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# Performance and emission analysis of algae-based biodiesel in compression ignition engines

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## Abstract

This research paper examines the performance characteristics and emission profiles of algae-based biodiesel in compression ignition engines. Through systematic laboratory testing and engine trials, this study evaluates the combustion behavior, engine performance parameters, and exhaust emissions of various algal biodiesel blends compared to conventional diesel fuel. Results indicate that algae-based biodiesel demonstrates promising combustion properties with significant reductions in particulate matter, hydrocarbons, and carbon monoxide emissions. However, nitrogen oxide emissions showed a moderate increase. Engine performance parameters, including brake thermal efficiency and brake specific fuel consumption, revealed competitive performance with slight variations from conventional diesel. This paper concludes that algae-based biodiesel represents a viable renewable alternative to petroleum diesel, offering significant environmental advantages while maintaining satisfactory engine performance characteristics.

**Keywords:** Algae Biodiesel; Compression Ignition Engines; Emissions Reduction; Alternative Fuels; Combustion Analysis; Engine Performance

## 1. Introduction

The global transportation sector faces dual challenges of ensuring energy security while simultaneously reducing environmental impact. Biodiesel has emerged as a promising alternative fuel for compression ignition (CI) engines due to its renewable nature and potential for reducing harmful emissions. Among the various feedstocks for biodiesel production, microalgae have gained significant attention due to their high oil yield potential, non-competition with food crops for arable land, rapid growth rate, and ability to capture carbon dioxide during cultivation (Chisti, 2007).

Algae can produce 10-100 times more oil per unit area compared to conventional oil crops such as soybean, rapeseed, or palm (Mata et al., 2010). Additionally, many algal species can grow in non-potable water, including wastewater and seawater, thus reducing freshwater demand. These characteristics position algae-based biodiesel as a potentially sustainable fuel source that could contribute significantly to meeting future energy demands while mitigating greenhouse gas emissions [1].

However, the successful implementation of algae-based biodiesel in the transportation sector requires comprehensive assessment of its performance characteristics and emission profiles in compression ignition engines. This research aims to evaluate:

- The physicochemical properties of algae-based biodiesel and its blends

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- Combustion characteristics in compression ignition engines
- Engine performance parameters including efficiency and power output
- Exhaust emission profiles compared to conventional diesel fuel
- Potential modifications or adaptations required for optimal engine operation

By examining these aspects, this study seeks to provide insights into the viability of algae-based biodiesel as an alternative fuel for transportation and stationary power generation applications.

## 2. Literature review

### 2.1. Algae as Biodiesel Feedstock

Microalgae have been extensively studied as a feedstock for biodiesel production due to their high lipid content and productivity. Table 1 compares oil yield and land use requirements of various biodiesel feedstocks, highlighting the significant advantages of microalgae.

**Table 1** Oil Yield Comparison of Various Biodiesel Feedstocks

| Feedstock | Oil Yield (L/ha/year) | Land Area Needed (Mha)* | Percent of Existing US Cropland |
|---|---|---|---|
| Corn | 172 | 1540 | 846% |
| Soybean | 446 | 594 | 326% |
| Canola | 1190 | 223 | 122% |
| Jatropha | 1892 | 140 | 77% |
| Coconut | 2689 | 99 | 54% |
| Oil palm | 5950 | 45 | 24% |
| Microalgae (30% oil by wt) | 58,700 | 4.5 | 2.5% |
| Microalgae (70% oil by wt) | 136,900 | 2.0 | 1.1% |

Numerous algal species have been investigated for biodiesel production, with selection criteria focusing on high lipid content, rapid growth rate, and ease of cultivation. Table 2 presents lipid content data for selected microalgal species with biodiesel potential.

### 2.2. Production of Algae-Based Biodiesel

The production of algae-based biodiesel involves algae cultivation, harvesting, oil extraction, and conversion to biodiesel through transesterification. The transesterification process converts triglycerides in algal oil to fatty acid methyl esters (FAME) using methanol in the presence of a catalyst, typically sodium or potassium hydroxide (Brennan & Owende, 2010).

Several researchers have investigated process optimizations to enhance the economic viability of algae biodiesel production. Integrated biorefinery approaches that utilize multiple components of algal biomass for different products (biofuels, animal feed, specialty chemicals) have been proposed to improve overall economics (Rawat et al., 2013).

**Table 2** Lipid Content of Selected Microalgal Species

| Microalgal Species | Lipid Content (% dry weight) |
|---|---|
| Botryococcus braunii | 25-75 |
| Chlorella vulgaris | 14-22 |
| Chlorella protothecoides | 14-57 |

| | |
|---|---|
| Crypthecodinium cohnii | 20-51 |
| Cylindrotheca sp. | 16-37 |
| Dunaliella primolecta | 23 |
| Isochrysis sp. | 25-33 |
| Nannochloropsis sp. | 31-68 |
| Neochloris oleoabundans | 35-54 |
| Nitzschia sp. | 45-47 |
| Phaeodactylum tricornutum | 20-30 |
| Schizochytrium sp. | 50-77 |
| Tetraselmis suecica | 15-23 |

### 2.3. Properties of Algae-Based Biodiesel

The physicochemical properties of biodiesel significantly influence its performance in compression ignition engines. Table 3 compares key properties of algae-based biodiesel with conventional diesel and international biodiesel standards.

**Table 3** Comparison of Fuel Properties - Algae Biodiesel, Conventional Diesel, and Biodiesel Standards

| Property | Algae Biodiesel | Conventional Diesel | ASTM D6751 (Biodiesel) | EN 14214 (Biodiesel) |
|---|---|---|---|---|
| Density at 15°C ($kg/m^3$) | 860-900 | 820-845 | - | 860-900 |
| Viscosity at 40°C ($mm^2/s$) | 3.5-5.2 | 2.0-4.5 | 1.9-6.0 | 3.5-5.0 |
| Flash point (°C) | 115-160 | 60-80 | >130 | >101 |
| Cloud point (°C) | -3 to 12 | -15 to 5 | Report | - |
| Pour point (°C) | -12 to 10 | -35 to -15 | - | - |
| Cetane number | 48-65 | 45-55 | >47 | >51 |
| Higher heating value (MJ/kg) | 39-41 | 42-46 | - | - |
| Acid value (mg KOH/g) | 0.1-0.5 | <0.5 | <0.5 | <0.5 |
| Iodine value (g $I_2$/100g) | 60-135 | - | - | <120 |
| Oxidation stability at 110°C (h) | 3-6 | >25 | >3 | >6 |

The fatty acid profile of algal biodiesel varies widely depending on the algal species and cultivation conditions. This profile significantly influences fuel properties such as cetane number, oxidative stability, cold flow properties, and viscosity (Knothe, 2009). Generally, saturated fatty acids contribute to higher cetane numbers and oxidative stability but poorer cold flow properties, while unsaturated fatty acids demonstrate the opposite trend [2].

## 3. Methodology

### 3.1. Algae Cultivation and Biodiesel Production

This study utilized biodiesel derived from three microalgal species: Chlorella vulgaris, Nannochloropsis sp., and Botryococcus braunii. These species were selected based on their varying lipid profiles and established cultivation protocols. Algae cultivation was conducted in photobioreactors under controlled conditions with optimal nutrient supply, light intensity, and temperature to maximize lipid production.

After harvesting via centrifugation, algal biomass was dried and subjected to oil extraction using a solvent extraction method with hexane. The extracted lipids underwent transesterification using a 6:1 molar ratio of methanol to oil with potassium hydroxide (1% w/w of oil) as catalyst at 60°C for 60 minutes. The resulting biodiesel was washed with warm water to remove residual catalyst, glycerol, and unreacted methanol, then dried to remove water content.

The algae-based biodiesel was analyzed for its physicochemical properties according to ASTM standards to ensure compliance with biodiesel quality requirements.

### 3.2. Test Fuel Preparation

The algae-based biodiesel was blended with conventional diesel fuel in various proportions to prepare test fuels. The following blends were used in this study:

- B0: 100% conventional diesel (reference fuel)
- B10: 10% algae biodiesel + 90% conventional diesel
- B20: 20% algae biodiesel + 80% conventional diesel
- B50: 50% algae biodiesel + 50% conventional diesel
- B100: 100% algae biodiesel

### 3.3. Engine Test Setup

Experiments were conducted on a single-cylinder, four-stroke, water-cooled direct injection diesel engine. The specifications of the test engine are presented in Table 4.

**Table 4** Test Engine Specifications

| **Parameter** | **Specification** |
|---|---|
| Engine type | Single cylinder, 4-stroke, DI |
| Bore × Stroke | 87.5 mm × 110 mm |
| Displacement volume | 661 cc |
| Compression ratio | 17.5:1 |
| Rated power | 5.2 kW at 1500 rpm |
| Injection timing | 23° BTDC |
| Injection pressure | 200 bar |
| Cooling system | Water-cooled |
| Dynamometer | Eddy current dynamometer |

The experimental setup included instrumentation for measuring:

- Fuel consumption: Electronic balance with data acquisition system
- Air flow: Orifice meter with U-tube manometer
- Exhaust gas temperature: K-type thermocouple
- In-cylinder pressure: Piezoelectric pressure transducer
- Crank angle: Crank angle encoder

Emissions were measured using a calibrated exhaust gas analyzer capable of detecting:

- Carbon monoxide (CO)
- Unburned hydrocarbons (HC)
- Nitrogen oxides (NOx)
- Carbon dioxide (CO2)
- Particulate matter (PM)

### 3.4. Experimental Procedure

The engine was operated at a constant speed of 1500 rpm under varying load conditions (0%, 25%, 50%, 75%, and 100% of rated load). For each test fuel blend, the engine was allowed to reach steady-state conditions before measurements were recorded. The following parameters were measured and calculated

- Brake specific fuel consumption (BSFC)
- Brake thermal efficiency (BTE)
- Exhaust gas temperature (EGT)
- Combustion parameters:
  - Ignition delay
  - Heat release rate
- Exhaust emissions:
  - CO, HC, NOx, CO2, and PM

Each test was repeated three times to ensure reproducibility, and average values were used for analysis. The test sequence was randomized to minimize systematic errors.

## 4. Results and Discussion

### 4.1. Fuel Properties Analysis

The physicochemical properties of algae-based biodiesel and its blends with conventional diesel are presented in Table 5.

**Table 5** Properties of Test Fuels

| Property | B0 (Diesel) | B10 | B20 | B50 | B100 (Algae Biodiesel) |
|---|---|---|---|---|---|
| Density at 15°C (kg/m$^3$) | 830 | 838 | 845 | 865 | 887 |
| Kinematic viscosity at 40°C (mm$^2$/s) | 2.8 | 3.0 | 3.2 | 3.9 | 4.8 |
| Flash point (°C) | 68 | 75 | 83 | 98 | 152 |
| Calorific value (MJ/kg) | 44.2 | 43.8 | 43.5 | 42.3 | 40.1 |
| Cetane number | 48 | 49 | 51 | 54 | 59 |
| Cloud point (°C) | -5 | -4 | -3 | 0 | 4 |
| Pour point (°C) | -18 | -16 | -15 | -10 | -5 |
| Acid value (mg KOH/g) | 0.05 | 0.10 | 0.15 | 0.25 | 0.42 |
| Oxidation stability at 110°C (h) | >40 | 32 | 25 | 12 | 4.5 |
| Oxygen content (wt%) | ~0 | 1.1 | 2.2 | 5.5 | 11.0 |

The properties of algae biodiesel and its blends with conventional diesel showed several trends:

- Density and viscosity increased with increasing biodiesel content, which can affect fuel atomization and spray characteristics.
- Flash point increased significantly with biodiesel content, enhancing fuel safety during handling and storage.
- Calorific value decreased with increasing biodiesel content due to the oxygen content in the biodiesel molecules.
- Cetane number increased with biodiesel content, potentially improving ignition quality.

These property variations influence the combustion behavior and performance characteristics of the fuel in compression ignition engines.

### 4.2. Engine Performance Analysis

*4.2.1. Brake Specific Fuel Consumption (BSFC)*

The BSFC values for different fuel blends at varying engine loads are presented in Table 6.

**Table 6** Brake Specific Fuel Consumption (g/kWh) at Different Engine Loads

| Fuel Type | 25% Load | 50% Load | 75% Load | 100% Load |
|---|---|---|---|---|
| B0 (Diesel) | 368 | 295 | 262 | 254 |
| B10 | 372 | 298 | 265 | 258 |
| B20 | 379 | 301 | 269 | 262 |
| B50 | 395 | 310 | 278 | 272 |
| B100 | 418 | 325 | 290 | 286 |

The BSFC increased with increasing biodiesel content across all load conditions. This trend can be attributed to:

- Lower calorific value of algae biodiesel compared to conventional diesel, requiring more fuel to produce the same power output
- Higher density and viscosity affecting fuel atomization and combustion efficiency
- Differences in combustion timing and duration

At full load, B100 showed approximately 12.6% higher BSFC compared to conventional diesel, while B20 showed only a modest increase of 3.1%.

*4.2.2. Brake Thermal Efficiency (BTE)*

Table 7 presents the brake thermal efficiency values for different fuel blends at varying engine loads.

**Table 7** Brake Thermal Efficiency (%) at Different Engine Loads

| Fuel Type | 0% Load | 25% Load | 50% Load | 75% Load | 100% Load |
|---|---|---|---|---|---|
| B0 (Diesel) | - | 21.5 | 28.3 | 32.4 | 33.2 |
| B10 | - | 21.4 | 28.1 | 32.2 | 33.0 |
| B20 | - | 21.2 | 27.9 | 31.8 | 32.7 |
| B50 | - | 20.6 | 27.3 | 31.0 | 31.9 |
| B100 | - | 19.8 | 26.4 | 29.8 | 30.5 |

The BTE generally decreased with increasing biodiesel content, though the reductions were relatively modest for lower blend ratios. At full load, B20 showed only a 1.5% reduction in BTE compared to conventional diesel, while B100 exhibited an 8.1% reduction.

The slight decrease in BTE can be attributed to:

- Higher viscosity leading to poorer fuel atomization
- Lower calorific value of biodiesel
- Different combustion characteristics including longer combustion duration

However, the oxygen content in biodiesel partially compensated for these factors by promoting more complete combustion, especially in fuel-rich zones within the combustion chamber.

#### *4.2.3. Exhaust Gas Temperature (EGT)*

Table 8 shows the exhaust gas temperatures recorded for different fuel blends at varying engine loads.

**Table 8** Exhaust Gas Temperature (°C) at Different Engine Loads

| Fuel Type | 0% Load | 25% Load | 50% Load | 75% Load | 100% Load |
|---|---|---|---|---|---|
| B0 (Diesel) | 145 | 235 | 342 | 438 | 520 |
| B10 | 147 | 238 | 345 | 442 | 525 |
| B20 | 150 | 241 | 348 | 445 | 530 |
| B50 | 156 | 248 | 357 | 454 | 542 |
| B100 | 162 | 258 | 368 | 468 | 558 |

Exhaust gas temperature increased with increasing biodiesel content across all load conditions. This trend may be attributed to:

- Extended combustion duration due to higher viscosity and lower volatility of biodiesel
- Advanced combustion timing due to higher cetane number
- Different heat release characteristics

The increase in EGT with higher biodiesel blends indicates potential implications for thermal management in engines designed for long-term operation with biodiesel fuels.

### 4.3. Combustion Analysis

#### *4.3.1. In-Cylinder Pressure and Heat Release Rate*

The peak cylinder pressure and its timing for different fuel blends at full load are presented in Table 9.

**Table 9** Peak Cylinder Pressure and Its Timing at Full Load

| Fuel Type | Peak Pressure (bar) | Timing (°CA ATDC) | Ignition Delay (°CA) | Combustion Duration (°CA) |
|---|---|---|---|---|
| B0 (Diesel) | 72.5 | 8.2 | 9.8 | 38.5 |
| B10 | 73.1 | 7.9 | 9.5 | 39.2 |
| B20 | 73.8 | 7.5 | 9.1 | 40.1 |
| B50 | 74.9 | 6.8 | 8.2 | 42.8 |
| B100 | 76.2 | 5.9 | 7.4 | 46.2 |

Several trends were observed in the combustion characteristics

- Peak cylinder pressure increased with increasing biodiesel content, with B100 showing approximately 5.1% higher peak pressure compared to conventional diesel.
- The timing of peak pressure advanced with increasing biodiesel content, occurring earlier in the expansion stroke.
- Ignition delay decreased with increasing biodiesel content, which can be attributed to the higher cetane number of algae biodiesels. This resulted in earlier start of combustion.
- Combustion duration increased with higher biodiesel content, with B100 showing approximately 20% longer combustion duration compared to conventional diesel.

These combustion characteristics explain many of the observed performance trends, including the slightly lower thermal efficiency and higher exhaust gas temperatures with increasing biodiesel content [3].

### 4.4. Emission Analysis

*4.4.1. Carbon Monoxide (CO) Emissions*

Table 10 presents the CO emission levels for different fuel blends at varying engine loads.

**Table 10** Carbon Monoxide Emissions (g/kWh) at Different Engine Loads

| Fuel Type | 25% Load | 50% Load | 75% Load | 100% Load | Average Reduction vs. B0 |
|---|---|---|---|---|---|
| B0 (Diesel) | 6.82 | 4.15 | 2.45 | 1.95 | - |
| B10 | 6.48 | 3.92 | 2.31 | 1.83 | 5.5% |
| B20 | 6.12 | 3.68 | 2.16 | 1.70 | 11.8% |
| B50 | 5.21 | 3.10 | 1.79 | 1.40 | 28.2% |
| B100 | 4.09 | 2.38 | 1.34 | 1.04 | 46.9% |

CO emissions decreased significantly with increasing biodiesel content across all load conditions. At full load, B100 showed approximately 46.7% lower CO emissions compared to conventional diesel, while B20 showed an 12.8% reduction.

This reduction in CO emissions can be attributed to:

- Higher oxygen content in biodiesel promoting more complete combustion
- Advanced combustion timing providing more time for CO oxidation
- Lower carbon-to-hydrogen ratio in biodiesel compared to conventional diesel

*4.4.2. Hydrocarbon (HC) Emissions*

Table 11 presents the HC emission levels for different fuel blends at varying engine loads.

**Table 11** Hydrocarbon Emissions (g/kWh) at Different Engine Loads

| Fuel Type | 25% Load | 50% Load | 75% Load | 100% Load | Average Reduction vs. B0 |
|---|---|---|---|---|---|
| B0 (Diesel) | 0.95 | 0.68 | 0.52 | 0.48 | - |
| B10 | 0.89 | 0.63 | 0.48 | 0.44 | 8.0% |
| B20 | 0.82 | 0.58 | 0.44 | 0.40 | 16.4% |
| B50 | 0.65 | 0.46 | 0.35 | 0.31 | 35.2% |
| B100 | 0.46 | 0.32 | 0.25 | 0.22 | 54.3% |

HC emissions decreased significantly with increasing biodiesel content across all load conditions. At full load, B100 showed approximately 54.2% lower HC emissions compared to conventional diesel, while B20 showed a 16.7% reduction.

The reduction in HC emissions can be attributed to similar factors as CO emissions

- Oxygen content in biodiesel promoting more complete combustion
- Higher cetane number resulting in better ignition quality and fewer locally rich regions
- Advanced combustion timing providing more time for hydrocarbon oxidation

*4.4.3. Nitrogen Oxides (NOx) Emissions*

Table 12 presents the NOx emission levels for different fuel blends at varying engine loads.

**Table 12** Nitrogen Oxide Emissions (g/kWh) at Different Engine Loads

| Fuel Type | 25% Load | 50% Load | 75% Load | 100% Load | Average Change vs. B0 |
|---|---|---|---|---|---|
| B0 (Diesel) | 4.85 | 5.92 | 6.45 | 6.98 | - |
| B10 | 4.94 | 6.05 | 6.60 | 7.15 | +2.5% |
| B20 | 5.05 | 6.20 | 6.78 | 7.35 | +5.3% |
| B50 | 5.38 | 6.59 | 7.22 | 7.84 | +12.3% |
| B100 | 5.72 | 7.05 | 7.72 | 8.43 | +20.8% |

Contrary to CO and HC emissions, NOx emissions increased with increasing biodiesel content across all load conditions. At full load, B100 showed approximately 20.8% higher NOx emissions compared to conventional diesel, while B20 showed a 5.3% increase.

This increase in NOx emissions can be attributed to several factors

- Higher in-cylinder temperatures due to advanced combustion timing
- Oxygen content in biodiesel providing more oxygen for NOx formation
- Reduced radiative heat transfer due to lower soot formation
- Different flame temperature profiles during combustion

The NOx increase presents a challenge for biodiesel implementation, as it conflicts with increasingly stringent emission regulations. However, the magnitude of increase for lower blend ratios (B10 and B20) may be manageable with existing emission control technologies.

*4.4.4. Particulate Matter (PM) Emissions*

Table 13 presents the PM emission levels for different fuel blends at varying engine loads.

**Table 13** Particulate Matter Emissions (g/kWh) at Different Engine Loads

| Fuel Type | 25% Load | 50% Load | 75% Load | 100% Load | Average Reduction vs. B0 |
|---|---|---|---|---|---|
| B0 (Diesel) | 0.185 | 0.223 | 0.248 | 0.312 | - |
| B10 | 0.170 | 0.202 | 0.224 | 0.280 | 10.1% |
| B20 | 0.154 | 0.180 | 0.198 | 0.246 | 21.2% |
| B50 | 0.113 | 0.129 | 0.141 | 0.174 | 44.2% |
| B100 | 0.068 | 0.076 | 0.082 | 0.099 | 68.3% |

PM emissions decreased dramatically with increasing biodiesel content across all load conditions. At full load, B100 showed approximately 68.3% lower PM emissions compared to conventional diesel, while B20 showed a 21.2% reduction.

This significant reduction in PM emissions can be attributed to

- Oxygen content in biodiesel promoting more complete combustion of soot precursors
- Lower aromatic content in biodiesel, which are major soot precursors
- Advanced combustion timing providing more time for soot oxidation
- Higher cetane number resulting in better ignition quality and fewer locally rich regions

The substantial reduction in PM emissions represents one of the most significant environmental benefits of algae-based biodiesel.

### 4.5. Comparison Between Algal Species

The three algal species used in this study (Chlorella vulgaris, Nannochloropsis sp., and Botryococcus braunii) produced biodiesel with slightly different properties due to variations in their fatty acid profiles. Table 14 compares key performance and emission parameters for B100 derived from each species at full load.

**Table 14** Comparison of B100 from Different Algal Species at Full Load

| Parameter | B100 (Chlorella) | B100 (Nannochloropsis) | B100 (Botryococcus) |
|---|---|---|---|
| BSFC (g/kWh) | 288 | 290 | 279 |
| BTE (%) | 30.2 | 29.8 | 31.4 |
| CO Emissions (g/kWh) | 1.08 | 1.12 | 0.92 |
| HC Emissions (g/kWh) | 0.23 | 0.24 | 0.19 |
| NOx Emissions (g/kWh) | 8.35 | 8.15 | 8.78 |
| PM Emissions (g/kWh) | 0.103 | 0.110 | 0.085 |
| Cetane Number | 58 | 56 | 63 |
| Iodine Value | 115 | 125 | 82 |

Biodiesel derived from Botryococcus braunii demonstrated the best overall performance among the three species, with higher thermal efficiency and lower emissions (except for NOx). This can be attributed to its higher cetane number and more favorable fatty acid composition, with a better balance between saturated and unsaturated fatty acids. The lower iodine value indicates lower unsaturation, which contributes to better oxidation stability but could potentially impact cold flow properties.

These differences highlight the importance of algal species selection in biodiesel production for specific applications and climate conditions [4].

## 5. Engine durability considerations

While this study focused primarily on performance and emissions, long-term engine durability is an important consideration for biodiesel implementation. Short-term durability tests were conducted using B20 and B100 from Chlorella vulgaris for 200 hours of operation. Key observations included:

- Fuel injector deposits: Slightly higher deposits were observed with B100 compared to conventional diesel, primarily attributed to higher viscosity and potential oxidation products.
- Lubricating oil dilution: B100 showed approximately 15% higher oil dilution compared to conventional diesel, which could necessitate more frequent oil changes.
- Fuel system elastomers: Some elastomer materials showed signs of degradation with B100, suggesting that biodiesel-compatible materials should be used in fuel systems intended for high-blend biodiesel operation.
- Engine wear: No significant differences in engine wear patterns were observed during the test period.

These preliminary durability observations suggest that while B100 may require some material compatibility considerations and maintenance adjustments, B20 appears to be compatible with existing engine technology with minimal adaptations.

## 6. Economic and Environmental Analysis

### 6.1. Economic Considerations

The economic viability of algae-based biodiesel depends on several factors, including production costs, scale of operation, co-product utilization, and policy incentives. Current production costs for algae biodiesel range from $3.00 to $7.50 per gallon, significantly higher than conventional diesel production costs of approximately $1.50 to $2.00 per gallon (excluding taxes and distribution costs) [5].

Major cost components in algae biodiesel production include:

- Algae cultivation (photobioreactors or open ponds)
- Harvesting and dewatering
- Oil extraction
- Conversion to biodiesel

Research indicates that integrated biorefinery approaches that utilize multiple components of algal biomass (lipids for biodiesel, proteins for animal feed, carbohydrates for ethanol) can significantly improve economic viability.

### 6.2. Environmental Benefits

Beyond the emissions benefits documented in this study, algae-based biodiesel offers several additional environmental advantages:

- Carbon dioxide sequestration during algae cultivation
- Potential for wastewater treatment during cultivation
- Reduced land use compared to crop-based biodiesel
- No competition with food production
- Reduced dependency on fossil fuels

## 7. Conclusion

The experimental analysis of algae-based biodiesel blends in a compression ignition engine has demonstrated the potential of this renewable fuel as a viable alternative to conventional diesel. Among the tested blends, B20 emerged as the most favorable in terms of overall performance and emissions. While there was a slight reduction in brake thermal efficiency and a marginal increase in brake specific fuel consumption, the significant reduction in carbon monoxide and unburned hydrocarbon emissions indicates improved combustion characteristics. However, the observed increase in nitrogen oxide emissions with higher biodiesel concentrations suggests the need for further optimization, possibly through engine modifications or exhaust after-treatment systems.

Overall, the study confirms that algae-based biodiesel can contribute meaningfully to sustainable energy goals by offering a cleaner-burning fuel option without major compromises in engine performance. With further research and technological advancements in cultivation, extraction, and processing, algae-derived biodiesel holds considerable promise for future applications in the transportation sector.

## Compliance with ethical standards

*Disclosure of conflict of interest*

No conflict of interest to be disclosed.

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