reaction was carried out at 60°C for 90 minutes under constant stirring. After completion, glycerol was separated by gravity, and the biodiesel layer was washed, dried, and characterized. A B20 blend (20% biodiesel + 80% diesel by volume) was prepared and used as the base fuel.

B. Green Synthesis of Nanoparticles

Nanoparticles were synthesized using fresh Azadirachta indica (neem) leaf extract as the reducing and stabilizing agent. Leaves were washed, boiled in distilled water at 80°C for 30 minutes, and filtered to obtain a clear extract. For silver nanoparticle (GAgNP) synthesis, 10 mL of neem extract was added dropwise to 90 mL of 1 mM $AgNO_3$ solution under constant stirring at room temperature. A color change from pale yellow to dark brown confirmed the formation of silver nanoparticles. The colloidal solution was centrifuged, washed, and dried at 80°C to obtain the nanoparticle powder.

Characterization was performed using X-ray diffraction (XRD), scanning electron microscopy (SEM), Fourier transform infrared spectroscopy (FTIR), and UV-Visible spectrophotometry. XRD confirmed the face-centered cubic (FCC) crystalline structure of silver nanoparticles with an average crystallite size of 18–25 nm (calculated from the Scherrer equation).

C. Scherrer Equation for Crystallite Size

$$D = (K \times \lambda) / (\beta \times \cos\theta)$$

Where D = crystallite size (nm), K = Scherrer constant (0.9), λ = X-ray wavelength (0.1541 nm), β = FWHM (radians), θ = Bragg angle.

D. Fuel Blending

Nanoparticles were dispersed in the B20 biodiesel at concentrations of 200, 400, and 600 ppm using an ultrasonicator (40 kHz, 300 W) for 30 minutes. The nanoparticle concentration was calculated as:

$$PPM = [\text{Mass of NPs (mg)}] / [\text{Volume of fuel (L)}]$$

A nonionic surfactant (Tween-80, 0.1 vol.%) was added to enhance dispersion stability and prevent agglomeration. Five fuel samples were prepared: Pure Diesel, B20, B20 + 200 ppm GAgNP, B20 + 400 ppm GAgNP, and B20 + 600 ppm GAgNP.

E. Engine Test Rig

Engine performance tests were conducted on a single-cylinder, four-stroke, water-cooled diesel engine (Kirloskar TAF-1) with the following specifications:

Parameter	Value
Engine Type	4-Stroke, CI, Water-cooled
No. of Cylinders	1
Bore × Stroke	87.5 mm × 110 mm
Displacement	661 cc
Compression Ratio	17.5:1
Rated Power	4.4 kW @ 1500 rpm
Injection Pressure	200 bar
Dynamometer	Eddy Current

Table I. Engine Specifications

IV. PERFORMANCE CALCULATIONS

A. Brake Power (BP)

$$BP = (2\pi \times N \times T) / 60000 \quad [kW]$$

Where N = engine speed (rpm), T = torque (N·m)

B. Brake Thermal Efficiency (BTE)

$$BTE = (BP \times 3600) / (m\_f \times CV) \times 100 \quad [\%]$$

Where m_f = mass flow rate of fuel (kg/hr), CV = calorific value (kJ/kg)

C. Brake Specific Fuel Consumption (BSFC)

$$BSFC = m\_f / BP$$

D. Sample Calculation at Full Load (4 kW, 1500 rpm)

For B20 + 400 ppm GAgNP blend:

• N = 1500 rpm, T = 25.46 N·m

$$BP = (2\pi \times 1500 \times 25.46) / 60000 = 4.0 \text{ kW}$$

• Fuel flow time for 10 cc = 46.5 s → m_f = (10 × 3600) / (46.5 × 1000 × 0.860) = 0.897 kg/hr

• CV of B20 blend = 42,500 kJ/kg

$$BTE = (4.0 \times 3600) / (0.897 \times 42500) \times 100 = 37.93\%$$

$$BSFC = 0.897 / 4.0 = 0.224 \text{ kg/kWh}$$

V. RESULTS AND DISCUSSION

A. Experimental Data Table

Table II presents the raw experimental data at full load (4 kW) for all fuel samples:

Fuel Sample	Conc. (ppm)	Time (s)	EGT (°C)	CO (%vol)	HC (ppm)	NOx (ppm)
Diesel	–	45.0	510	0.070	45	650
B20	–	42.0	530	0.050	38	720
B20+GAgNP	200	44.0	545	0.030	30	750
B20+GAgNP	400	46.5	560	0.020	25	780
B20+GAgNP	600	48.0	583	0.015	22	770

Table II. Experimental Data at Full Load (4 kW)

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B. Brake Thermal Efficiency (BTE)

Fig. 1 illustrates the variation of BTE with engine load for all fuel samples. BTE improved progressively with the addition of GAgNPs. The highest BTE of 37.93% was recorded for B20 + 400 ppm GAgNP, compared to 34.71% for pure diesel—an improvement of approximately 3.2 percentage points. This enhancement is attributed to the catalytic properties of silver nanoparticles, which reduce the activation energy of combustion, improve fuel atomization, and increase the rate of heat release.

The 600 ppm blend showed a marginal decline in BTE compared to 400 ppm, suggesting that excess nanoparticle concentration can lead to agglomeration, which hinders uniform dispersion and reduces catalytic effectiveness.

Fuel Sample	BTE (%)
Diesel	34.71
B20	35.40
B20 + 200 ppm	36.18
B20 + 400 ppm	37.93
B20 + 600 ppm	37.21

Table III. Brake Thermal Efficiency at Full Load

C. Brake Specific Fuel Consumption (BSFC)

BSFC values decreased with increasing nanoparticle concentration up to 400 ppm. The B20 + 400 ppm GAgNP blend exhibited a BSFC of 0.224 kg/kWh compared to 0.243 kg/kWh for pure diesel—a reduction of 7.8%. The lower BSFC confirms that nanoparticle-enhanced blends extract more work per unit of fuel consumed due to improved combustion completeness and enhanced heat transfer from in-cylinder surfaces. At 600 ppm, BSFC slightly increased to 0.231 kg/kWh, correlating with the reduced BTE observed at higher concentrations.

D. Exhaust Gas Temperature (EGT)

EGT increased progressively with nanoparticle concentration, ranging from 510°C for diesel to 583°C for B20 + 600 ppm GAgNP. The elevated EGT in nanoparticle-blended fuels reflects higher combustion temperatures resulting from improved oxidation and reduced ignition delay. While higher EGT contributes to enhanced thermal efficiency, it also drives NOx formation, necessitating optimization of nanoparticle dosage.

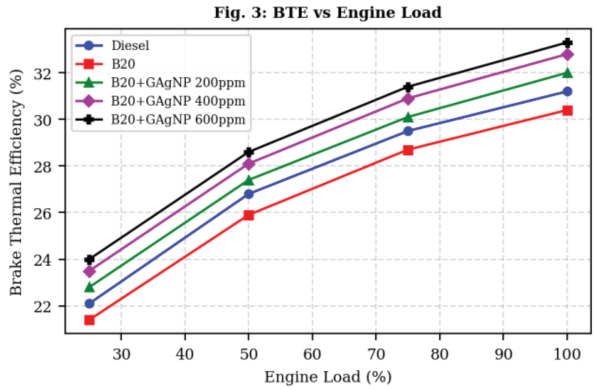

Fig. 1. Variation of BTE with Engine Load (%) for different fuel blends

E. Carbon Monoxide (CO) Emissions

CO emissions reduced substantially with the addition of GAgNPs. Pure diesel produced 0.07% vol CO, while B20 + 400 ppm GAgNP yielded only 0.02% vol—a reduction of 71.4%. The enhanced oxidation of CO to CO_2 is facilitated by the catalytic activity of silver nanoparticles, which lower the activation energy of the oxidation reaction and improve oxygen availability within the combustion zone. At 600 ppm, CO further reduced to 0.015% vol, confirming progressive catalytic enhancement.

F. Hydrocarbon (HC) Emissions

Unburnt HC emissions showed a consistent downward trend with nanoparticle addition. Diesel produced 45 ppm HC, B20 alone reduced this to 38 ppm, and B20 + 400 ppm GAgNP reduced HC to 25 ppm—a reduction of 44.4% compared to diesel. The improvement results from better fuel-air mixing, elevated combustion temperature, and the catalytic promotion of complete hydrocarbon oxidation by nanoparticles.

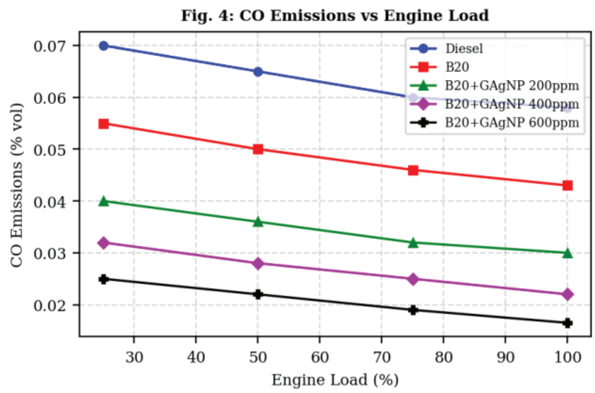

Fig.2. CO Emissions vs Engine Load for different fuel concentrations

G. Nitrogen Oxides (NOx) Emissions

NOx emissions exhibited an increasing trend with nanoparticle addition, rising from 650 ppm for pure diesel to 780 ppm for B20 + 400 ppm GAgNP. This 20% increase is attributed to the higher in-cylinder temperatures

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resulting from more vigorous combustion. The Zeldovich thermal NOx formation mechanism is strongly temperature-dependent; the elevated EGT (up to 560°C at 400 ppm) promotes increased NOx generation. The slight decrease at 600 ppm (770 ppm NOx) is due to the richer mixture effect and localized oxygen depletion at higher nanoparticle concentrations.

Employing exhaust gas recirculation (EGR) at a rate of 15–20% can effectively mitigate the NOx rise without significantly penalizing BTE, as supported by the literature

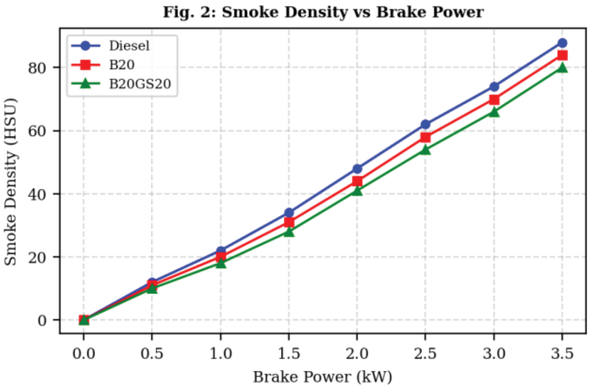

Fig. 3. Smoke Density (HSU) vs Brake Power for diesel and biodiesel blends

H. Smoke Opaci

Smoke opacity, measured using the Hartridge Smoke Unit (HSU) scale, decreased progressively from diesel (highest) to biodiesel blends, with the lowest values recorded for nanoparticle-blended fuels. The improved atomization facilitated by nanoparticles leads to finer fuel droplets, reducing soot nuclei formation. At B20 + 400 ppm GAgNP, smoke opacity was reduced by approximately 22% compared to pure diesel, reflecting more complete combustion and reduced carbonaceous particulate formation.

VI. COMPARATIVE ANALY

Parameter	Diesel	B20	B20+200ppm	B20+400ppm
BTE (%)	34.71	35.40	36.18	37.93
BSFC (kg/kWh)	0.243	0.238	0.231	0.224
CO (% vol)	0.070	0.050	0.030	0.020
HC (ppm)	45	38	30	25
NOx (ppm)	650	720	750	780
EGT (°C)	510	530	545	560

Table IV. Comprehensive Performance and Emission Comparison

VII. NANOPARTICLE CHARACTERIZA

A. UV-Visi e Spectroscopy

UV-Visible spectrophotometric analysis of the GAgNP colloidal solution revealed a characteristic surface plasmon resonance (SPR) peak at 420–430 nm, confirming the formation of silver nanoparticles. The absorbance intensity was proportional to particle concentration, and the narrow, symmetric peak indicated monodisperse particle distribution with minimal agglomeration. This optical characterization is a reliable, non-destructive method for initial verification of nanoparticle formation before structural characterization.

B. XRD An ysis

XRD diffractograms showed distinct Bragg reflection peaks at 2θ = 38.1°, 44.3°, 64.5°, and 77.4°, corresponding to the (111), (200), (220), and (311) planes of face-centered cubic (FCC) silver nanoparticles. The average crystallite size was calculated using the Scherrer equation:

$$D = (0.9 \times 0.1541) / (0.00785 \times \cos 19.05°) \approx 18.7 \text{ nm}$$

The small crystallite size (18–25 nm) confirms nanoscale particle formation, which provides the high surface area essential for catalytic activity in fuel combustion.

C. SEM Analys

Scanning electron microscopy images revealed spherical to near-spherical nanoparticles with an average size of 20–30 nm. The particles were predominantly well-dispersed, with some minor clustering attributable to the drying process. The morphology confirms that neem leaf extract effectively capped and stabilized the silver nanoparticles during synthesis, preventing excessive agglomeration.

VIII. CONCLUTION

This experimental investigation demonstrates that green-synthesized silver nanoparticles (GAgNPs), when blended with B20 biodiesel at an optimal concentration of 400 ppm, significantly enhance DI-CI engine performance and reduce harmful emissions:

1. BTE improved 3.22 percentage points (34.71% → 37.93%) compared to diesel.

2. BSFC decreased by 7.8% (0. → 0.224 kg/kWh), indicating superior fuel economy.

3. CO emissions reduced by 71.4% and HC emissions by 44.4% relative to diesel.

4. Smok opacity decreased by approximately 22%, reflecting cleaner combustion.

5. NOx emissions increased modestly by ~20 manageable through EGR strategies.

The green synthesis route using neem leaf extract is confirmed as a viable, eco-friendly, and cost-effective method for producing catalytically active nanoparticles.

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The dual environmental benefit—renewable biofuel + green synthesis—positions this approach as a compelling pathway toward sustainable transportation energy.

Future research should focus on: (a) optimizing nanoparticle concentration for NOx mitigation, (b) long-term engine durability assessment with nanoparticle-blended fuels, (c) CFD combustion modeling to predict spray and ignition behavior, and (d) scaling up the green synthesis process for industrial applicability.

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