

Analysis of the Compatibility of Alternative and Green Fuels with Internal Combustion Engines: A Mini-Review

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Abstract

Burning fossil fuels for different applications and requirements emits harmful emissions into the atmosphere. As a result, global greenhouse gas (GHG) emissions increase, and climate change is observed worldwide. Stringent environmental regulations have been proposed and implemented across all fossil fuel-using sectors that emit high levels of GHGs. The transportation sector is highly dependent on fossil fuels, and internal combustion engines (ICEs) play a major role in this use. To address this harmful emissions challenge, alternative fuels have been proposed as replacements for conventional fossil fuels. Alternative fuels show promising results when used as replacement fuels. In fact, the first diesel engine model (1890s) ran on alternative fuels (peanut oil). Therefore, in this review, a technical discussion on how well the existing ICEs are compatible with these alternative and clean burning fuels, specifically biodiesel, hydrogen and methanol fuels, is provided based on the significant fuel oil properties, combustion performance and emission characteristics. Based on these discussions, comprehensive conclusions are drawn using three compatibility categories: high, moderate, and conditional.

Keywords: Biodiesel; Methanol; Hydrogen; Compatibility analysis

1. Introduction

Internal combustion (IC) engines play an important role in different industries and sectors, including transportation and agriculture. Hydrocarbon fuels obtained from distillation are the primary input fuels for the successful operation of these IC engines. Hydrocarbon fuels, including petrol, diesel, heavy fuel oil, marine diesel oil, and low- and ultra-low-sulfur fuel oils, have high heating values [1]. As a result, these fuels are widely used in IC engines because of their availability and the established infrastructure for processing crude oil into final products, making hydrocarbon fuels a preferred choice for most IC engines. However, the major concern with these fuels is the harmful exhaust emissions, such as CO₂, CO, UHC, NO_x, SO_x, and soot. These harmful emissions, especially CO₂, contribute to greenhouse gas (GHG) emissions and affect global climate change [2]. The increase in GHG levels will trap heat in the Earth's atmosphere, allowing sunlight to pass through but restricting heat from escaping back into space. As a result, global warming and climate change alter the entire planet's energy balance and disrupt global climate systems [2].

Climate change and greenhouse gas effects are slow processes, and their immediate effects may not yet be observed. However, if they are not properly regulated and addressed, they will significantly impact Earth's entire ecosystem. In fact, their influence is evident in rising sea levels, melting ice, ocean degradation, extreme weather

events, and rising global temperatures, among other effects. Therefore, global efforts are underway to combat these GHGs, and key initiatives include the United Nations Framework Convention on Climate Change (UNFCCC), founded in 1992, which hosts annual climate summits. In 1997, the Kyoto Protocol was adopted to reduce industrial GHG emissions. In 2015, the Paris Agreement brought almost all nations together to pledge to limit global warming to below 2 °C. As shown in Figure 1 and Figure 2 [3], despite these positive initiatives, GHG emissions are still rising to alarming levels.

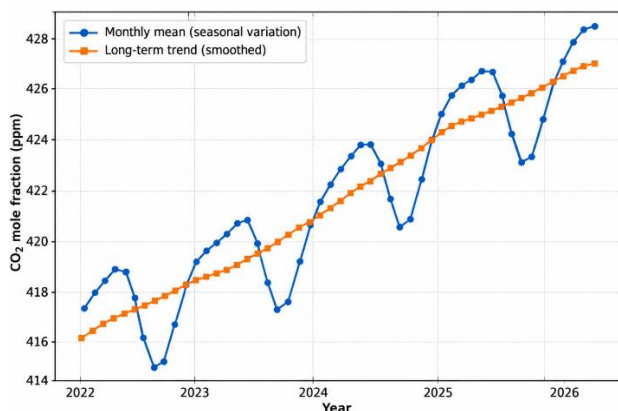


Figure 1. Recent global monthly means taken on 28th June 2026 [3]

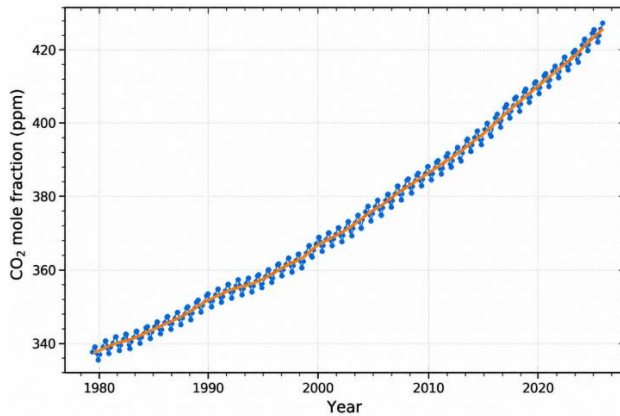


Figure 2. Global monthly means since 1980, taken on 28th June 2026 [3]

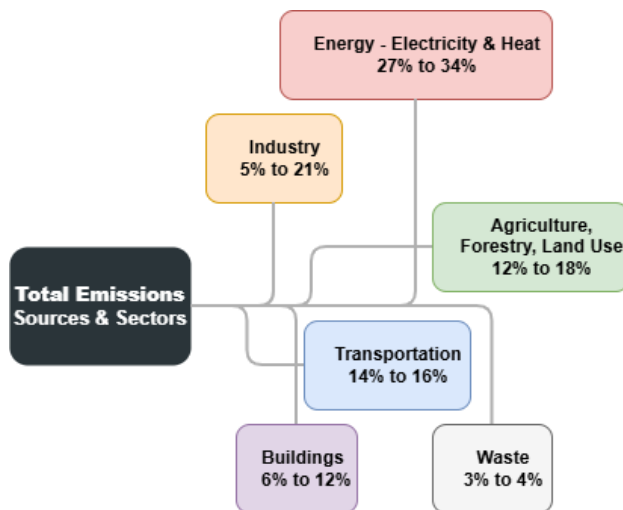


Figure 3. Global emissions from different sectors [5]

According to Climate TRACE data, global GHG emissions reached an all-time high of approximately 60.63 billion tonnes of CO₂ equivalent. This shows that a year-over-year increase of roughly 0.50% is occurring amid rising emissions from fossil-fuel-driven systems, particularly in the transportation sector [3]. Therefore, to mitigate the challenge, key measures such as reducing emissions intensity, adopting renewable energy, and implementing carbon trading are being pursued globally to achieve net-zero by mid-century, i.e., 2050 [4].

Some of the top global emitters of GHG emissions (approximately) by sector are shown in Figure 3, which highlights that the energy sector records the highest 27% to 34% of global emissions, mainly due to fossil fuel combustion, followed by industry at around 21% due to the production process of steel, cement and chemical products. The transportation sector contributes 14% to 16%, with road transportation dominating. Due to deforestation and livestock methane emissions, agriculture, forestry, and land use will contribute 12% to 18% of global emissions. Heating, cooling, and cooking are considered building emissions, which contribute 6% to 12%, and the remaining waste emissions, primarily methane from landfills, account for approximately 3% to 4%. Nationwide, China, the USA, India, and the EU are the largest contributors to GHG emissions [5].

To mitigate GHG emissions, these industries also implement strategic preventive measures. These include expanding renewable energy, modernizing the electrical

power grid, deploying carbon capture and storage, and deploying nuclear power, which are feasible options for energy, electricity, and heat applications [6]. For the transportation sector, adopting sustainable fuels and transitioning to electric vehicles are the best choices. For industries, replacing conventional coal-based energy with green hydrogen is a key option. Similarly, for building applications, heat pump adoption, net-zero building envelopes, LED and smart automation are preferred [7].

These discussions show that global GHG emissions are still increasing despite the implementation of different mitigation strategies. Therefore, this study examines transportation sector GHG emissions, specifically the role of internal combustion engines using sustainable fuels as an alternative to conventional hydrocarbon fuels to reduce harmful exhaust emissions, including GHG emissions. This study selected and examined popular alternative fuels such as biodiesel, methanol, and hydrogen for their key properties, performance, and emissions. This analysis may help understand the IC engine's compatibility with these emerging alternative fuels.

2. Alternative Fuels

Alternative renewable fuels are well known for their sustainability and environmental friendliness. These fuels serve as replacements for existing hydrocarbon fuels, and most alternative fuels will be derived from natural sources or, in their production, utilize clean energy sources such as solar, wind, tidal, and biomass [8]. In simple terms, alternative fuels are less polluting than hydrocarbon fuels and cause less damage. There are different types of alternative fuels available in the market, of which we are interested in biodiesel, methanol, and hydrogen. Figure 4 shows a generalized layout of alternative fuels for IC engines, with hydrogen as a zero-carbon fuel and biodiesel and methanol derived from biomass.

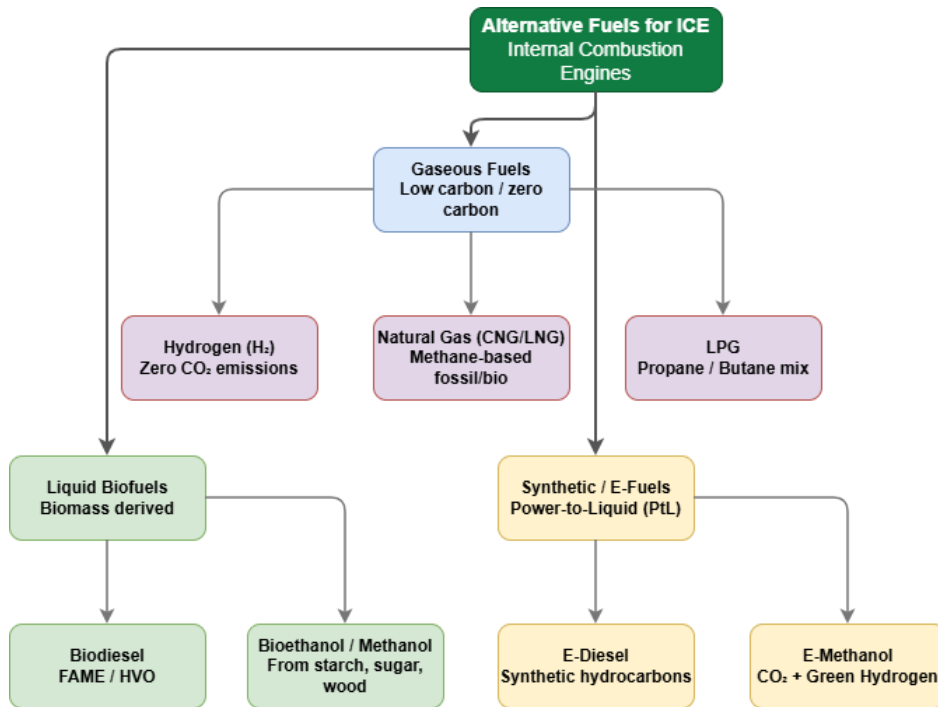


Figure 4. Widely used alternative fuels for IC engines

2.1. Biodiesel

Biodiesel is a promising alternative fuel for IC engines, as it is sulfur-free and biodegradable. In general, biodiesel can be produced from plant, animal, and vegetable oils by following a chemical treatment process called transesterification [9], [10], as shown in Figure 5. Before the discovery of petrodiesel fuel, the IC engines were run with edible oil, and in fact, the first demonstrated IC engine ran with peanut oil. After the discovery of hydrocarbon fuels, the utilization of highly viscous edible and non-edible oils gradually declined due to several factors, including their properties. As hydrocarbon fuels possess a high calorific value, edible and non-edible oils show lower calorific values. Now, the question is not to produce high torque or mechanical efficiency from IC engines [11]. Now the focus is on how much harmful emissions are released during IC engine operations. It is obvious that hydrocarbon fuels like petrol and diesel will emit high levels of harmful gases (CO_2 , CO , SO_x , NO_x , PM, UHC, Soot, etc) during their use in IC engines. Therefore, clean-burning fuels are gaining popularity, and biodiesel is one among the various alternative fuels, which can be produced from 2nd- and 3rd-generation oils such as non-edible oils, waste cooking oils, and algae oils [12].

Some important properties of biodiesel are highlighted in Table 1, compared with existing diesel fuel. These properties reveal significant information, for instance, that biodiesel has a high cetane number (50-60), which reduces the ignition delay during combustion, and that its high flash and fire points are advantageous for safe storage and transportation. Biodiesel is an environmentally friendly fuel because it is highly biodegradable compared to diesel fuel and contains almost no sulfur [13].

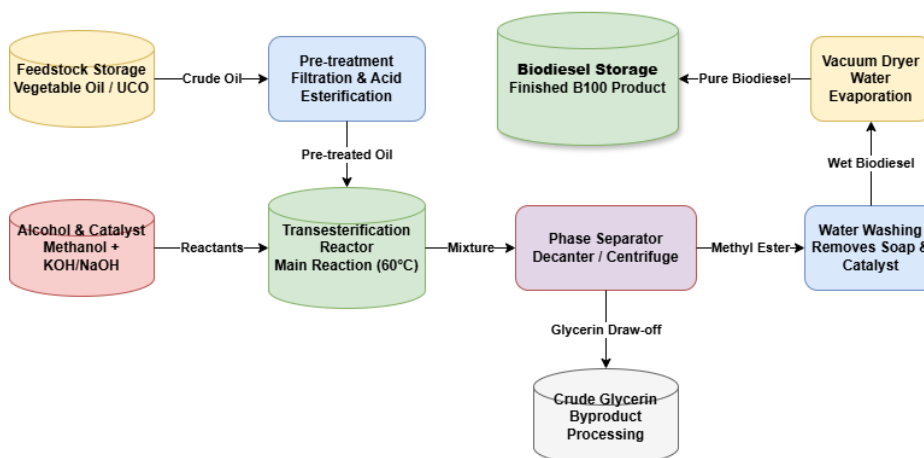


Figure 5. Schematic layout of the biodiesel production process [9]

Table 1. Significant properties of biodiesel [9], [12], [13]

S.No	Property	Biodiesel (B100)	Diesel Fuel
1	Density at 15°C (Kg/m ³)	~860-900	~820-845
2	Kinematic Viscosity at 40 °C (mm ² /s cSt)	~3.5-5.0	~2.0-3.0
3	Lower heating value (MJ/kg)	~37-39	~42-43
4	Flash Point (°C)	~120-170	~52-95
5	Fire Point (°C)	~130-190	~60-110
6	Autoignition Temperature (°C)	~250-300	~210-260
7	Cloud Point (°C)	~ -3-15	~ -15-5
8	Pour Point (°C)	~ -15-10	~ -35-15
9	Cetane number	~50-60	~45-55
10	Sulfur content (ppm)	~10-15 ppm	~ <10ppm
11	Bulk modulus (MPa)	~1500-1700	~1300-1500
12	Biodegradability (%)	~ >90	~10-15
13	Lubricity	High	Low

The compatibility of a fuel for practical applications depends on several parameters, among which fuel properties, combustion performance, and emission characteristics are vital. The important properties that determine the suitability of biodiesel for existing engines are a higher cetane number, superior lubricity, negligible sulfur content, a high flash point, and inherent oxygen content. These properties contribute to reliable ignition, safer handling, reduced engine wear and cleaner combustion [14]. However, biodiesel also exhibits relatively high viscosity and density, a lower heating value, and poor cold-flow characteristics compared to diesel fuel, which may influence atomization and fuel consumption. Nevertheless, when biodiesel complies with established international fuel quality standards such as ASTM D6751 or EN 14214, it allows its use in existing diesel engines with little or no hardware modification, particularly at lower blend ratios [15].

The combustion compatibility of biodiesel is mainly governed by its higher cetane number and oxygenated molecular structure, which help achieve shorter ignition delay and more complete combustion. As a result, biodiesel generally exhibits combustion characteristics similar to those of diesel fuel, with cylinder pressures and heat release rates comparable to those of diesel fuel [16]. Although biodiesel has a lower calorific value, it results in slightly increased brake-specific fuel consumption, but engine power and brake thermal efficiency are often maintained at acceptable levels, particularly for biodiesel blends. Different experimental studies [17], [18], [19], [20] have demonstrated that biodiesel can deliver satisfactory combustion performance without major modifications.

The exhaust emissions characteristics of biodiesel demonstrate excellent compatibility with existing diesel engines due to its oxygen-rich composition and sulfur-free nature. The enhanced oxygen availability promotes more complete oxidation of the fuel, resulting in a significant reduction in carbon monoxide, unburnt hydrocarbons, smoke opacity, and particulate matter emissions. Although certain biodiesel fuels may exhibit a slight increase in nitrogen oxide emissions due to high local combustion temperatures and advanced combustion phasing [21]. Overall, biodiesel provides a cleaner emissions profile than diesel fuel, making it an environmentally compatible alternative for diesel engines.

2.2. Hydrogen (H₂)

Hydrogen is widely recognized as one of the most promising alternative fuels for achieving sustainable, low-carbon energy systems due to its high specific energy and clean combustion characteristics. Unlike conventional fossil fuels, hydrogen does not contain carbon; therefore, its combustion ideally produces water vapour as the main product and eliminates direct carbon dioxide emissions [22]. Hydrogen can be produced by electrolysis, and various feedstocks, including coal, natural gas, and biomass, can be utilized. Figure 6 represents the production pathways for hydrogen fuel, and it is evident that, depending on the feedstocks and production techniques, hydrogen can be divided into three categories: grey, blue, and green hydrogen. Grey hydrogen uses coal or natural gas for the water electrolysis process, and the grey technique emits carbon into the atmosphere. The limitation of the grey technique is overcome by the blue hydrogen process, which utilizes carbon capture techniques so that carbon emissions are not released into the atmosphere. Finally, the green hydrogen production process is the most promising, as it utilizes clean energy sources, including solar, wind, and hydro, for the water electrolysis process [23].

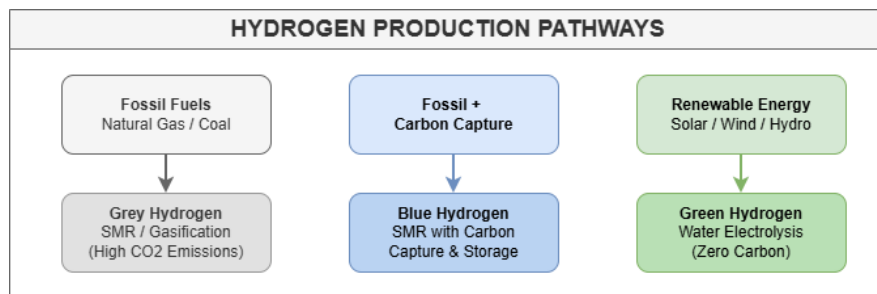


Figure 6. Grey, blue and green hydrogen production pathways [23]

Hydrogen can be produced from a variety of feedstocks using different techniques. In simple terms, hydrogen production involves separating hydrogen atoms from compounds such as water or hydrocarbons. Because hydrogen does not occur freely in nature in large quantities, it must be extracted from these sources before it can be used as a fuel. Some of the popularly used techniques for hydrogen production are Steam methane reforming (SMR), water electrolysis, coal gasification and biomass gasification. Figure 7 demonstrates a water electrolysis process, highlighting a provision for using renewable energy [24]. The important properties of hydrogen compared with conventional hydrocarbon fuels, diesel and gasoline, are presented in Table 2, which indicates that hydrogen has key advantages in terms of high gravimetric energy, zero carbon emissions, wide flammability limits, high flame speed, low ignition energy, high diffusivity, and no sulfur.

Nowadays, hydrogen is emerging as a promising fuel, as it possesses unique physicochemical properties that make it an attractive alternative to internal combustion engines. Some of the key properties are its highest gravimetric energy content (~120 MJ/kg), enabling a large amount of energy to be released per unit mass of fuel. Its wide flammability limits (~4 to 75% by volume), high flame speed, and very low ignition energy promote rapid flame propagation and stable combustion over a wide range of operating conditions. In addition, hydrogen is free of carbon and sulfur, so direct carbon and sulfur emissions will be eliminated. Some challenges with hydrogen fuel include its low volumetric energy density, high auto-ignition temperature, and low cetane number, which prevent reliable auto-ignition at conventional diesel engine compression ratios. In addition, its gaseous nature necessitates specialized storage systems such as cryogenic tanks [25].

The combustion characteristics of hydrogen fuel are exceptionally favourable. Its high flame speed and excellent diffusivity promote rapid air-fuel mixing, lower combustion duration, and improved combustion efficiency. In dual-fuel injection engines, hydrogen is introduced through port or direct injection, while a small quantity of diesel serves as the ignition source. This combustion strategy enables stable engine operation without relying on hydrogen auto-ignition. Different studies [26], [27], [28], [29], [30] showed that hydrogen enrichment can improve brake thermal efficiency, enhance combustion stability, and reduce combustion variability, specifically at medium and high engine

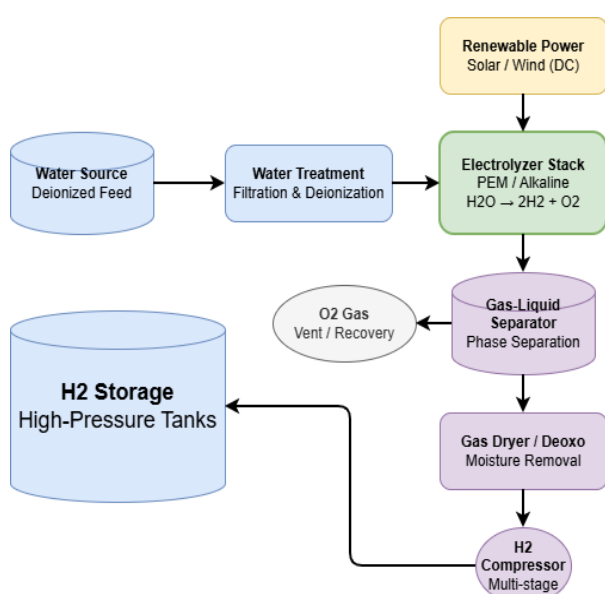


Figure 7. Hydrogen production process via water electrolysis [23, 24]

loads. However, due to high combustion temperatures, there may be increased thermal loading and a higher rate of rise in combustion pressure. Therefore, although hydrogen exhibits better combustion performance, its effective utilization may require optimized injection timing, appropriate hydrogen-substitute ratios, and engine control strategies.

Hydrogen offers a significant advantage in terms of exhaust emissions due to its carbon-free composition. Harmful emissions, including CO, HC, PM, CO₂, and smoke opacity, will be substantially reduced or virtually eliminated. These characteristics make hydrogen fuel a clean-burning fuel for internal combustion engines. However, hydrogen combustion produces high flame temperatures, which may raise combustion temperatures and lead to thermal NO_x formation, particularly at higher engine loads [28], [29].

Table 2. Significant properties of hydrogen fuel comparison with hydrocarbon fuels [25]

S.No	Property	Hydrogen	Diesel fuel	Gasoline
1	Density at 15°C (Kg/m ³)	~0.0899	~830-850	~720-780
2	Volumetric energy density (MJ/L)	~0.0108 (gas at 1atm)	~35-36	31-32
3	Lower heating value (MJ/kg)	~120	~42-43	~43-44
4	Flammability limits in Air (% Vol)	~4-75	~0.6-7.5	~1.4-7.6
5	Detonation limits (% Vol)	~18-59	~1-6	~1.1-3.3
6	Autoignition Temperature (°C)	~585	~210	~280
7	Laminar flame speed (m/s)	~ 2.5-3.0	~0.30-0.40	~0.35-0.45
8	Carbon content	None	High	High
9	Sulfur content	None	Tracible	Negligible

2.3. Methanol Fuel (CH₃OH)

Methanol (CH₃OH), also known as methyl alcohol or wood alcohol, is one of the promising alternative fuels available. The chemical structure of methanol reveals that it is a simple alcohol consisting of one carbon atom, four hydrogen atoms, and one oxygen atom, making it the simplest liquid alcohol fuel. Methanol can be produced from a wide range of feedstocks, including natural gas, coal, biomass, municipal solid waste, and renewable energy sources, using carbon capture techniques (e-methanol). The production process of methanol involves the conversion of carbon-containing materials into synthesis gas, also called syngas, which consists of carbon monoxide (CO), carbon dioxide (CO₂), and hydrogen (H₂) [31]. This syngas is critically converted into methanol under high pressure and moderate temperatures. Figure 8 represents the schematic layout of the methanol production process. The commonly used methods for methanol production include steam reforming, coal gasification, biomass gasification, CO₂ hydrogenation, and waste-to-methanol production [32].

The physicochemical properties of methanol fuel make it a favourable alternative fuel. Some of them are high octane number, high latent heat of vaporization, oxygen content (approximately 50% by weight), and methanol is a sulfur-free fuel [33]. Some significant fuel properties are presented in the table for comparison with conventional hydrocarbon fuels. Several significant fuel properties of methanol compared with conventional hydrocarbon fuels are presented in Table 3. The physicochemical properties of methanol fuel are attractive and also suitable for internal combustion engines. At ambient conditions, methanol remains a liquid and can be stored, transported, and distributed using existing liquid fuel infrastructure, with comparatively fewer challenges than gaseous fuels such as hydrogen. Methanol possesses high oxygen in its molecular structure, approximately 50% by weight, which helps in achieving better and cleaner combustion by enhancing fuel oxidation [33], [34]. Methanol is also sulfur-free, eliminating SO_x emissions. In addition, methanol exhibits a high-octane number and a high latent heat of vaporization, which may contribute to better combustion efficiency under appropriate operating conditions. On the other hand, methanol has certain limitations, including a lower cetane number, a lower heating value, lower viscosity, and higher auto-ignition temperatures than diesel fuel. These limitations make methanol fuel unsuitable for direct auto-ignition in conventional internal combustion engines. Therefore, for the direct methanol fuel application in internal combustion engines, certain modifications are essential, specifically to the fuel injection system, or methanol can be used in dual-fuel mode with a pilot fuel [35].

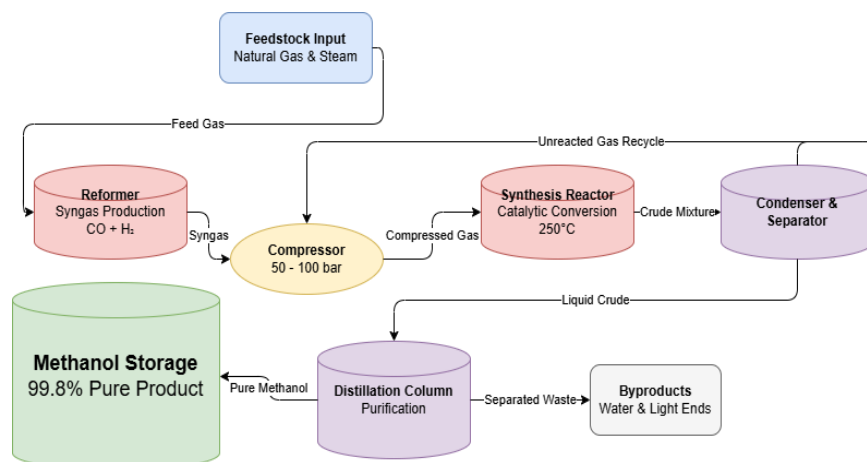
**Figure 8.** Methanol production process: a schematic layout [32]

Table 3. Significant properties of methanol fuel [33]

S.No	Property	Methanol	Diesel fuel
1	Density at 15°C (Kg/m ³)	~790-795	~820-845
2	Kinematic Viscosity at 40 °C (mm ² /s cSt)	~0.5-0.6	~2.0-3.0
3	Lower heating value (MJ/kg)	~19.2-20.2	~42-43
4	Flash Point (°C)	~11-12	~52-95
5	Cetane number	~3-5	~45-55
6	Autoignition Temperature (°C)	~464-470	~210-260
7	Octane number	~109-110	-
8	Latent heat of vaporization (kJ/kg)	~1100-1170	~250-300
9	Oxygen content (% by weight)	~50	~0
10	Sulfur content (ppm)	Nil	~ <15ppm
11	Carbon content (% by weight)	~ 37.5	~86
12	Boiling Point (°C)	64.7	180-360
13	Flammability limits in Air (% by volume)	~ 6-36	0.6-7.5

Fuel properties play an important role in examining the combustion performance. Methanol fuel is primarily influenced by its oxygenated molecular structure, its high latent heat of vaporization, and its low cetane number. The presence of oxygen helps achieve more complete combustion and may improve thermal efficiency, whereas its high latent heat cooling effect may further increase volumetric efficiency and suppress knocking, making conventional diesel engine combustion difficult without ignition assistance [36]. Therefore, in CI engines, methanol is recommended for dual-fuel operation, pilot diesel injection, or a dedicated high-pressure direct injection system. Experimental studies [37], [38], [39] on methanol fuel have demonstrated that appropriately optimized methanol combustion can achieve brake thermal efficiency comparable to or slightly higher than that of diesel fuel. Nevertheless, the lower heating value of methanol leads to high brake-specific fuel consumption, and other parameters, including engine calibration, injection timing, and compression ratio optimization, are often required to obtain satisfactory performance. Overall, methanol exhibits good combustion compatibility when suitable engine modifications and optimized combustion strategies are implemented.

Methanol fuel offers significant environmental benefits due to its high oxygen content and low carbon content. The presence of high molecular oxygen in methanol fuel promotes more complete fuel oxidation, resulting in lower harmful exhaust emissions of PM, smoke opacity, and sulfur oxides compared to conventional diesel fuel [39]. Similarly, the CO and HC emissions are generally reduced under optimized combustion conditions. Incomplete combustion may also occur during cold start or at low-load operations, which increases these emissions [40]. Furthermore, methanol fuel contains less carbon per unit of energy than diesel fuel, which may contribute to lower carbon dioxide emissions [41]. The lower combustion temperature associated with methanol's high latent heat of vaporization will reduce thermal NO_x formation at different operating conditions. Overall, methanol fuel shows promising results in controlling harmful exhaust emissions, offering significant reductions in soot and greenhouse gas emissions while requiring suitable combustion control and exhaust after-treatment to minimize oxygenated pollutant emissions.

3. Conclusions

The compatibility of alternative fuels with internal combustion engines may not be determined solely by their fuel properties; it must also be comprehensively evaluated based on other combustion parameters, engine performance, and exhaust emission characteristics. Each of these significant aspects provides valuable insight into the technical feasibility, operational reliability and environmental sustainability of the recommended fuels. The compatibility analysis of the three fuels, i.e. biodiesel, hydrogen and methanol, represents different levels of readiness for implementation in existing internal combustion engines. Biodiesel fuel represents a near-drop-in replacement requiring minimal engine modifications, while hydrogen fuel is a transformative zero-carbon fuel that necessitates significant modifications to engine design and to fuel storage and transport infrastructure. Whereas methanol fuel is a liquid alternative requiring moderate combustion and fuel system adaptations.

It is concluded that biodiesel demonstrates high compatibility, as its properties closely resemble those of conventional hydrocarbon diesel fuel, allowing direct utilization in existing engines with minimal modifications. Methanol exhibits moderate compatibility, requiring improvements in ignition strategy and fuel system design due

to its low cetane number and low energy density. Hydrogen fuel is considered conditionally compatible, although it possesses the greatest potential for carbon-free combustion. Hydrogen fuel requires substantial modifications for storage, transportation and combustion before it can be effectively utilized in existing internal combustion engines. Finally, biodiesel offers a feasible, immediate solution for existing diesel engines, methanol provides a practical pathway through liquid-fuel adaptation, and hydrogen represents the long-term, zero-carbon option for next-generation internal combustion engines. Therefore, selecting an appropriate alternative fuel should be based on the intended application, engine configuration, available infrastructure, economic considerations, and the desired level of greenhouse gas emission reduction.

Nomenclature

B100	Pure Biodiesel	IC	Internal Combustion
CI	Compression Ignition	ICEs	Internal Combustion Engines
CO	Carbon monoxide	LED	Light Emitting Diode
CO ₂	Carbon dioxide	O ₂	Oxygen
DC	Direct Current	PEM	Proton Exchange Membrane
GHG	Green House Gas	PM	Particulate matter
H ₂	Hydrogen	SMR	Steam Methane Reforming
HC	Hydrocarbon	UHC	Unburnt Hydrocarbons

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