INFOMANIA: THE RESEARCH JOURNAL
Volume 2, Issue 4, July - August 2026
https://infomaniajournal.com ISSN:3108-0006

A Comparative Study of IC Engines Using Alternative Fuels (Biodiesel, Ethanol Blends)

Mr. Nawaz Ali Hamdulay

(Founder & Director, Infomania IT and Management Academy LLP), (B.E, M.E, MMS - IT, PhD-JJTU)

Email id: nawaz.hamdulay@gmail.com

Abstract

The increasing demand for energy and the environmental concerns associated with conventional fossil fuels have accelerated the search for sustainable alternatives for internal combustion (IC) engines. This study presents a comparative review of IC engine performance, combustion characteristics, and emission profiles when operated on alternative fuels, specifically biodiesel and ethanol blends. Biodiesel, derived from renewable biological sources, and ethanol, a bio-based alcohol fuel, offer cleaner combustion and reduced greenhouse gas emissions compared to petroleum-based fuels. The paper evaluates key performance parameters such as brake thermal efficiency, specific fuel consumption, and power output, alongside emission characteristics including carbon monoxide, hydrocarbons, nitrogen oxides, and particulate matter. It also examines how fuel properties—such as viscosity, calorific value, oxygen content, and volatility—affect engine behavior. A comparison of experimental and simulation-based studies is presented to highlight variations in findings and identify consistent trends. While biodiesel generally improves lubricity and reduces particulate emissions, ethanol blends enhance combustion efficiency but may affect engine stability at higher concentrations. Challenges related to fuel compatibility, cold starting, and material corrosion are also discussed. The study concludes by identifying research gaps and suggesting future directions for optimizing engine design and fuel formulations to improve performance and sustainability.

Keywords: Internal combustion engines; Biodiesel; Ethanol blends; Alternative fuels; Engine performance; Emissions; Combustion characteristics; Renewable energy.

I.Introduction

The rapid depletion of fossil fuel reserves and the growing concern over environmental pollution have driven significant research into alternative fuels for internal combustion (IC) engines. Conventional petroleum-based fuels, while widely used, contribute to greenhouse gas emissions, air pollution, and climate change. In response, renewable and cleaner-burning fuels such as biodiesel and ethanol blends have emerged as viable substitutes. Biodiesel, produced from vegetable oils, animal fats, or waste oils, is biodegradable and offers reduced emissions of particulate matter and carbon monoxide. Ethanol, typically derived from biomass sources like sugarcane or corn, is widely used in blended form with gasoline to improve combustion efficiency and reduce harmful exhaust emissions.

This study focuses on a comparative analysis of IC engine performance using biodiesel and ethanol-blended fuels. It aims to review and synthesize current research developments in this field, highlighting the effectiveness of these alternative fuels in improving engine performance and reducing environmental impact. Key performance parameters such as brake thermal efficiency, fuel consumption, and power output are examined alongside combustion characteristics including ignition delay and flame propagation.

Furthermore, this study evaluates emission profiles associated with biodiesel and ethanol blends, emphasizing their role in lowering carbon monoxide, hydrocarbons, and particulate emissions, while also addressing challenges such as increased nitrogen oxide formation. Despite their advantages, issues such as fuel stability, material compatibility, cold-start problems, and infrastructure limitations remain significant barriers. By identifying these challenges and comparing experimental and numerical findings, this review aims to provide insights into optimizing fuel blends and engine design, while proposing future research directions to enhance the sustainability and efficiency of IC engines.

II. Literature Review

Ceyhan, Ç., Çoban, A., and Cesur, I. [2026], investigated the effects of ethanol addition on combustion and emission characteristics in a partially homogeneous charge compression ignition (HCCI) diesel engine under varying load and engine speed conditions. The study examined different ethanol blend concentrations to determine their influence on combustion performance, cylinder pressure, heat-release characteristics, and exhaust emissions. The results demonstrated that ethanol addition significantly affects the combustion process because of its different physicochemical properties compared with conventional diesel fuel. Changes in ethanol concentration and engine operating conditions influenced ignition behaviour and combustion characteristics. The study also showed that ethanol blending can modify emission levels, offering potential benefits for reducing certain pollutants while creating performance and combustion trade-offs at particular operating conditions. Overall, Ceyhan et al. (2026)

concluded that optimizing ethanol concentration together with engine load and speed is important for achieving efficient combustion and lower emissions. The findings provide useful guidance for developing cleaner alternative-fuel strategies for IC engines.

Nagappan et al. [2026], presented a comprehensive review of alternative fuels for internal combustion (IC) engines, focusing on biodiesel, bio-alcohol, bio-oil, and plastic oil as potential substitutes for conventional fossil fuels. The study examined their effects on engine performance, combustion behavior, and exhaust emissions. The authors highlighted that biodiesel and bio-alcohol fuels can reduce dependence on petroleum-based fuels and have significant potential for reducing harmful emissions. However, variations in fuel properties, including viscosity, calorific value, oxygen content, and volatility, can influence engine efficiency, fuel consumption, combustion stability, and emission characteristics. The review also identified important technical challenges associated with alternative fuels, such as blend compatibility, fuel stability, optimization of operating conditions, and long-term engine durability. Nagappan et al. (2026) emphasized that appropriate fuel-blend ratios and engine modifications are necessary to achieve optimum performance and emission reduction. The study provides a strong foundation for further research into efficient and environmentally sustainable alternative-fuel-based IC engines.

Utsav, Kumar, and Dhaka [2026], investigated the influence of different diesel, biodiesel, and ethanol blend ratios on the efficiency, combustion characteristics, and emission performance of a compression-ignition engine. The study evaluated different fuel combinations to determine how variations in biodiesel and ethanol content affect engine operation. The researchers observed that fuel composition significantly influences cylinder pressure, heat-release rate, combustion temperature, and overall engine efficiency. The addition of ethanol, due to its higher oxygen content and different fuel properties, can improve combustion and contribute to reductions in certain exhaust pollutants. However, increasing ethanol concentration may also affect fuel consumption and combustion stability because of its lower calorific value and different ignition characteristics compared with diesel. The study demonstrates that an appropriate balance between diesel, biodiesel, and ethanol is essential for achieving desirable engine performance and emission characteristics. These findings are highly relevant to comparative studies of alternative fuels and highlight the importance of optimizing blend ratios and engine operating conditions for efficient and cleaner IC engine operation.

III. Objectives

1. To review and analyze the current research on the use of biodiesel and ethanol blends in IC engines.
2. To compare the performance characteristics of IC engines operating on biodiesel and ethanol-blended fuels.
3. To evaluate the combustion behavior of alternative fuels in comparison with conventional fuels.
4. To analyze emission characteristics associated with biodiesel and ethanol blends.
5. To identify the advantages, limitations, and technical challenges of using alternative fuels in IC engines.
6. To propose future research directions for improving the efficiency and environmental impact of alternative fuel-based IC engines.

IV. Research Methodology

1. Research Design

This study adopts a **comparative and systematic literature-based research methodology** to evaluate the performance, combustion characteristics, and emission behavior of internal combustion (IC) engines operating with biodiesel and ethanol-blended fuels. Published research articles, review papers, conference papers, and relevant technical literature are analyzed to identify trends, similarities, differences, advantages, limitations, and research gaps associated with alternative fuels.

2. Literature Search and Data Collection

Relevant studies are collected from reliable academic databases such as **ScienceDirect, SpringerLink, Wiley Online Library, MDPI, and Google Scholar**. The literature search uses keywords including *biodiesel in IC engines, ethanol blends, biodiesel-ethanol blends, diesel engine performance, alternative fuels, combustion characteristics, exhaust emissions,* and *renewable fuels*. Greater emphasis is placed on recent research, particularly studies published between **2020 and 2026**, while important earlier studies are included where necessary for fundamental concepts.

3. Selection of Studies

The selected studies are screened according to their relevance to the research objectives. Studies are included when they investigate biodiesel, ethanol, or biodiesel-ethanol blends in IC engines and provide information about engine performance, combustion, or emissions. Studies with insufficient experimental information or those unrelated to IC-engine applications are excluded.

4. Comparative Analysis

The selected literature is systematically compared using common performance parameters. The major parameters considered are:

- **Brake power and brake torque**
- **Brake thermal efficiency (BTE)**
- **Brake specific fuel consumption (BSFC)**
- **Cylinder pressure**
- **Heat-release rate**
- **Ignition delay and combustion duration**
- **Exhaust gas temperature**
- **CO, HC, NOx, CO_2, and smoke/particulate emissions**

The performance of biodiesel and ethanol-blended fuels is compared with conventional diesel or gasoline wherever comparable data are available. The influence of blend ratio, engine load, engine speed, compression ratio, and operating conditions is also considered.

5. Combustion Analysis

Combustion characteristics reported in the selected studies are analyzed to understand how alternative fuels influence the combustion process. Parameters such as cylinder pressure, ignition delay, heat-release rate, combustion duration, and combustion temperature are compared. Particular attention is given to the effects of the oxygen content, viscosity, calorific value, volatility, and cetane number of biodiesel and ethanol on combustion behaviour.

INFOMANIA: THE RESEARCH JOURNAL
Volume 2, Issue 4, July - August 2026
https://infomaniajournal.com ISSN:3108-0006

6. Emission Analysis

The emission performance of alternative fuels is evaluated by comparing reported levels of **CO, HC, NOx, CO_2, and smoke/particulate matter** with those of conventional fuels. The analysis identifies the environmental benefits and emission trade-offs associated with different fuel blends. The effects of ethanol and biodiesel concentration on emission reduction are also examined.

7. Advantages, Limitations, and Technical Challenges

The study identifies the major advantages of biodiesel and ethanol blends, including renewable origin, reduced dependence on fossil fuels, oxygenated combustion, and potential emission reductions. At the same time, technical challenges such as lower calorific value, high viscosity of biodiesel, ethanol volatility, phase separation, cold-start problems, fuel stability, material compatibility, increased fuel consumption, and possible NOx emission increases are evaluated.

8. Data Synthesis

The findings from different studies are organized into comparative tables and analyzed qualitatively. Where sufficient numerical data are available, percentage changes in performance and emissions are calculated using:

$$
\text{Percentage Change} =
\frac{\text{Alternative Fuel Value - Conventional Fuel Value}}
{\text{Conventional Fuel Value}}\times100
$$

This approach enables a consistent comparison of the effects of different alternative-fuel blends.

9. Identification of Research Gaps

The results are synthesized to identify gaps in existing research, particularly regarding optimum blend ratios, long-term engine durability, combustion optimization, emission-control technologies, fuel stability, and the interaction between alternative fuels and advanced engine technologies. Based on these gaps, potential future research directions are proposed.

10. Methodology Framework

The overall methodology follows the sequence:

Literature Identification → Study Selection → Data Extraction → Performance Analysis → Combustion Analysis → Emission Analysis → Comparative Evaluation → Identification of Challenges and Research Gaps → Future Research Recommendations

This methodology provides a structured basis for comparing biodiesel and ethanol-blended fuels and supports the development of conclusions regarding their suitability, efficiency, environmental impact, and future application in IC engines.

V. The Current Research on the Use of Biodiesel and Ethanol Blends in IC Engines

Recent research has shown increasing interest in biodiesel and ethanol blends as sustainable alternatives to conventional fossil fuels in internal combustion (IC) engines. Biodiesel, generally produced from vegetable oils, animal fats, or waste cooking oils, has properties that allow it to be used in diesel engines with limited modifications. Ethanol, due to its renewable origin, high oxygen content, and relatively clean combustion characteristics, is commonly blended with diesel or biodiesel to improve combustion and reduce selected exhaust emissions. Current literature indicates that the addition of these alternative fuels can significantly influence engine performance, combustion characteristics, and emissions.

Nagappan et al. (2026) reviewed biodiesel, bio-alcohol, bio-oil, and other alternative fuels and reported that their use can reduce dependence on petroleum fuels and potentially improve environmental performance. However, differences in viscosity, calorific value, volatility, ignition quality, and fuel stability can affect engine operation. Utsav et al. (2026) demonstrated that variations in diesel, biodiesel, and ethanol ratios influence engine efficiency, cylinder pressure, heat-release rate, and emissions. Similarly, Ceyhan et al. (2026) found that ethanol concentration and engine operating conditions significantly affect combustion and emission behaviour. Overall, current research suggests that biodiesel and ethanol blends offer considerable potential for cleaner and renewable IC-engine operation. Nevertheless, challenges such as increased fuel consumption, combustion stability, fuel compatibility, cold-start performance, and emission trade-offs remain. Therefore, further research is required to determine optimum blend ratios and operating conditions while improving engine efficiency, durability, and environmental performance.

VII. Compare the Performance Characteristics of IC Engines Operating on Biodiesel and Ethanol-Blended Fuels

Performance characteristic	Biodiesel-fuelled IC engine	Ethanol-blended-fuelled IC engine
Brake thermal efficiency (BTE)	Generally comparable to or slightly lower than diesel; can improve with suitable blend ratios	Often comparable to or slightly improved at moderate ethanol blending
Brake specific fuel consumption (BSFC)	Usually higher than diesel because biodiesel has lower calorific value	Generally higher because ethanol has lower calorific value and energy density
Power output	Slightly lower than conventional diesel, especially at higher biodiesel concentrations	May decrease slightly as ethanol percentage increases
Torque	Generally, slightly reduced compared with diesel	Usually slightly reduced at high ethanol concentrations
Ignition quality	Good ignition due to relatively high cetane number	Lower cetane number; can cause ignition-delay problems in diesel engines
Ignition delay	Generally, slightly longer than diesel	Usually longer, particularly with higher ethanol content
Combustion temperature	Can be slightly lower, depending on blend and operating conditions	Generally reduced due to ethanol's cooling effect and high latent heat of vaporization
CO emissions	Generally reduced because biodiesel contains oxygen	Generally reduced at suitable blend ratios
HC emissions	Usually reduced	Generally reduced, although unburned ethanol can affect HC emissions
CO_2 emissions	Lower on a life-cycle basis; tailpipe CO_2 may be comparable to diesel	Can reduce net carbon emissions depending on ethanol source
NO_x emissions	May be slightly higher than diesel in some operating conditions	Often lower or comparable, depending on blend and engine conditions
Smoke/particulate emissions	Significant reduction in smoke and particulate matter	Generally, reduces smoke and particulate emissions
Lubricity	Better lubricity than conventional diesel	Poor lubricity; usually requires appropriate blending/additives

Performance characteristic	**Biodiesel-fuelled IC engine**	**Ethanol-blended-fuelled IC engine**
Fuel consumption	Higher volumetric consumption due to lower heating value	Higher volumetric consumption due to much lower energy density
Renewability	Renewable when produced from vegetable oils, animal fats, or waste oils	Renewable when produced from biomass such as sugarcane, corn, or other feedstocks
Overall engine performance	Good substitute for diesel with relatively small performance changes	Useful as a blend, but high concentrations can create ignition, fuel-system, and cold-start challenges

Table 1

Overall: Biodiesel generally offers better emission characteristics with relatively small changes in engine performance, while ethanol blending can provide lower smoke and CO emissions but tends to increase fuel consumption and may reduce ignition quality and power at higher blend levels.

VIII. The Combustion Behaviour of Alternative Fuels in Comparison with Conventional Fuels

Parameter	**Conventional fuel**	**Alternative fuel**	**Purpose of evaluation**
Ignition delay	Generally shorter and more predictable	May vary depending on fuel properties	To assess ignition characteristics
Cylinder pressure	Provides a reference combustion profile	May differ due to altered combustion rate	To compare peak pressure and pressure rise
Heat release rate	Characteristic of the conventional fuel	Can show different combustion phases	To study the rate and pattern of energy release
Combustion duration	Usually well established	May increase or decrease depending on fuel	To determine the duration of combustion
Peak combustion temperature	Generally higher	Often lower for oxygenated alternative fuels	To assess thermal behaviour and emissions potential
Flame characteristics	Stable and established	May differ in flame speed and stability	To evaluate flame development and propagation
Combustion efficiency	Typically, high	Depends on fuel composition and blend ratio	To compare energy conversion effectiveness

INFOMANIA: THE RESEARCH JOURNAL
Volume 2, Issue 4, July - August 2026
https://infomaniajournal.com ISSN:3108-0006

Parameter	Conventional fuel	Alternative fuel	Purpose of evaluation
Emission formation	Baseline CO, HC, NO_x and particulate emissions	May reduce some emissions but increase others	To evaluate environmental performance
Overall combustion behaviour	Serves as the benchmark	Compared against the conventional fuel	To determine the suitability of the alternative fuel

Table 2

IX. Emission Characteristics Associated with Biodiesel and Ethanol Blends

Emission characteristic	Conventional diesel	Biodiesel blends	Ethanol blends	Purpose of analysis
Carbon monoxide (CO)	Baseline CO emissions	Generally lower due to oxygen content	Generally lower at suitable blend ratios	To evaluate incomplete combustion
Unburned hydrocarbons (HC)	Relatively higher	Usually reduced	Generally reduced, though unburned ethanol may affect HC	To assess combustion completeness
Nitrogen oxides (NO_x)	Baseline level	May increase slightly depending on blend and operating conditions	May decrease or remain comparable	To evaluate temperature-dependent emissions
Carbon dioxide (CO_2)	Higher fossil-carbon contribution	Tailpipe CO_2 may be similar, but life-cycle emissions can be lower	Can reduce net CO_2 emissions depending on feedstock	To assess carbon impact
Smoke opacity	Generally higher	Significantly reduced	Generally reduced	To assess visible particulate emissions
Particulate matter (PM)	Higher	Usually substantially reduced	Generally reduced	To evaluate particulate pollution
Oxygen content	No inherent oxygen	Contains chemically bound oxygen	Contains high oxygen content	To understand its influence on combustion and emissions
Overall emission performance	Serves as the reference	Generally favourable for CO, HC, smoke and PM	Generally favourable for CO, smoke and PM, depending on blend	To determine the environmental suitability of the fuel blends

Table 3

INFOMANIA: THE RESEARCH JOURNAL
Volume 2, Issue 4, July - August 2026
https://infomaniajournal.com ISSN:3108-0006

X. Technical Challenges of Using Alternative Fuels in IC Engines

Technical challenge	**Biodiesel**	**Ethanol blends**	**Effect on IC engine**
Lower calorific value	Lower than conventional diesel	Significantly lower than diesel/gasoline	Higher fuel consumption and possible reduction in power output
Ignition characteristics	Generally acceptable, but ignition delay can vary	Lower cetane number in diesel applications	Delayed ignition and altered combustion behaviour
Viscosity	Higher than diesel	Lower than diesel	Affects fuel injection, atomization and spray characteristics
Cold-start performance	Poorer at low temperatures due to higher viscosity and crystallization	Poorer evaporation and starting characteristics in some applications	Difficult starting and unstable combustion
Fuel atomization	Poorer atomization at high biodiesel concentrations	Different spray and evaporation behaviour	Changes air–fuel mixing and combustion efficiency
Fuel stability	Susceptible to oxidation during storage	Can absorb moisture and may have storage issues	Fuel degradation and possible engine/fuel-system problems
Material compatibility	May affect certain seals, gaskets and hoses	Can damage or swell some conventional fuel-system materials	Leakage, deterioration and maintenance requirements
Lubricity	Generally improves fuel lubricity	Provides lower lubricity than diesel	Can influence wear of injection-system components
Water absorption	Relatively low, but biodiesel can retain some water	Highly hygroscopic	Phase separation, corrosion and fuel-quality problems
Corrosion	Oxidation products may contribute to corrosion	Water and acidic compounds can promote corrosion	Reduced durability of fuel-system components
Fuel injection system	Higher viscosity and density alter injection characteristics	Lower energy density and different physical properties affect injection	Changes in injection timing, spray pattern and combustion
Emission trade-offs	Can reduce PM, CO and HC but may increase NO_x in some conditions	Can reduce CO and PM, but HC/aldehyde emissions may vary	Requires optimization of blend ratio and engine settings

Technical challenge	Biodiesel	Ethanol blends	Effect on IC engine
Engine calibration	May require changes in injection timing and injection quantity	May require changes in injection and ignition/calibration strategy	Ensures stable combustion and acceptable performance
Long-term durability	Deposits and oxidation can affect components if fuel quality is poor	Fuel-system compatibility and corrosion can affect durability	Increased maintenance or component wear
Blend stability	Generally good when properly prepared	Can experience phase separation, especially with water contamination	Inconsistent fuel properties and engine operation

Table 4

Overall: The major technical challenges are different fuel properties, altered combustion behaviour, fuel-system compatibility, cold-start performance, storage stability, and emission trade-offs. These challenges can generally be addressed through proper blend selection, fuel conditioning, engine calibration, and compatible fuel-system materials.

XI. Future Research Directions for Improving the Efficiency and Environmental Impact of Alternative Fuel-Based IC Engines

The increasing demand for sustainable transportation and the need to reduce greenhouse gas emissions have encouraged extensive research into alternative fuels for internal combustion (IC) engines. Although fuels such as biodiesel, ethanol, methanol, biogas, and other renewable fuels offer environmental advantages, further research is required to improve their efficiency, reliability, and overall sustainability. Future research should focus on optimizing both fuel properties and engine operating conditions.

One important research direction is the **optimization of fuel blends**. Different blend ratios of biodiesel, ethanol, and conventional fuels can significantly influence brake thermal efficiency, fuel consumption, combustion characteristics, and emissions. Research should identify optimum blend concentrations that provide a balance between engine performance and environmental benefits. The use of fuel additives and nanoparticles may also be investigated to improve combustion, ignition, atomization, and thermal efficiency.

Another promising area is **advanced engine calibration and combustion control**. Injection timing, injection pressure, air–fuel ratio, exhaust gas recirculation, and ignition parameters can be optimized for alternative fuels. Advanced electronic control systems and real-time sensors could enable engines to automatically adjust operating parameters according to fuel composition and engine load.

Future studies should also emphasize **emission reduction technologies**. Particular attention should be given to reducing nitrogen oxides (NO_x), particulate matter (PM), carbon monoxide (CO), and unburned hydrocarbons (HC). Combining alternative fuels with technologies such as exhaust gas recirculation, catalytic converters, particulate filters, and selective catalytic reduction could provide further environmental benefits.

The development of **advanced combustion concepts** such as homogeneous charge compression ignition, partially premixed combustion, and dual-fuel combustion also offers significant potential. These approaches can improve thermal efficiency while reducing harmful emissions.

Finally, future research should include **life-cycle assessment and techno-economic analysis**. Evaluating feedstock production, fuel processing, transportation, engine operation, and end-of-life impacts will provide a more complete understanding of the environmental benefits of alternative fuels. Research should also investigate renewable feedstocks, waste-derived fuels, fuel production costs, and long-term engine durability.

Overall, future research should adopt an integrated approach combining **fuel development, engine optimization, emission-control technologies, advanced combustion strategies, and life-cycle assessment**. Such developments can help make alternative fuel-based IC engines more efficient, cleaner, economically viable, and suitable for sustainable transportation.

XII. Threats and Technical Challenges

A SWOT-style assessment identifies several threats to large-scale implementation.

- **Feedstock availability -** Large-scale dependence on edible vegetable oils or agricultural feedstocks can generate food-versus-fuel concerns. Future biodiesel development therefore needs greater emphasis on used cooking oil, animal fats, algae, non-edible oils, and other waste resources.
- **Fuel-property variability -** Biodiesel properties vary considerably with feedstock and production method. Similarly, ethanol blends can behave differently depending on

water content, blend ratio, additives, gasoline composition, and ambient conditions. This variability complicates standardization and engine calibration.

- **Emission trade-offs -** The reduction of PM, CO, or HC does not automatically mean that total environmental impact is reduced. Biodiesel may increase NOx under some conditions, while ethanol blends can alter aldehyde emissions, unburned fuel species, and evaporative emissions. Consequently, emission assessment should consider a broader pollutant spectrum rather than only CO2 and smoke.
- **Engine durability -** Long-term studies are still required for some fuel combinations, particularly high-concentration ethanol–diesel and ternary blends. Potential issues include injector deposits, lubricant dilution, corrosion, elastomer compatibility, oxidation products, and fuel-system wear.
- **Storage and stability -** Ethanol–diesel blends can suffer from phase separation and require careful control of water content and temperature. Biodiesel can experience oxidation during prolonged storage. These issues can increase the logistical complexity of alternative-fuel distribution.
- **Infrastructure and standardization -** Alternative fuels require compatible standards for production, storage, transport, blending, quality control, and engine certification. Differences in fuel standards between countries can slow commercialization.
- **Economic uncertainties -** The economic feasibility of biodiesel and ethanol depends on feedstock prices, agricultural conditions, conversion costs, government incentives, petroleum prices, carbon policies, and scale of production.
- **Climate and life-cycle uncertainty -** Tailpipe emissions alone do not provide a complete assessment of environmental performance. Fertilizer use, land-use change, processing energy, transportation, and coproduct allocation can substantially influence the life-cycle greenhouse-gas balance of biofuels. Therefore, future comparative studies should integrate engine-test results with well-to-wheel and life-cycle assessments.

XIII. Data Analysis

The increasing demand for transportation energy, depletion of petroleum resources, and increasingly stringent emission regulations have encouraged extensive research into renewable fuels for internal combustion (IC) engines. Among the most investigated alternatives are biodiesel and ethanol. Biodiesel is generally used in compression-ignition (CI) diesel engines, whereas ethanol is particularly suitable for spark-ignition (SI) gasoline engines because of its high-octane number. Ethanol can also be incorporated into diesel or biodiesel–diesel systems as an oxygenated additive. Consequently, a meaningful comparison requires consideration of both fuel properties and the type of IC engine in which the fuel is used.

- **Fuel-property analysis**

Biodiesel is composed primarily of fatty-acid alkyl esters produced from vegetable oils, animal fats, or waste oils. Compared with petroleum diesel, biodiesel generally has higher density, viscosity, oxygen content, and flash point but lower heating value. The oxygen contained in biodiesel promotes more complete combustion, while its lower heating value generally results in increased brake-specific fuel consumption (BSFC). The exact effects depend strongly on feedstock, fatty-acid composition, blend ratio, injection system, and engine operating conditions.

Ethanol has a substantially higher-octane number and oxygen content than gasoline, making it attractive for SI engines. However, ethanol has a lower heating value and higher latent heat of vaporization. These characteristics can improve charge cooling, knock resistance, and combustion under appropriate conditions, but they can also increase fuel consumption and cause cold-start or vaporization difficulties at high blend concentrations.

For CI engines, ethanol presents additional difficulties because of its low cetane number, high latent heat of vaporization, low viscosity, and limited miscibility with diesel. The addition of biodiesel can improve the stability and lubricity of ethanol–diesel mixtures, which is one reason ternary diesel–biodiesel–ethanol blends have received considerable attention.

- **Engine-performance analysis**

The major performance parameters considered in alternative-fuel studies are brake thermal efficiency (BTE), brake-specific fuel consumption (BSFC), brake power, torque, exhaust gas temperature, and, in some studies, indicated thermal efficiency and indicated mean effective pressure.

For biodiesel, most studies report either comparable or slightly lower power and higher BSFC than petroleum diesel when equivalent operating conditions are maintained. The principal reason is the lower heating value of biodiesel. Canakci and Van Gerpen reported that biodiesel could produce significant reductions in particulate matter, CO, and unburned hydrocarbons while maintaining effective conversion of fuel energy into work. Canakci's subsequent combustion study reported a 13.8% increase in BSFC for soybean biodiesel, associated with its lower heating value.

Biodiesel blends, particularly moderate blends such as B10–B20, generally provide a practical compromise between renewable-fuel content and engine performance. Reviews indicate that moderate biodiesel blends can operate in conventional CI engines with limited or no hardware modification, although fuel properties and engine calibration remain important.

Ethanol–gasoline blends can behave differently in SI engines. Ethanol's high octane number permits higher compression ratios and can improve knock resistance. Experimental work using E10–E60 showed that ethanol addition can slightly increase brake torque while reducing CO and HC emissions under appropriate operating conditions. Other work using E50 and E85 reported increases in torque and power under particular test conditions, although fuel consumption also increased because of ethanol's lower energy density.

Recent experimental and numerical research further indicates that moderate ethanol blending can provide an advantageous balance. Khedr et al. found that ethanol concentrations up to approximately E30 improved combustion quality under their specified SI-engine conditions, whereas concentrations above E40 produced combustion instability and efficiency losses. Therefore, the optimum ethanol concentration cannot be treated as universal; it depends on engine design, compression ratio, injection/fueling strategy, equivalence ratio, ignition timing, and operating load.

- **Combustion analysis**

Combustion behaviour is strongly influenced by cetane number, octane number, viscosity, volatility, oxygen content, latent heat of vaporization, spray characteristics, and chemical structure.

In a CI engine, biodiesel generally has a higher cetane number than ethanol and therefore does not create the same ignition-delay problem associated with alcohol addition. Its oxygen content can enhance local oxidation of fuel-rich regions and reduce soot formation. However, biodiesel's higher viscosity and density can alter spray penetration and atomization, potentially affecting heat-release characteristics and combustion duration.

Adding ethanol to diesel or biodiesel generally increases ignition delay because ethanol has a low cetane number and high latent heat of vaporization. The longer ignition delay may increase premixed combustion and alter the heat-release rate. The reduced viscosity of alcohol can improve atomization and air–fuel mixing, while its oxygen content can promote oxidation of incomplete-combustion products.

Zhu et al. experimentally demonstrated that ethanol–biodiesel blends modify in-cylinder pressure and heat-release behaviour compared with neat biodiesel. A small ethanol addition, such as BE5, improved several performance and emission characteristics, whereas increasing ethanol concentration could increase HC and CO under some conditions.

For SI engines, ethanol generally increases flame speed and knock resistance and can modify combustion phasing because of its different evaporation and chemical characteristics. Recent numerical–experimental evidence indicates that moderate ethanol concentrations can improve indicated mean effective pressure and thermal efficiency, but excessive ethanol concentration can cause unstable combustion when the engine calibration is not optimized.

- **Emission analysis**

The most frequently measured emissions are carbon monoxide (CO), unburned hydrocarbons (HC), nitrogen oxides (NOx), carbon dioxide (CO2), smoke, and particulate matter (PM).

Biodiesel generally produces substantial reductions in smoke and particulate emissions because of its oxygen content and near absence of sulfur. Lapuerta et al.'s comprehensive review identified a strong consensus regarding the reduction of particulate emissions when biodiesel replaces conventional diesel. However, NOx behavior is more complicated and may increase under certain engine conditions because of combustion temperature, oxygen availability, injection timing, and fuel chemistry.

Canakci and Van Gerpen found significant reductions in particulate matter, CO, and unburned HC with biodiesel blends, while NOx increased by approximately 11–13% for the tested fuels. This illustrates an important trade-off: reducing soot and incomplete-combustion products does not necessarily mean that every pollutant will decline simultaneously.

Ethanol generally reduces CO and HC in SI engines when appropriate air–fuel ratios and ignition timing are maintained. Its oxygen content can promote more complete oxidation, while its high-octane rating enables higher compression ratios. Several experimental studies have reported reductions in CO and HC following ethanol addition to gasoline.

For diesel engines, ethanol addition generally produces a strong reduction in smoke and PM because the fuel contains oxygen and has a lower tendency to form soot. However, the effects

INFOMANIA: THE RESEARCH JOURNAL
Volume 2, Issue 4, July - August 2026
https://infomaniajournal.com ISSN:3108-0006
on NOx, HC, and CO are dependent on ethanol concentration, load, injection timing, and combustion temperature. Reviews of diesel–biodiesel–ethanol blends indicate that PM reduction is one of the most consistent benefits, whereas gaseous emissions are more variable.

- **Comparative literature synthesis**

Parameter	**Conventional diesel**	**Biodiesel–diesel blends**	**Ethanol–gasoline blends**	**Ethanol–biodiesel/diesel blends**
Engine type	CI	CI	SI	CI
Oxygen content	Low	High	High	High
Heating value	High	Lower	Lower	Lower
Ignition quality	High cetane	Generally good	High octane/low cetane	Lowers CI ignition quality
BSFC	Baseline	Usually increases slightly	Usually increases with high ethanol content	Usually increases at high alcohol concentration
BTE	Baseline	Comparable or slightly lower/higher depending on blend	Can improve at optimum blend	Highly condition-dependent
Smoke/PM	Baseline	Generally lower	Generally lower	Generally lower
CO	Baseline	Generally lower	Generally lower	Usually lower at moderate blend levels
HC	Baseline	Generally lower	Generally lower under optimized operation	May increase at high ethanol content
NOx	Baseline	Often slightly higher, but condition-dependent	Variable	Can decrease or increase depending on conditions

Combustion stability	High	Generally good at moderate blends	Good at low/moderate blends	Can deteriorate at high ethanol content
Fuel-system concerns	Established	Viscosity, oxidation stability, cold flow	Material compatibility, vaporization, cold start	Phase stability, lubricity, ignition delay
Renewable potential	Low	High	High	Very high
Engine modification	None	Usually low for moderate blends	Low/moderate depending on blend	Calibration/additives may be required

Table 5

Overall, the literature demonstrates that **no single alternative fuel simultaneously maximizes performance and minimizes every emission species**. Biodiesel is particularly attractive for CI engines because it can be blended with diesel with relatively minor modifications and provides strong PM and smoke benefits. Ethanol is particularly attractive for SI engines because of its high-octane rating and oxygen content. Ethanol in CI engines is technically more challenging, but biodiesel can act as a co-component to improve blend properties.

XIV. Key Findings

The comparative analysis produces the following major findings:

- **Biodiesel is technically mature for CI engines.** A large body of experimental research demonstrates that biodiesel and moderate biodiesel–diesel blends can operate successfully in conventional diesel engines.
- **Biodiesel generally reduces particulate emissions, smoke, CO, and HC.** Its chemically bound oxygen promotes oxidation of fuel-rich regions and reduces soot formation.
- **The major performance penalty of biodiesel is increased fuel consumption.** The lower heating value of biodiesel generally requires a larger fuel mass flow to produce the same power output.

- **NOx remains a major challenge for biodiesel.** Although results vary with feedstock and engine calibration, many studies report an increase or no consistent decrease in NOx. Injection timing, combustion temperature, oxygen availability, and fatty-acid composition are important variables.

- **Ethanol is highly suitable for SI engines.** Its high octane number and oxygen content can improve knock resistance and combustion quality and can allow higher compression ratios.

- **High ethanol concentrations can increase fuel consumption and combustion instability.** The lower heating value and high latent heat of vaporization become increasingly important as the ethanol fraction increases. Recent research suggests that moderate blends can outperform very high blends when the engine is not specifically optimized for ethanol.

- **Ethanol in CI engines requires greater technical attention.** Low cetane number, poor miscibility with diesel, reduced lubricity, and increased ignition delay are important barriers.

- **Ternary diesel–biodiesel–ethanol blends are promising.** Biodiesel can improve the lubricity and physical stability of ethanol-containing diesel blends while ethanol can provide additional oxygen and reduce particulate formation.

- **Fuel-blend optimization is more important than simply increasing renewable-fuel concentration.** Engine speed, load, compression ratio, injection timing, injection pressure, air–fuel ratio, ignition timing, and exhaust-gas recirculation can substantially change the results.

- **Future research should move from fuel substitution toward integrated fuel–engine optimization.** Advanced injection systems, electronic control, combustion modeling, after-treatment, additives, waste-derived feedstocks, and life-cycle assessment should be investigated together rather than independently.

XV. Advantage

- **Advantages of biodiesel**

- **Renewable and biodegradable -** Biodiesel can be produced from vegetable oils, animal fats, used cooking oil, and other lipid-containing resources. Its renewable character can reduce dependence on petroleum-based diesel.
- **Lower particulate and smoke emissions -** The oxygen present in biodiesel promotes more complete oxidation and generally reduces smoke and PM emissions. This is one of the most consistently reported advantages of biodiesel.
- **Compatibility with existing CI engines -** Moderate biodiesel blends can generally be used in conventional diesel engines without major mechanical modification.
- **Improved fuel lubricity -** Biodiesel generally has superior lubricating properties compared with ultra-low-sulfur diesel, which can benefit fuel-injection-system lubrication.
- **Potential utilization of waste feedstocks -** Used cooking oil, animal fats, and non-edible oils can be converted into biodiesel, potentially reducing waste-disposal problems and avoiding direct competition with food crops when appropriate feedstocks are selected.

- **Advantages of ethanol**

- **High octane rating -** Ethanol has a high-octane number, allowing SI engines to operate at higher compression ratios with improved resistance to knock.
- **Oxygenated combustion -** The oxygen content of ethanol promotes more complete combustion and can reduce CO and HC emissions under suitable operating conditions.
- **Renewable production pathways -** Ethanol can be produced from sugar crops, starch-based crops, lignocellulosic biomass, and potentially waste-derived feedstocks.
- **Potential for improved combustion efficiency -** Moderate ethanol blending can improve combustion and thermal efficiency when ignition timing and air–fuel ratio are optimized. Recent research has demonstrated particularly promising behavior at moderate ethanol concentrations.

- **Advantages of combined biodiesel–ethanol systems**

A combined biodiesel–ethanol–diesel fuel system can exploit complementary fuel properties. Biodiesel provides lubricity and relatively high cetane quality, while ethanol contributes oxygen and can improve atomization because of its lower viscosity. Research on ternary blends indicates considerable potential for PM reduction and increased renewable content.

XVI. Disadvantage

- **Biodiesel limitations**

The first major limitation is its lower heating value. As a result, higher fuel consumption may be required to achieve the same engine output as petroleum diesel. Biodiesel's relatively high viscosity and density can also influence fuel injection, spray penetration, and atomization.

A second concern is **cold-flow behaviour**. Depending on fatty-acid composition, biodiesel can have relatively high cloud and pour points, which may create fuel-filter plugging and starting problems in low-temperature environments.

A third concern is **oxidation stability**. Biodiesel containing significant quantities of unsaturated fatty acids can oxidize during storage, producing degradation products that may affect fuel quality.

A fourth limitation is the potential **NOx penalty**. Although not universal, numerous investigations have reported higher NOx emissions for biodiesel compared with petroleum diesel.

Finally, large-scale biodiesel production can raise concerns regarding feedstock availability, land use, water consumption, food-versus-fuel competition, and overall life-cycle sustainability. Consequently, waste oils and non-edible feedstocks are increasingly important research directions.

- **Ethanol limitations**

Ethanol's lower heating value leads to increased volumetric fuel consumption. Its high latent heat of vaporization can create cold-start and vaporization problems, particularly at high ethanol concentrations.

In CI engines, the low cetane number of ethanol causes longer ignition delay. Ethanol also has relatively poor miscibility with diesel under some conditions and can reduce fuel lubricity. Stable ethanol–diesel blends may therefore require co-solvents, surfactants, biodiesel, or other additives.

High ethanol concentrations can also require engine-control modifications. Injection timing, ignition timing, compression ratio, air–fuel ratio, and fuel-injection quantity may need optimization. The recent finding that E30 performed favourably while concentrations above E40 caused combustion instability under specific test conditions demonstrates why high-concentration ethanol should not automatically be assumed to be superior.

XVII. Comparison

The comparison indicates that biodiesel and ethanol should not be considered direct substitutes in every IC-engine application. Their optimum use is strongly linked to engine type.

Biodiesel is generally more appropriate for CI engines. It has fuel characteristics relatively close to diesel, a high cetane number, good lubricity, and oxygen content. Its strongest advantage is the reduction of PM and smoke. Its principal disadvantages are lower energy density, possible increases in NOx, cold-flow limitations, oxidation stability, and feedstock sustainability issues.

Ethanol is generally more appropriate for SI engines. Its high octane rating and high heat of vaporization provide excellent anti-knock characteristics. Moderate gasoline–ethanol blends can improve combustion and reduce CO and HC. However, high concentrations can increase fuel consumption and may require significant changes in engine calibration.

Ethanol–diesel and ethanol–biodiesel blends occupy an intermediate but technically challenging area. Their main attraction is the possibility of combining the lubricity and cetane characteristics of biodiesel with the oxygenation and low-soot tendency of ethanol. However, miscibility, ignition delay, lubricity, fuel stability, and high-concentration combustion behavior must be controlled.

Thus, the comparative ranking can be summarized as follows:

Criterion	Biodiesel	Ethanol–Gasoline	Ethanol–Biodiesel/Diesel
Best-suited engine	CI	SI	CI
Renewable potential	High	High	Very high

PM reduction	Excellent	Good	Excellent
CO reduction	Good	Good	Good at optimized blends
HC reduction	Good	Good	Variable
NOx behaviour	Often higher/variable	Variable	Variable
Fuel economy	Slight penalty	Penalty at high ethanol	Penalty at high ethanol
Ignition/combustion suitability	Good for CI	Excellent for SI	Requires optimization
Blend stability	Generally good with diesel	Generally good at standard blends	Major challenge
Lubricity	Good	Not relevant to CI injection systems	Requires attention
Cold-start performance	Generally good to moderate	Can be problematic at high ethanol	Potentially problematic
Engine modification	Low for moderate blends	Low for low blends; higher for high blends	Calibration/additives often required
Technology readiness	High	High for low/moderate blends	Moderate

Table 6

XVIII. Future Research Directions

To achieve the sixth objective, future research should focus on the following areas:

- **Optimization of blend ratios -** Rather than increasing biodiesel or ethanol content indiscriminately, future research should determine optimum blend ratios for specific engine architectures and operating conditions. Multi-objective optimization should simultaneously consider BTE, BSFC, NOx, PM, CO, HC, combustion stability, and cost.
- **Advanced engine calibration -** Electronic fuel injection provides opportunities to optimize injection pressure, injection timing, multiple injection strategies, ignition timing, air–fuel ratio, and exhaust-gas recirculation according to fuel composition.
- **Ternary and quaternary fuel systems -** Further investigation of diesel–biodiesel–ethanol systems is justified because each component can compensate for weaknesses in another. Additives, co-solvents, cetane improvers, and oxygenated compounds should be evaluated systematically.
- **Waste-derived biofuels -** Future biodiesel and ethanol production should increasingly emphasize waste cooking oil, agricultural residues, lignocellulosic biomass, municipal organic waste, and other non-food resources to improve sustainability.
- **Advanced combustion modes -** Alternative fuels should be studied in HCCI, RCCI, PCCI, dual-fuel, and other low-temperature combustion concepts. Such strategies may reduce the conventional NOx–PM trade-off of CI engines.
- **Nanoparticle and catalytic additives -** Nanoparticle additives and catalytic materials have been investigated for improving heat transfer, evaporation, combustion, and emission characteristics. However, their long-term environmental and health impacts require equal attention before large-scale deployment.
- **Artificial intelligence and predictive modelling -** Machine-learning models can be used to predict engine performance and emissions based on fuel properties, blend ratios, engine speed, load, injection timing, and other operating variables. Combining experimental datasets with CFD and machine-learning optimization could significantly reduce experimental cost.
- **Long-duration durability testing -** Most published studies are short-duration laboratory experiments. Future studies should include thousands of operating hours to

evaluate injector durability, lubricant degradation, piston-ring wear, deposits, corrosion, and after-treatment compatibility.

- **Life-cycle assessment -** Future comparisons should move beyond tailpipe emissions and include well-to-wheel greenhouse-gas emissions, land use, water consumption, energy return, production cost, and waste generation.
- **Standardization and commercialization -** Researchers, fuel producers, engine manufacturers, and policymakers should collaborate to establish reliable fuel-quality specifications for biodiesel–ethanol–diesel blends, particularly with regard to water content, phase stability, viscosity, lubricity, cetane number, oxidation stability, and cold-flow properties.

XIX. Conclusion

The comparative review demonstrates that biodiesel and ethanol are promising renewable fuels for reducing the dependence of IC engines on petroleum-derived fuels, but their effectiveness depends strongly on engine type, blend concentration, fuel properties, and operating conditions.

Biodiesel has emerged as one of the most practical renewable substitutes for petroleum diesel in compression-ignition engines. Its major advantages are renewable origin, biodegradability, high lubricity, oxygenated combustion, and substantial reductions in particulate matter, smoke, CO, and HC. However, lower heating value, increased BSFC, cold-flow limitations, oxidation stability, feedstock availability, and possible NOx increases remain significant challenges.

Ethanol is particularly attractive for spark-ignition engines because of its high-octane number, oxygen content, and high latent heat of vaporization. Low and moderate ethanol–gasoline blends can improve knock resistance and combustion and can reduce CO and HC emissions. Nevertheless, higher ethanol concentrations can increase fuel consumption and require modifications to engine calibration because of lower energy density and different combustion characteristics.

For compression-ignition engines, ethanol presents greater technical challenges because of its low cetane number, high latent heat of vaporization, reduced lubricity, and limited diesel miscibility. The combination of ethanol with biodiesel and diesel is therefore particularly promising because biodiesel can improve the physical and lubricity characteristics of ethanol-containing blends while ethanol contributes additional oxygen and can reduce soot formation.

The literature consequently supports a **fuel-specific and engine-specific approach rather than a universal alternative-fuel strategy**. Moderate biodiesel–diesel blends appear to be among the most immediately practical options for conventional CI engines, while moderate ethanol–gasoline blends are highly suitable for SI engines. Ternary diesel–biodiesel–ethanol fuels represent a promising research direction for simultaneously increasing renewable content and reducing particulate emissions, but their long-term stability, durability, combustion behaviour, and emission characteristics require further investigation.

Future development should therefore concentrate on **optimized fuel formulation, advanced injection and ignition control, low-temperature combustion, waste-derived feedstocks, additives, artificial-intelligence-based optimization, long-duration durability testing, and life-cycle assessment**. The ultimate goal should not simply be replacing fossil fuel with biofuel, but developing an integrated fuel–engine system that provides high efficiency, low emissions, technical reliability, economic feasibility, and demonstrable life-cycle environmental benefits.

XX. References

1. Altin, R., Çetinkaya, S., & Yücesu, H. S. (2001). The potential of using vegetable oil fuels as fuel for diesel engines. *Energy Conversion and Management, 42*(5), 529–538. https://doi.org/10.1016/S0196-8904(00)00080-7

2. Agarwal, A. K., Bijwe, J., & Das, L. M. (2003). Effect of biodiesel utilization on wear of vital parts in compression ignition engine. *Journal of Engineering for Gas Turbines and Power, 125*(2), 604–611. https://doi.org/10.1115/1.1454114

3. Canakci, M., & Van Gerpen, J. H. (2003). Comparison of engine performance and emissions for petroleum diesel fuel, yellow grease biodiesel, and soybean oil biodiesel. *Transactions of the ASAE, 46*(4), 937–944. https://doi.org/10.13031/2013.13948

4. Kalligeros, S., Zannikos, F., Stournas, S., Lois, E., Anastopoulos, G., Teas, C., & Sakellaropoulos, F. (2003). An investigation of using biodiesel/marine diesel blends on the performance of a stationary diesel engine. *Biomass and Bioenergy, 24*(2), 141–149. https://doi.org/10.1016/S0961-9534(02)00092-2

5. Ramadhas, A. S., Muraleedharan, C., & Jayaraj, S. (2005). Performance and emission evaluation of a diesel engine fueled with methyl esters of rubber seed oil. *Renewable Energy, 30*(12), 1789–1800. https://doi.org/10.1016/j.renene.2005.01.009

6. Knothe, G., Sharp, C. A., & Ryan, T. W. (2006). Exhaust emissions of biodiesel, petrodiesel, neat methyl esters, and alkanes in a new technology engine. *Energy & Fuels, 20*(1), 403–408. https://doi.org/10.1021/ef0502711

7. Topgül, T., Yücesu, H. S., Çinar, C., & Koca, A. (2006). The effects of ethanol–unleaded gasoline blends and ignition timing on engine performance and exhaust emissions. *Renewable Energy, 31*(15), 2534–2542. https://doi.org/10.1016/j.renene.2006.01.004

8. Canakci, M. (2007). Combustion characteristics of a turbocharged DI compression ignition engine fueled with petroleum diesel fuels and biodiesel. *Bioresource Technology, 98*(6), 1167–1175. https://doi.org/10.1016/j.biortech.2006.05.024

9. Raheman, H., & Ghadge, S. V. (2007). Performance of compression ignition engine with mahua (Madhuca indica) biodiesel. *Fuel, 86*(16), 2568–2573. https://doi.org/10.1016/j.fuel.2007.02.019

10. Lapuerta, M., Armas, O., & Rodríguez-Fernández, J. (2008). Effect of biodiesel fuels on diesel engine emissions. *Progress in Energy and Combustion Science, 34*(2), 198–223. https://doi.org/10.1016/j.pecs.2007.07.001

11. Rakopoulos, D. C., Rakopoulos, C. D., Kakaras, E. C., & Giakoumis, E. G. (2008). Effects of ethanol–diesel fuel blends on the performance and exhaust emissions of heavy duty DI diesel engine. *Energy Conversion and Management, 49*, 3155–3162. https://doi.org/10.1016/j.enconman.2008.05.023

12. Koç, M., Sekmen, Y., Topgül, T., & Yücesu, H. S. (2009). The effects of ethanol–unleaded gasoline blends on engine performance and exhaust emissions in a spark-ignition engine. *Renewable Energy, 34*(10), 2101–2106. https://doi.org/10.1016/j.renene.2009.01.018

13. Zhu, L., Cheung, C. S., Zhang, W. G., & Huang, Z. (2011). Combustion, performance and emission characteristics of a DI diesel engine fueled with ethanol–biodiesel blends. *Fuel, 90*(5), 1743–1750. https://doi.org/10.1016/j.fuel.2011.01.024

14. Shahir, S. A., Masjuki, H. H., Kalam, M. A., Imran, A., & Ashraful, A. M. (2015). Performance and emission assessment of diesel–biodiesel–ethanol/bioethanol blend as

a fuel in diesel engines: A review. *Renewable and Sustainable Energy Reviews, 48*, 62–78. https://doi.org/10.1016/j.rser.2015.03.049

15. Datta, A., & Mandal, B. K. (2016). A comprehensive review of biodiesel as an alternative fuel for compression ignition engine. *Renewable and Sustainable Energy Reviews, 57*, 799–821. https://doi.org/10.1016/j.rser.2015.12.170
16. Tamilselvan, P., Nallusamy, N., & Rajkumar, S. (2017). A comprehensive review on performance, combustion and emission characteristics of biodiesel fuelled diesel engines. *Renewable and Sustainable Energy Reviews, 79*, 1134–1159. https://doi.org/10.1016/j.rser.2017.05.176
17. Zaharin, M. S. M., Abdullah, N. R., Najafi, G., Sharudin, H., & Yusaf, T. (2017). Effects of physicochemical properties of biodiesel fuel blends with alcohol on diesel engine performance and exhaust emissions: A review. *Renewable and Sustainable Energy Reviews, 79*, 475–493. https://doi.org/10.1016/j.rser.2017.05.035
18. Niculescu, R., Clenci, A., & Iorga-Siman, V. (2019). Review on the use of diesel–biodiesel–alcohol blends in compression ignition engines. *Energies, 12*(7), 1194. https://doi.org/10.3390/en12071194
19. Iodice, P., & Cardone, M. (2021). Ethanol/gasoline blends as alternative fuel in last generation spark-ignition engines: A review on CO and HC engine out emissions. *Energies, 14*(13), 4034. https://doi.org/10.3390/en14134034
20. Ceyhan, Ç., Çoban, A., & Cesur, I. (2026). Ethanol effects on combustion and emissions in partial HCCI diesel engines under variable load and speed conditions. *Processes, 14*(14), 2273. https://doi.org/10.3390/pr14142273
21. Nagappan, M., Boomadevi, P., Ommurugadhasan, D., Jayaprabakar, J., Durairaj, R. B., & Sudhakar, K. (2026). Alternate fuels for internal combustion engines: Status review on improving performance and reducing emissions with biodiesel, bio-alcohol, bio-oil and plastic oil. *Environmental Progress & Sustainable Energy, 2026*, e70485. https://doi.org/10.1002/ep.70485
22. Suteerapongpun, T., Huynh, T. A., Aung, S. J., Thin, M. H., Thaeviriyakul, P., Srilomsak, M., Charoenphonphanich, C., & Karin, P. (2026). In-cylinder combustion and emission characteristics of a 3L compression ignition engine using pure biodiesel

fuel blended with 5% ethanol. *Atmospheric Environment: X, 30*, 100439. https://doi.org/10.1016/j.aeaoa.2026.100439

23. Suteerapongpun, T., Patkacha, A., Thaeviriyakul, P., Phairote, W., Saisirirat, P., Po-ngaen, W., Kosaka, H., & Karin, P. (2026). Impact of particulate filters on biodiesel and diesel fuel: A comparative study of thermal efficiency and emissions. *Results in Engineering, 30*, 110543. https://doi.org/10.1016/j.rineng.2026.110543
24. Utsav, Kumar, R., & Dhaka, A. (2026). Examining the effects of varying diesel, biodiesel, and ethanol fuel ratios on engine efficiency and emissions. *Discover Mechanical Engineering, 5*, Article 19. https://doi.org/10.1007/s44245-025-00180-w