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# Alternative Fuels for Diesel Engines: New Frontiers

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## Abstract

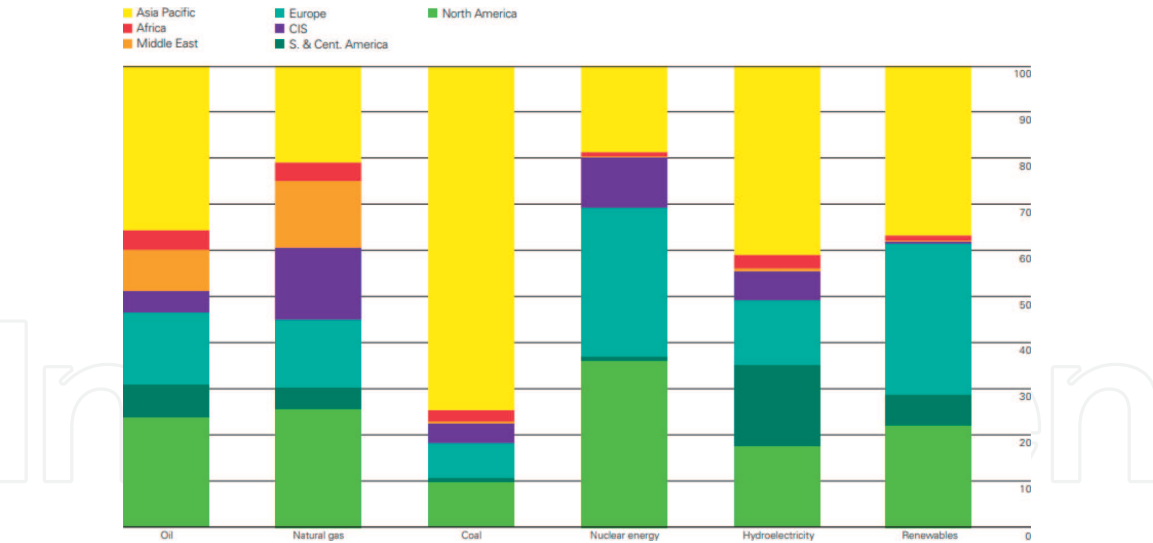
The world at present is mainly dependent upon petroleum-derived fuels for meeting its energy requirement. However, perturbation in crude prices, which concerns about long-term availability of these fuels coupled with environmental degradation due to their combustion, has put renewable alternative fuels on the forefront of policy maker's agenda. The diesel engines are considered workhorse in the global economy due to better thermal efficiency, ruggedness, and load carrying capacity. They, however, are also the main contributor to air pollution as they emit more oxides of nitrogen, suspended particulate matter as compared to gasoline engines. The most potential fuel either to supplement or to substitute diesel is biodiesel, butanol, producer gas, dimethyl ether, hydrogen, and so on. This chapter presents the developments about the use of alternative fuels in diesel engines. The exhaustive literature has evolved the main trends in the development of alternative fuels around the world. The chapter also describes the research directions on production and use of alternative fuels in off-road and transport vehicles powered by diesel engines.

**Keywords:** alternative fuels, biodiesel, Butanol, producer gas, hydrogen, dimethyl ether

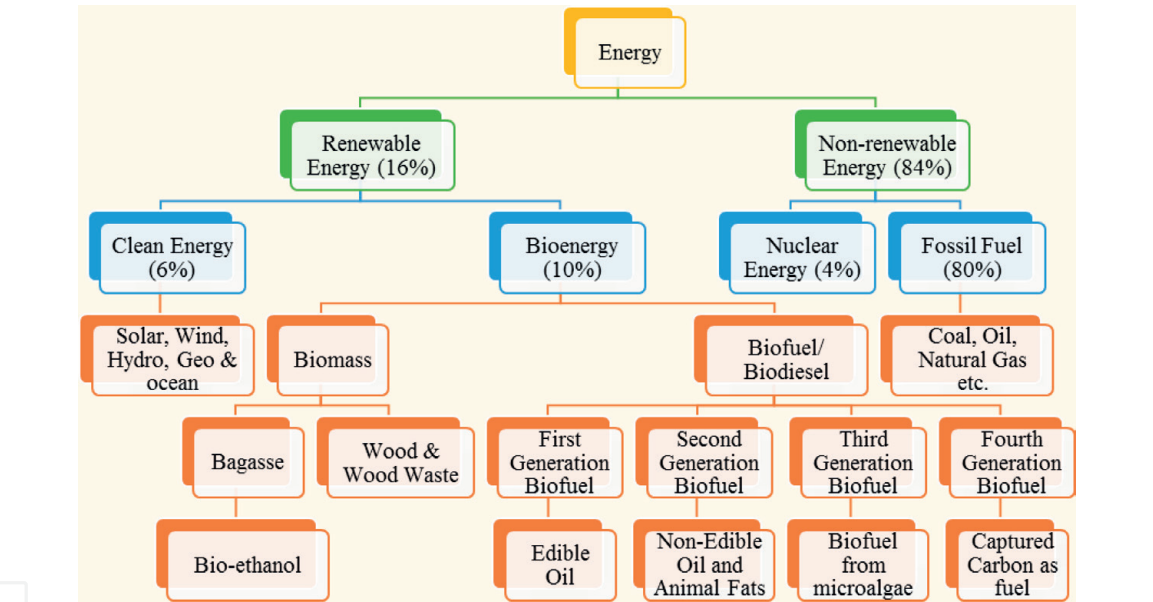
## 1. Introduction

World's 80% population resides in the developing countries, but these consume only 40% of the total energy consumption. Per capita energy consumption gauges the prosperity and economic growth of any country. The significant energy demand of the world is fulfilled by the petroleum sources. The fuel consumption region wise is shown in **Figure 1** for the year 2017–2018. It is seen that Asia is the leading consumer of coal, oil, hydroelectricity, and renewable power. North America leads in consuming natural gas and nuclear energy. Asia's consumption of coal is nearly 74.5% of the world coal consumption [1]. The fast depletion of petroleum resources is a major concern for the economic development of many countries. Therefore, the energy crisis is debated on all forums, and evolution from conventional to sustainable energy sources has become very relevant to maintain the momentum of economic growth. Renewable sources of energy can provide the energy sustainably and without harming the environment. **Figure 2** shows the broad classification of renewable energy sources.

Biofuels are the most effective and efficient form of renewable energy. They can be easily extracted from the biomass, and they are biodegradable and are environment-friendly [3]. Their combustion is almost similar to fossil fuels [4], and

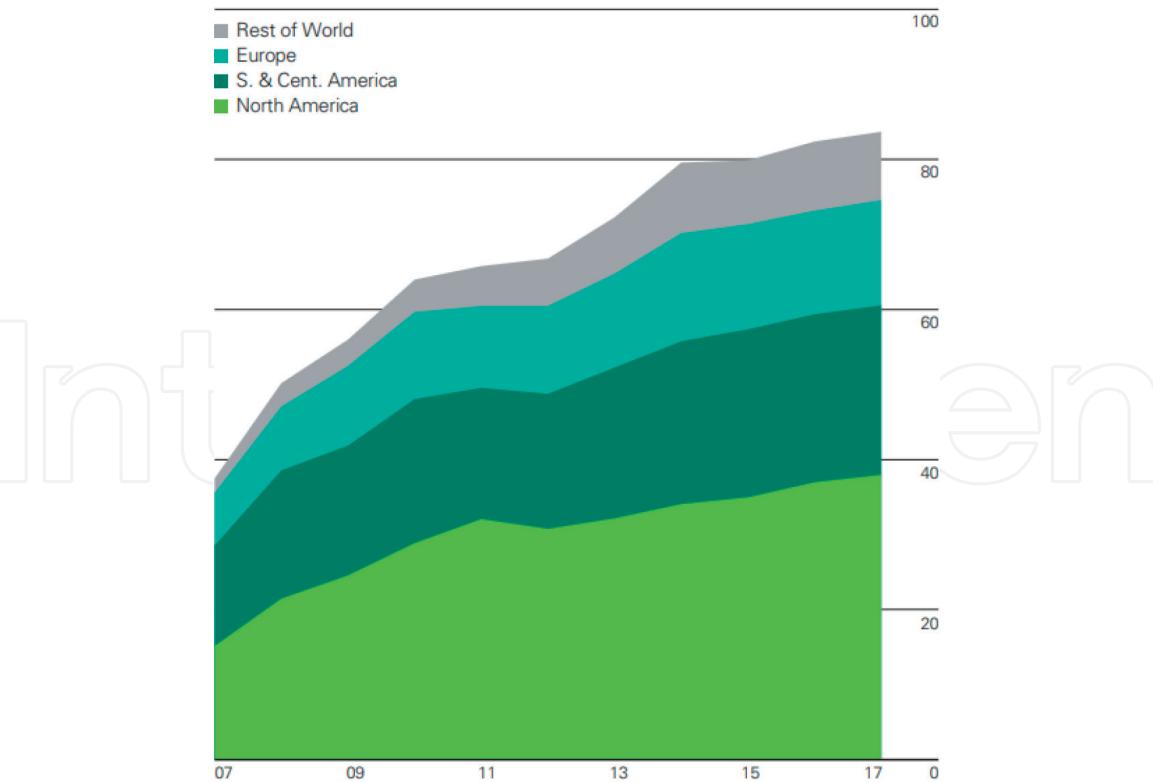


**Figure 1.**  
Fuel consumption (in percentage) region wise for the year 2017 [1].



**Figure 2.**  
Classification of energy by source type [2].

they produce less toxic compounds [5, 6]. The biomass absorbs carbon dioxide from the atmosphere, and when they are used as energy source, they release the carbon dioxide back into the atmosphere. However, the amount of carbon dioxide released into the atmosphere is less than that absorbed by the biomass [7]. The biofuels' production of the world increased by 3.5% in 2017, shown in **Figure 3**. The United States alone provided the largest increment of 950 ktoe. Ethanol production grew at the rate of 3.3% and contributed over 60% of the total biofuels' growth. Biodiesel production also rose by 4% on the account of growth in Argentina, Brazil, and Spain [1]. Several alternatives in diesel engines are available and can be used with minor or no modification. The advantages of these fuels include lower emissions, and since most of them are derived from renewable biomass sources, it will decrease the dependency on nonrenewable petroleum. The most potential fuel either to supplement or to substitute diesel is biodiesel, butanol, producer gas, dimethyl ether, hydrogen, and so on.



**Figure 3.**  
*World biofuels' production (million tons of oil equivalent).*

## 2. Biodiesel

Biodiesel appears more attractive for many factors because it is nontoxic and biodegradable. It is the substitution of petroleum diesel for either power generation or motive power without major modification. Furthermore, it releases significantly low aromatic compounds, sulfates, and chemical matters that pollute the atmosphere. Emissions of carbon dioxide are relatively low when the life cycle analysis is considered. Presently, biodiesel has been utilized throughout the world such as the United States, Brazil, Germany, Indonesia, Italy, France, Malaysia, and European countries. Consequently, there is a great prospect for its production and utilization. As of now, annual biodiesel production in the world is around 28 billion liters [1].

Over 350 oil-bearing crops were identified worldwide, which are appropriate for the production of biodiesel. Biodiesel feedstocks are regionally diversified [8]. It mainly depends on the soil conditions, climate, methods of cultivation and harvesting, and geographical locations of the country [9, 10]. The availability of potential feedstock plays a major role, which contributes to nearly 75% of the total cost of biodiesel [11, 12]. Therefore, it is very important to select an economical feedstock for improving the economics of biodiesel production.

Apart from that, the percentage of oil in the feedstock and the yield per hectare are also significant factors. Several edible oil resources namely sunflower, rice bran, palm oil, rapeseed, soybean, peanut, and coconut are considered the first-generation feedstock of biodiesel. However, food versus fuel is a major concern for the researchers. Also, it is felt that plantation of feedstocks for biodiesel may require deforestation, reduction in available cultivatable land, and damage to soil resources. Moreover, the raw vegetable oil cost has seen a steep rise in the last decade that has changed the cost-effectiveness of biodiesel production [13, 14]. Furthermore, a

number of countries are unable to cope with the growing gap between their demand and supply, which has created a challenge for them to produce cost-effective biodiesel from edible oil resources.

Several nonedible oils, waste oils, greases, and animal fats are considered as the second-generation biodiesel feedstocks [15]. Despite a large list of feedstocks of the second generation, it was believed that these might not be sufficient to fulfill the energy requirements. Moreover, animal fats and saturated fats have under-performed in low-temperature regions [16]. Collection mechanism of waste cooking oil [17] is tough because of its scattered sources, and there is always a problem of contamination with foreign particles [11, 16].

Numerous new researches are carried out nowadays to highlight the limitations of edible oils and the advantages of nonedible oils as a biodiesel feedstock. Nonedible oils for producing biodiesel can help in providing the key to tackle the problems of harmful emissions, cost-effectiveness, and the never-ending debate of food versus fuel [18]. Moreover, the plants used to produce seeds for nonedible oils can be cultivated on marginal lands, which can be degraded forests, arid lands, vacant lands, along highways, railways, and irrigation waterways and poverty-stricken areas. Various rural and low-income communities can take advantage of adopting the methods of production of biodiesel from nonedible sources to empower them. They also help in providing energy security and self-reliance. Nonedible feedstocks of biodiesel being sustainable shall be very advantageous as a substitute for diesel [11, 19].

Biodiesel or similar fuels can be produced by various methods such as pyrolysis, blending with other fuels, forming microemulsions and transesterification. These methods are briefly discussed later.

Pyrolysis is carried out at high temperatures in the presence of catalyst and the absence of oxygen for decomposing the organic matters. The materials that are normally used for pyrolysis are oils derived from seeds, methyl esters of fatty acids, and animal fats. Several investigations were carried out in the past to obtain a diesel substitute by pyrolysis. Aromatics, alkanes, carboxylic acids, alkenes, alkadienes, and small quantities of gaseous products are produced by pyrolysis [20]. When compared to diesel, the fats and oils that have been pyrolyzed have a lower pour point, flash point, viscosity, and comparable calorific values. Other benefits of pyrolyzed vegetable oils include acceptable levels of copper corrosion values, sulfur, and water content. However, lower cetane number, ash, and carbon residual make their usage in diesel engine challenging [21]. It is worthwhile to mention that the pyrolysis process is a good alternative to diesel because of its simplicity, effectiveness, and pollution-free nature [15, 22].

To make vegetable oil suitable for usage in a diesel engine, they are normally blended or simply diluted with diesel. The main benefit of blending is a reduction in viscosity of the blend and also improves the overall performance of the engine [23]. Hundred percent vegetable oil can be used in a diesel engine, but it gives rise to certain new challenges, which question its practical use on a long run [14, 24, 25]. Therefore, vegetable oil/diesel blends up to 25% shall be one of the choices for diesel engine [14, 24, 25]. However, the usage of vegetable oil and diesel blends in engines also brings some unwanted problems that need to be addressed thoroughly.

Dimensions of a colloidal dispersion of optically isotropic fluid fall in the range of 1–150 nm that forms a microemulsion. It consists of one and more ionic amphiphiles and two immiscible liquids. Microemulsion of vegetable oils can be formed with alcohols, surfactant, cetane improver, or with an ester and dispersant (cosolvent) [22]. Microemulsion is beneficial due to their viscosity being similar to diesel. It has been observed that for both microemulsions (ionic and nonionic), the short-term performances are nearly equal to diesel [14, 24–26].



Transesterification also known as alcoholysis is one of the most popular, cost-effective, and simple chemical processes of conversion of high viscosity vegetable oils to a very low viscosity substance known as biodiesel. In transesterification process, 1 mole of vegetable oil and 3 moles of alcohol are allowed to react in the presence of a catalyst to produce 3 moles of alkyl ester and 1 mole of glycerine [27]. The triglycerides are first converted into diglycerides, which are further converted to monoglyceride and finally to glycerol. The products thus formed can be separated into two layers on its own by gravity. Biodiesel floats in the upper region, and glycerol settles at the bottom. In the cosmetic industry, glycerol is used extensively. Methanol and ethanol being economical are used commonly in the transesterification process. However, various higher chain alcohols namely propanol, butanol, and octanol could also be used for the production of biodiesel.

Transesterification process can be carried out by catalytic and noncatalytic methods. In the catalytic method, the catalyst is added to alcohols to increase its solubility, which enhances the reaction rate. Catalytic transesterification can be processed by an alkaline or an acid catalyst. Use of an alkaline catalyst is preferred because of its fast reaction, high yield, and economical nature. It is commonly seen that alkaline catalyst gives 4000 times faster reactions than acid catalyst [28, 29]. Alkaline catalyst namely sodium hydroxide, potassium hydroxide, potassium methoxide, and sodium methoxide are extensively used. Despite the higher cost of potassium and sodium hydroxide, they are most preferred due to their higher yields.

Alkaline catalysts are normally employed when the free fatty acid (FFA) level of the oil or fat is lower than 3%. Beyond this limit, the reaction proceeds with difficulty and challenges such as soap formation and reduced ester yields [30]. Some other limitations of the alkaline catalytic process include higher energy for production of biodiesel, difficulty in removal of unused catalyst from the final product, difficulty in glycerol recovery, and wastage of water during washing [10, 31].

Hydrochloric acid, phosphoric acid, sulfuric acid, ferric sulfate acid, para toluene sulfonic acid (PTSA), and Lewis acid ( $\text{AlCl}_3$  or  $\text{ZnCl}_2$ ) are normally used as an acid catalyst. The acid catalyst is preferable over alkaline catalysts for their better results with high FFA oil and the presence of water. However, the time taken for the reaction is much more (3–48 h). It is observed that wet washing of the oil uses a large quantity of water for the removal of unreacted acid or base catalyst and the leftover salt of the neutralization process [32].

Transesterification process has relatively high conversion efficiency, small energy usage, and lower cost of catalyst and reactants [10, 31]. The transesterification process has certain challenges including long reaction time, poor catalyst solubility, and poor separation of the products. Besides this, the wastewater produced during the process can cause environmental issues. To overcome these challenges, other faster methods such as supercritical fluid methods have been developed, which complete in a very short time (2–4 min).

Furthermore, the absence of catalyst helps in easy recovery of glycerol and purification of biodiesel, which makes the process environment-friendly [10, 25, 33]. However, the method is having a limitation of the higher cost of equipment and working at high temperature and pressures. Methanol requirement is also higher (methanol to oil molar ratio—40:1) [34, 35]. Transesterification reaction is dependent upon several factors. For better yield, reaction time, temperature, agitation speed, molar ratio, and catalyst concentration need to be set in the right manner [14, 31].

## 2.1 Biodiesel as a fuel in diesel engines

As described in the previous section, biodiesel is a preferable choice as an alternative to diesel. Jatropha biodiesel has received a great attention due to high conversion and its relatively competitive cost. Several exhaust and performance characteristics were evaluated by Chauhan et al. [36] on blends of diesel and biodiesel derived from oil of Jatropha in an unmodified diesel engine. The authors reported that for the test blends, performance and emission parameters were better, with some higher  $\text{NO}_x$  emissions and BSFC than that of diesel. Similar studies were conducted by Nalgundwar et al. [37], and Huang et al. [38], which showed the same characteristics of Jatropha biodiesel. According to Bari et al. [39], combustion characteristics of 20% Jatropha biodiesel (B20) blend and D100 were comparable. Due to heavier particles and low volatility of biodiesel, B20 takes more combustion time than D100. The authors concluded that in a conventional diesel engine, B20 (a blend of diesel and Jatropha biodiesel) can be used without any modification. Similarly, Ganapathy et al. [40] conducted experiments on a full-factorial design using diesel and Jatropha biodiesel with 27 runs for each fuel. Some increase in BTE was observed with an advancement in injection timing. This has also caused a reduction in HC, CO, smoke emissions, and BSFC. For Jatropha biodiesel, small increments are observed for  $\text{HRR}_{\text{max}}$ ,  $P_{\text{max}}$ , and NO emission. Injection timing of 340 crank angle degree (CAD) increased  $\text{HRR}_{\text{max}}$ ,  $P_{\text{max}}$ , and BTE. Mofijur et al. [41] evaluated the feasibility of biodiesel derived from Jatropha oil in Malaysia. Interestingly, only 10 and 20% of biodiesel was blended with diesel to consider engine performance and emission as compared to 100% diesel. There is 4.67% reduction in brake power (BP) for B10 and 8.86% for B20. It was seen that there is some increase in BSFC with the increase in the amount of biodiesel in the blends. In comparison to D100, 16 and 25% reduction in CO emission, 3.8 and 10.2% reduction in HC emission and 3 and 6% increase in  $\text{NO}_x$  emission using B10 and B20 blends were observed. The authors concluded that up to 20% biodiesel can be a potential substitute to diesel, which can be used without alteration in the diesel engine.

Karanja biodiesel is another substitute in which researcher showed more interest. Dhar and Agarwal [42] investigated several characteristics of blends of diesel and Karanja biodiesel on the engine. The engine is set to run at variable loads and speed. The authors observed that 10 and 20% Karanja biodiesel blends exhibited higher values of maximum torque than diesel. However, for higher biodiesel concentrations in the blends, maximum torque attained was slightly lower. It is also observed that the BSFC of biodiesel blends increases with a percentage increase of biodiesel in the blends, while, for lower concentrations, it is very close to diesel. From emission results, it is seen that HC, CO, and smoke emissions were lower for the blends than diesel with slightly higher  $\text{NO}_x$  emissions. The authors concluded that up to 20% blends of Karanja biodiesel and petroleum diesel are well suited for an unmodified diesel engine. Similar outcomes were found by Raheman and Phadatare [43] and Nabi et al. [44]. The engine emissions including CO and smoke reduced with some reduction in engine noise, but  $\text{NO}_x$  emissions increased in small quantities. Hundred percent KME reduced CO emissions from the diesel engine by 50% and smoke emissions by 43%, while  $\text{NO}_x$  emission increased by 15%. Chauhan et al. [45] conducted transesterification of Karanja oil and observed that all the properties were within the standard limits. The engine trials confirmed that BTE for Karanja biodiesel blended with diesel in a ratio of 5, 10, 20, 30, and 100% was about 3–5% lower with respect to neat diesel. It was also revealed by the engine trials that CO,  $\text{CO}_2$ , UBHC, and smoke emissions were lowered by the use of biodiesel derived from Karanja oil. However, Karanja biodiesel and its blends as compared to diesel produced a little higher quantities of  $\text{NO}_x$  emissions with lower values of HRR and

peak cylinder pressure. The results suggested that Karanja biodiesel and its blends will be a viable alternative to diesel, and they shall also be beneficial for small- and medium-energy production.

Sahoo et al. [46] explored Polanga (*Calophyllum inophyllum*) biodiesel and its blends (0–100%) as a substitute in a single-cylinder diesel engine at varying loads. It was found that the Polanga methyl ester fueled engine has better brake-specific energy consumption (BSEC), BTE, lower smoke emissions, and lower value of all other emissions including NO<sub>x</sub>. Moreover, 100% biodiesel has 0.1% superior BTE than other fuels. BSEC also followed the similar trend with lower values of exhaust emissions. For B60, a 35% reduction in smoke was observed in comparison to baseline diesel. Owing to the reduction in exhaust gas temperature, NO<sub>x</sub> emissions decreased by nearly 4% for B100 at full load. In another study, Sahoo et al. [47] tested various neat and blended biodiesels in a single-cylinder diesel engine at different loads. Various engine combustion analyses were carried out on biodiesel obtained from Jatropha, Karanja, and Polanga and their blends, which revealed that for Jatropha biodiesel, ignition delay was shorter by 4.9–5.2°C. Similar trends were observed with the ignition delay of other biodiesels in comparison to neat diesel. Moreover, B20 Polanga biodiesel has shown the maximum peak cylinder pressure.

Raheman and Ghadge [48] used biodiesel derived from Mahua (*Madhuca indica*) in different proportions with diesel. The authors determined different properties of the test fuels and found them similar to diesel. Engine performance (BSFC, BTE, and exhaust gas temperature) was reduced. However, BSFC increased with an increase in brake power. Emissions (CO, smoke density, and NO<sub>x</sub>) were also reduced. In another study, Godiganur et al. [49] assessed the performance of mahua methyl ester and its blends (0, 20, 40, 60, and 100) with diesel under varying loads and constant speeds. Exhaust emissions namely HC and CO reduced considerably by increasing the percentage of biodiesel in the blends with some penalty on fuel consumption and NO<sub>x</sub> emission as compared to diesel. Moreover, the performance parameters, that is, BTE improved, whereas BSEC reduced slightly for 20% biodiesel blends. Puhan et al. [50] performed an analysis of methyl ester of Mahua oil in a diesel engine. It was reported by the authors that BTE of the fuel sample decreased by 13%. Puhan et al. [51] in a different study evaluated ethyl ester of Mahua oil as diesel fuel and found comparable thermal efficiency. In another study by Puhan et al. [52], Mahua oil ethyl ester revealed significantly lower HC, CO, NO<sub>x</sub>, and smoke emissions than diesel in a single-cylinder diesel engine. Similarly, its performance tests revealed power loss with biodiesel. A 20% lower HC and 26% lower CO emissions were observed with biodiesel compared to petroleum diesel, whereas NO<sub>x</sub> emission was reduced by 4% for Mahua biodiesel compared to diesel.

Hajra et al. [53] produced biodiesel from Sal oil (*Shorea robusta*) using the transesterification. NO<sub>x</sub>, HC, and CO emissions were reduced by 12, 25, and 45%, respectively, with a marginal difference in BTE. Based on this study, it is concluded that the Sal methyl ester can be a possible substitute to diesel, which can be employed without modifications in the engine. Sharma and Singh [54] produced biodiesel using Kusum oil (*Schleichera triguga*) and found that various physical and chemical parameters of Kusum biodiesel are very well suited to diesel engine operation. In another study, Silitonga et al. [55] found that *Schleichera oleosa* possesses the desired benefits for biodiesel production.

Some researcher showed their interest in waste cooking oil biodiesel. In this sequence, Muralidharan et al. [56] tested biodiesel blends (20, 40, 60, and 80%) in a single-cylinder VCR engine at 21 CR and a constant speed of 1500 rpm. The performance parameters included brake power, specific fuel consumption, brake thermal efficiency, exhaust gas temperature, mechanical efficiency, and indicated



mean effective pressure. The exhaust gas emission was found to contain nitrogen oxides, hydrocarbon, carbon monoxide, and carbon dioxide. The results confirmed substantial improvement in the performance parameters and exhaust emissions as compared to diesel. The blends helped in reduction of hydrocarbon, carbon monoxide, and carbon dioxide with slightly higher nitrogen oxide emissions. It has been deduced that waste cooking oil biodiesel and diesel blend combustion characteristics are very close to diesel.

### **3. Butanol**

Butanol in the last decade has emerged as a promising biofuel for its application in the diesel engines. Like ethanol, butanol is a biomass-based renewable fuel that may be produced by fermentation [55–58]. It is a next-generation greener fuel and also known as 1-butanol, n-butanol, or butyl alcohol. Efforts are made by the research community to explore efficient methods for obtaining this alcohol in bio-refineries, wherein higher alcohols are produced from shorter alcohols [59, 60]. Butanol is linear four carbon aliphatic alcohol having a molecular weight of 74.12 g/mol. It has a distinct aroma with a strong alcoholic odor. It is low hydrophobic colorless and flammable liquid.

Ethanol has received more attention the world over. However, butanol is a better option with high energy content and better physicochemical properties. Butanol was discovered in 1852 by Wirtz, and in 1862, Pasteur concluded that butyl alcohol was a direct product of anaerobic conversion [57].

Butanol having excellent fuel qualities is very suitable as a diesel engine fuel. Butanol being renewable is not only sustainable but also possesses higher cetane number and heating value than ethanol. It has a higher flash point making it safer, and it has a lower vapor pressure. Butanol is hydrophilic in nature and easy miscible with diesel. This eliminates the problems, which are experienced with lower alcohols such as nonmiscibility [58]. The important properties of n-butanol, ethanol, and diesel are shown in **Table 1**.

#### **3.1 Production of butanol**

Production of butanol is carried through the chemical process, that is, fermentation by bacteria. *Clostridium acetobutylicum* is the most popular species of bacteria used for fermentation. The process is abbreviated as ABE because of the end products—acetone, butanol, and ethanol are obtained from it. Butanol production is carried out by molasses (consists of fermentable sugars—55 wt.% and nonfermentable solids—30 wt.%), water, and nutrients in the reactor. Nutrients and diluted molasses are allowed to combine in the tank. Sterilization of the mixture is continuously carried out. The broth containing ethanol, acetone, and butanol is removed from the reactor. It also contains small quantities of butyric acids, acetic acids, proteins, cells, and molasses (in the form of nonfermentable solids), which are then separated in distillation columns to give the final products [60].

#### **3.2 n-Butanol as a fuel in diesel engine**

Some experimental studies have highlighted the favorable effects of n-butanol/diesel fuel blend in diesel engine [61]. Work of different researchers is highlighted later.

Properties	Diesel fuel	n-Butanol	Ethanol
Chemical formula	C <sub>14.09</sub> H <sub>24.78</sub>	C <sub>4</sub> H <sub>9</sub> OH	C <sub>2</sub> H <sub>5</sub> OH
Specific gravity	0.85	0.81	0.79
Boiling point	190–280	108.1	78.3
Net heating value (MJ/kg)	42.6	33	27
Heat of vaporization (KJ/kg)	600	578.4	900
Octane number	NA	94	92
Cetane number	45	17	8
Flash point (°C)	65–88	35	13
Viscosity (mm <sup>2</sup> /s) at 40°C	1.9–3.2	2.63	1.2
Auto-ignition temperature (°C)	210	385	434
Stoichiometric air/fuel ratio	14.6	11	9
Molecular weight	193.9	74	46
Latent heat of evaporation (kJ/kg)	265	585	900
Bulk modulus (bar)	16,000	15,000	13,200
Lubricity (μm)	310	590	950
% of carbon (wt.)	86.7	64.9	52.1
% of hydrogen (wt.)	12.7	13.5	13.1
% of oxygen (wt.)	0	21.5	34.7
C/H ratio	6.8	4.8	4

**Table 1.**  
*Properties of diesel, n-butanol, and ethanol [57–59].*

Atmanli et al. performed an engine trial on wide operating conditions at varying blend of diesel fuel, cotton oil, and n-butanol using RSM. Homogeneity was observed along with no phase separation. BMEP, brake power, and thermal efficiency of the blend were reduced; however, BSFC has increased marginally. Emissions namely HC, NO<sub>x</sub>, and CO of the blends have reduced [62]. Yilmaz et al. studied the emissions and performance characteristic of butanol/biodiesel blends in a multi-cylinder, indirect injection diesel engine. Butanol blended with biodiesel was compared with standard diesel (D100) and neat biodiesel (B100) at four engine loads. Lower exhaust gas temperatures and nitrogen oxide (NO<sub>x</sub>) emissions with higher CO and HC emissions were found [63]. Zhu et al. [64] carried experiments on n-butanol blends, EGR rate, and injection timing on a modified diesel engine. The results suggested that with increased EGR rate, NO<sub>x</sub> emissions reduce, but smoke emissions increase. With the increase of n-butanol fraction, smoke emissions were found to decrease with a small increase in NO<sub>x</sub>.

Dogan conducted some studies on a diesel engine at four different loads. No phase separation was observed in 20% butanol/diesel blend. The performance was slightly improved in comparison to diesel. Gaseous emissions, for example, NO<sub>x</sub>, CO, smoke content, and exhaust gas temperature reduced with the blends [65]. Butanol/diesel blends (8, 16, and 24%) were prepared by Rakopoulos et al., and it was found during the trial that the smoke opacity, NO<sub>x</sub>, and CO emissions were significantly reduced. However, the HC emissions were higher. Greater SFC and BTE and slightly lesser exhaust gas temperatures were noted in comparison to petroleum diesel [66]. In a similar study, Karabektas et al. evaluated the suitability

of butanol-diesel blends in a diesel engine. Four blends were prepared consisting of 5, 10, 15, and 20% butanol by volume. Brake power was lower, whereas BSFC rose with the addition of butanol. CO and NO<sub>x</sub> levels were lower for blends; however, there was a considerable increase in HC emissions [67]. In another study, Lebedevas et al. conducted investigations on a multi-cylinder diesel engine.

Two types of test fuels were prepared. The first is comprised of diesel, rapeseed methyl ester (RME), and butanol, and the second consisted of diesel, rapeseed oil butyl esters (RBE), and butanol. Almost the same efficiency was observed, and there was a significant reduction in CO and HC emissions. NO<sub>x</sub> emissions remained almost the same; however, there was a reduction in smoke emissions for all butanol-based fuels as compared to petroleum diesel [68]. The above studies suggest that butanol-diesel blends are potential alternative fuel in a diesel engine.

#### **4. Producer gas**

Biomass-based producer gas is a viable alternative to conventional fuels, where there is a large availability of the biomass as a primary source. Biomass feasible for producer gas is dry materials such as wood, charcoal, rice husks, and coconut shell. Producer gas is produced by gasifying these dry carbonaceous organic materials. In the gasification process, the solid biomass is broken down by the use of heat. The gasification system consists of a reactor or container into which the biomass is fed along with a gasification agent such as air, oxygen, and steam. According to the supply, producer gas with different calorific values is produced. When air is used, the gas with 4–6 MJ/Nm<sup>3</sup> calorific value is produced, and the gas can be used for direct combustion or as an internal combustion engine fuel. With oxygen, the gas produced has 10–15 MJ/Nm<sup>3</sup> calorific value. The producer gas with 13–20 MJ/Nm<sup>3</sup> calorific value is produced with steam as a gasifying agent, and the gas can be subsequently used as a feedstock for methane and methanol production [69, 70].

Producer gas was produced from sugarcane bagasse and carpentry waste by Singh and Mohapatra [71]. The authors mixed the raw materials thoroughly in the ratio 1:1, and the major steps followed for gasification are mentioned here. (1) In the first step, the mixed raw material is fed from the top into a downdraft gasifier, and air enters over air inlets through which firing also takes place using a diesel torch. After operation of the gasifier for 15–20 min, the gas constantly comes out of the gasifier at a temperature of nearly 450°C. (2) In the second step, the gas is cooled and cleaned in the scrubber. As the gas is passed through a jet of cold water, the particulates, dust, and gases such as HCl, H<sub>2</sub>S, SO<sub>2</sub>, and NH<sub>3</sub> are removed as they are water soluble. All the tar present in the gas is also washed in the scrubber. (3) In the third step, the gas is passed through a drum-shaped secondary filter containing a mixture of wood chips and powder. As the gas passes through the filter, the particulate matter is absorbed along with the excessive moisture present. Gas with high purity and temperature of nearly 50°C comes out of the filter. (4) In the final step, the gas is passed through a safety filter, which contains a paper filter. The minute soot particles are absorbed by the filter and gas with higher purity, and 35°C temperature is obtained.

In spark ignition engines, the use of producer gas is already established. However, its use in a dual fuel CI engine as an inducted fuel is still a topic of research [72]. In dual fuel engines, the producer gas is inducted along with the air into the cylinder, and it is ignited by injecting a small quantity of diesel or other similar fuel such as biodiesel. Some of the research on producer gas being used as a dual fuel compression ignition engine fuel is discussed here. Ramadhas et al. [73] used producer gas produced from coir pith and wood for fueling a dual fuel engine with diesel as the direct injected fuel. The authors observed a reduction in brake thermal efficiency

with dual fuel operation as compared to neat diesel operation. The energy consumption of dual fuel operation was also higher. At part-load conditions, carbon monoxide and carbon dioxide emissions were higher with dual fuel operations. The smoke density was similar for all the tested fuels. The authors found that producer gas (made from wood chips) fueled dual fuel operation performed well than coir pith engine operation. Also, the engine could be run only to 50–60% of the maximum load. In another study by Ramadhas et al. [74], coir pith was used to produce producer gas, and rubber seed oil was used as the direct injected fuel. The authors observed that with diesel and rubber seed oil, the engine performance reduced in dual fuel mode. The fuel consumption with rubber seed oil as direct injected fuel is more than diesel as a pilot fuel. At all loads, the carbon monoxide and carbon dioxide emissions are higher with rubber seed oil-fueled dual fuel operation on account of higher fuel consumption due to lower calorific value of fuel. The other exhaust emissions are almost the same. Similar study was conducted by Singh and Mohapatra [71], who directly injected diesel and inducted producer gas in the air produced from sugarcane bagasse and carpentry waste mixed equally during gasification. The authors observed a maximum reduction of 45.7% in consumption of diesel and 69.5% reduction in  $\text{NO}_x$  emissions along with a slight increase in engine noise.

Singh et al. [75] blended refined rice bran oil (75% v/v) with diesel and used producer gas produced from wood in a three-cylinder diesel engine. It was observed that at 84% of the maximum engine load with a compression ratio of 18.4:1, the pollutant concentration reduced by 48.28, 61.06, and 80.49% for HC, NO, and  $\text{NO}_2$ , respectively; however, in comparison to diesel, CO emission increased by 16.31%. The authors also observed an increase in noise levels with producer gas induction at all the loads. Honge oil and Honge oil methyl ester were used as a pilot fuel with producer gas as the injected fuel with and without carburetor by Banapurmath and Tiwari [76]. The authors found that producer gas and honge oil engine operation resulted in higher emission levels and low thermal efficiency due to lower heat content and high viscosity of honge oil along with the low burning speed of producer gas. With methyl ester of honge oil and producer gas in dual-fuel engine operation, brake thermal efficiency improves on account of higher calorific value and low viscosity. Overall, with dual fuel operation, smoke and  $\text{NO}_x$  emissions reduce, whereas HC and CO emissions increase considerably.

Carlucci et al. [77] used biodiesel and a synthetic producer gas for a dual fuel engine operation. The authors initially varied the injection pressure, injection timing of biodiesel with a single-pilot injection, and also varied the producer gas flow rate. The results revealed that the combustion is affected by both injection timing and pressure. The thermal efficiency was higher with slightly advanced injection timing along with low injection pressure. Lowering of unburned hydrocarbons and carbon monoxide emissions was observed, whereas an increase in  $\text{NO}_x$  emission occurs. In the second phase, the splitting of the pilot fuel injection was carried out, which leads to improved fuel efficiency and reduced pollutants compared to single-pilot fuel injection at low loads. The authors also concluded that injection pressure plays a vital role in reducing gaseous emissions.

## 5. Hydrogen

Hydrogen is a colorless, odorless gas, which produces heat and water when combusted with oxygen at high pressure and temperature. Hydrogen has high energy content as compared to other fuels. However, its density is low, that is, the storage space required for a vehicle to run on hydrogen for the same distance is more than gasoline [78]. **Table 2** compares the properties of hydrogen with diesel and gasoline.



Property	Gasoline	Diesel	Hydrogen
Density at 1 atm. and 15°C (kg/m <sup>3</sup> )	721–785	833–881	0.0898
Stoichiometric A/F	14.8	14.5	34.3
Flammability limits (Vol.% in air)	1.4–7.6	0.6–7.5	4–75
Auto-ignition temperature (°C)	246–280	210	585
Lower calorific value at 1 atm. and 15°C (kJ/kg)	44,500	42,500	120,000

**Table 2.**  
*Properties of gasoline, diesel, and hydrogen.*

The flammability limits of hydrogen are wide, which make its use suitable for a wide range of air-fuel mixture. The engine can be operated at lean mixtures, which considerably improves the fuel economy as complete combustion takes place with few residues. Hydrogen has high diffusivity and flame speed because of which faster combustion takes place at near constant volume. However, due to its high auto-ignition temperature, it is suitable for a spark ignition engine, whereas for its use in a diesel engine, a low auto-ignition temperature fuel is required to initiate combustion. Also, the engine may knock or detonate due to its low ignition energy requirement.

Hydrogen in gaseous state is not available on Earth due to its low density as it is pushed out from the gravitational pull of the Earth. However, it exists in the combined form in natural resources such as coal, natural gas, fossil fuels, and water. Presently, small amount of hydrogen is produced using renewable sources such as wind, solar, geothermal energy, and biomass, and nearly 95% of hydrogen is produced from fossil fuels. Therefore, the hydrogen production is costly, and a large amount of emissions are produced. For a true hydrogen economy to exist, the hydrogen needs to be produced abundantly and economically from renewable sources. Hydrogen can be produced by natural gas reforming, gasification of biomass, and electrolysis of water.

Methane reforming is the most common method of hydrogen production in the United States. In this method, methane and steam are reformed at 3–25 bar pressure and 700–1000°C temperature in the presence of a catalyst. The by-products of the reaction are carbon monoxide and carbon dioxide. Heat is required for the process as it is endothermic. The carbon monoxide subsequently is reacted with steam in the presence of a catalyst, resulting in the formation of carbon dioxide and hydrogen. This reaction is called water gas shift reaction. Lastly, using the pressure-swing adsorption process, the gas is freed of all the carbon dioxide and other impurities, which leaves only pure hydrogen [79]. The steam reforming can also be carried out on other fuels such as ethanol, propane, and even gasoline. This process can become truly renewable if hydrogen is produced from renewable sources.

Hydrogen can be produced by gasification of biomass and coal. Biomass is a renewable source, which includes crop residue, forest residue, algae, crops grown specifically for energy use (switchgrass), municipal wastes, and animal waste. Since carbon dioxide is captured from the atmosphere by biomass itself, the net carbon emissions of the process are low. In gasification process, the carbon-rich material at a temperature greater than 700°C is converted to hydrogen, carbon monoxide, and carbon dioxide in the presence of oxygen and/or steam. Water is then reacted with carbon monoxide to form carbon dioxide and more amount of hydrogen via the water-gas shift mechanism. Gasification process can also be carried out using solar energy [80].

Hydrogen and oxygen can form by passing an electric current through water. The process is called electrolysis, and this process consumes the highest energy for production of hydrogen [81]. However, the process is clean and free of emission if the energy source used for electricity production is renewable.

Hydrogen can also be produced from other sources such as reforming of renewable liquid, splitting of water using solar, high-temperature thermochemical water splitting, and microbes [82, 83].

## 5.1 Use of hydrogen in compression ignition (CI) engines

Hydrogen is a carbon-free substance; therefore, no greenhouse gas emissions take place from its combustion in an IC engine. Hydrogen has good heat transfer characteristics, which increases the combustion temperature resulting in improved engine efficiency even at lean mixture operation [84]. This section describes the methods and the compression ignition engine performance characteristics when operated in dual fuel mode with hydrogen.

Back in 1978, Homan et al. [85] used hydrogen to operate a diesel engine. The authors realized that the engine has limited operation range because of its high auto-ignition temperature, which could not be resolved by even increasing the compression ratio up to 29. They later investigated the use of glow plugs and a multiple strike spark plug. The results showed that both the methods resulted in providing reliable ignition and smooth engine operation. The authors also observed reduction in ignition delay; however, the indicated mean effective pressure was higher than diesel-fueled engine operation. Moreover, the cyclic variations in ignition delay were significant along with the formation of high amplitude waves in the combustion chamber [86].

An indirect injection single-cylinder diesel engine was operated with hydrogen only by Ikegami et al. [87, 88]. The authors found that the engine had limited operation range with hydrogen. The authors were able to extend the operating limit and attain smoother combustion by injecting small amounts of pilot fuel in the swirl chamber as the pilot fuel became the source of ignition for the hydrogen. However, excessive pilot fuel presence resulted in its auto-ignition resulting in rough engine operation.

Direct use of hydrogen as CI engine fuel is possible within a limited operating range due to its high auto-ignition temperature. To increase the engine's operation range, hydrogen needs to be supplemented by a low auto-ignition temperature fuel such as diesel, vegetable oils, and biodiesel. Such an engine is called dual fuel engine, wherein hydrogen is either inducted in a carburetor or injected in the intake manifold or the intake port. The low auto-ignition fuel, called pilot fuel, is injected directly into the combustion chamber when the piston is approaching top dead center and the fuel ignites the hydrogen-air mixture. It has been observed that port injection of hydrogen shows better engine performance and reduction of emissions in comparison to manifold injection or use of a carburetor [89–91].

Varde and Frame [92] aspirated small amounts of hydrogen in the intake of a single-cylinder diesel engine for investigating the possibility of smoke reduction. They observed that the smoke levels reduced at part- and full-load conditions. The optimum hydrogen energy share for smoke reduction lies between 10 and 15%. At optimum energy share, the smoke reduced by nearly 50 and 17% at part- and full-load conditions, respectively. Unburned hydrocarbon emission was not affected by hydrogen injection; however,  $\text{NO}_x$  emission increased with an increase in hydrogen addition especially at loads above 50% of full load. The  $\text{NO}_x$  emission increase is due to the increase in the combustion temperature, which increases with an increase in hydrogen addition as well as load. Lilik et al. [93] also observed an increase in  $\text{NO}_x$  emission for a hydrogen dual fuel engine with diesel as a pilot fuel. The authors injected hydrogen in the intake air up to 15% of the energy share. The authors also observed a shift in the ratio of nitrogen oxide to nitrogen dioxide, wherein the nitrogen oxide decreased and nitrogen dioxide increased.

Exhaust gas recirculation (EGR) has been proved to be the best method for  $\text{NO}_x$  reduction and for suppressing knocking in a hydrogen dual fuel engine [94–96]. In EGR, the exhaust gas is reintroduced in the cylinder. As it has high-specific heat, it absorbs the combustion heat and reduces the cylinder temperature leading to reduction in  $\text{NO}_x$  formation. However, introducing the exhaust gas also reduces the amount of oxygen available resulting in increase in smoke, CO, and HC emission. Although these emissions may increase, they will be still lower than diesel operation [97].

Bose and Maji [95] compared the performance and emission characteristics with and without EGR of a neat diesel engine and a hydrogen diesel dual-fuel engine. The brake thermal efficiency without EGR for hydrogen fueled engine was higher than neat diesel operation. Higher flow rates of hydrogen deteriorated the engine efficiency. The engine efficiency was adversely affected by EGR. The smoke emissions reduced with hydrogen induction; however, with EGR, the smoke levels increased, but they were still lower than neat diesel operation. The authors observed that in order to reduce  $\text{NO}_x$  emissions by 40%, 20% EGR is necessary.

Saravanan and Nagarajan [98] injected hydrogen in a dual-fuel diesel engine using a carburetor, injector placed in the port (TPI) and injector placed in the manifold (TMI). The port injector and manifold injector were located 5 and 100 mm from the intake valve seat, respectively. The injection timing used for diesel was  $23^\circ\text{BTDC}$ . The optimized injection timing for hydrogen port injection was  $5^\circ$  before gas exchange top dead center (BGTDC) with  $30^\circ\text{CA}$  injection duration. The observations made during running of the engine at different operating conditions were as follows: (a) engine operation was unstable during the late injection ( $30^\circ\text{AGTDC}$ ) especially at higher loads and with the injection duration of  $90^\circ\text{CA}$ , (b) knocking of the engine at flow rates greater than 25 lpm, and (c) with port and manifold injection of hydrogen greater than 20 lpm flow rate, smoke emissions increased rapidly. The brake thermal efficiency and peak heat release rate were high for both port and manifold injections. The engine efficiency with carburetion was lower than neat diesel operation.  $\text{NO}_x$  was higher for both TPI and TMI modes. HC, CO,  $\text{CO}_2$ , and smoke emissions reduced with all the three modes. It was concluded that using  $\text{H}_2$  as a fuel and adopting TPI gave better efficiency and emission reduction than all the other modes.

The challenge with hydrogen induction is that at high loads, the engine performance is limited due to knocking. EGR is one of the ways to extend the knock limit of the engine, but as discussed earlier, it tends to increase the harmful emissions. Another way of reducing the knock at higher loads is injection of water as it can control the combustion phase. Chintala and Subramanian [99] inducted water at various specific water consumption (SWC) in a hydrogen-fueled dual fuel engine. The authors found that the optimum SWC of 200 h/kWh lead to a knock-free operation up to 20% hydrogen energy share resulting in 24%  $\text{NO}_x$  emission reduction and 5.7% reduction in efficiency. The carbon monoxide emission increased from 0 g/kWh without water injection to 1.2 g/kWh with water injection. The authors conducted another study [100], wherein they were able to increase the hydrogen energy share without knocking of the engine from 18 to 24 and 36% by retarding the injection timing and injecting water, respectively.

Natural gas can also be used as an injected fuel in a dual fuel engine. However, the engine efficiency is low followed by high emissions due to slow rate of burning of natural gas. Hydrogen can be used to supplement natural gas such that the engine's performance can improve and the emissions can reduce. One such study was conducted by McTaggart-Cowan et al. [101], wherein the authors used a single-cylinder engine fueled with natural gas blended with 10 and 23% hydrogen (by volume). In this study, the mixture of hydrogen and methane was injected directly into the cylinder, and diesel was used as a pilot fuel. Diesel was injected approximately 1 ms prior to the natural gas to initiate the combustion process.



The dual fuel injector used concentric needles. The results show that with 10% H<sub>2</sub>, NO<sub>x</sub>, and PM emissions remained almost the same though CO and THC were slightly reduced. With 23% H<sub>2</sub>, NO<sub>x</sub> increased slightly, while CO, THC, and CO<sub>2</sub> were reduced. Also, the peak heat release rate was 20% higher than natural gas. With PM, significant influence was seen at latest injection timings (15° ATDC), where it was found to decrease. At such timings, the burn duration for 23% H<sub>2</sub> was also substantially reduced. The combustion variability (COVGIMEP) for 10% H<sub>2</sub>/methane fuel reduced only at late timings, while with 23% H<sub>2</sub>, it reduced for all injection timings. The combustion stability was found to improve, and the effect of hydrogen addition was observed to be consistent with variations in injection timings and pressure.

Biodiesel and its blends with diesel have also been used by many researchers as a pilot fuel in a hydrogen-fueled dual fuel engine. Geo et al. [102] used rubber seed oil and rubber seed oil methyl ester as the direct injected fuel and hydrogen as the injected fuel in the intake port in a dual fuel engine to reduce smoke and increase the engine's thermal efficiency. The brake thermal efficiency of the engine increased by nearly 1.5%, whereas the smoke emission reduced by more than 30% with hydrogen induction. The maximum hydrogen energy share at full load that the engine can tolerate was 12.69% with diesel, 11.2% with rubber seed oil methyl ester, and 10.76% with rubber seed oil. The HC and CO emissions reduced at all loads with hydrogen induction for all the fuels. However, the NO<sub>x</sub> emissions increased for all the fuels with an increase in hydrogen induction. The authors attributed the increase to high combustion temperature because of high premixed combustion. The authors also observed higher emission values and lower efficiency with rubber seed oil due to poor mixture formation because of high viscosity of the fuel.

Palm oil methyl ester was blended with diesel in various proportion, and the blends were used as a pilot fuel in a single-cylinder dual fuel engine along with hydrogen as the injected fuel [103]. The performance and emission characteristics of the engine were recorded at 50% load and full load. The authors observed that at 25% blend of palm oil methyl ester in a liter of diesel, the engine gave the best efficiency at 5 lpm flow rate of hydrogen. Hydrogen induction resulted in drastic reduction in carbon monoxide emissions. However, unburnt hydrocarbon emissions increased at 5 lpm flow rate, but with increase in flow rate to 10 lpm, some reduction in emission level was observed.

Biodiesel produced from waste cooking oil can also be used as a pilot fuel in a hydrogen dual fuel engine. Kumar and Jaikumar [104] used waste cooking oil (WCO) and emulsion of waste cooking as direct injected fuel and hydrogen as manifold injected fuel in a dual fuel engine. Dual fuel operation reduced CO, HC, and smoke emissions with waste cooking oil as a pilot fuel at all loads; however, thermal efficiency reduced at 40% load. The ignition delay with WCO emulsion is higher than neat WCO, which further increases with hydrogen induction. The authors observed improvement in engine performance with hydrogen induction at high loads and fall in performance at low loads with WCO emulsion as a pilot fuel.

## 6. Dimethyl ether

Dimethyl ether (DME) is the simplest ether with chemical formula of CH<sub>3</sub>OCH<sub>3</sub>. DME in gaseous state is colorless, nontoxic, and highly flammable with a slight narcotic effect. By slightly pressurizing the gas, it can also be handled as a liquid fuel. DME and liquefied petroleum gas have similar properties. Moreover, the cetane number of DME is greater than 55. A blue flame is visible while burning DME, and it has wide flammability limits [105–108]. **Table 3** shows the physicochemical properties of DME and diesel.



Property	DME	Diesel
Vapor pressure at 20°C (bar)	5.1	<0.01
Boiling temperature (°C)	−25	~150–380
Liquid density at 20°C (kg/m <sup>3</sup> )	660	800–840
Liquid viscosity at 25°C (kg/ms)	0.12–0.15	2–4
Gas specific gravity (vs air)	1.59	–
Lower heating value (MJ/kg)	28.43	42.5
Cetane number	55–60	40–55
Stoichiometric A/F ratio (kg/kg)	9.0	14.6
Enthalpy of vaporization at normal temperature and pressure (kJ/kg)	460 (−20°C)	250

**Table 3.**  
*Properties of DME and diesel [109].*

Advantages of dimethyl ether are as follows: (a) high content of oxygen and the absence of any bond between carbon atoms result in low smoke formation, (b) low boiling point results in quick evaporation of fuel spray, and (c) auto-ignition temperature of DME is low, and its cetane number is high, which reduces the physical ignition delay [110]. The disadvantages of DME are as follows: (a) the calorific value is less due to the presence of oxygen molecules, hence the fuel required to produce the same power is more; (b) it has viscosity lower than diesel, which causes leakage in the fuel system, and due to its low lubricity, the fuel injection system surface wear may be high; and (c) its bulk modulus of elasticity is low, it can be compressed nearly four to six times that of diesel, and more work has to be put in the fuel pump to compress the fuel to the same level of diesel [111].

DME is usually used as a spray-can propellant and in cosmetics. Both fossil fuels and renewable energy sources can be used to produce DME. Dehydrogenation of methanol and direct conversion of syngas [112] are the two processes used for DME production. The two methods are essentially similar.

In the direct conversion method, syngas can be used to simultaneously produce DME and methanol using suitable catalysts. The first step of the direct conversion process is the conversion to syngas by either reforming natural gas using steam or partial oxidation of coal and biomass by using pure oxygen. In the second step, a copper-based catalyst is used to synthesize methanol from syngas. In the third step, alumina or zeolite-based catalyst is used to dehydrogenate methanol to form DME. Lastly, the raw product is purified as it may contain some amount of methanol and water. Bio-DME can be produced using renewable sources; however, the production route is costly relative to diesel [110].

**6.1 Use of dimethyl ether as a CI engine fuel**

DME can be used in an engine as a neat fuel or by blending it with diesel, bio-diesel, or LPG. This section briefly describes the effect of DME on a diesel engine in terms of its efficiency, combustion, and the exhaust emissions.

A direct injection single-cylinder diesel engine was used by Sato et al. [113] for operating with DME. The engine was supercharged with a multiple hole injector. The authors observed that heat release and combustion pressure with DME-fueled engine are higher than diesel. Also, the engine had lower ignition delay and higher indicated mean effective pressure with DME engine operation than diesel engine

operation. The authors found NO<sub>x</sub> emission reduction by one-third with DME with an increase in the exhaust gas recirculation rate. Carbon dioxide emission was lower than diesel. In middle- and low-load conditions, the energy consumption was higher than diesel.

The fuel injection system of a diesel engine needs to be redesigned for operating with DME due to its low lubricity, viscosity, lower heating value, and elasticity. Lubricity can be improved by adding additives; however, for other issues, new materials need to be developed. DME is soluble in hydrocarbons, which make it a lucrative proposition, such as propane blending improves the calorific value of the blend or biodiesel blending improves the lubricity and viscosity of the blend.

Ying et al. [114] blended DME with diesel in various proportions and found decrease in lower heating value, kinematic viscosity, and aromatic fraction of the blends. Cetane number, carbon to hydrogen ratio, and oxygen content of the blends increased. The authors found low fuel consumption for the blends at high engine speed than diesel operation. At high engine speeds, the velocity of the plunger is high in the fuel pump, which makes the pressure in the plunger lower than DME vapor pressure, hence vaporizing the DME in the plunger, thereby reducing the effective stroke of the plunger and fuel delivered per stroke. However, at lower speed, the vaporizing rate is not much, hence more quantity of blended fuel is delivered due to high delivery pressure and the fuel consumption is higher. The impact on emissions due to blends varies with varying load conditions. At high loads, the effect of blends on smoke is significant, whereas at low loads, the smoke emission is slightly affected. NO<sub>x</sub> emission decreases a little, whereas HC and CO emissions increase at all operating conditions. The decrease in NO<sub>x</sub> emission is due to lower combustion temperature caused by shorter ignition delay and less amount of fuel prepared for premixed combustion caused by high cetane number and lower auto-ignition temperature [113, 115]. Also, the blend injection timing is delayed due to low elasticity [116] than diesel, which further reduces the NO<sub>x</sub> emission.

Rapeseed oil was blended with DME at 2, 4, 6, and 10% volume by volume ratio by Wang and Zhou [117]. The results show that engine performance is good with different blends in all operating conditions. With the increase in rapeseed oil percentage in the blend, the power and torque output of the engine increase as well as the NO<sub>x</sub> emission increases. Smoke emissions were insignificant up to 6% of rapeseed oil in the blend; however, with further increase in rapeseed percentage, the emission level increased drastically. The authors also observed increase in the heat release rate and the fraction of the fuel burned in premixed combustion phase with an increase in rapeseed oil mass fraction.

In another study, Hou et al. [118] used blends of used cooking oil and DME in a turbocharged compression ignition engine. The authors also observed that increase of DME proportion in the blends reduced the peak in-cylinder temperature, pressure, ignition delay, and peak heat release rate. The authors varied the nozzle hole diameter (0.35 and 0.4 mm) and found that peak cylinder pressure and heat release are higher for 0.35 mm nozzle, and the combustion phase is also advanced. NO<sub>x</sub> emissions with 0.4 mm diameter are lower than 0.35 mm diameter at 100% DME, whereas at 50% blend of DME, NO<sub>x</sub> emission is higher with 0.4 mm diameter than 0.35 mm diameter. HC and CO emissions are lower with 0.4 mm diameter at 50% blend of DME, and the emissions increased when 100% DME is used with 0.4 mm diameter nozzle.

Since DME and LPG have similar physicochemical properties, DME can be handled and stored in a similar manner. Also, the infrastructure used to supply LPG

can be used for DME supply for DME-fueled vehicles [119, 120]. DME and LPG can be easily blended, and they compensate for each other's disadvantage namely LPG's low cetane number and DME's low calorific value.

Lee et al. [121] used a single-cylinder diesel engine for operating with blends of n-butane and DME. The n-butane was varied from 0 to 40% by mass in the blend. The n-butane content above 30% resulted in poor self-ignition and unstable combustion, especially at low loads. The increase in n-butane content led to late start of combustion due to ignition delay caused by reduced cetane number. High HC and CO emissions were observed with higher n-butane content due to partial burning of the charge caused by over mixing of the unburnt charge and the burnt charge. NO<sub>x</sub> emissions were higher at low loads and low n-butane content, which are mainly due to early start of combustion giving more time for NO<sub>x</sub> formation. Whereas, at high load and high n-butane content, the NO<sub>x</sub> emission is higher. Also, the NO<sub>x</sub> emissions are lower with blended fuels than diesel engine operation. Less smoke emissions were detected for medium and low loads.

## **7. Conclusions**

As already highlighted, depleting petroleum reserves and climate change is mandating the use of alternative fuel to give a new life to millions of off- and on-road engines. The benefits of alternative fuels are enormous for developing countries such as energy security, social empowerment, employment generation, and substantial savings of foreign exchange. The fossil fuels are neither sustainable nor inexhaustible, and alternatives must be explored to address different issues with the use of petroleum-derived fuels.

There are greater challenges with the use of alternative fuels due to their adaptability with the vital parts of engines, cost, availability of feedstocks, and so on. Also, knowledge of important chemical, physical, thermodynamic, and logistics features of the alternative fuel are very much required for large-scale adaptation. Moreover, production of alternative fuels is a complex process, and keeping track of constantly upgrading technology shall be very helpful to drastically reduce the cost and production time.

It is not possible for a single-alternative fuel to completely replace the diesel, and various options have both positive and negative attributes. The alternative fuels reduce the risk to health as they are clean burning. The engine performance is quite similar, and well-to-wheel analysis is required for estimating the operating cost. Since various disciplines are linked with production and adaptation of alternative fuels, synergy is necessary among research fraternity to understand the efficacy of different options. Some of the fuels are very promising, but further research is required to prove their potential. It is envisaged that with the enforcement of more stringent norms, the alternative fuels would become more attractive either as a drop in fuels or blend. It can be concluded that diesel engines can be fueled in an efficient and sustainable way with various options of alternative fuels with some trade-off on price and performance; however, they are capable of bringing a new era of green environment.

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