

# Biodiesel and Ternary Blends in Compression-Ignition (CI) Engines: A Comprehensive Review

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**Abstract**— The increasing energy demand, environmental concerns, and depletion of fossil fuel reserves have motivated extensive research on renewable and sustainable alternatives for compression-ignition (CI) engines. Biodiesel derived from renewable feedstocks and alcohol-based ternary blends have emerged as promising candidates to replace or partially substitute diesel fuel. Among alcohols, *n*-octanol has attracted significant attention due to its long carbon chain, high energy density, better miscibility, and favorable physicochemical properties compared to short-chain alcohols such as methanol or ethanol. This review consolidates findings from 50 experimental studies that investigated biodiesel, diesel, and *n*-octanol-based ternary blends in CI engines. The review emphasizes key performance parameters such as brake thermal efficiency (BTE), brake-specific fuel consumption (BSFC), and engine power, as well as combustion behavior, emission characteristics, and sustainability implications. Comparative analysis reveals that ternary blends generally enhance combustion stability, reduce unburned hydrocarbons (HC) and carbon monoxide (CO), and can achieve lower smoke opacity, although nitrogen oxides (NOx) emissions show variable trends. Identified research gaps include inadequate exploration of spray dynamics, particulate morphology, durability of engine components, and the integration of life-cycle assessments (LCA). Future research directions suggest the optimization of blend ratios, advanced injection strategies, and hybridization with after-treatment technologies. The review concludes that *n*-octanol-based ternary blends represent a viable pathway for cleaner and more efficient CI engine operation, aligning with global goals for sustainable transportation.

**Index Terms**— biodiesel, diesel, *n*-octanol, ternary blends, CI engine, performance, combustion, emissions, sustainability.

## 1. INTRODUCTION

Global energy demand has been steadily increasing due to industrialization, transportation needs, and urbanization. Fossil fuels, particularly petroleum diesel, have long served as the primary source of energy for the transport sector. However, their continuous consumption contributes to severe environmental challenges such as greenhouse gas emissions, particulate matter pollution, and global climate change (Demirbas, 2009; Atabani et al., 2012). Moreover, the finite nature of petroleum resources has intensified research on renewable and sustainable fuel alternatives.

Biodiesel, produced from renewable sources such as waste cooking oil, vegetable oils, and animal fats, has emerged as a viable candidate for CI engines. It exhibits properties such as oxygen content, higher cetane number, and near-zero sulfur content, which contribute to reduced carbon monoxide (CO), hydrocarbons (HC), and particulate matter (PM) emissions (Knothe, 2010; Xue et al., 2011). However, biodiesel has limitations, including higher viscosity, poor cold-flow properties, and sometimes elevated nitrogen oxide (NOx) emissions.

To overcome these drawbacks, researchers have explored the blending of biodiesel with alcohols and diesel to form ternary blends. Alcohols such as methanol and ethanol improve atomization and reduce viscosity but are often limited by low miscibility with diesel and low energy density. Long-chain alcohols like *n*-butanol and *n*-octanol offer better miscibility, higher calorific values, and enhanced combustion stability (Lapuerta et al., 2009; Rakopoulos et al., 2010). In particular, *n*-octanol, with its favorable cetane number and high energy density, has recently gained interest as a third component in ternary blends with biodiesel and diesel.

Numerous experimental studies have evaluated the effects of biodiesel-diesel-*n*-octanol blends on engine performance, combustion characteristics, and emissions. While these studies report promising results, systematic synthesis is necessary to identify consistent trends, research gaps, and future directions.

This review is designed to:

1. Consolidate findings from 50 experimental studies on biodiesel-diesel-*n*-octanol blends in CI engines.
2. Critically analyze performance, combustion, and emission characteristics.
3. Identify research gaps and propose directions for future research.

## 2. METHODOLOGY

The methodology adopted for this review involved systematically compiling and analyzing 50 experimental studies from the years 2010 to 2025. The primary data set was provided in tabulated form, including information on authors, year of publication, type of engine (single-cylinder, multi-cylinder), type of biodiesel feedstock (waste cooking oil, soybean, palm, jatropha, etc.), proportion of diesel, biodiesel, and *n*-octanol in ternary blends, key findings, and identified research gaps.

The selection criteria for inclusion were as follows:

- Studies must involve experimental investigations on CI engines.
- The fuel composition must include diesel, biodiesel, and *n*-octanol as major components.
- Reported outcomes must include at least one of the following: performance, combustion, or emission characteristics.

Excluded were simulation-based studies without experimental validation, as well as papers involving only binary blends (diesel-biodiesel or diesel-alcohol).

The analysis framework applied in this review included:

- Performance metrics: brake thermal efficiency (BTE), brake-specific fuel consumption (BSFC), brake power, torque.
  - Combustion characteristics: ignition delay, cylinder pressure, heat release rate (HRR), combustion duration.
  - Emission parameters: CO, HC, NO<sub>x</sub>, smoke opacity, and particulate emissions.
  - Sustainability and environmental impacts: life-cycle aspects, feedstock availability, and techno-economic feasibility.
- The 50 papers were categorized into performance-focused, combustion-focused, and emission-focused studies, with overlaps noted. Comparative tables summarizing the key findings and gaps are included in subsequent sections.

### 3. PERFORMANCE CHARACTERISTICS OF BIODIESEL–DIESEL–NOCTANOL BLENDS

Engine performance parameters such as brake thermal efficiency (BTE), brake-specific fuel consumption (BSFC), and torque output provide critical insight into the suitability of alternative fuels for CI engines. The addition of *n*-octanol to biodiesel–diesel blends influences these performance parameters due to its physicochemical properties such as lower viscosity, higher volatility compared to biodiesel, and high energy density.

#### 3.1 Brake Thermal Efficiency (BTE)

BTE reflects the efficiency with which the engine converts chemical energy into mechanical work. Several studies (e.g., Patel et al., 2018; Sharma et al., 2020; Kumar et al., 2022) reported an **increase in BTE** when biodiesel–diesel blends were supplemented with 10–20% *n*-octanol. The improvement is attributed to better atomization, reduced viscosity, and enhanced oxygen availability during combustion. For example, Sharma et al. (2020) demonstrated that a ternary blend of 70% diesel, 20% biodiesel, and 10% *n*-octanol yielded a **4–6% higher BTE** compared to pure biodiesel blends.

However, at higher *n*-octanol fractions (>30%), a **decline in BTE** is often observed (Khan et al., 2021; Li et al., 2023). This is due to lower cetane number and longer ignition delay of *n*-octanol, which can cause incomplete combustion at high substitution levels.

#### 3.2 Brake-Specific Fuel Consumption (BSFC)

BSFC is another critical metric, inversely related to fuel economy. Most studies reported a **slight increase in BSFC** with ternary blends compared to diesel, mainly due to the lower calorific value of biodiesel and *n*-octanol relative to diesel (Patil et al., 2019). For instance, experiments conducted by Li et al. (2023) showed that BSFC increased by 5–8% for blends containing 20% biodiesel and 10% *n*-octanol.

Nevertheless, the improved combustion efficiency at moderate *n*-octanol levels often offsets the adverse calorific value effect. Some reports (e.g., Zhang et al., 2021) found that optimized injection timing could minimize BSFC penalties for ternary blends.

#### 3.3 Power and Torque Output

The influence of ternary blends on brake power and torque varies with blend ratio and operating conditions. Studies consistently show a **marginal reduction in peak power output** compared to diesel (Kumar et al., 2022). This reduction is attributed to the lower heating value of biodiesel and alcohol components. However, when compared to binary biodiesel–diesel blends, ternary blends with *n*-octanol often deliver **superior torque and power** due to improved combustion and volatility characteristics (Sharma et al., 2020).

#### 3.4 Comparative Analysis

To consolidate findings, Table 1 summarizes the key performance outcomes of selected studies on biodiesel–diesel–*n*-octanol blends.

*Table 1. Performance outcomes of biodiesel–diesel–*n*-octanol blends in CI engines*

Authors (Year)	Engine type	Blend composition (D:B:O)*	Key performance findings	Research gaps identified
Sharma et al. (2020)	Single-cylinder, DI	70:20:10	↑ BTE by 5%; slight ↑ BSFC; marginal ↓ power	Long-term durability not studied
Patel et al. (2018)	Multi-cylinder, DI	60:20:20	↑ BTE at part load; ↓ torque at high load	Cold flow properties untested
Khan et al. (2021)	Single-cylinder, DI	60:10:30	BTE ↓ at high octanol; ↑ ignition delay	Spray atomization behavior unknown
Kumar et al. (2022)	Single-cylinder, CRDI	70:15:15	Stable BTE; slight ↓ brake power compared to diesel	Needs advanced injection strategy
Li et al. (2023)	Multi-cylinder, DI	70:20:10	↑ BSFC by 6%; moderate ↑ efficiency	Limited to steady-state tests
Zhang et al. (2021)	Single-cylinder, DI	80:10:10	Optimized injection timing reduced BSFC penalty	Not tested for transient cycles

### 3.5 Key Insights on Performance

- Moderate substitution of *n*-octanol (10–20%) in biodiesel–diesel blends generally improves BTE while minimizing BSFC penalties.
- Excessive *n*-octanol (>30%) can negatively impact ignition quality, leading to lower efficiency and unstable performance.
- Comparative studies indicate that ternary blends outperform binary biodiesel–diesel blends in terms of torque and smooth engine operation.
- Identified research gaps include:
  - Lack of long-term durability and wear studies with ternary blends.
  - Limited investigations on cold-flow and low-temperature operability.
  - Sparse studies under transient driving cycles or real-world operating conditions.

## 4. COMBUSTION CHARACTERISTICS OF BIODIESEL–DIESEL–*N*-OCTANOL BLENDS

Combustion analysis provides vital insights into ignition delay, cylinder pressure development, heat release rate (HRR), and overall combustion duration. The addition of *n*-octanol significantly influences these parameters due to its oxygenated structure, high boiling point, and lower cetane number relative to diesel.

### 4.1 Ignition Delay (ID)

Ignition delay is defined as the time between the start of injection and the onset of combustion. The low cetane number of *n*-octanol tends to **increase ignition delay** when used in higher proportions (Khan et al., 2021). This effect is more pronounced in blends with >20% *n*-octanol. However, moderate additions (10–15%) often lead to a balanced ignition delay, aided by the oxygenated nature of biodiesel that promotes faster pre-mixed combustion (Patel et al., 2018).

### 4.2 Cylinder Pressure

Cylinder pressure traces are a key indicator of combustion efficiency and stability. Many studies report that ternary blends yield **comparable or slightly higher peak cylinder pressures** than diesel at moderate load conditions (Sharma et al., 2020). This improvement is linked to enhanced oxygen content and improved volatility. However, at high *n*-octanol fractions, delayed combustion phases lead to lower peak pressures and extended combustion durations (Li et al., 2023).

### 4.3 Heat Release Rate (HRR)

HRR analysis shows that ternary blends with *n*-octanol enhance the **premixed combustion phase** due to longer ignition delays and better atomization. As a result, a sharper HRR peak is often observed in blends containing 10–20% *n*-octanol (Zhang et al., 2021). However, excessive *n*-octanol (>30%) produces broader HRR curves, reflecting incomplete combustion and prolonged diffusion burning (Kumar et al., 2022).

### 4.4 Combustion Duration

Ternary blends tend to have **slightly longer combustion durations** than neat diesel due to slower burning of alcohol fractions. The oxygen in biodiesel offsets this to some extent, but at higher *n*-octanol content, longer tail-burning is evident (Patil et al., 2019). This can adversely affect efficiency and emissions if not optimized with injection strategies.

*Table 2. Combustion characteristics of biodiesel–diesel–*n*-octanol blends in CI engines*

Authors (Year)	Engine type	Blend (D:B:O)	Combustion findings	Research gaps identified
Patel et al. (2018)	Multi-cylinder, DI	60:20:20	Balanced ignition delay; ↑ premixed burn fraction	Lack of HRR–emission correlation
Sharma et al. (2020)	Single-cylinder, DI	70:20:10	↑ cylinder pressure; sharper HRR peak	Transient operation not tested
Khan et al. (2021)	Single-cylinder, DI	60:10:30	Longer ignition delay; broader HRR	Needs CFD + experimental validation
Kumar et al. (2022)	CRDI, SC engine	70:15:15	Stable pressure rise; prolonged combustion duration	Injection timing optimization needed
Li et al. (2023)	Multi-cylinder, DI	70:20:10	Slight ↓ peak pressure; extended burn duration	Inadequate study of cyclic variations
Zhang et al. (2021)	Single-cylinder, DI	80:10:10	↑ HRR during premixed phase	Relationship with NO <sub>x</sub> not clarified

#### 4.5 Key Insights on Combustion

1. Moderate *n*-octanol levels (10–20%) enhance premixed combustion, increase cylinder pressure, and sharpen HRR peaks.
2. Higher *n*-octanol proportions (>30%) lengthen ignition delay and combustion duration, reducing combustion efficiency.
3. Most studies confirm that biodiesel's inherent oxygen helps stabilize combustion despite *n*-octanol's lower cetane number.
4. Major research gaps include:
  - Lack of cyclic variability analysis across wide load/speed conditions.
  - Insufficient correlation between HRR and emissions such as NO<sub>x</sub> or particulates.
  - Limited work on advanced injection strategies (e.g., split injection, pilot injection) for ternary blends.
  - Absence of combined computational fluid dynamics (CFD) + experimental validation studies.

### 5. EMISSION CHARACTERISTICS OF BIODIESEL–DIESEL–*N*-OCTANOL BLENDS

Emission behavior is a central concern when assessing alternative fuels for CI engines. The oxygen content and physical properties of biodiesel and *n*-octanol alter in-cylinder combustion temperatures, flame structure, and soot formation pathways — leading to characteristic changes in regulated pollutants: CO, HC, NO<sub>x</sub>, PM (particulate matter), and smoke opacity. The following subsections synthesize experimental findings from the 50-paper dataset and note mitigation strategies and outstanding uncertainties.

#### 5.1 Carbon Monoxide (CO) and Hydrocarbons (HC)

Across most experimental studies, ternary blends show **decreases in CO and HC emissions** relative to neat diesel. The primary drivers are: (a) enhanced oxygen availability from biodiesel and octanol, which promotes more complete oxidation of partially burned species, and (b) improved atomization (lower viscosity) with octanol additions that favor finer spray and better mixing.

Representative results:

- Sinha et al. (2019) reported CO reductions of up to ~25–30% and HC reductions of ~15–25% for blends containing 10–20% *n*-octanol compared to neat diesel under medium-load conditions.
- Sharma et al. (2020) observed that a 70:20:10 blend (D:B:O) reduced CO by ~20% at full load versus baseline diesel. However, reductions in CO/HC are not uniform across all operating points. At very high octanol fractions (>30%), incomplete vaporization and longer ignition delays in some tests produced localized regions of incomplete combustion, partially offsetting CO/HC benefits (Khan et al., 2021).

#### 5.2 Nitrogen Oxides (NO<sub>x</sub>)

NO<sub>x</sub> shows the most consistent and concerning trade-off: **NO<sub>x</sub> emissions tend to increase** with ternary blends in many studies. The reasons are well documented:

Increased oxygen concentration in the charge promotes higher local flame temperatures.

Improved premixed combustion with sharper heat release peaks elevates peak temperatures, favoring thermal NO<sub>x</sub> formation.

Typical observations:

- Ashok et al. (2019) and Kochetkov et al. (2018) reported NO<sub>x</sub> increases in the range of ~5–25% depending on load and blend ratio.
- Li et al. (2023) found NO<sub>x</sub> penalties correlated with increases in peak cylinder pressure and earlier combustion phasing for certain blends.

**Mitigation strategies studied (but not widely tested with ternary blends) include:**

- Exhaust Gas Recirculation (EGR): Lowers peak temperatures; few experiments have combined EGR with octanol blends.
- Injection timing retardation: Reduces peak temperature but can increase smoke/HC.
- Selective Catalytic Reduction (SCR) and Lean NO<sub>x</sub> Traps (LNT): After-treatment systems that can offset NO<sub>x</sub>, but integration with fuel chemistry and particulate characteristics requires more investigation.

#### 5.3 Particulate Matter (PM) and Smoke Opacity

One of the most favorable and consistent outcomes is **reduction in smoke opacity and mass-based particulate emissions** with ternary blends at moderate octanol levels. Oxygen-rich fuels reduce soot precursor formation, and improved atomization reduces local fuel-rich pockets.

**Key points:**

- Multiple studies (e.g., Patel et al., 2018; Zhang et al., 2021) reported smoke opacity decreases of 10–40% for blends with 10–20% octanol versus diesel.
- Mass-based PM typically declined, but particle number (PN) and ultrafine/nanoparticle fractions were less frequently measured.

**Critical gaps:**

- Few studies report **particle size distributions, PN counts, or morphology** (e.g., aggregate structure, fractal dimension). These metrics are essential for assessing health impacts and filtration needs.
- There is limited knowledge on how ternary blends affect the **volatile** versus **solid** fraction of PM — important for DPF (diesel particulate filter) regeneration and after-treatment design.

**5.4 Unregulated Emissions & Aldehydes**

Oxygenated fuels can increase formation of intermediate oxygenated species (e.g., formaldehyde, acetaldehyde) in some combustion regimes. Very few of the reviewed experiments measured aldehydes or other toxic oxygenated organics, creating an important knowledge gap for evaluating public health impacts.

**5.5 Transient, Cold-Start, and Real-World Driving Emissions**

Most experimental work uses steady-state engine mapping; comparatively few studies examine transient operation, cold starts, or real-world duty-cycles:

- Cold-start conditions can worsen HC and CO for biodiesel-containing blends due to higher viscosities at low temperature and slower vaporization.
- Transient loads may change the NO<sub>x</sub>–PM trade-off in ways not captured by steady-state tests.

**5.6 After-treatment Compatibility**

Compatibility with after-treatment systems (DOC, DPF, SCR) is underexplored:

- Lower PM mass may reduce DPF loading rate, but changes in PM composition (ash, sulfate, metal content) from biodiesel feedstocks affect filter longevity and ash accumulation.
- Fuel-bound oxygen and different combustion chemistries may affect SCR ammonia slip and catalyst poisoning pathways.

**Table 3. Emission outcomes for selected studies on biodiesel–diesel–*n*-octanol blends**

Authors (Year)	Engine type	Blend (D:B:O)	CO/HC change	NO <sub>x</sub> change	PM/Smoke change	Notes / Gaps
<b>Sinha et al. (2019)</b>	Single-cylinder, DI	70:20:10	CO ↓ ~25%; HC ↓ ~20%	NO <sub>x</sub> ↑ ~12%	Smoke ↓ ~30%	No PN data
<b>Ashok et al. (2019)</b>	Multi-cylinder DI	70:15:15	CO ↓; HC ↓	NO <sub>x</sub> ↑ ~10–20%	PM mass ↓	EGR not tested
<b>Patel et al. (2018)</b>	Multi-cylinder DI	60:20:20	CO ↓ ~18%	NO <sub>x</sub> ↑ ~8%	Smoke ↓ ~20%	Particle morphology missing
<b>Li et al. (2023)</b>	Multi-cylinder DI	70:20:10	CO ↓; HC ↓	NO <sub>x</sub> ↑ ~15%	PM ↓ but PN ?	Transient tests absent
<b>Zhang et al. (2021)</b>	Single-cylinder DI	80:10:10	CO ↓	NO <sub>x</sub> small ↑	Smoke ↓	Aldehyde speciation not measured

(Arrows: ↑ increase; ↓ decrease)

**5.7 Synthesis & Practical Implications**

- **Net benefit for CO/HC/Smoke:** Ternary blends (10–20% *n*-octanol) reliably reduce CO, HC, and smoke opacity compared with neat diesel. This suggests air quality benefits in urban and occupational settings where soot and smoke are critical.
- **NO<sub>x</sub> penalty remains primary challenge:** Without integrated after-treatment or combustion strategies, NO<sub>x</sub> increases can offset the gains in other pollutants. Practical deployment must consider combined engine calibration and after-treatment solutions.

- **Insufficient PM microphysical data:** Health assessments and after-treatment sizing require particle number, size distribution, and chemical composition — data scarce in current literature.
- **Limited transient and cold-start data:** Real-world benefits and drawbacks are underconstrained; fleet-level or duty-cycle studies are needed.

## 5.8 Recommended Emission-Focused Research Priorities

- **Comprehensive PM characterization:** Include PN, size distributions, TEM/SEM morphology, and volatile/solid fractions for representative blends under varied loads.
- **Aldehyde and VOC speciation:** Measure formaldehyde, acetaldehyde, and other oxygenated intermediates to evaluate toxic emissions.
- **Integrated mitigation experiments:** Systematically test EGR, injection timing strategies, and after-treatment (SCR + DPF) together with ternary blends.
- **Transient and cold-start testing:** Evaluate emission dynamics over standardized transient test cycles (e.g., WHSC, FTP) and cold ambient conditions.
- **After-treatment aging studies:** Determine how biodiesel feedstock and octanol affect catalyst poisoning, ash loading, and DPF regeneration frequency.

## 6. SUSTAINABILITY AND ENVIRONMENTAL IMPLICATIONS

The sustainability of biodiesel–diesel–*n*-octanol ternary blends must be assessed holistically, considering feedstock availability, life-cycle greenhouse gas (GHG) emissions, energy balance, and techno-economic feasibility.

### 6.1 Feedstock and Resource Utilization

Biodiesel is commonly derived from edible and non-edible oils, waste cooking oils (WCO), and animal fats. The use of WCO and non-edible feedstocks (e.g., jatropha, karanja, neem) addresses the **food vs. fuel** debate while contributing to waste valorization and circular economy models (Atabani et al., 2012). Octanol can be synthesized through **biomass fermentation pathways**, such as the *Clostridium acetobutylicum* process, or via catalytic upgrading of biomass-derived intermediates, supporting renewable origins.

### 6.2 Life-Cycle Greenhouse Gas Emissions

LCA studies on biodiesel generally indicate **40–80% lower CO<sub>2</sub>-equivalent emissions** compared to diesel, depending on feedstock and process energy inputs (Demirbas, 2009; Xue et al., 2011). While detailed LCA data on ternary blends is scarce, extrapolations suggest that replacing 20–30% of diesel with biodiesel + octanol could achieve meaningful reductions in well-to-wheel GHG emissions. However, this depends heavily on the renewable content of octanol production.

### 6.3 Energy and Exergy Analysis

Exergy analyses indicate biodiesel has slightly lower exergy efficiency due to oxygenated structure, while octanol's higher energy density helps offset this penalty. Several works recommend combining **energy–exergy–economic** analyses for ternary blends to assess their real-world feasibility.

### 6.4 Economic Viability

Biodiesel costs are sensitive to feedstock price, whereas octanol production cost from biomass is still relatively high compared to ethanol or butanol. Scaling up renewable octanol production via biorefineries and catalytic processes remains a challenge. Co-product utilization (e.g., glycerol, fermentation byproducts) is necessary to enhance process economics.

### 6.5 Alignment with Global Sustainability Goals

Ternary blends support multiple **UN Sustainable Development Goals (SDGs)**, including SDG 7 (Affordable and Clean Energy), SDG 12 (Responsible Consumption and Production), and SDG 13 (Climate Action). However, their sustainability must be benchmarked against competing options such as hydrogen, e-fuels, and electrification.

## 7. RESEARCH GAPS AND FUTURE DIRECTIONS :

From the synthesis of 50 experimental papers, the following research gaps and opportunities are identified:

- **Combustion and Spray Physics**  
Limited data on spray breakup, evaporation, and atomization dynamics for ternary blends.  
Need for combined **optical diagnostics + CFD modeling** to better capture combustion mechanisms.
- **Durability and Engine Wear**  
Long-term studies (>500 hours) on injector fouling, piston ring wear, and lubrication interactions are scarce.
- **Cold Flow and Low-Temperature Performance**  
Insufficient evaluation of cold-start operability and pour point depression strategies.
- **Particulate Matter Characterization**  
Most studies only report smoke opacity; little is known about nanoparticle number, morphology, and chemical speciation.

- **After-treatment and Hybrid Strategies**  
Integration with EGR, SCR, and DPF systems has not been systematically explored.  
Emerging opportunities in **dual-fuel RCCI (reactivity controlled compression ignition)** using octanol and biodiesel.
- **Sustainability and LCA**  
No full well-to-wheel assessments yet for ternary blends including octanol.  
Economic viability of renewable octanol remains a bottleneck.

## 8. CONCLUSION:

This review synthesized results from 50 experimental studies on biodiesel–diesel–*n*-octanol ternary blends in CI engines. The evidence indicates that moderate inclusion of *n*-octanol (10–20%) in biodiesel–diesel blends:

- Improves brake thermal efficiency and reduces smoke, CO, and HC emissions.
- Increases ignition delay, enhances premixed combustion, and can elevate NO<sub>x</sub> emissions.
- Offers potential for sustainable fuel diversification when coupled with renewable feedstock sourcing.
- Key challenges remain in NO<sub>x</sub> control, particulate characterization, long-term durability, and economic production of renewable octanol. Addressing these gaps requires **multi-scale research** that combines engine experiments, CFD modeling, emission diagnostics, LCA, and techno-economic analysis.
- With strategic advancements, biodiesel–diesel–*n*-octanol ternary blends could contribute significantly to cleaner and more sustainable CI engine operations, serving as a transitional technology in the pathway toward low-carbon transportation.

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