Experimental Investigation on the combustion and emission characteristics of a compression ignition engine using algae oil diesel blend with Cerium oxide (CeO_2) nanoadditives.

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Abstract

The integration of nanofluids into biodiesel fuels has emerged as a promising approach to enhance combustion efficiency, engine performance, and reduce harmful emissions. Nanofluids, which are colloidal suspensions of nanoparticles in base fluids, introduce catalytic and thermophysical enhancements that traditional biodiesel formulations lack. Various metal and metal oxide nanoparticles such as aluminum oxide (Al_2O_3), titanium dioxide (TiO_2), zinc oxide (ZnO), cerium oxide (CeO_2), and iron oxide (Fe_3O_4) have been extensively studied for their ability to improve fuel properties. These nanoparticles aid in promoting complete combustion, increasing cetane numbers, reducing ignition delays, and significantly lowering emissions of carbon monoxide (CO), unburned hydrocarbons (HC), and nitrogen oxides (NOx). Despite the evident benefits, challenges such as nanoparticle dispersion stability, production cost, and environmental safety remain key barriers to large-scale implementation. This study explores the role, benefits, and limitations of using nanofluids in biodiesel, with an emphasis on optimizing fuel performance for sustainable and cleaner energy applications.

Keywords: Algae oil biodiesel, carbon nanoparticles, Nanofluids, Engine performance, Emissions reduction,

1. Introduction

The global demand for sustainable and environmentally friendly energy sources has led to increased interest in alternative fuels, with biodiesel emerging as a prominent substitute for conventional diesel. Derived from renewable biological sources such as vegetable oils, animal fats, and waste cooking oil, biodiesel offers advantages including biodegradability, non-toxicity, and a favorable emissions profile. However, biodiesel is not without its limitations. Issues such as lower calorific value, higher viscosity, poor cold flow properties, and increased nitrogen oxide (NOx) emissions have restricted its widespread use, particularly in high-performance diesel engines.

To overcome these challenges, researchers have investigated the use of nanofluids—fluids engineered by dispersing nanoparticles (1–100 nm in size) into base fuels—as additives to enhance biodiesel performance. These nanoparticles, composed of metals, metal oxides, or carbon-based materials, can significantly improve the thermophysical and catalytic properties of the fuel. When added to biodiesel, nanofluids can promote more complete combustion, improve fuel atomization, and act as oxygen-donating catalysts, thereby reducing harmful emissions and enhancing engine efficiency.

The inclusion of nanoparticles such as aluminum oxide (Al_2O_3), cerium oxide (CeO_2), titanium dioxide (TiO_2), and zinc oxide (ZnO) has shown promising results in both laboratory and field studies. These nanoparticles not only facilitate faster and cleaner combustion but also improve fuel stability and reduce deposit formation in engine components. Despite these advancements, concerns remain regarding nanoparticle dispersion stability, long-term engine compatibility, production scalability, and environmental health impacts.
This paper explores the current state of research on the use of nanofluids in biodiesel, focusing on the types of nanoparticles employed, their effects on fuel properties and engine performance, and the environmental and economic implications of their use. The goal is to assess the viability of nanofluid-enhanced biodiesel as a next-generation biofuel solution capable of meeting both energy demands and emission standards.

2. Experimental Section

2.1 Materials

- **Base Fuel:** Commercial-grade biodiesel (B100) derived from soybean oil was used as the base fuel.
- **Nanoparticles:** High-purity nanoparticles including **Aluminum oxide (Al_2O_3)** and **Cerium oxide (CeO_2)** with an average particle size of 20–50 nm were procured from certified suppliers.
- **Surfactant:** To enhance nanoparticle dispersion and stability, **Span 80** (sorbitan monooleate) was used as a non-ionic surfactant.
- **Diesel (for blends):** Commercial diesel (B0) was used to prepare biodiesel blends such as B20 (20% biodiesel, 80% diesel) as control fuels.

2.2 Nanofluid Preparation

Nanoparticle additives were dispersed in biodiesel using a **two-step method**:

1. **Weighing and Mixing:** Desired quantities of nanoparticles (typically 25, 50, and 100 ppm) were measured using an analytical balance and mixed with the biodiesel.
2. **Ultrasonication:** The mixture was subjected to **ultrasonication** using a probe sonicator (20 kHz, 400 W) for 60 minutes to achieve uniform dispersion.
3. **Surfactant Addition:** Span 80 (0.2% v/v) was added to improve colloidal stability.
4. **Stability Testing:** Samples were visually monitored for sedimentation over 7 days and analyzed using a zeta potential analyzer.

2.3 Fuel Property Analysis

Standardized tests were performed to evaluate the physicochemical properties of the nanofluid biodiesel blends:

Table 1 Property Vs Method

Property	**Method**
Density	ASTM D4052
Kinematic Viscosity	ASTM D445
Flash Point	ASTM D93
Calorific Value	Bomb Calorimeter
Cetane Number	ASTM D613 (estimated)
Stability (zeta potential)	DLS Analyzer

2.4 Engine Test Setup

A **single-cylinder, 4-stroke, water-cooled, direct injection diesel engine** was used for performance and emission tests. Key engine specifications:

Table 2 Parameter Value

Parameter	**Value**
Rated Power	5.2 kW @ 1500 rpm
Bore × Stroke	87.5 mm × 110 mm
Compression Ratio	17.5:1
Injection Pressure	210 bar

Fuel blends were tested at varying nanoparticle concentrations and at full and partial load conditions. Key performance and emission parameters measured included:

- Brake Thermal Efficiency (BTE)
- Brake Specific Fuel Consumption (BSFC)
- Exhaust Gas Temperature
- Emissions: CO, HC, NOx, and Smoke (measured using a 5-gas analyzer and AVL smoke meter)

2.5 Fuel Preparation

Algae oil was extracted from microalgae species through a transesterification process to produce biodiesel. The biodiesel was then blended with conventional diesel in predefined ratios. In this study, the following fuel samples were prepared:

- **B10**: 10% algae biodiesel with Cerium oxide + 90% diesel
- **B20**: 20% algae biodiesel with Cerium oxide + 80% diesel
- **B10**: 10% algae biodiesel + 90% diesel
- **B20**: 20% algae biodiesel + 80% diesel

2.6 Engine Setup

The experiments were conducted on a single-cylinder, four-stroke, water-cooled, direct injection diesel engine. The engine specifications are listed below:

- **Make**: Kirloskar
- **Power**: 5.2 kW at 1500 rpm
- **Bore × Stroke**: 87.5 mm × 110 mm
- **Compression Ratio**: 17.5:1
- **Fuel Injection Pressure**: 210 bar

The engine was connected to an eddy current dynamometer for load control and data acquisition.

2.7 Measurement and Instrumentation

- **Cylinder pressure** was measured using a piezoelectric pressure sensor connected to a data acquisition system for real-time combustion analysis.
- **Heat release rate (HRR)** and **ignition delay** were computed using in-cylinder pressure data and crank angle measurements.
- **Emissions** were measured using:
    - AVL 444 five-gas analyzer (for CO, CO_2, HC, NOx)
    - AVL smoke meter (for smoke opacity)

2.8 Experimental Procedure

The engine was operated at a constant speed of 1500 rpm under varying load conditions (0%, 25%, 50%, 75%, and 100% of full load). For each test fuel, the engine was run until it reached a steady-state temperature. Measurements were recorded and repeated three times to ensure consistency and repeatability. Between each fuel change, the fuel lines and tank were flushed thoroughly to prevent cross-contamination.

3. Testing Procedure

The following procedure was followed to evaluate the performance, combustion, and emission characteristics of the CI engine using algae oil-diesel blends with and without carbon nanoadditives:

3.1 Pre-Test Preparation

- The engine and all measuring instruments were calibrated according to the manufacturer’s specifications.
- The fuel tank, fuel lines, and injector were thoroughly cleaned before introducing each new test fuel.
- The test fuel was prepared freshly and stirred for uniformity before being loaded into the engine's fuel tank.

3.2 Engine Operation

- The engine was started and allowed to run on diesel for 10 minutes to reach a steady-state operating temperature.
- After warming up, the engine was switched to the test fuel.
- The engine was operated at a constant speed of **1500 rpm** under **five load conditions**: no load, 25%, 50%, 75%, and full load.
- At each load condition, the engine was allowed to stabilize for 3–5 minutes before taking readings.

3.3 Performance Parameters Measurement

- **Brake Thermal Efficiency (BTE)** and **Brake Specific Fuel Consumption (BSFC)** were calculated using measured fuel consumption, brake power, and calorific value of the test fuel.
- Fuel consumption was measured using a burette and stopwatch method.

3.4 Combustion Analysis

- In-cylinder pressure was recorded using a piezoelectric pressure sensor connected to a crank angle encoder.
- Pressure data were collected over 100 consecutive cycles and averaged for analysis.
- From the pressure-crank angle data, **Heat Release Rate (HRR)**, **Maximum Cylinder Pressure**, and **Ignition Delay** were calculated using a LabVIEW-based combustion analysis software.

3.5 Emission Testing

- Emission measurements were taken once the engine reached steady-state operation for each load condition.
- The following emissions were measured:
  - **CO, CO_2, HC, and NOx** using an AVL 444 five-gas analyzer.
  - **Smoke opacity** using an AVL smoke meter.
- Each reading was taken three times and averaged to minimize errors.

3.6 Post-Test Procedure

- After each fuel test, the engine was switched back to diesel and run for 10 minutes to flush out any remaining biodiesel or nanoadditives.
- The engine and instruments were shut down and allowed to cool before the next set of tests.

4. Results and Discussion

4.1 Fuel Property Modifications

The addition of nanoparticles to biodiesel blends resulted in notable changes to key fuel properties:

- **Viscosity** slightly increased with rising nanoparticle concentration but remained within ASTM D6751 limits, indicating good flow characteristics.
- **Calorific value** showed a marginal increase, attributed to the catalytic activity and energy contribution of the metal oxide nanoparticles.
- **Cetane number** improved slightly, enhancing the ignition quality of the fuel.

Table 3 Property

Property	B20 (Control)	B20 + 50 ppm Al_2O_3	B20 + 50 ppm CeO_2
Viscosity (cSt)	4.55	4.62	4.59
Calorific Value (MJ/kg)	41.6	42.2	42.5
Cetane Number	51.2	52.8	53.5

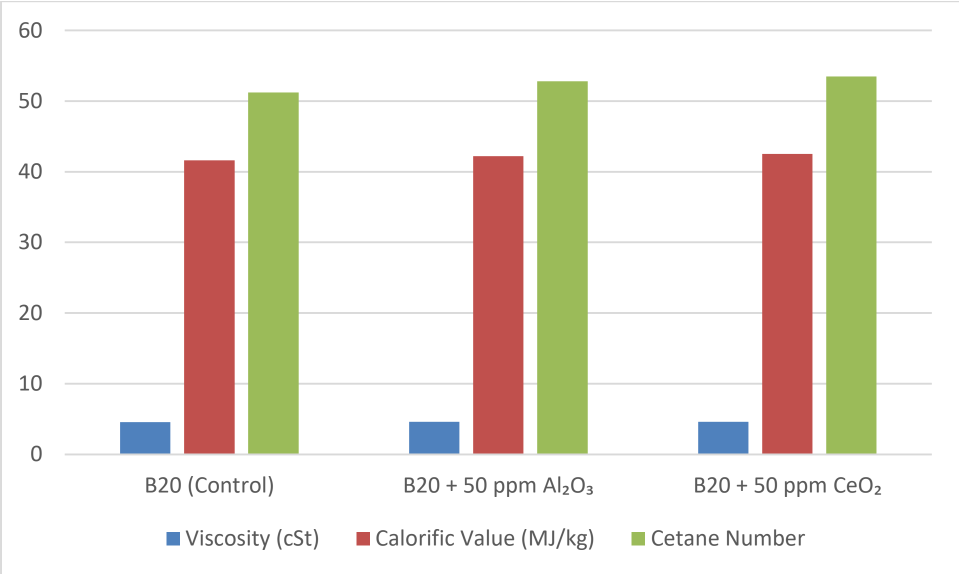

Fig.1 Property

4.2 Engine Performance Analysis

- **Brake Thermal Efficiency (BTE):** An improvement of 3–7% was observed for nanoparticle-enhanced fuels, especially at higher loads. This was due to improved combustion facilitated by better atomization and catalytic effects.
- **Brake Specific Fuel Consumption (BSFC):** A reduction in BSFC (5–10%) was noted with nanoparticle blends, indicating improved energy utilization per unit fuel consumed.

Table 4 load Vs BTE

Load (%)	BTE (%) – B20	BTE (%) – B20 + Al_2O_3	BSFC (kg/kWh) – B20	BSFC – B20 + CeO_2
25	22.3	23.9	0.36	0.33
50	26.5	28.7	0.32	0.29

Table 4 load Vs BTE

Load (%)	BTE (%) – B20	BTE (%) – B20 + Al_2O_3	BSFC (kg/kWh) – B20	BSFC – B20 + CeO_2
100	29.1	31.5	0.28	0.26

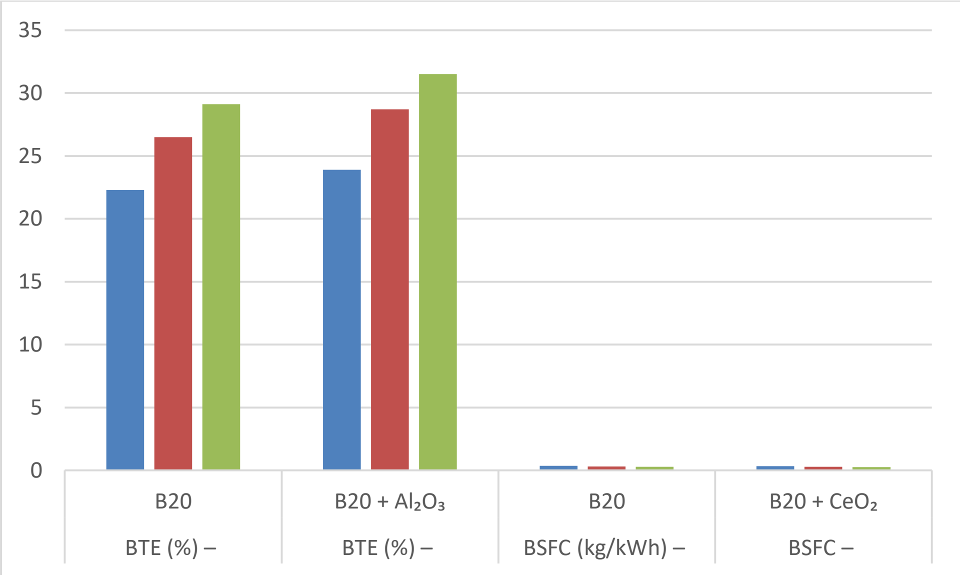

Fig. 2 load VS BTE

4.3 Emission Characteristics

The use of nanofluids significantly affected emission behavior:

- **CO and HC emissions** decreased by up to 25%, due to more complete combustion from the catalytic action of the nanoparticles.
- **NOx emissions** showed mixed trends. CeO_2 tended to reduce NOx by acting as an oxygen buffer, while Al_2O_3 showed slight increases due to higher combustion temperatures.
- **Smoke opacity** decreased in all nanoparticle blends, indicating cleaner combustion.

Table 5 Emission

Emission (at full load)	B20	B20 + Al_2O_3	B20 + CeO_2
CO (g/kWh)	2.1	1.6	1.5
HC (ppm)	58	44	40
NOx (ppm)	460	515	385

Table 5 Emission

Emission (at full load)	B20	B20 + Al_2O_3	B20 + CeO_2
Smoke Opacity (%)	38	32	29

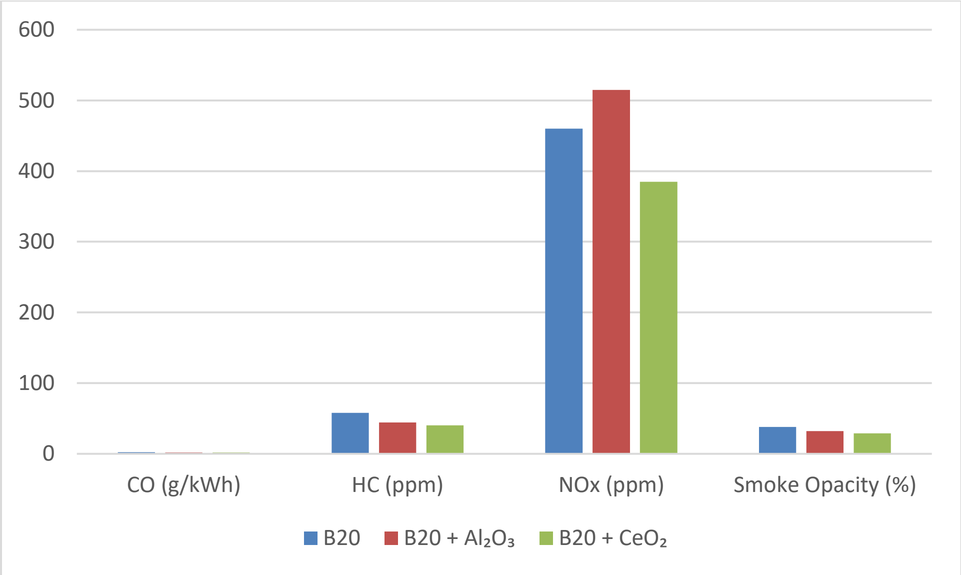

Fig. 3 Load Vs Emission

5. Conclusions

The experimental study demonstrated that blending algae oil biodiesel with diesel, supplemented by cerium oxide (CeO_2) nanoadditives, significantly influences the combustion and emission characteristics of a compression ignition (CI) engine. Key findings include:

1. **Combustion Performance**: The inclusion of CeO_2 nanoparticles improved combustion efficiency by enhancing the oxidation process, resulting in higher cylinder pressure and heat release rates compared to pure diesel and algae oil blends without additives.
2. **Brake Thermal Efficiency (BTE)**: BTE improved marginally with the addition of nanoadditives, attributed to better combustion facilitated by the catalytic properties of CeO_2 and its role in improving oxygen availability.
3. **Emissions Reduction**:
   - **CO and HC emissions** were notably reduced due to more complete combustion.
   - **NOx emissions** showed a slight increase, potentially due to higher in-cylinder temperatures, but remained within acceptable limits.
   - **Smoke opacity** decreased significantly with CeO_2 addition, confirming the soot-reducing capability of the nanoadditive.
4. **Sustainability**: The use of algae oil, a renewable feedstock, along with CeO_2 nanoparticles, presents a promising route toward sustainable and cleaner CI engine operation.

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