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# Combustion Efficiency and Emission Control of Alternative Fuels: A Comprehensive Review

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A B S T R A K

Meningkatnya permintaan akan sumber energi bersih dan efisien telah mendorong pengembangan berbagai bahan bakar alternatif untuk menggantikan bahan bakar fosil, yang masih mendominasi sektor transportasi dan industri. Artikel ini menyajikan tinjauan komprehensif tentang karakteristik pembakaran dan emisi dari empat jenis bahan bakar alternatif utama: bioetanol, biodiesel, biogas, dan hidrogen. Tinjauan ini didasarkan pada literatur ilmiah terpilih yang diterbitkan antara tahun 2020 dan 2024, dengan fokus pada efisiensi termal, profil emisi (CO, HC, $NO_x$, PM), dan teknologi pengendalian emisi yang relevan. Analisis menunjukkan bahwa setiap bahan bakar memiliki karakteristik unik dalam hal kinerja pembakaran dan perilaku emisi. Hidrogen menawarkan efisiensi termal tertinggi dan emisi karbon nol, tetapi memerlukan sistem pembakaran dan penyimpanan khusus. Bioetanol dan biodiesel relatif kompatibel dengan mesin konvensional, meskipun menghadapi keterbatasan teknis dan risiko emisi sekunder. Biogas menunjukkan potensi yang tinggi, terutama ketika ditingkatkan menjadi biometana. Studi ini juga menyoroti pentingnya mengintegrasikan pemilihan bahan bakar dengan strategi pengendalian emisi yang tepat. Temuan ini diharapkan dapat menjadi referensi strategis untuk pengembangan sistem energi berkelanjutan di sektor otomotif dan industri.

A B S T R A C T

The growing demand for clean and efficient energy sources has driven the development of various alternative fuels to replace fossil fuels, which continue to dominate the transportation and industrial sectors. This article presents a comprehensive review of the combustion and emission characteristics of four major types of alternative fuels: bioethanol, biodiesel, biogas, and hydrogen. The review is based on selected scientific literature published between 2020 and 2024, with a focus on thermal efficiency, emission profiles (CO, HC, $NO_x$, PM), and relevant emission control technologies. The analysis shows that each fuel exhibits unique characteristics in terms of combustion performance and emission behavior. Hydrogen offers the highest thermal efficiency and zero carbon emissions but requires specialized combustion and storage systems. Bioethanol and biodiesel are relatively compatible with conventional engines, though they face technical limitations and risks of secondary emissions. Biogas demonstrates high potential, particularly when upgraded to biomethane. This study also highlights the importance of integrating fuel selection with appropriate emission control strategies. The findings are expected to serve as a strategic reference for the development of sustainable energy systems in the automotive and industrial sectors.

## 1. Introduction

The growth of population and industrialization has significantly increased global energy demand, which remains largely dependent on fossil fuels. This dependency raises concerns regarding energy sustainability and contributes substantially to greenhouse gas (GHG) emissions, such as carbon dioxide ($CO_2$), nitrogen oxides ($NO_x$), and particulate matter (PM), particularly in the transportation and industrial sectors [1].

To support the transition toward a low-carbon energy system, interest in the development and utilization of alternative fuels such as bioethanol, biodiesel, biogas, and hydrogen continues to grow [2], [3], [4], [5]. These fuels promise reduced emissions and improved combustion efficiency compared to conventional fuels, especially when employed in optimized engine systems. However, each alternative fuel has distinct physical and chemical properties, leading to challenges in energy conversion efficiency and specific emission control [6].

Combustion efficiency and emission reduction are two key parameters for evaluating the feasibility of alternative fuels. Numerous experimental and numerical studies have been conducted to analyze the thermal performance and emission

profiles of these fuels. Nevertheless, these findings remain fragmented and lack systematic integration.

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This article aims to provide a comprehensive literature review on the combustion and emission characteristics of various alternative fuels, along with an evaluation of the emission control technologies currently applied. The review focuses on comparative thermal efficiency, emission patterns (CO, HC, $NO_x$, PM), and innovations in emission control systems. It is expected to serve as a valuable reference for energy policy development and the adoption of environmentally friendly technologies in future transportation and industrial sectors.

## 2. Classification and Characteristics of Alternative Fuels

Alternative fuels refer to non-fossil energy sources that can be utilized in internal combustion engines or other energy systems (Ramly et al., 2020). These fuels include various types such as bioethanol, biodiesel, biogas, and hydrogen. Each type possesses distinct physical and chemical properties that influence the combustion process, thermal efficiency, and emission characteristics.

### *2.1. Bioethanol*

Bioethanol is a liquid fuel produced through the fermentation of carbohydrate-rich biomass, such as sugarcane, corn, or agricultural [7]. With a high-octane number (approximately 108 RON), bioethanol supports cleaner and more efficient combustion in spark-ignition engines [8]. However, its lower heating value (~27 MJ/kg) compared to gasoline (~45 MJ/kg) leads to higher fuel consumption [9], [10].

Bioethanol contains approximately 35% oxygen by mass, which enhances combustion completeness and reduces emissions of carbon monoxide (CO) and hydrocarbons (HC) [11]. A study by Jarkoni et al. demonstrated that the use of bioethanol–diesel blends in homogeneous charge compression ignition (HCCI) engines can significantly reduce CO and $NO_x$ emissions [12]. Nevertheless, at higher concentrations (e.g., E85), bioethanol may increase aldehyde emissions such as formaldehyde and acetaldehyde, and also poses a risk of fuel system corrosion [13].

Table 1. Properties of bioethanol and gasoline blends [11]

| Properties | Fuel Blend | | | | |
|---|---|---|---|---|---|
| | E0 | E10 | E30 | E50 | E70 |
| Density, kg/m$^3$ | 736.00 | 741.75 | 75.01 | 763.96 | 774.59 |
| C | 86.00 | 82.39 | 75.33 | 68.47 | 61.80 |
| H | 13.998 | 13.91 | 13.73 | 13.55 | 13.38 |
| O | 0.002 | 3.70 | 10.94 | 17.98 | 24.82 |
| C/H | 6.14 | 5.92 | 5.49 | 5.05 | 4.62 |
| MJ/kg | 43.50 | 41.74 | 38.30 | 34.96 | 31.71 |

Based on the properties of pure fuels, the relevant characteristics are listed in Table 1. Increasing the concentration of bioethanol in gasoline blends leads to a significant decrease in the carbon mass fraction and a substantial increase in the oxygen mass fraction of the fuel mixture. These compositional changes result in noticeable alterations in the fuel's physical and chemical properties. Table 1 also demonstrates that such variations in fuel composition directly affect the combustion process.

### *2.2. Biodiesel*

Biodiesel is increasingly recognized as a sustainable and environmentally friendly alternative fuel for diesel engines. It is produced through the transesterification of vegetable oils or animal fats, resulting in fatty acid methyl esters (FAME) [14].

Biodiesel has demonstrated strong potential in reducing harmful pollutant emissions such as carbon monoxide (CO), hydrocarbons (HC), and particulate matter (PM). This is attributed to its inherent oxygen content, which promotes more complete combustion, thereby reducing emission levels—particularly in diesel engines operating with biodiesel blends [15]. A study by Siddique et al. reported that biodiesel could reduce $CO_2$ emissions by up to 24% compared to conventional diesel, due to its higher oxygen content [16]. Furthermore, research conducted by Tamrat et al. showed that when biodiesel is used in combination with diesel or as a blend, HC emissions are also significantly reduced [17].

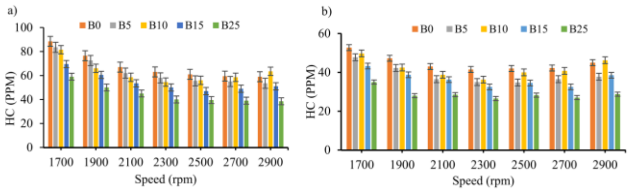


Fig 1. Unburned hydrocarbons emission versus engine speed for all blend ratios. (a) HC Emission without CeO2 Nano particle, (b) HC Emission with CeO2 Nano particle (Tamrat et al., 2024).

Despite its many advantages, biodiesel also presents certain challenges. The increased viscosity and density resulting from biodiesel blends can lead to energy losses during the combustion process. A study by Kandasamy et al. indicated that engine power output tends to decrease as the proportion of biodiesel in the fuel blend increases. [18].

### *2.3. Biogas*

Biogas is a gaseous fuel produced through the anaerobic fermentation of organic matter, typically containing 50–70% methane ($CH_4$), 25–45% carbon dioxide ($CO_2$), and trace amounts of hydrogen sulfide ($H_2S$) [19], [20]. To improve its quality, biogas is upgraded to biomethane through methods such as zeolite-based adsorption or membrane separation, both of which are effective in reducing $CO_2$ levels and increasing methane concentration [21].

Biomethane exhibits excellent combustion properties due to its high methane content, resulting in high thermal efficiency when used in internal combustion engines. Studies have shown that biomethane produces lower emissions of CO, $NO_x$, and particulate matter compared to fossil fuels [22]. Jadhav et al. reported a significant reduction in greenhouse gas (GHG) emissions, while Caposciutti et al. found that biomethane provides energy conversion efficiency comparable to that of natural gas [23], [24].

Despite these advantages, the use of biomethane as a vehicle fuel still faces several challenges. Factors such as production variability and the need for adequate storage and distribution infrastructure must be carefully considered [25].

### *2.4 Hydrogen*

Hydrogen has increasingly been recognized as a promising renewable energy source, offering a clean and efficient alternative to reduce carbon dioxide emissions and dependence on fossil fuels. With a high energy density of approximately 142 kJ/g (142 MJ/kg), hydrogen presents a viable solution for future energy sustainability [26].

Hydrogen can be produced through various methods, including water electrolysis, biomass gasification, and hydrocarbon reforming. Among these, electrolysis is considered one of the most promising techniques, particularly when powered by renewable sources such as solar and wind energy. Research shows that high-efficiency electrolysis, especially using seawater, can enhance hydrogen production with improved energy efficiency [26], [27]. A study by Simbolon et al. demonstrated that using hydrogen as a vehicle fuel can improve fuel efficiency and reduce exhaust emissions. Combining hydrogen with biogas, for instance, has been shown to increase engine generator efficiency by up to 29.26% [28].

Hydrogen combustion primarily produces water ($H_2O$) and small amounts of nitrogen oxides ($NO_x$). As no carbon dioxide ($CO_2$) is released during the combustion process, hydrogen offers clear environmental advantages over fossil fuels. The thermal efficiency of hydrogen combustion in engines can be remarkably high; in certain studies, hydrogen-powered vehicles have achieved efficiencies of up to 33.62% [28].

Despite its advantages, several challenges remain in the development and large-scale adoption of hydrogen as a fuel. The high production cost particularly through electrolysis continues to be a major barrier [29].

## 3. Results and discussion Combustion Efficiency of Alternative Fluels

Combustion efficiency is a key parameter for evaluating the energy performance of alternative fuels. Several indicators such as heating value, cetane/octane number, ignition delay, and thermal efficiency are used to assess the ability of fuels to generate energy effectively in internal combustion systems. The four major alternative fuels bioethanol, biodiesel, biogas, and hydrogen exhibit distinct characteristics that affect their performance in both spark ignition (SI) and compression ignition (CI) engines.

In terms of heating value, hydrogen holds a clear advantage, ranging from 120 to 142 MJ/kg, significantly surpassing biodiesel (37–40 MJ/kg), bioethanol (~27 MJ/kg), and biogas (21–23 MJ/m³ in raw form). This high energy content allows hydrogen to produce more power per unit mass, although technical challenges remain in terms of storage and combustion temperature control. On the other hand, bioethanol's lower heating value results in higher fuel consumption to achieve the same energy output, but its high-octane rating supports efficient combustion in gasoline engines, especially under high load conditions.

Thermal efficiency is also strongly influenced by the compatibility of the fuel with engine type. Biodiesel, with a high cetane number (48–65), is well-suited for diesel engines, enabling rapid and stable combustion. Studies show that biodiesel's thermal efficiency improves under full load but may decline at lower temperatures due to its high viscosity and suboptimal atomization. Bioethanol, with its high-octane number (~108 RON), performs well in SI engines, contributing to cleaner and faster combustion. Purified biogas or biomethane exhibits combustion efficiency comparable to that of natural gas, and its performance is further enhanced when used in dual-fuel systems with methanol or diesel [30]. Hydrogen offers the highest thermal efficiency, particularly in lean-burn systems and high-compression engines such as HCCI and fuel cell hybrids, although it requires precise control of the air–fuel mixture and combustion temperature.

Efficiency optimization challenges arise from the intrinsic properties of each fuel. Biodiesel requires injection systems capable of handling high viscosity, while bioethanol necessitates ECU calibration to adjust the stoichiometric ratio due to its oxygen and moisture content. Unrefined biogas can lower combustion efficiency due to $CO_2$ dilution and the presence of contaminants such as $H_2S$ [31]. Hydrogen combustion also demands strategies to mitigate $NO_x$ formation caused by high flame temperatures, which can be addressed through lean combustion and EGR techniques.

Based on the reviewed literature, Table 2 presents a summary of key parameters affecting the combustion efficiency of each alternative fuel. This summary is intended to complement the narrative analysis by providing structured and comprehensive technical insights.

Table 2. Comparison of Combustion Efficiency Parameters of Alternative Fuels

| Parameter | Bioethanol | Biodiesel | Biogas / Biomethane | Hydrogen |
|---|---|---|---|---|
| **Heating value (MJ/kg)** | ~27 | 37–40 | 21–23 (biogas), ~50 $CH_4$ | 120–142 |
| **Octane/Cetane number** | RON ~108 | 48–65 | (~130 $CH_4$) | RON >130 |
| **Ignition delay** | Short | Very shor | Moderate | Very short |
| **Thermal efficiency** | Relatively high | High | High if purified | Very high |
| **Main challenges** | Low heating value | High viscosity | Requires $CO_2$/$H_2S$ removal | $NO_x$ control & storage issues |

Table 2 reveals that hydrogen has a distinct advantage in terms of heating value and thermal efficiency, but it requires more complex combustion and storage systems. In contrast, bioethanol and biodiesel are more compatible with existing engine systems, although each presents limitation in terms of energy density and operational stability. Biogas or biomethane occupies an intermediate position, offering good efficiency with low emissions, provided that proper purification processes are applied. This comparison highlights the importance of a contextual approach in selecting alternative fuels, based on system requirements and application conditions.

Based on the reviewed studies, it can be concluded that combustion efficiency is highly influenced by the compatibility between fuel characteristics and engine type. However, few studies have systematically examined the

performance of different alternative fuels across various engine configurations. Therefore, this article attempts to address this gap by comparing actual efficiency outcomes based on experimental data from multiple engine types and modern combustion technologies.

## 4. Emissions and Emission Control Technologies

Exhaust emissions are a critical indicator for assessing the environmental impact of alternative fuel usage. Four major pollutants carbon monoxide (CO), hydrocarbons (HC), nitrogen oxides ($NO_x$), and particulate matter (PM) are emitted in varying concentrations depending on the fuel's characteristics and the combustion system employed. Emission control technologies are therefore essential to ensure that alternative fuels truly contribute to air quality and environmental sustainability.

In general, oxygenated fuels such as bioethanol and biodiesel tend to produce lower CO and HC emissions than fossil fuels, due to their ability to support more complete combustion. Bioethanol, with its simple molecular structure and high oxygen content, significantly reduces CO and HC emissions in gasoline engines. However, higher bioethanol concentrations in fuel blends can increase aldehyde emissions particularly formaldehyde and acetaldehyde which are carcinogenic and require additional oxidation catalyst systems for effective mitigation.

Biodiesel exhibits a cleaner emission profile than conventional diesel, especially in terms of reduced PM and HC emissions. Nevertheless, its high cetane number and resulting high combustion temperatures often lead to increase $NO_x$ emissions. Technologies such as selective catalytic reduction (SCR) and exhaust gas recirculation (EGR) have proven effective in addressing this issue (Lee et al., 2021; Wardana & Lim, 2023).

Purified biogas or biomethane produces very low emissions due to its high methane content, which enables cleaner combustion. However, raw biogas often contains hydrogen sulfide ($H_2S$), which can damage combustion systems and catalysts. Thus, pretreatment using $H_2S$ filters or membrane separation is essential before use. Biogas is also well-suited for dual-fuel systems, which have been shown to significantly reduce CO emissions.

Hydrogen, as a carbon-free fuel, produces virtually no $CO_2$ or PM emissions. Nevertheless, its high flame temperature can trigger $NO_x$ formation. Common strategies to mitigate $NO_x$ emissions from hydrogen combustion include low-temperature combustion, steam dilution, and precise stoichiometric control.

To clarify emission trends and relevant mitigation strategies, Table 3 summarizes the relationships between fuel characteristics, dominant emissions, and applicable emission control technologies. This information supports an integrative approach to the selection and application of sustainable alternative fuels.

Table 3. Comparison of Emission Patterns and Emission Control Technologies for Alternative Fuels

| Fuel Type | General Emissions | Emission Challenges | Recommended Emission Control Technologies |
|---|---|---|---|
| **Bioethanol** | CO↓, HC↓, $NO_x$→ | Aldehyde emissions formaldehyde ↑ | Oxidation catalyst (DOC), aldehyde sensors |
| **Biodiesel** | CO↓, HC↓, PM↓ | $NO_x$ ↑ | SCR, EGR, injection timing adjustment |
| **Biogas** | CO↓, PM↓ | $H_2S$ ↑ (if unrefined) | $H_2S$ filters, gas sensor-based injection systems |
| **Hydrogen** | $CO_2$ = 0, PM = 0 | $NO_x$ ↑ at high temperatures | Lean combustion, EGR, steam dilution |

Simulations and experimental studies have shown that combining alternative fuels with modern after-treatment systems can achieve high efficiency while significantly reducing emissions, meeting even stringent standards such as Euro VI. Therefore, the selection strategy for alternative fuels must incorporate an integrated consideration of both combustion efficiency and the effectiveness of emission control systems.

## 5. Challengs and Development Recommendations

Although alternative fuels offer numerous benefits in terms of combustion efficiency and emissions, their real-world implementation still faces a range of complex challenges. These challenges can be classified into technical, economic, environmental, and policy-related aspects.

From a technical standpoint, the physical and chemical properties of alternative fuels are often not fully compatible with conventional engine designs. For example, biodiesel has higher viscosity and flash point, which necessitate modified injection systems. Bioethanol, due to its high-water content, can cause corrosion in engine components. Hydrogen, meanwhile, requires significantly more complex storage systems and combustion control mechanisms than liquid fuels.

Economically, production costs and distribution infrastructure remain major barriers. Technologies such as biogas purification, hydrogen production via electrolysis, and biofuel feedstock processing are still relatively expensive particularly without large-scale production or government subsidies. Additionally, the availability of local feedstock such as agricultural waste, vegetable oil, or seawater also determines the long-term sustainability of the supply chain.

From an environmental perspective, although alternative fuels significantly reduce greenhouse gas (GHG) emissions, the life cycle of their production (Life Cycle Assessment, LCA) must be thoroughly evaluated. Agricultural activities for biofuel crops and the energy consumed in water electrolysis may contribute to carbon footprints if not managed sustainably.

On the policy side, the lack of national standards for the quality and distribution of alternative fuels, along with uneven incentives for producers and users, hinders widespread adoption. Therefore, synergy among research institutions, the automotive industry, and the government is essential to establish a supportive regulatory framework.

## 6. Conclusions

This article has systematically reviewed the combustion efficiency and emission characteristics of four major alternative fuels: bioethanol, biodiesel, biogas, and hydrogen. Each fuel offers distinct advantages such as the compatibility of bioethanol and biodiesel with conventional engines, the low emissions of purified biogas, and the high efficiency and zero carbon emissions of hydrogen. However, the implementation of each fuel requires technical adjustments, including air fuel ratio calibration, combustion temperature control, and specialized injection and storage systems.

Emission control technologies such as oxidation catalysts, selective catalytic reduction (SCR), exhaust gas recirculation (EGR), and lean combustion have proven effective in reducing harmful emissions, but their application must be tailored to the specific characteristics of each fuel. This review confirms that there is no universal solution; the selection of alternative fuels and related technologies must account for technical compatibility, efficiency, and environmental impact.

An integrated effort involving research, technological development, and policymaking is essential to accelerate the adoption of alternative fuels. With a holistic approach, these fuels can play a vital role in the transition toward a cleaner, more efficient, and sustainable energy system.

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