

Review

Biofuels and Their Blends—A Review of the Effect of Low Carbon Fuels on Engine Performance

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Abstract: Energy is an important aspect concerning global economic development and environmental conservation. Economic growth has been accompanied by extensive use of fossil fuels, resulting in significant emissions of greenhouse gases and other pollutants. Therefore, researchers have turned their attention to low / zero carbon fuels. Among these, biofuels have attracted wide attention due to their relatively low cost, clean combustion products and renewability. This article reviews the combustion, performance and emission characteristics of internal combustion (IC) engines fueled with biofuels categorized into three generations by their raw material sources. According to most research findings, biofuels generally exhibit poorer combustion performance in IC engines compared to fossil fuels due to their high viscosity and low lower heating value. However, these biofuels, characterized by a high oxygen content, facilitate more complete combustion and reduce emissions of CO, UHC and smoke, albeit increasing NO_x emission and fuel consumption. Both thermal efficiency and brake power also tend to decrease, but various optimization strategies such as advanced combustion modes or injection control methods can partially compensate for these drawbacks. In conclusion, biofuels should be a promising low-carbon fuel for IC engines in the future.

Keywords: low / zero carbon; biofuels; combustion; performance; emission; thermal efficiency



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1. Introduction

1.1. Research Background

Global carbon emissions have shown a continuous upward trend since the 1970s, closely correlated with economic development. The total global carbon emissions reached 34.05 billion tons in 2018, setting a new historical record [1]. Due to rapid economic development over the past few decades, the Asia–Pacific region has become the world’s largest carbon emission region [2]. Electricity and heat production, transportation, manufacturing and construction are the primary sources of carbon emissions, mainly due to extensive use of fossil fuels in these sectors. Currently, transportation is the world’s second-largest source of carbon emissions, encompassing land, maritime and aviation transports. According to the International Maritime Organization (IMO), maritime transport accounts for over 90% of global freight transport [3], so the reduction of carbon emissions from shipping is crucial for global decarbonization efforts. In 2018, the IMO introduced the “Initial Strategy on Reduction of Greenhouse Gas (GHG) Emission from Ships” to guide the reduction of carbon emissions for shipping. According to this regulation, GHG emissions from shipping should be completely eliminated by 2050 [4] and the plan is divided into three phases: short-term from 2018 to 2023, focusing on technological innovations for existing and new ships; medium-term from 2023 to 2030, aiming to regulate the shipping market and develop new low-carbon fuels; and long-term from 2030 to 2050, targeting the development of zero-carbon fuels to achieve true carbon neutrality. Specific timelines are illustrated in Figure 1.

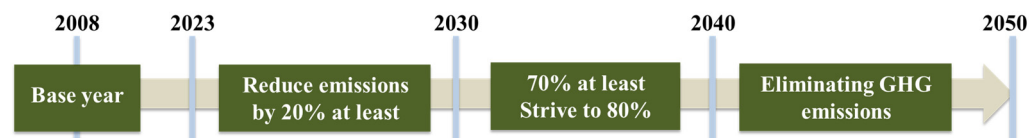


Figure 1. The Initial Strategy on Reduction of Greenhouse Gas (GHG) Emission from Ships introduced by the IMO.

Fuel decarbonization has always been a hot topic in the maritime industry. To date, most marine engines still rely on non-renewable sources such as fossil fuels, and their continued large-scale use will disrupt climate stability. To address this issue, the concept of green shipping has emerged, which aims to consider the use of widely available and renewable energy sources like solar, wind and hydroelectric power. However, the output of these energy sources is not always stable [5]. Therefore, it is necessary to consider new types of sustainable and storage energy sources, such as alternative fuels [6,7].

Liquefied natural gas (LNG), methanol, ammonia (NH_3), hydrogen and biofuels are the promising alternative fuels which can replace traditional diesel fuels for marine application.

LNG contains about 90% methane in volume fraction and minimal sulfur, resulting in lower GHG, NO_x and particulate matter emissions [8]. The extraction of LNG is relatively simple, the relevant regulations are mature, and its application as a low-carbon fuel in marine engines is widespread, although the cost is relatively high [9].

Methanol contains 50% oxygen in mass fraction and no sulfur, and it can be produced from various feedstocks including coal, LNG and biomass [10]. The combustion of methanol can achieve low CO and NO_x emissions. In addition, methanol has a high safety standard and is less prone to safety incidents during its storage, transportation and use [11]. Despite methanol being regarded as a promising low-carbon fuel for marine engines, there are still some challenges, such as its relatively high cost and low lower heating value (LHV).

Ammonia and hydrogen fuels are ideal zero-carbon fuels for IC engines, offering excellent GHG emission reduction capabilities [12]. However, challenges related to their combustion properties have not been completely addressed, which limits the potential for widespread adoption of ammonia and hydrogen fuels. In addition, hydrogen easily causes explosion accidents, while liquid ammonia has strong corrosivity and toxicity. Therefore, higher safety standards must be established when using them.

Biofuels are always derived from biomass, such as from animals, plants or microalgae. They possess excellent combustion efficiency, outstanding safety, good engine compatibility, environmental sustainability, renewable characteristics and ultra-low sulfur content [13,14]. As a fuel, they can be used either independently or blended with existing fossil fuels, which means there is almost no need for retrofitting existing marine engines. Compared to fossil fuels, GHG and sulfur oxide emissions can be significantly reduced with biofuels. Their costs are only slightly higher than traditional diesel fuel. Through numerous studies and experiments in recent years, it has been demonstrated that the use of biofuels can significantly reduce pollutant emission. For instance, unburned hydrocarbons (UHCs) decrease by 55% to 60%, particulate matter by 20% to 50% and CO by over 30%. Moreover, biofuels derived from vegetable oils or waste oils can achieve “zero growth” in carbon emissions. This means the amount of CO_2 released during combustion is nearly balanced by the CO_2 absorbed during the source formation process [15]. Considering these factors, biofuels have been regarded as one of the transitional solutions for the current low-carbon development of ships. In this study, a comprehensive overview of the combustion, engine performance and emission characteristics of different biofuels in IC engines over the past two decades is provided, as well as a comparison with the characteristics of conventional diesel. The costs and volumes for the total capacities of diesel fuel and some alternative fuels for a bulk vessel are shown in Figure 2.

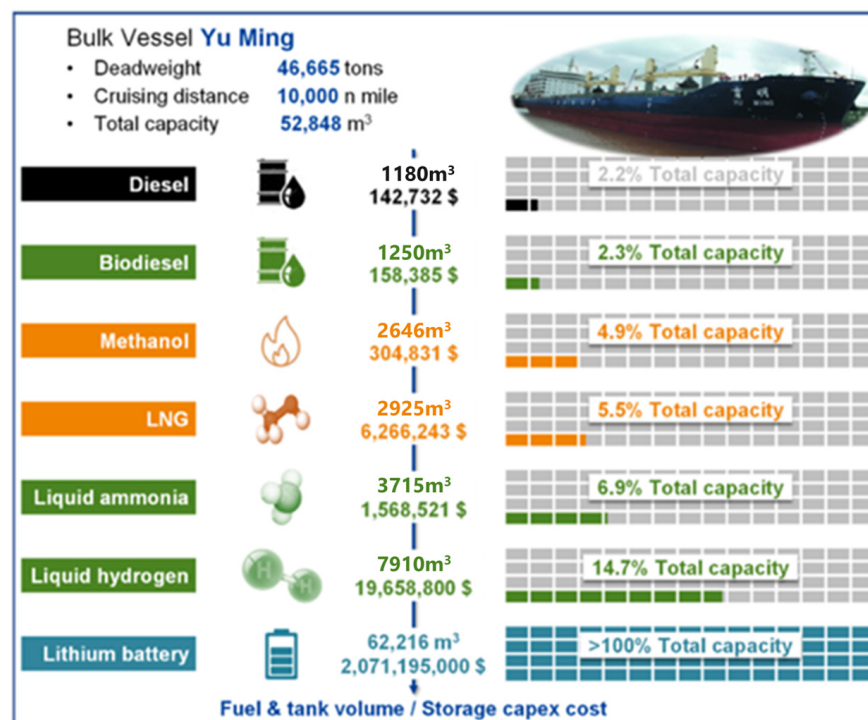


Figure 2. Costs and volumes for the total capacities of diesel fuel and alternative fuels for a bulk vessel.

1.2. Biofuel Introduction

1.2.1. The Generations of Biofuels Based on Their Raw Material Sources

Biofuels can be classified into three generations based on their raw material sources: (1) First-generation biofuels, such as vegetable oils, bio-alcohols, biogas and solid biofuels, are produced using conventional technologies from food sources like sugars, starches, vegetable oils and animal fats. (2) Second-generation biofuels, such as biodiesel, bio-alcohol and syngas, are produced using cellulose-based biofuels and waste biomass, such as straw from wheat and corn and wood, which are sourced from non-food crops. (3) Third-generation biofuels, such as algae oil, are produced by extracting oils from algae [16].

The preparation processes of the three generations of biofuels are categorized by the raw materials. They involve using vegetable oils, animal oils, waste oils or microbial oils. Biofuels are produced through a transesterification process using methanol or ethanol with acid–base catalysts. In addition, there are methods that use biocatalysts or operate under supercritical conditions to esterify the oils. Essentially, the main components of the three generations of biofuels include small molecules of esters, such as fatty acid methyl esters, fatty acid ethyl esters and various plant oil esters [17].

Besides various primary ester substances, biofuels may also contain small amounts of glycerol, methanol, free fatty acids and catalysts. These are typically unreacted parts of the raw materials, intermediate products or residual impurities. Different raw materials and production processes of biofuels result in different chemical compositions and engine characteristics.

A detailed introduction of the three generations of biofuels mentioned before is provided in the next section, to illustrate the differences among them.

1.2.2. First-Generation Biofuel

First-generation biofuels are products made through esterification reactions by converting edible vegetable oils or animal fats with methanol or ethanol [16]. Compared to traditional diesel fuel, first-generation biofuels exhibit significant differences in molecular structure and chemical composition, which supports their outstanding environmental

performance. They do not contain sulfur and aromatic hydrocarbons, which allows for a substantial reduction in SO_x , CO and PM emissions during their combustion.

The technology of first-generation biofuel utilization developed relatively early and has become more mature. It is commonly employed as a fuel source in the transportation sector. Its ability to blend with traditional diesel fuel in specific ratios requires minimal adjustments, making it a convenient option for existing engines.

First-generation biofuels also face some unresolved issues, such as their high solidification point [18], which limits their use at low temperature conditions. Additionally, considering they are typically made from food crops, there are concerns about the competition for land resources used in food production and issues related to harvesting costs. Some parameters of the first-generation biofuels are shown in Table 1. Additionally, some application examples are shown as follows.

Table 1. Physicochemical parameters of first-generation biofuels.

	Viscosity	Cetane Number	LHV	Flash Point	Density
	mm^2/s		MJ/kg	$^{\circ}\text{C}$	kg/m^3
Rapeseed oil methyl ester	4.92	47.2	39.9	/	0.89
Corn oil methyl ester	2.45–2.56	58.4–59	44.9–45	/	/
Soybean oil methyl ester	4.1–4.5	45–57	33.5–39.8	130–165	0.84–0.88
Sunflower oil methyl ester	4.04	51.25	/	179	0.88
Lard methyl ester	4.45	/	40.1	134	0.895
Fatty acid methyl ester	4.43	55.2	38.3	165	0.882
Trout oil methyl ester	4.25	51.3	37.8	116	0.885
Fish oil ethyl ester	4.74	52.6	40.1	114	0.885
Tea seed methyl ester	4.95	52	37.5	>120	0.884
Pithecellobium dulce seed methyl ester	3.54	68	39.5	158	0.87
Diesel fuel	2.94	50	42.8	70.5	0.83

At the beginning of the 20th century, the inventor of the diesel engine, Rudolf Diesel, conducted engine experiments using peanut oil as fuel [19], which can be seen as the initial exploration of biofuel applications. Although biofuel technology has gradually developed, it only existed as an alternative to petroleum due to its high cost for a long time. In the 1990s, shipping companies began to apply biofuels. Some Finnish and German companies conducted experiments on the applications of biofuels. At that time, biofuels were mainly first-generation biofuels that were produced from food crops. The Finnish shipping company Meriaura conducted the first biofuel trial voyage on the tugboat “Aura” in 1992 [20]. Throughout the 1990s, the Wärtsilä and MAN companies began exploring and testing the feasibility of engine operation with biofuels. In 2003, Germany inaugurated its first commercial power plant fueled by biofuels [13]. According to preliminary estimates, the cost of retrofitting conventional engines for biofuel compatibility is less than 5% of the total engine cost. The primary expenses for these modifications are mainly used to update the fuel compartment.

Today, several countries have implemented policies and standards to promote the use of first-generation biofuels [21]. As environmental awareness and sustainable development grow in importance in people’s minds, the global fuel market is no longer dominated solely by traditional diesel. For instance, in 2015, GoodFuels Marine from the Netherlands partnered with Wärtsilä from Finland to launch a biofuel pilot program aimed at accelerating sustainable, reliable and economically viable biofuel development in the maritime sector. In 2019, widespread trials of biofuels began in the shipping industry, with Maersk, the world’s largest container shipping operator, initiating trials. These trials were followed by numerous experimental voyages using biofuels. By February 2023, CMA CGM reported

that dozens of vessels in their fleet have been using first-generation biofuels blended at ratios exceeding 25% with traditional diesel fuel. In September 2023, Kawasaki Kisen Kaisha, Ltd. (K Line) announced their certification from ClassNK in Japan, confirming their successful reduction in carbon dioxide emissions using first-generation biofuels in their maritime fleet.

1.2.3. Second-Generation Biofuel

Unlike first-generation biofuels, second-generation biofuels are less dependent on food crops and can utilize non-edible raw materials. This approach helps avoid competition with food production and potential negative environmental issues [16,22].

The second-generation biofuels primarily utilize waste oils such as used cooking oil, industrial oils and grease trap oils. Additionally, they include non-edible plant oils like jatropha, cellulose biomass, wood chips and straw [22]. These oil feedstocks have abundant sources and large reserves, effectively addressing waste oil pollution. However, they also have some unresolved issues, such as high impurity levels, decentralized sourcing and high labor costs [23]. Some performance parameters of the second-generation biofuels are shown in Table 2.

Table 2. Physicochemical parameters of second-generation biofuels.

	Viscosity	Cetane Number	LHV	Flash Point	Density
	mm ² /s		MJ/kg	°C	kg/m ³
Jatropha oil methyl ester	2.35–5.48	51–63.3	38.5–41.6	172–175	0.85–0.88
Palm oil methyl ester	4.6	56.5–62	38.3–40.5	184.8	0.87
Rice bran oil methyl ester	8.04	/	39	173	0.896
Waste oil methyl ester	4.57–4.9	44–52	40.5–41	<120	0.86–0.89
Waste cooking oil methyl ester	4.95	48.7	40.4	116	0.862
Honge oil biofuel	5.6	42	36	163	0.89
Pine oil biofuel	1.3	11	42.8	52	0.875
Karanja vegetable biofuel	6.95	55	37	205	0.883
Millettia pinnata biofuel	5.04	55	38	181	0.867
Eucalyptus biofuel	2.99	53	40	105	0.896
Rubber seed oil biofuel	5.81–5.96	43	38.5	/	0.860–0.881
Diesel fuel	2.94	50	42.8	70.5	0.83

Due to the more readily available raw materials, the second-generation biofuels have found numerous applications in today's global market, with an increasing number of ships experimenting with these fuels in recent years. For example, in 2019, Maersk collaborated with the Dutch Sustainable Growth Coalition and Shell, and successfully conducted trials on a container ship using biofuels derived from used cooking oil, which were blended in a ratio of over 20%. In July 2020, the Mediterranean Shipping Company (MSC) in Geneva, Switzerland pioneered the large-scale use of biofuel blends of up to 47% on container ships. By the end of 2021, South Korea Seoul's container shipping company HMM (formerly Hyundai Merchant Marine) validated the efficacy of biofuels in reducing

greenhouse gas emissions compared to traditional fuels for the first time. Additionally, HMM tested the emission characteristics of “bio-heavy oil”, which was made from animal and plant oils, waste oils and by-products of biofuel processing, on its vessel “HMM Dream”. After more than two weeks of testing, they confirmed that bio-heavy oil emits significantly less carbon than traditional diesel fuel. In April 2021, Broken Hill Proprietary Billiton Ltd. (BHP) in Melbourne, Australia successfully completed the first marine biofuel bunkering in Singapore. Following this, in August 2022, TotalEnergies’ marine fuel division announced the first trial of sustainable marine biofuels with China COSCO Shipping, further promoting biofuel applications in shipping. In September 2022, the China Ship Power Research Institute successfully conducted biofuel tests on a large-scale ship engine with a diameter of 520 mm, marking the first time biofuels were used in large ship engines in China. In 2023, China Zhejiang Seaport International Trading Co., Ltd. and China Zhejiang Zhoushan Petroleum Co., Ltd., supplied 325 tons of B24 blended fuel to the ocean-going container ship “Xin Mingzhou 60”. B24 blended fuel consists of 24% biofuels and 76% conventional low-sulfur fuel. Sinopec Sinochem Marine Fuel supplied 300 tons of B24 biofuel to China COSCO Shipping Bulk Transportation Co., Ltd.’s vessel “Bao Ningling” in Shanghai, China, which was the first marine biofuel oil bunkering. In January 2024, the first demonstration of B5 biofuel water bunkering in the domestic river shipping sector was completed at Sinopec Fuel Oil Guangdong Sui Nan Water Bunkering Station, showcasing the potential application of biofuels in inland river shipping.

1.2.4. Third-Generation Biofuel

Third-generation biofuels typically refer to those derived from microalgae, which require extracting biomass from the microalgae and then processing it into biofuels using various methods [16]. Microalgae are single-celled organisms with the characteristics of rapid growth and high lipid content. Theoretically, microalgae are highly adaptable and can thrive in various environments, even in harsh conditions such as wastewater and stagnant water. Cultivating microalgae does not compete for land resources and provides abundant, low-cost and renewable biomass. Additionally, microalgae possess the ability to sequester carbon, which helps reduce atmospheric CO₂ levels [24]. Some performance parameters of microalgae biofuels are shown in Table 3.

Table 3. Physicochemical parameters of third-generation biofuels.

	Viscosity	Cetane Number	LHV	Flash Point	Density
	mm ² /s		MJ/kg	°C	kg/m ³
Microalgae oil biofuel	4.49	57	37.6	141	0.881
Chaetoceros gracili biofuel	3.4	51	39.5	/	0.885
Cryptocodinium cohnii methyl ester	5.06	46.5	37.4	/	0.912
Chlorella algae biofuel	4.85	58.6	38.8	157	0.867
Spirulina maxima microalgae biofuel	4.47	55	38.43	178	0.872
Microalgae Chlorella protothecoides biofuel	4.22	52	37.5	124	0.9
Spirulina microalgae biofuel	5.26	52.2	41	>128	0.861
Diesel fuel	2.94	50	42.8	70.5	0.83

Currently, research on microalgae biodiesel primarily focuses on cultivation and preparation, such as how to increase lipid content, optimize cultivation conditions, develop efficient harvesting and extraction technologies and improve the conversion processes of microalgae biofuels. However, the production costs of algae-based biofuels are considerable

and there are technical challenges in the cultivation and harvesting processes [25]. Therefore, algae-based biofuels have not yet been widely applied at scale.

1.2.5. Other Generation Methods

The previous section introduced a classification method for biofuels, but there are other classification methods as well. Biofuels can also be divided into three generations based on their production methods.

First-generation biofuels mainly consist of fatty acid methyl esters, primarily produced by transesterification. This process involves reacting high-viscosity animal and plant oils with methanol or ethanol, short-chain alcohols, under the catalytic action of acids or alkalis, to produce low-viscosity fatty acid methyl esters [16]. First-generation biofuels have a high oxygen content but lower LHV compared with traditional diesel fuel, and their chemical structure differs significantly from the traditional diesel fuel. The three generations of biofuels mentioned before, based on raw materials, can generally be categorized into this type, as they are mostly prepared through transesterification reactions.

The second-generation biofuels are primarily composed of saturated hydrocarbons. They are mainly produced by catalytic hydroprocessing and hydroisomerization. Specifically, this involves converting triglycerides from animal and plant oils into saturated straight-chain hydrocarbons under hydrogenation conditions. These hydrocarbons are then further processed through hydroisomerization to form isomeric hydrocarbons, characterized by high cetane numbers and free from sulfur and aromatic compounds. This biofuel differs from those prepared through esterification reactions, as it does not contain oxygen and has better combustion properties, but the production costs are higher. This is currently a research hotspot [26].

Third-generation biofuels mainly consist of synthetic biofuels, primarily produced by gasification, where biomass materials are high-temperature gasified in gasifiers, followed by catalysis, hydrogenation and other processes for synthesis [27]. These biofuels have properties similar to traditional diesel fuel, with high cetane values. However, this method has issues such as the high costs of gasification units and suboptimal conversion efficiencies.

The examples above illustrate that the application of biofuels in shipping is a continually evolving and improving process. With ongoing policy support, technological innovations and deeper market practices, the use of biofuels as marine fuels is increasingly widespread. As technology matures and markets expand, biofuels are expected to occupy a more significant position in the global marine fuel market.

This study will offer a detailed analysis and evidence based on the relevant literature over the past two decades in the next section, focusing on the combustion characteristics, performance characteristics and emission characteristics of the three generations of biofuels classified by raw materials. This will help to determine the differences between biofuels and traditional diesel fuel and analyze the reasons for these differences.

2. Combustion Characteristics in IC Engines Fueled with Biofuels

The combustion performance of biofuels is generally evaluated by certain key combustion parameters of the engine, such as cylinder pressure (CP), peak pressure, heat release rate (HRR), etc. These parameters are all influenced by the combustion conditions inside the cylinder, which reflect the combustion process inside the engine. In this study, the combustion characteristics of various biofuels are presented in the order of the first generation, the second generation and the third generation of biofuels in each section. The causes of the observed phenomena, which are related to the properties of the biofuels, are also discussed.

2.1. Cylinder Pressure

The pressure variation curve inside the cylinder during fuel combustion is referred to as the CP. When biofuels are used as fuel, most researchers observe a lower CP compared to that of traditional diesel fuel, while only a few studies report an increase in CP with

biofuels [28]. Puskar et al. conducted tests and research on the effects of different proportions of biofuel blended with ultra-low sulfur diesel on the operational characteristics of a six-cylinder direct-injection engine with a bore of 100 mm. The results indicated that, as the proportion of biofuels in the test fuel increases, the ignition delay (ID) decreases, the combustion speed accelerates and the CP rises; however, the peak of the HRR decreases significantly. However, further increases in the biofuel content lead to a tendency for the CP to decrease at high loads for the same mass, possibly due to the poor combustion performance caused by the high viscosity of biofuels [29]. Elumala et al. investigated the dual fuel combustion process that microalgae biofuels undergo when injected as high-reactivity fuels directly into the cylinder, while various proportions (10%, 20%, 30% and 40%) of compressed natural gas (CNG) as low-reactivity fuel were injected into the intake manifold on a four-stroke single-cylinder engine with a bore of 110 mm. Then, these results were evaluated and compared with the combustion and emission characteristics of pure microalgae biofuel. As shown in Figure 3, the peak cylinder pressures were 74.49 bar (for pure biofuel), and 70.21, 72.32, 76.72 and 69.67 bar, respectively, corresponding to different CNG energy fractions. The increase in the CNG fraction caused longer ID and combustion durations, but when CNG was mixed with biofuel, the combustion was enhanced, resulting in the increase of CP [30].

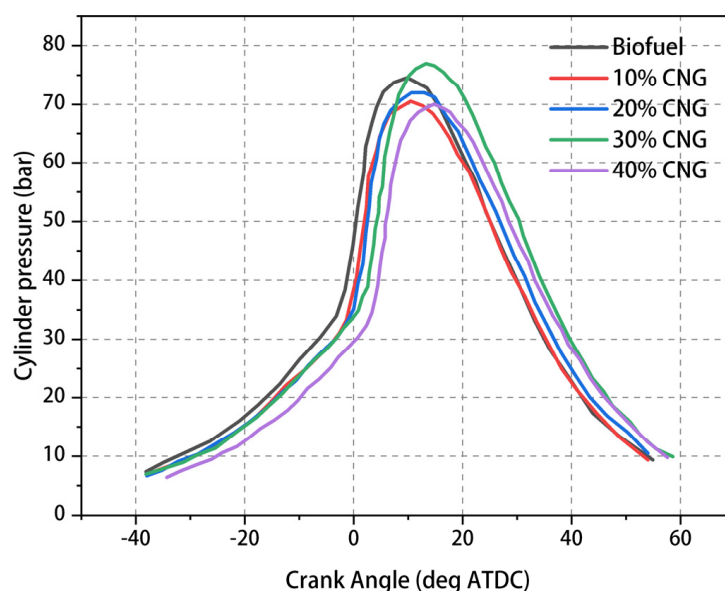


Figure 3. CP of microalgae biofuel with different proportions of CNG as additions [30].

2.2. Heat Release Rate

The HRR is the amount of heat release measured per crank angle during fuel combustion. It is one of the most important indicators for characterizing the combustion progress within the cylinder. The HRR generally depends on the physicochemical properties of the fuel and the combustion condition in the cylinder. Most IC engines using biofuels tend to exhibit a lower HRR during combustion compared to those using traditional diesel, primarily due to the higher viscosity and lower volatility of biofuels [31]. For example, Mourad et al. conducted experimental research on the effects of fuel preheating on combustion and emission characteristics when using biofuel made from sunflower oil. The experiments were conducted on a single-cylinder air-cooled diesel engine with a bore of 114 mm. Biofuels were preheated by a heat exchanger before combustion. As shown in Figure 4, the peak HRR of the engine using biodiesel was 7% lower than that of the original engine, possibly due to the high viscosity of the biofuel [32].

However, using biofuels may also increase the HRR under the influence of external conditions. For example, Medhat et al. extracted crude oil from *Scenedesmus obliquus* algae to prepare biofuel as the fuel of the experiment by esterification. Experiments

were conducted on an engine with a bore of 110 mm, using different concentrations (5 mL/L, 10 mL/L and 15 mL/L) of n-pentane as additives to improve engine combustion performance. The results indicated that the maximum HRR of the blended fuel, consisting of biofuel and 15 mL/L n-pentane, exceeded that of the original engine across various loads. This was attributed to the shortened ID and enhanced combustion performance resulting from the addition of n-pentane [33]. Sathish et al. evaluated the combustion performance of *Chlorella vulgaris* biofuel and its mixture (B20) with traditional diesel fuel in an IC engine under various load conditions with a dual-fuel mode. In this setup, B20 was used as the pilot fuel and injected into the intake manifold while traditional diesel fuel was directly injected into the cylinder (B20B). The experiments then tested the combustion performance of B20 direct injection (B20I), B20B and traditional diesel fuel. As shown in Figure 5, both B20B and B20I exhibited peak HRRs that were more than 10% higher than that of traditional diesel fuel at high loads. This could be attributed to the premixed combustion and the reduction in ignition delay [34].

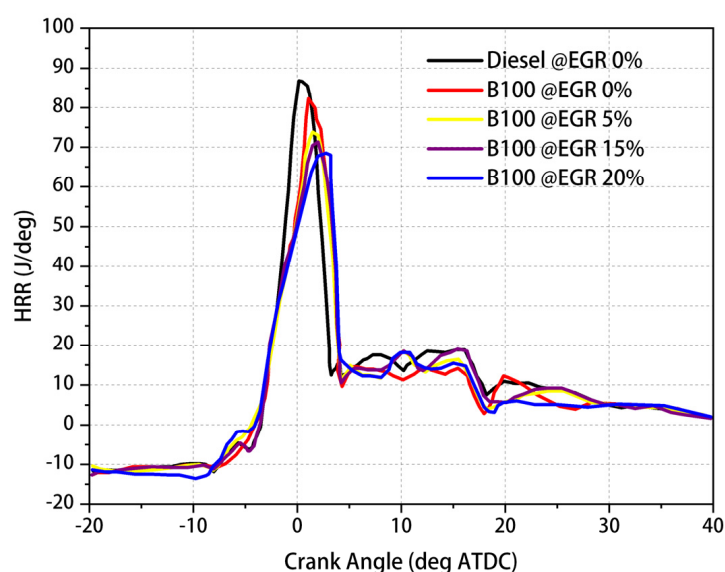


Figure 4. HRR of traditional diesel fuel and sunflower biofuel at different EGR rates [32].

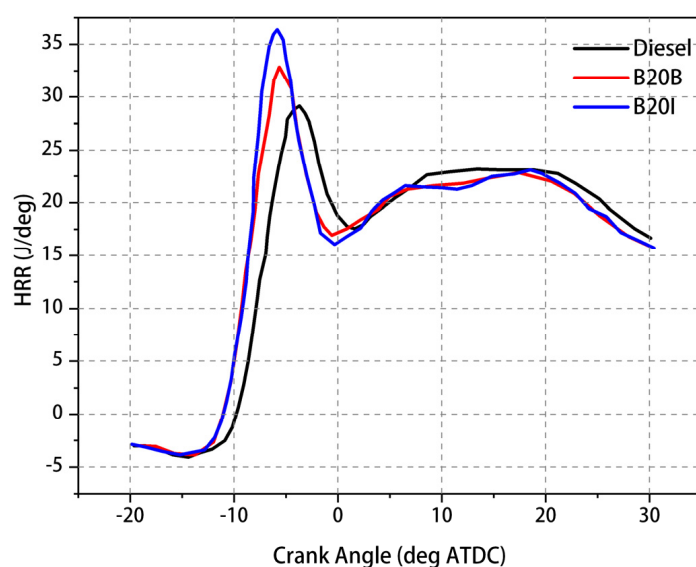


Figure 5. HRR of B20I, B20B and traditional diesel fuel [34].

2.3. Ignition Delay

The time interval between fuel injection and the start of combustion is known as the ignition delay. ID is influenced by the properties of fuel and the physical or chemical processes that occur after the injection of fuel, including atomization, evaporation, mixing and pre-combustion reactions. It plays a crucial role in the combustion and emission characteristics in IC engines.

Zhang et al. prepared four different types of biofuels (rapeseed methyl ester (RME), sunflower methyl ester (SFME), spirulina microalgae ester (SME), cottonseed methyl ester (CSME)) to investigate the influence of fatty acid methyl ester (FAME), the main components of these biofuels, on the combustion characteristics on a four-cylinder marine diesel engine with a bore of 190 mm. The results indicated that in the combustion of biofuels, the dynamic viscosity of the biofuels played a significant role in the ID. Due to the high viscosity and low LHV of biofuels, the ID for these biofuels was longer than that of traditional diesel fuel at low loads. As the load increased, improvements in evaporation and combustion processes reduced the differences in IDs between biofuels and traditional diesel fuel; however, this effect remained relatively minor [35]. Karl et al. studied the combustion characteristics of hydrotreated vegetable oil (HVO), rapeseed methyl ester (RME) and traditional diesel fuel. The experiments were conducted in a compression ignition chamber with optical access having engine-like thermodynamic conditions; the chamber had the specification of a four-stroke single-cylinder engine with a bore of 130 mm. As shown in Figure 6, the IDs of all three fuels were negatively correlated with temperature, with HVO having the shortest ID, igniting first, followed by RME, and then traditional diesel fuel was ignited last, which aligns with their respective cetane numbers. The smallest spread in IDs was found for the high temperature cases for all fuels, indicating that the higher gas temperatures yield a more stable ignition. Generally, the ID asymptotically approaches infinity as the gas temperature decreases, resulting in it having a high sensitivity to the gas temperature for lower gas temperature cases [36].

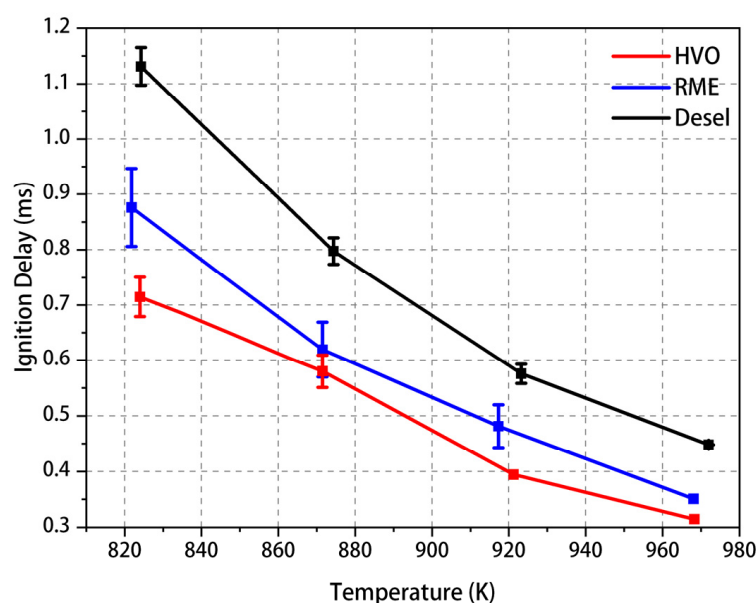


Figure 6. The relationship between ID and temperature of different biofuels and traditional diesel fuel [36].

Dhamodaran et al. compared the combustion characteristics of three different unsaturated biofuels (rice bran methyl ester (RBME), neem oil methyl ester (NME), cottonseed methyl ester (CSME)) and their mixtures with traditional diesel fuel (20% biofuel by volume) by conducting experiments in a constant speed single-cylinder IC engine with a bore of 87.5 mm. The results, as shown in Figure 7, indicated that the traditional diesel fuel

had the longest ID, while the RBME blended fuel had the shortest ID, with a difference exceeding 15% between them. The IDs of all fuels decreased with the increasing of the load, because of the retention of heat generated in previous cycles, exhaust gas dilution and the wall temperature of the combustion chamber. Additionally, higher cylinder temperatures can accelerate fuel vaporization rates, leading to a reduction of the ID [37].

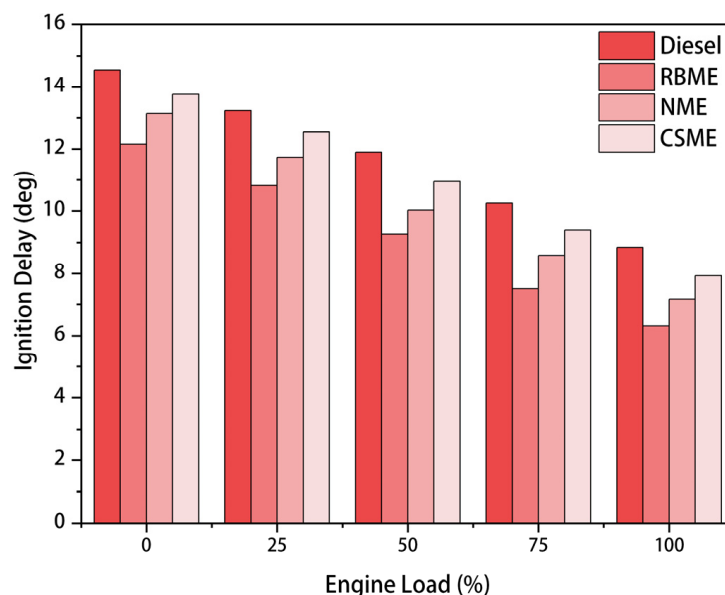


Figure 7. The relationship between ID and engine load of different biofuels and traditional diesel fuel [37].

Sathish et al. determined the ID of traditional diesel fuel, B20B and B20I at 100% load. Owing to the higher cetane number of B20I compared to other fuels, its premixed combustion was faster, leading to a more significant reduction in ID for B20I. Additionally, the IDs for both B20B and B20I were 15% lower than traditional diesel fuel [34].

In addition to the chemical properties of the fuel, the physical properties also affect the ID. Elumalai et al. conducted experiments by combining ammonia with algal biofuel to operate in the Reactivity Controlled Compression Ignition (RCCI) mode in a single-cylinder engine with a bore of 110 mm. The aim of these experiments was to investigate the impact of various factors on performance and emission, in order to optimize the ammonia energy fraction under RCCI operation [38]. The results indicated that as the ammonia energy fraction (AEF) increases, the ID also increases. Specifically, when the AEF rose from 20% to 50%, the ID of the biofuel was 9% to 26.12% higher than that of traditional diesel fuel. This increase in ID was due to the fact that the complete evaporation of ammonia required more time and heat. However, the RCCI mode enhanced the atomization and mixing of fuel, which tended to reduce the ID. Ultimately, the combined effect of these two factors resulted in an ID for the ammonia-added mode that was comparable to that of pure biofuels [39].

Overall, most biofuels exhibit poorer combustion characteristics, such as the CP and HRR, compared to traditional diesel fuel, but the differences are not significant, generally ranging from 10% to 20%. This is primarily due to the poorer physicochemical properties of biofuels, such as a lower LHV and higher viscosity and density, which result from their preparation methods and raw materials.

3. Performance Characteristics in IC Engines Fueled with Biofuels

The performance characteristics of biofuels generally refer to the attributes and properties describing their efficiency or effectiveness. Key parameters include brake thermal efficiency (BTE), brake specific fuel consumption (BSFC), brake power (BP), etc. Similar to the combustion characteristics, research on the performance characteristics of biofuels is introduced in generational order in the next section, and the causes are explained.

3.1. Brake Thermal Efficiency

BTE is a key parameter for evaluating the performance of IC engines, as it measures the efficiency with which heat is converted into useful work. The BTE is influenced by engine specifications, fuel properties and combustion-related parameters such as load and speed. Due to the physicochemical properties of biofuels, most IC engines using them directly as fuel struggle to achieve high BTE [30,31,33].

Dhar et al. prepared karanja oil methyl ester (KOME) and its mixtures with traditional diesel fuel (KOME05, KOME10, KOME20, KOME50 and KOME100) at different blending ratios and experimentally investigated the impact of these blends on engine performance, emission and combustion characteristics in a direct-injection IC engine at various speeds and loads. The results indicated that the BTEs of biofuel blends were approximately 10% lower than that of traditional diesel fuel at low loads, which may be due to the high viscosity and latent heat of the vaporization of the biofuel. However, at high loads, the BTEs of all fuels were nearly identical. This was attributed to the increase of air temperature, which facilitated the evaporation of the biofuel. Moreover, the presence of oxygen in the biofuel also can improve combustion efficiency [40]. Perumal et al. observed a similar trend when using biofuel derived from animal fats and comparing it with traditional diesel fuel in their experiments. The results showed that at low loads, engines running on biofuels had significantly lower BTE than those running on traditional diesel. However, at high load, the BTE of biofuels was slightly higher than that of traditional diesel fuel. This was again due to the high air temperature at high loads and the beneficial effect of the oxygen content in the biofuel [41]. Sanjid et al. produced mustard biofuel from low-quality mustard oil by esterification and its mixtures with traditional diesel fuel (B0, B10, B20 and B100). Then, these biofuel blends were investigated for the combustion, performance and emission characteristics of the engine under different speeds and full load conditions using a four-cylinder IC engine. As shown in Figure 8, traditional diesel fuel exhibited the highest BTE, while pure biofuel had the lowest BTE, with a difference exceeding 20%. This discrepancy was primarily due to the low LHV of biofuel, as well as its high density and viscosity, which impaired atomization and combustion after injection [42].

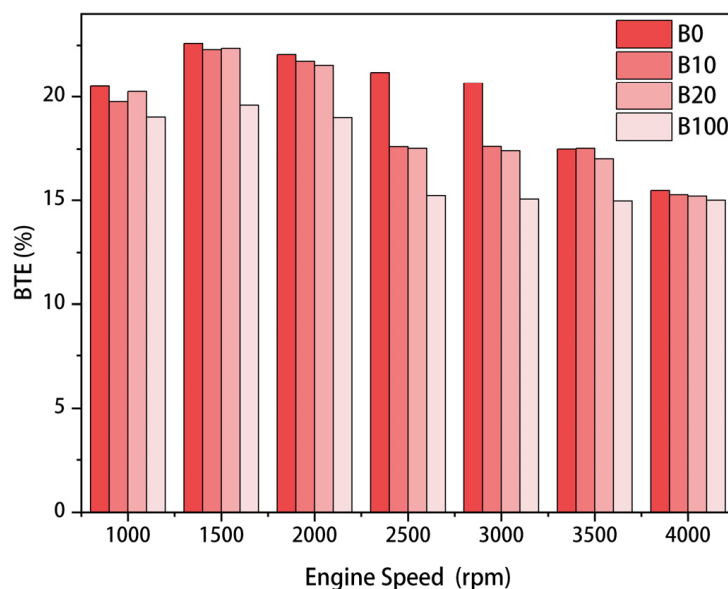


Figure 8. The relationship between BTE and engine speed of mustard biofuel blends with different proportions [42].

Dhamodaran et al. compared the combustion characteristics of biofuels which were prepared from three different sources (rice-bran, neem and cottonseed) with those of traditional diesel fuel. The experimental results indicated that traditional diesel fuel exhibited the highest BTE. The BTE ranking, from highest to lowest, was as follows:

traditional diesel, CSME, NME and RBME. At 100%, the average BTE of the three biofuels' load was 9.19% lower than that of traditional diesel fuel. This discrepancy was attributed to the higher viscosity of the biofuels, leading to poorer atomization upon injection, thereby reducing their BTE compared to traditional diesel fuel [37]. Savariraj et al. prepared Mahua biofuel and its mixtures (B0, B25, B50, B75 and B100) with traditional diesel fuel and analyzed the performance of these biofuel blends in a single-cylinder IC engine with a bore of 87.5 mm. The experiments showed that the BTE consistently decreased with the increasing of the Mahua biofuel proportions of the blended fuel. The BTE of B25 was nearly identical to that of traditional diesel fuel. However, as the biofuel content increased in the blend fuel, the reduction in BTE exceeded 20%. This low BTE of Mahua biofuel was due to the combined effect of the high viscosity, high density and low LHV of Mahua biofuel [43].

Due to their physical properties, such as high viscosity and latent heat of vaporization, biofuels and their blends often exhibit poor combustion conditions. Therefore, other strategies are needed to compensate for the decrease in BTE. The physical properties of biofuels lead to poor atomization and evaporation after fuel injection, thereby affecting BTE [44], so one simple way to improve the combustion of biofuels is by increasing the injection pressure. For instance, Mohite et al. investigated the engine performance and emission characteristics of algae biofuel–hydrogen dual fuels under various pilot fuel injection pressures (PFIP) and engine load conditions in a water-cooled single-cylinder four-stroke direct-injection IC engine. Higher injection pressure improved fuel atomization and evaporation, facilitating more complete combustion and releasing more energy, which ultimately increased BTE. At the PFIP of 240 bar, the BTE of the hydrogen–algae biofuel test mode was 13.88% higher than that of pure biofuels, which was attributed to improved fuel atomization and performance [45]. Another approach to enhance biofuel combustion is blending them with other fuels that have better combustion performance. For example, Ramesha et al. blended oil extracted from waste plastics (WPO) with algae oil methyl ester (AOME) and evaluated the combustion performance of the mixture (B20AOME10WPO) in a single-cylinder four-stroke, direct-injection, water-cooled IC engine. The experimental results are shown in Figure 9, which indicates that the BTE of B20AOME10WPO was the highest among the tested fuels, 15.7% higher than traditional diesel fuel [46]. This enhancement was due to the oxygen content within the biofuel and plastic molecules, which improved combustion [47]. Annamalai et al. attempted to enhance the engine performance of biofuel blends extracted from algae by introducing hydrogen (at rates of 10.4 g/h, 21.6 g/h, 32.4 g/h, 43.2 g/h and 54 g/h) into pure biofuel in a single-cylinder diesel IC engine. Experimental results showed that the BTE of traditional diesel fuel was over 13% higher than that of biofuels without added hydrogen. However, the addition of hydrogen significantly increased the BTE of biofuels, with the BTE being 1.3% higher than traditional diesel fuel [48]. The improvement was because the addition of hydrogen accelerated the flame speed, promoted faster combustion, enhanced combustion stability and led to more complete combustion [49]. Jegan et al. utilized nanotechnology by mixing metal oxide nanoparticles, such as CeO_2 , SiO_2 and TiO_2 , at the concentration of 150 mg/L into biofuel derived from algae oil to enhance fuel combustion performance in a single-cylinder four-stroke IC engine. The base fuel in this experiment was a B25 blend that consisted of a 25% volume of algae biofuel and a 75% volume of traditional diesel fuel. Experimental findings revealed that adding any of these metal oxide nanoparticles increased the BTE of the biofuel. On average, the BTE of biofuel with added metal oxide nanoparticles was 5.01% higher than that of traditional diesel fuel [50]. Additionally, due to the high evaporation rate of CeO_2 nanoparticles [51], the BTE of the B25 CeO_2 blend was the highest among all the groups.

These two different strategies, including blending biofuels with other fuels and increasing the injection pressure, can effectively improve the combustion efficiency of biofuels and are relatively cost-effective methods. Blending biofuels with other fuels generally involves directly mixing the biofuel with the base fuel. In some cases, port fuel injection is required, which only necessitates minor modifications to the system, such as adding an additional

injector in the intake manifold. This approach can result in a noticeable improvement in efficiency and the cost are relatively low.

Another strategy is to increase the injection pressure. Most modern engines use electronically controlled injection systems, which theoretically can achieve injection pressures exceeding 200 MPa. However, this is a theoretical value and most engines currently operate with injection pressures between 100 and 200 MPa, rarely exceeding 200 MPa, due to considerations of material strength.

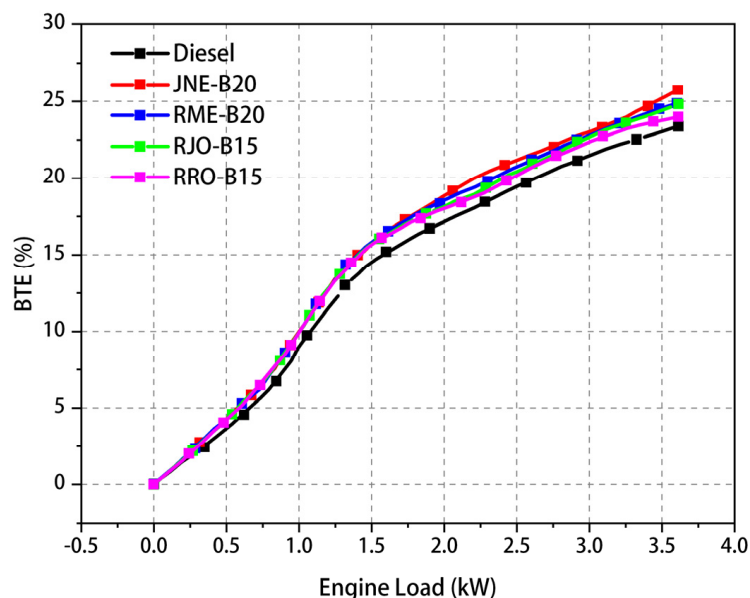


Figure 9. The relationship between BTE and engine load of different biofuel blends with different proportions and traditional diesel fuel [47].

Overall, blending biofuels is a reasonable approach in terms of cost, efficiency and implementation difficulty, making it highly suitable for current conditions.

3.2. Brake Specific Fuel Consumption

The fuel consumption of an engine over one hour at an output power of one kilowatt is known as the BSFC. It represents the ratio of fuel consumed to the BP of the engine and indicates the efficiency of the engine in converting fuel into useful work [52,53]. Generally, due to their low LHV and high viscosity, biofuels typically exhibit a higher BSFC compared to traditional diesel fuel when producing the same amount of heat [54,55].

For example, Yesilyurt et al. investigated the combustion performance of biofuel/diesel/1-butanol (5%, 10% and 15% C4 alcohol) and biofuel/diesel/pentanol (5%, 10% and 15% C5 alcohol) blended fuels in a single-cylinder four-stroke direct-injection IC engine. As shown in Figure 10, the traditional diesel fuel exhibited the lowest BSFC. Furthermore, the BSFC of the biofuel blends increased with the proportion of biofuel and alcohol. On average, the BSFC of the biofuel blended fuels was 4.43% higher than that of traditional diesel fuel. This difference was attributed to the low LHV of the blended fuels, meaning they required more fuel to produce the same amount of output [56,57].

Baiju et al. investigated the combustion performance of biofuels derived from Karanja oil esters (methyl ester KOMe and ethyl ester KOEE) and their blends with traditional diesel fuel (B20 and B100) in a single-cylinder four-stroke naturally aspirated constant speed IC engine. After esterification, the viscosity of the biofuels decreased and became similar to that of traditional diesel fuel. Experimental results indicated that the BSFC of these blended fuels was higher than that of traditional diesel fuel in most cases, except for the B20KOMe fuel, which had a slightly lower BSFC than traditional diesel fuel at 100% load. Whether KOMe or KOEE, the BSFC of B100 biofuels was highest among all the fuels, with B100KOMe exhibiting the highest BSFC level, which was 10% higher than that

of traditional diesel fuel at 100% load [58]. This also demonstrated that the LHV of biofuel and alcohols is lower than that of traditional diesel fuel.

Krishania et al. investigated the combustion characteristics of a single-cylinder four-stroke IC engine using a blend of Jatropha biofuel, tyre pyrolysis oil and spirulina microalgae biofuel as mixed fuels (20% by volume). This experiment indicated that the BSFC of these biofuel blends was at least 8.4% higher than that of traditional diesel fuel. This was attributed to the high viscosity and low LHV of the biofuels [59]. Attar et al. used preheated *Schizochytrium* sp. raw microalgae oil (MAO B100) and traditional diesel fuel in a single-cylinder four-stroke IC engine and compared the main performance parameters of these two fuels. Experimental results indicated that at a compression ratio of 21, the BSFC of MAO was over 20% higher than that of traditional diesel fuel. This was also attributed to the high viscosity and low LHV of the biofuel [60]. Mao et al. compared the performance, emission and combustion characteristics of B0 (100% traditional diesel fuel) and B5 (5% volume of *Chlorella vulgaris* biodiesel fuel (CVBF) and 95% traditional diesel fuel) in a single-cylinder four-stroke direct-injection IC engine. The results showed that B0 had a lower BSFC than B5 at all loads and this difference became more pronounced at high load, with the maximum difference reaching 14.4%. This was also attributed to the high viscosity and low LHV of the biofuels [61]. Indraredy et al. investigated the combustion and emission characteristics of biofuel extracted from algae and its mixtures with traditional diesel fuel in a common rail direct injection (CRDI) IC engine. The experiment used B10 and B15 blends (10% and 15% volume ratios of algae biofuel to traditional diesel fuel) as fuels. The results showed that, due to poor atomization of the blended fuels, the BSFC of the biofuel blends was higher than that of traditional diesel fuel at lower injection pressures. However, high injection pressure improved atomization of the blended fuels during injection, leading to more efficient combustion and thereby reducing the BSFC of the biofuel blends to levels lower than that of traditional diesel fuel [62].

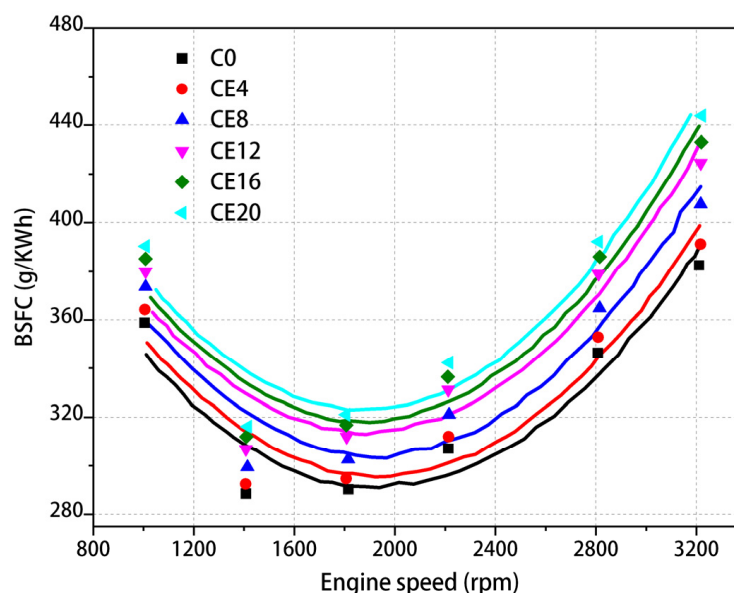


Figure 10. The relationship between BSFC and engine speed of cottonseed biofuel–ethanol blends with different proportions at 100% load [57].

In most cases, pure biofuels exhibit higher BSFCs compare to traditional diesel fuel. However, a few researchers have reported instances where biofuel blends resulted in lower BSFCs than traditional diesel fuel. For example, El-Baz et al. prepared biofuel from algae oil through transesterification and its mixtures with traditional diesel fuel (B10 and B20), then experimentally compared the performance parameters of these blended fuels and traditional diesel fuel in a single-cylinder four-stroke water-cooled direct-injection IC engine. As shown in Figure 11, the BSFCs of B10 and B20 were approximately 7% and

10% lower, respectively, than that of traditional diesel fuel. This reduction may be attributed to the density and LHV of these biofuel blends being closer to those of traditional diesel fuel at these proportions [63]. Govindasamy et al. investigated the performance, combustion and emission parameters of the blends of *Spirulina* algae biofuel and traditional diesel fuel at different volume ratios (20%, 40%, 60% and 80%) in a single-cylinder four-stroke IC engine. The experiment indicated that the BSFC of the biofuel blends was approximately 20% lower than that of traditional diesel fuel at compression ratios of 15, 16 and 17.5. Only at the compression ratio of 16 was the BSFC of the B60 blend slightly higher than that of traditional diesel fuel, possibly due to the better fuel characteristics of the blends [64]. Sharif et al. found that the BSFC of B20B was 10.06% lower than that of traditional diesel fuel [31].

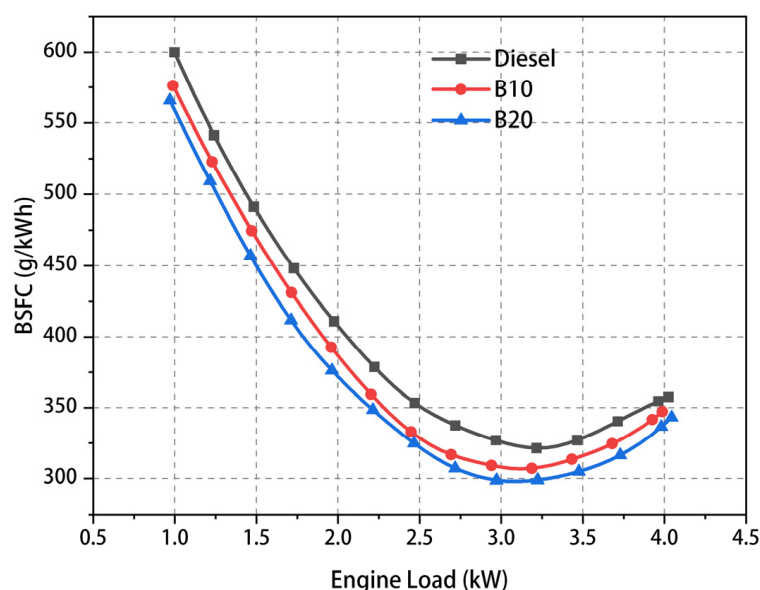


Figure 11. The relationship between BSFC and engine load of algae oil biofuel mixtures with different proportions and traditional diesel fuel [63].

Various strategies can be employed to reduce the BSFC of biofuel engines. For instance, Jegan et al. enhanced the combustion of biofuel blends by incorporating different metal oxides. Their study demonstrated that the addition of any oxide led to a decrease of BSFC, with the group containing TiO_2 showing the lowest BSFC, which was 14.4% lower than that of traditional diesel fuel [50]. Tayari et al. prepared biofuel from microalgae *Chlorella* and its mixtures with traditional diesel fuel (B0, B10 and B20). The combustion and emission characteristics of these blends were investigated in a single-cylinder four-stroke air-cooled IC engine, along with the effects of different hydrogenation rates (H0, H5 and H10) on engine performance and exhaust emission. Experimental research revealed that adding 10% H_2 to the *Chlorella* microalgae biofuel reduced the BSFC of this blend by 6% [65].

3.3. Brake Power

BP refers to the actual useful output power of an engine. Due to the physicochemical properties of biofuels, most researchers report that biofuels generally result in a lower BP compared to traditional diesel fuel.

Mourad et al. investigated the effect of preheated biofuels. As shown in Figure 12, the initial difference in BP between traditional diesel fuel and biofuel was 0.49 kW. After preheating the biofuel to 70 °C, the BP difference decreased to 0.10 kW. However, the BSFC of biofuel still did not reach the level of traditional diesel fuel. This was attributed to the high viscosity and low LHV of the biofuel [32].

Zareh et al. prepared biofuels from castor bean oil (CAB), coconut oil and waste cooking oil through esterification. These biofuels were then blended with traditional diesel

fuel at various volume ratios (B5, B10, B20 and B30). The performance and emission parameters of these blends were experimentally evaluated on a direct-injection four-cylinder four-stroke IC engine. The results indicated that the BP of all biofuel blends was lower than that of traditional diesel fuel. This was primarily due to the low LHV, high density and high viscosity of the biofuels [66].

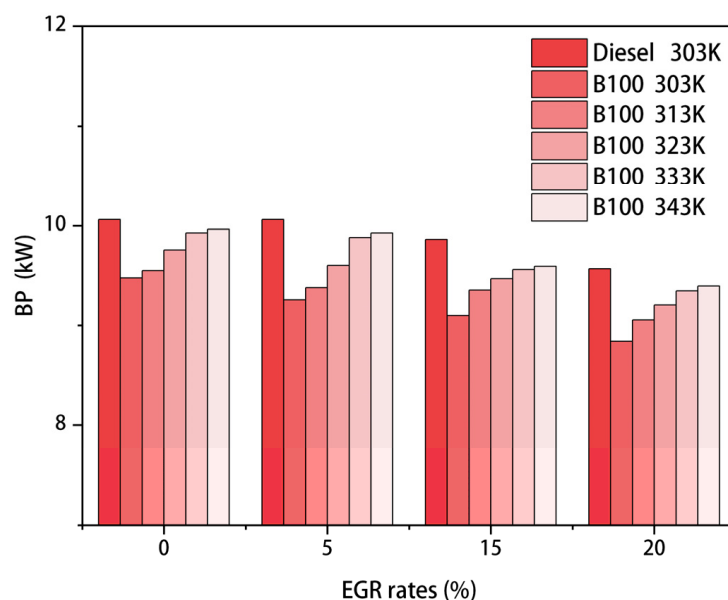


Figure 12. The relationship between BP, EGR rates and preheating temperatures of sunflower biofuel and traditional diesel fuel at 100% load [32].

Al-Iwayzy et al. prepared microalgae biofuel from the microalgae marine *Chlorella protothecoides* MCP-B, and then blended it with traditional diesel fuel at different volume ratios to obtain blends (B100, B50 and B20). These blends were used as fuels to analyze and compare their performance, emission and fuel characteristics with traditional diesel fuel in a four-stroke single-cylinder air-cooled IC engine. The experiments showed that, due to the low LHV, high density and high viscosity of the biofuel blends, the BP of B20 was slight lower than that of traditional diesel fuel, with a reduction of approximately 6% [67]. Tüccar et al. blended microalgae biofuel with traditional diesel fuel to obtain blends at volume ratios of 5%, 10%, 20% and 50%, then compared the characteristics of these mixtures with pure microalgae biofuel and traditional diesel fuel in a four-stroke four-cylinder IC engine. As shown in Figure 13, the use of blended fuels resulted in a decrease in the BP of the engine. Specifically, the BP of B100 was 6% lower than that of traditional diesel fuel, which may be attributed to the low cetane number of the microalgae biofuel [68].

In contrast, there are fewer reports indicating an increase in BP when using biofuels as fuel. For example, Ahmed et al. produced biofuels from three different algae species (*Spirogyra*, *Cladophora* and *Gracilaria*) through esterification. These biofuels were blended with traditional diesel fuel at various volume ratios (B0 and B10) and used to conduct engine performance tests on a four-cylinder four-stroke indirect-injection IC engine. Results showed that the maximum BP for traditional diesel fuel was 10.3 kW at 1600 rpm, while for B10, it was 11.2 kW. This indicated that the BP of B10 exceeded that of traditional diesel fuel by 8.7%, which may be due to the more efficient combustion of the biofuel blends [69]. Additionally, Govindasamy et al. investigated the performance of different ratios of *Spirulina* biofuel blends in an IC engine and found that the BP of the biofuel blends was higher than that of diesel. Among these blends, B20 showed the highest BP, possibly due to the low volatility and high cetane number of *Spirulina* biofuel blends [64].

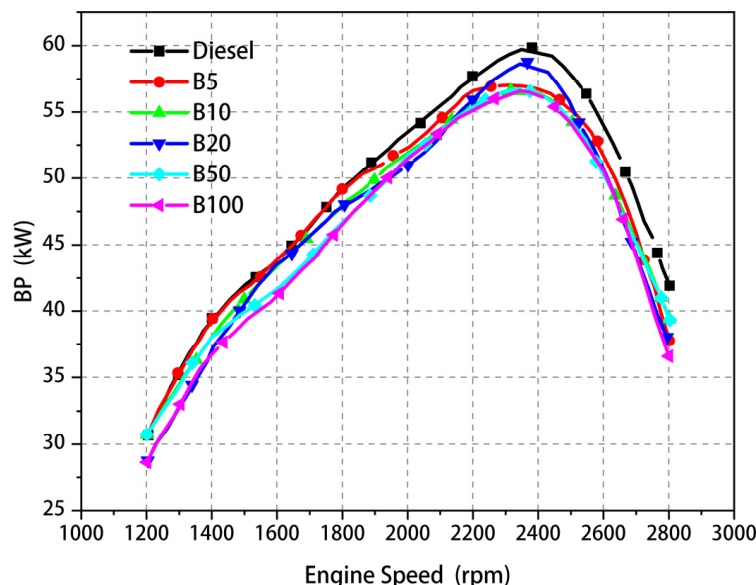


Figure 13. The relationship between BP and engine speed of microalgae biofuel mixtures with different proportions and traditional diesel fuel [68].

The results from the related literature indicate that due to the lower LHV and higher viscosity of biofuels, the BP when using biofuels is generally lower than that of traditional diesel. Solutions to this issue have been proposed in the previous sections, such as blending biofuels with fuels that have better combustion performance or increasing the injection pressure. These strategies can significantly improve the combustion of biofuels, leading to substantial increases in BTE, CP and BP, as well as reducing the BSFC [45,46,50].

The performance characteristics of biofuels are similar to their combustion characteristics, with most biofuels showing poorer performance compared to traditional diesel fuel. Whether it is the BTE, BSFC or BP, the differences are generally within 10% to 20%. This is also due to the poorer physicochemical properties of most biofuels. However, this situation can be mitigated by implementing other strategies, such as increasing injection pressure or blending biofuels with other fuels that have better performance. These strategies can significantly improve the performance parameters of biofuels. The occasional instances where biofuels exhibit higher performance characteristics highlight the significant differences in physicochemical properties among different biofuels.

4. Emission Characteristics in IC Engines Fueled with Biofuels

The emission trends of various exhaust pollutants emitted by engines during operation are referred to as emission characteristics, such as carbon monoxide (CO), carbon dioxide (CO₂), nitrogen oxide (NO_x), etc. Biofuels are considered to be a green and clean energy source due to their low emissions and environmental friendliness. Since this section shows the decarbonization capability of biofuels as low carbon fuels, it is more detailed than the previous content. The issue of higher CO₂ emission with some biofuels than traditional diesel fuel is discussed, based on the results of previous research.

4.1. NO_x Emission

NO_x emission is influenced by various parameters, including combustion quality, temperature, oxygen content, chemical composition, fuel type and engine speed. The combustion of fatty acid methyl ester (FAME), with long chain lengths and high unsaturation, tends to increase NO_x emission, whereas the emission decreases with low unsaturation. In most cases, due to the high oxygen content, presence of unsaturated long-chain fatty acids and high combustion temperature of biofuels, NO_x emission is typically higher than that of traditional diesel fuel. Moreover, NO_x emission tends to correlate positively with the proportion of biofuels in the blended fuel [31,70].

Senthil et al. used Annona methyl ester (AME) and its mixtures with traditional diesel fuel (A0, A20, A40, A60, A80 and A100) as fuels to compare engine performance, emission and combustion characteristics on a single-cylinder four-stroke water-cooled IC engine at different loads. The results showed that traditional diesel fuel had the lowest NO_x emission among all tested fuels. Among the blends, the A20 blend had the lowest NO_x emission, with a 6.6% higher emission than that of traditional diesel fuel at 100% load. A100, which was pure biofuel, exhibited the highest NO_x emission. This may be attributed to the presence of oxygen in the biofuel, which allows for a higher temperature atmosphere inside the cylinder, consequently leading to an increase in NO_x emission during biofuel combustion [71]. Can et al. blended canola biofuel at ratios of 5%, 10%, 15% and 20% (by volume) with traditional diesel fuel to obtain blended fuels. These blends were then used as fuels to compare the emission characteristics on a single-cylinder four-stroke stationary IC engine at four different loads (4.8, 3.6, 2.4 and 1.2 bar BMEP). The results indicated that at any load, the combustion of canola biofuel blends would lead to an increase of NO_x emissions. Compared with traditional diesel fuel, NO_x emission from the blended fuels increased by 3.3% to 8.9%. This increase was also attributed to the presence of oxygen in the biofuels, which led to higher combustion temperature inside the cylinder. However, this effect may be mitigated by pre-injecting biofuels to reduce NO_x emission [72,73]. Kshirsagar et al. conducted experimental research using Calophyllum inophyllum methyl ester (CIME) and its mixtures with traditional diesel fuel (CIME10, CIME15, CIME20 and CIME25) as fuels on a single-cylinder four-stroke naturally aspirated IC engine. The experiments were conducted under various injection pressures, injection timings and load conditions to test the experimental fuels. The results showed that the NO_x emissions of CIME blended fuels were higher than that of traditional diesel fuel, and the higher proportions of CIME in the blended fuel led to even higher NO_x emissions. They found the optimal fuel injection pressure, where the CIME20 exhibited a 3.64% higher NO_x emission than traditional diesel fuel. This increase was due to the presence of oxygen elements in the biofuel, which enhanced combustion and led to a rise of NO_x emission [74]. Özener et al. prepared biofuel using soybean oil as raw material and then blended it with traditional diesel fuel (B10, B20 and B50) to experimentally compare the emission characteristics of these biofuel mixtures with traditional diesel fuel. The experiments were conducted under steady-state conditions and crossed the entire speed range (1200–3000 rpm) of a single-cylinder direct-injection IC engine. According to the experimental results that are shown in Figure 14, the NO_x emissions of the biofuel blends increased by 6.95% to 17.62% compared to that of traditional diesel fuel. The main factor contributing to the increase of NO_x emissions was the oxygen content of the biofuel blends. As the oxygen content increased, the peak temperature during combustion also increased, leading to a rise in NO_x formation [75].

Abu-Jrai et al. prepared renewable treated waste cooking oil (TWCO) biofuel from restaurant waste cooking oil through esterification, then tested the emission characteristics of its blended fuel with traditional diesel fuel (TD50) on a water-cooled engine naturally aspirated four-stroke direct-injection IC engine. The experiments showed that the high volumetric modulus of TD50 fuel [76] resulted in a high speed of sound in this fuel, causing a more rapid transfer of the pressure wave from the fuel pump to the injector nozzle. This advanced the injection timing and consequently increased the CP and temperature. Consequently, the TD50 fuel led to higher NO_x emission due to the increased CP and temperature compared to traditional diesel fuel. TD50 fuel exhibited an over 22% increase in NO_x emission than traditional diesel fuel [77]. Gharehghani et al. prepared biofuel from waste fish oil (WFO) and blended it with traditional diesel fuel at various volume ratios (B25, B50 and B75). They then compared the combustion and emission characteristics of the biofuel, its blends and traditional diesel fuel on a single-cylinder variable compression ratio Ricardo E6 IC engine. The results showed that the NO_x emission from the biofuel and its blends was higher than that from traditional diesel fuel at any load. Key factors contributing to the higher NO_x emission in the experiments included the high oxygen content and cetane number of the biofuel, which increased the temperature inside the

cylinder, leading to an increase in NO_x emission. The NO_x emission from the blended fuels increased by 1.9% to 12.8% compared with traditional diesel fuel [78]. Khanda et al. investigated the performance, combustion and engine emissions of Honge oil biofuel (HOB, derived from *Pongamia Pinnata*) on a single-cylinder four-stroke water-cooled common rail direct injection (CRDI) engine, using different fuel injection timing (t), fuel injection pressure (p) and exhaust gas recirculation (EGR) ratio strategies. The results showed that the NO_x emission of HOB increased with higher injection pressures. However, it was still lower than the NO_x emission of pure HOB, which was measured at 1009 ppm, and was 46.7% higher than CRDI operation [79]. Vallinayagam et al. investigated the emission characteristics of a renewable fuel derived from distilled pine oil resin (pine oil biofuel) and its mixtures with traditional diesel fuel in different volume ratios (B6, B16, B20, B24 and B36) on a single-cylinder four-stroke direct-injection engine. Due to its favorable evaporation characteristics, the engine performance and emission characteristics were tested under dual-fuel injection conditions: pine oil biofuel blends were injected into the intake manifold, while traditional diesel fuel was directly injected into the cylinder. The results showed that the NO_x emission of the biofuel blends continued to rise as the proportion of biofuel in the blend increased. At B36, the NO_x emission was approximately 30% higher than that of traditional diesel fuel. This increase was attributed to the oxygen content in the pine oil biofuel, which facilitated nitrogen oxidation, and the subsequent increase in combustion chamber temperature further enhanced the NO_x emission [80].

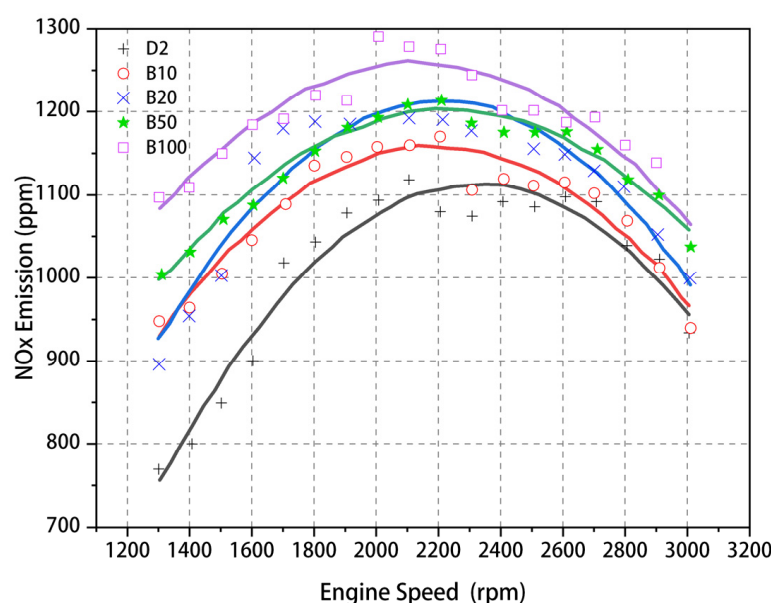


Figure 14. The relationship between NO_x emission and engine speed of soybean oil biofuel mixtures with different proportions and traditional diesel fuel [75].

Islam et al. tested biofuels and their blends derived from marine microalgae *Cryptocodinium cohnii* and waste cooking oil in different volume ratios (10%, 20% and 50% microalgae oil methyl ester and 20% waste cooking oil methyl ester) on a four-cylinder turbo-charged diesel engine. The experiments were conducted at four loads (25%, 50%, 75% and 100%) to compared the emission characteristics of these blends with traditional diesel fuel. The results showed that nearly all the blends of microalgae biofuels emitted higher NO and NO_x emissions than traditional diesel fuel under all load conditions. Specifically, the NO emission increased by 5% to 10% for D80A20 and D80WCO20, while the NO emission increased by 14% to 26% for D50A50, compared with traditional diesel fuel. This increase was likely due to the presence of oxygen in these biofuel blends, which may promote NO_x formation [81]. Yasar et al. investigated the combustion and emission characteristics of biofuel extracted from *Chlorella protothecoides* and its mixture with traditional diesel fuel in a 20% volume ratio (B20) on a four-cylinder IC engine under varying load conditions at

a constant engine speed of 1500 rpm. The results, as shown in Figure 15, indicated that the NO_x emission of the biofuel blend was higher than that of traditional diesel fuel. The NO_x emission of the blend was 0.5% to 1.3% higher than that of traditional diesel fuel, while the pure biofuel emitted 4.5% to 9.2% more NO_x compared with traditional diesel fuel under different load conditions. The primary reason for this phenomenon included the increase in cylinder temperature and the effects of viscosity during fuel injection [28]. Yadav et al. conducted a comparative investigation on the combustion and emission characteristics of algae oil methyl ester (AOME) and its mixtures with traditional diesel fuel at various volume ratios, as well as traditional diesel fuel on a single-cylinder IC engine. The experiments were conducted at varied loads (0, 3, 6, 9 and 12 kg) and compression ratios (13, 14, 15, 16 and 17). The results showed that the NO_x emission of the biofuel blends, which was positively correlated with engine load and the proportion of biofuel in the blend, was higher than that of traditional diesel fuel. The NO_x emission of AOME05 increased by only 5%, while that of AOME50 increased by more than 30% compared to that of traditional diesel fuel. The increase in NO_x emission was primarily attributed to the high oxygen content, volumetric modulus, humidity and viscosity in the blended fuel, which led to an increase in combustion temperature and, consequently, an increase in NO_x emission [82]. Joshi et al. prepared biofuel from *Chlorella* algae oil and blended it with traditional diesel fuel (5%, 10%, 20% and 30% by volume). The engine performance, emission and combustion characteristics of these blends were then evaluated and compared on a single-cylinder four-stroke direct-injection IC engine at a constant speed of 1500 rpm and compression ratio of 18. The results indicated that the NO_x emission of the algae biofuel blends was 13% higher than that of traditional diesel fuel. This increase was also attributed to factors such as the high cetane number, oxygen content, carbon chain length, oxidative stability, engine exhaust temperature and peak combustion temperature [83].

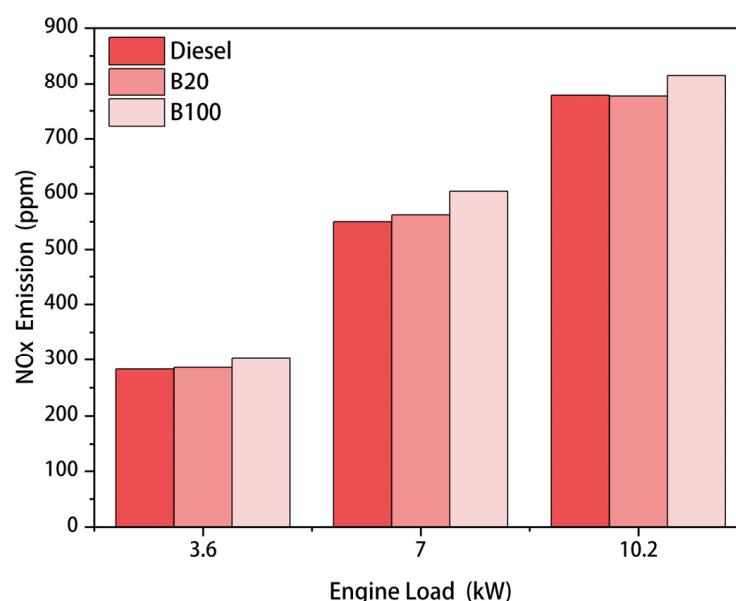


Figure 15. The relationship between NO_x emission and engine load of *Chlorella protothecoides* biofuel mixtures with different proportions and traditional diesel fuel [28].

Additionally, some researchers have reported that using biofuels can lead to a reduction in NO_x emission. For example, Bajpai et al. blended Karanja vegetable oil (KVO) with traditional diesel fuel at different volume ratios (5%, 10%, 15% and 20%) and investigated their performance and emission characteristics on a single-cylinder direct-injection IC engine at various loads (0% to 100%). The results showed that almost all KVO blends exhibited lower NO_x emission than traditional diesel fuel at high loads. Specifically, the NO_x emission of the KVO20 blend fuel was approximately 4% lower than that of traditional diesel fuel at 80% load. This difference was likely due to the shorter residence time of

the KVO blend, which resulted in lower temperature and, consequently, reduced NO_x emission [84].

Wahlen et al. investigated the combustion and emission characteristics of biofuels derived from *Chaetoceros gracilis* on a four-stroke two-cylinder indirect-injection IC engine operating at 3500 rpm and then compared them with that of traditional diesel fuel. The results showed that NO_x emission from the microalgae biofuel was the lowest among all the tested fuels, approximately 7.76% lower than that of traditional diesel fuel [54].

Jagadevkumar et al. prepared heterotrophic *Chlorella protothecoides* (HCP) microalgae biofuel and blended it with traditional diesel fuel at different volume ratios (HCO05, HCO10, HCP15 and HCP20). They then tested the performance and emission characteristics of these blends on a direct-injection IC engine. The experimental results demonstrated that the HCP biofuel blends emitted less NO_x than traditional diesel fuel. Specifically, the NO_x emission of HCP100 was reduced by 13.54% compared to that of traditional diesel fuel. This reduction was attributed to the low LHV of the HCP microalgae biofuel, which led to lower peak combustion temperatures and, consequently, reduced NO_x emission [85].

4.2. CO Emission

Compared with traditional diesel fuel, most biofuels emit less CO during combustion due to their higher oxygen content and cetane number [86,87]. Many researchers have also reported a downward trend in CO emission when using biofuels [71,78,82]. For example, Buyukkaya et al. tested trout oil methyl ester (TOME) and its mixtures with traditional diesel fuel at different volume ratios (B10, B20, B40 and B50) on a single-cylinder direct-injection IC engine and conducted a comparative experiment. The results showed that the average CO emission from TOME and its blends was reduced by approximately 13% compared to traditional diesel fuel. This reduction was attributed to the presence of a certain amount of oxygen in TOME, which facilitated the oxidation of CO [88]. Sakthive et al. prepared biofuel from fish oil and conducted experiments to evaluate the performance, emission and combustion characteristics of the fish oil biofuel and its mixtures with traditional diesel fuel on a single-cylinder direct-injection IC engine. The experimental results showed that the CO emission was negatively correlated with the proportion of biofuel in the blends. The CO emission of the blended fuels was 11% to 33.7% lower than that of traditional diesel fuel. This decrease was also attributed to the presence of oxygen in the fish oil and its blends, which increased the combustion temperature and facilitated the oxidation of CO [89]. Tripathi et al. analyzed and compared the engine performance, combustion and emission characteristics of soya soap stock-based acid oil biofuel and traditional diesel fuel. The experiments were conducted on a single-cylinder four-stroke direct-injection IC engine rated at 5.59 kW, under conditions of maximum torque and maximum power. The results indicated that the CO, unburned hydrocarbons and smoke emission of the acid oil biofuel were significantly lower than those from traditional diesel fuel. Specifically, under maximum torque conditions, the CO emission from the biofuel was reduced by 19.92% to 77.16%, and while under maximum power conditions, the reduction was 61.97% to 75.64%. This reduction was attributed to the high oxygen content in the biofuel, which increased the temperature in the cylinder, thereby facilitating better conversion of CO to CO₂ [90].

Palash et al. evaluated the engine combustion and emission characteristics of *Aphanamixis polystachya* methyl ester (APME), a biofuel extracted from *Aphanamixis polystachya* oil in Bangladesh. Experimental tests were conducted on a four-cylinder four-stroke direct-injection IC engine to compare the performance of APME and its mixtures with traditional diesel fuel at different volume ratios (APME05 and APME10). The results showed that the APME biofuel blends could reduce CO and hydrocarbon emissions more than traditional diesel fuel. Specifically, the CO emission of APME10 was reduced by 4.69% compared to that of traditional diesel fuel. This reduction was attributed to the combined effects of the oxygen content and cetane number. A high cetane number shortened the ID of the fuel combustion, while the oxygen content of the biofuel enhanced the fuel combustion efficiency, both of which contributed to the reduction in CO emission [91]. Ruhul et al.

extracted biofuels from *Millettia pinnata* (MP) and *Croton megalocarpus* (CM) and then used these biofuels to prepare mixtures with traditional diesel fuel at a 20% (by volume) ratio (MP20 and CM20). The experiments were conducted to evaluate and compare the performance, combustion and emission characteristics of these blended fuels and traditional diesel fuel on a single-cylinder IC engine under variable load and speed conditions. The results showed that the biofuel blends exhibited a lower CO emission than traditional diesel fuel, which was attributed to the high oxygen content and cetane number in the biofuels [92]. Yatish et al. prepared *Bauhinia variegata* methyl ester (BVME) and its mixtures with traditional diesel fuel at different volume ratios (B10, B20, B30, B40 and B100) to investigate and compare the performance, combustion and emission characteristics of traditional diesel fuel and these blends on a single-cylinder IC engine. The results indicated that the mixtures with low proportions (B10, B20, B30 and B40) of biofuel showed lower CO and HC emissions than traditional diesel fuel. At different loads, the CO emission of these blends reduced by approximately 30% on average. Specifically, the CO emission of B30 was reduced by up to 46.07% at 100% load. This reduction was attributed to the unsaturation and high oxygen content of the biofuel, which facilitated the oxidation of CO and HC, resulting in the reduction of CO emission [93]. Perumal et al. prepared biofuel from *Cleome viscosa* plant oil and blended it with traditional diesel fuel at different volume ratios (B100, B80, B60, B40 and B20). A comparative analysis was conducted to evaluate the performance, combustion and emission characteristics of these biofuel blend fuels on a single-cylinder four-stroke direct-injection engine. The results showed that CO emission decreased continuously with an increase in the proportion of biofuels and load. Specifically, the emission was reduced by 30% compared to that of traditional diesel fuel with B100 and 100% load. This reduction was attributed to the high oxygen content of the biofuel, which enhanced the oxidation of CO [94].

Singh et al. prepared two B100 biofuel samples from the marine microalgae *Chlorella variabilis* (BA) and *Jatropha curcas* (BJ). The transient performance and emission characteristics of these biofuels and standard gasoline diesel were then evaluated in transient cycle tests on a heavy-duty four-stroke water-cooled direct-injection diesel engine. As shown in Figure 16, the CO emission from traditional diesel fuel was consistently the highest among the three fuels in various operating modes, while the CO emissions from the other two biofuels were reduced by over 30% compared to that of traditional diesel fuel. This reduction was attributed to the oxygen content of the biofuels, which could increase the combustion temperature during relative operation and thus reduce CO emission [95]. Rahman et al. extracted biofuels from *Spirulina maxima* microalgae and prepared its mixtures with traditional diesel fuel at B20 and B40 (by volume). The performance and emission characteristics of these blends and traditional diesel fuel were then analyzed on a four-stroke single-cylinder IC engine. The results showed that the CO emission from the biofuel blends reduced by 9.3% to 13.9% compared to that of traditional diesel fuel. This reduction was attributed to the high oxygen content in the biofuel blends, which facilitated more complete combustion and allowed for a higher temperature in the cylinder. The elevated temperature helped to oxidize CO into CO₂, thereby reducing the CO emission [96]. Aydın prepared biofuels from animal, vegetable and microalgae oils. These biofuels were then blended at 10% by volume with ultra-low sulfur diesel (ULSD) to create three different biofuel blends: AOB10, VOB10 and MOB10. Tests were conducted to analyze and compare the combustion, performance and emission characteristics of these blends and ULSD on a four-stroke four-cylinder direct-injection IC engine at different loads and a constant speed of 1500 rpm. The results showed a significant reduction in CO emission for all biofuel blends than that of ULSD across all engine loads. Among the tested fuels, AOB10 exhibited the lowest CO emission, approximately 25% lower across all tested engine loads. This reduction was likely due to the additional oxygen content in the biofuel blends, which facilitated complete combustion and a high cylinder temperature, contributing to the low CO emission [97].

However, some researchers reported an opposite trend, indicating that biofuels could lead to an increase in CO emission. For example, Morsy investigated the effects of injecting ethanol/water mixtures with different volume ratios (25%, 50%, 75% and 100%) into the intake manifold of a single-cylinder IC engine. Ethanol/water with different volume mixing ratios (25%, 50%, 75% and 100%) were injected into the intake manifold as low-reactivity fuels, while traditional diesel fuel was injected directly into the cylinder as a high-reactivity fuel. The study explores the combustion and emission characteristics of this dual-fuel combustion mode. The results showed that the CO emission of all blend fuels was higher than that of traditional diesel fuel. Specifically, the CO emission increased as the proportion of the blend decreased. At full load, the CO emission of the 25% blending mixture was 15% higher than that of traditional diesel fuel. This increase was attributed to the incomplete combustion, leading to a low cylinder temperature and combustion delay, primarily due to the low cetane number of ethanol [98]. Daho et al. investigated the combustion and emission characteristics of cottonseed oil (CSO) biofuels and its mixtures with traditional diesel fuel at different volume ratios (CSO20, CSO40, CSO60, CSO80 and CSO100) on a four-stroke single-cylinder direct-injection IC engine. As shown in Figure 17, the experimental results indicated that the CO emission of the blends was positively correlated with the proportion of the mixture, although the relationship was not linear. The impact of CSO blends on CO emission was most significant at low loads (below 60%), attributed to slow evaporation and poor preparation of the air/fuel mixture under these conditions. At high loads (above 80%), excessive fuel and insufficient oxygen were the main factors that lead to the increased CO emission. Depending on the engine load, the CO emission of the biofuel blends increased by 9.8% to 25.3% [99]. Arangarajan et al. prepared *Chlorella vulgaris* microalgae (CVM) biofuels and its mixture with traditional diesel fuel at a 25% volume ratio (B25), then evaluated and compared the emission characteristics of this mixture and traditional diesel fuel on a four-stroke single-cylinder constant speed (1500 rpm) direct-injection IC engine equipped with the common rail direct injection (CRDI) system, which provided varying fuel injection pressures ranging from 22 to 42 MPa. Experimental results indicated that at low injection pressures (22MPa), the poor viscosity and high density of the CVM biofuel blends led to an increase in CO emission by approximately 6.4%. However, at high injection pressures (above 32MPa), the improved air-fuel mixing and atomization of the CVM blend resulted in better combustion and a subsequent reduction in CO emission. Depending on the fuel injection pressure, the CO emission was reduced by up to 15%. At 22 MPa, the CO emission of B25 comprised 0.33% of the total volume, whereas at 32 and 42 MPa, the volume of the CO emission decreased to 0.25% and 0.21%, respectively. In comparison, for traditional diesel fuel, the CO emission was approximately 0.31% [100].

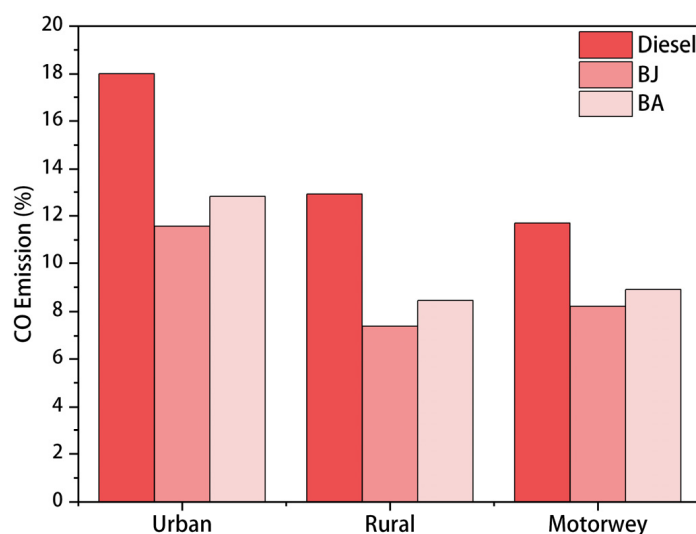


Figure 16. Mode-wise percentage distribution of CO emissions for different fuels [95].

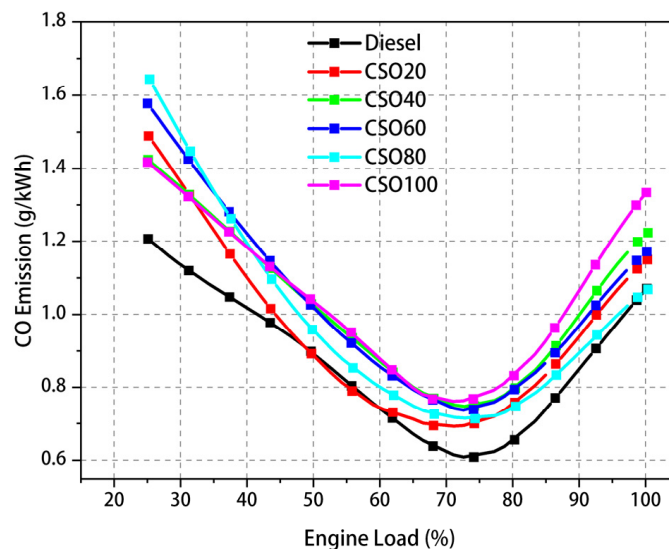


Figure 17. The relationship between CO emission and engine load of CSO mixtures with different proportions and traditional diesel fuel [99].

4.3. CO₂ Emission

Most biofuels have a high oxygen content and a significant amount of carbon, which can improve combustion quality and increase the combustion temperature. At these higher combustion temperatures, biofuels tend to produce more CO₂ compared to traditional diesel fuel. In most studies, the reduction in CO emission also supports this, as CO is oxidized to CO₂, leading to a decrease in CO emission and an increase in CO₂ emission [90,94,97]. This phenomenon also indicates better combustion of the fuel [101].

Dhinesh et al. produced a new biofuel from *Cymbopogon flexuosus* and blended it with traditional diesel fuel at volume ratios of 10%, 20%, 30%, 40% and 100%. Experiments were conducted to analysis the performance, emission and combustion characteristics of these blends on a single-cylinder direct-injection IC engine operating at 1500 rpm. As shown in Figure 18, all blends had a higher CO₂ emission compared to traditional diesel fuel. B30D70 exhibited the highest CO₂ emission, nearly 50% higher than that of traditional diesel fuel. The other blends also showed a CO₂ emission more than 20% higher than that of traditional diesel fuel. This increase in CO₂ emission was attributed to the high oxygen content in the biofuel, leading to more complete combustion [102]. Serin et al. prepared biofuel from tea seed oil, then blended it with traditional diesel fuel at different volume ratios (B10 and B20). Experiments were conducted to evaluate the effects of hydrogen enrichment on the emission characteristics of traditional diesel fuel and the blends of tea seed oil (B10 and B20) on a four-stroke direct-injection IC engine. The results indicated that the CO₂ and NO_x emissions of the biofuel blends were higher than that of traditional diesel fuel. However, there was a reduction in the CO emission. Specifically, the CO₂ emissions for B10 and B20 increased by 15.92% and 18.10%, respectively, compared to that of traditional diesel fuel. This increase was attributed to the high oxygen content in the biofuel's chemical structure, which led to more complete combustion and, consequently, higher CO₂ emission [103]. Chandra Sekhar et al. produced methyl ester of *Pithecellobium dulce* seed oil (*Pithecellobium dulce* seed oil methyl esters—PDSOME) through esterification, then prepared blends of PDSOME with traditional diesel fuel at volume ratios of 20%, 40%, 60% and 80%. Experiments were conducted to analyze the combustion and emission characteristics of the biofuel blends and traditional diesel fuel on a four-stroke single-cylinder water-cooled IC engine operating at a constant speed of 1500 rpm. The results showed that the CO₂ emission of the blends continually increased with an increasing proportion of PDSOME. The CO₂ emission of blends was always higher than that of traditional diesel fuel. At 5.2 kW, the increase in the CO₂ emission was 6.25%, 7.70%, 10.44%, 11.76% and 14.28% for PDSOME20, PDSOME40, PDSOME60, PDSOME80 and pure PDSOME, respectively.

The high oxygen content in PDSOME enhanced combustion and facilitated the oxidation of CO, which was the main reason for the increased CO₂ [104].

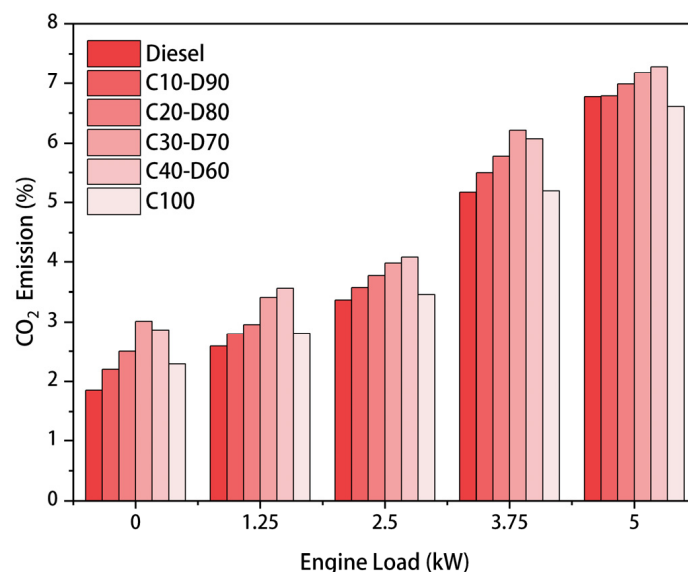


Figure 18. The relationship between CO₂ emission and engine load of *Cymbopogon flexuosus* biofuel mixtures with different proportions and traditional diesel fuel [102].

Sharon et al. produced methyl ester (biofuel) from used palm oil through esterification, then prepared its mixtures with traditional diesel fuel at volume ratios of 25%, 50% and 75%. Tests were conducted to analyze the performance, emission and combustion characteristics of these biofuel blends and traditional diesel fuel on a constant speed variable load (20% to 100%) direct-injection water-cooled single-cylinder IC engine diesel engine. The results indicated that the CO₂ emission of any proportion of the biofuel mixture was more than 10% higher compared to that of traditional diesel fuel. This increase was attributed to the more complete combustion facilitated by the high oxygen content in the biofuel [105]. Dubey et al. prepared biofuels using *Jatropha* biodiesel and turpentine oil, then blended them at different volume ratios (BT50, BT70, BT90 and BT100). Experiments were conducted to compared the combustion and emission characteristics of these blends and traditional diesel fuel on a single-cylinder direct-injection IC engine. The results indicated that the CO₂ emission of the dual-fuel blends was higher than that of traditional diesel fuel under any load condition. Specifically, at 100% load, the CO₂ emission of each blend ratio increased from 3.7% to 10.8% compared to that of traditional diesel fuel. The BT50 exhibited the highest CO₂ emission among all tested fuels at all load conditions due to its most complete combustion [106].

Rajak et al. prepared biofuel derived from *Spirulina* microalgae (SMB) and blended it with traditional diesel fuel at volume ratios of 20%, 40%, 60% and 80%. Experiments were conducted to evaluate the combustion and emission performance of these blends and traditional diesel fuel on a single-cylinder direct-injection water-cooled IC engine at various loads. As shown in Figure 19, the blends containing SMB exhibited higher CO₂ emission compared to SMB0 (traditional diesel fuel), and the proportion of SMB in blends was positively correlated to the CO₂ emission. At 100% load, the CO₂ emission of blends was approximately 3.4% to 6% higher than that of traditional diesel fuel [107]. In Rahman's research, it was also demonstrated that as the proportion of algae biofuels increased, the CO₂ emission also increased. The CO₂ emission of the blended fuels was more than 20% higher than that of traditional diesel fuel. This increase was also attributed to the more complete combustion facilitated by the high oxygen content in the biofuel [96].

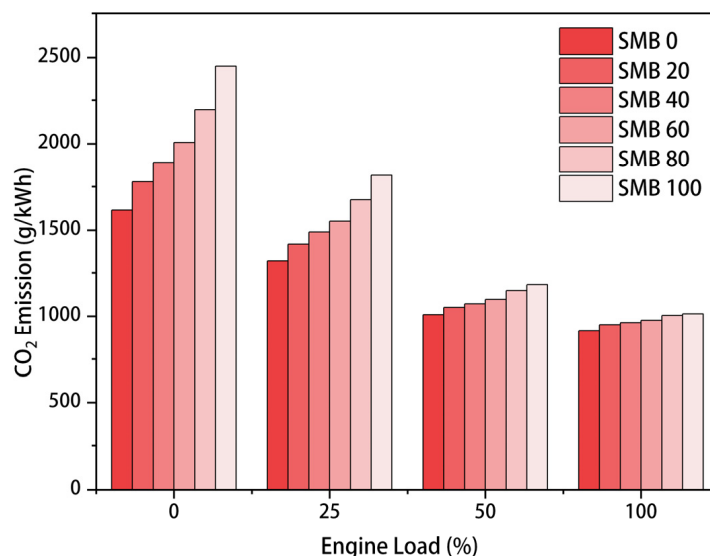


Figure 19. The relationship between CO₂ emission and engine load of SMB mixtures with different proportions [107].

Additionally, some researchers have reported contrary conclusions, indicating that the combustion of certain biofuels leads to a reduction in both CO and CO₂ emissions, and it is clear that these biofuels are relatively more compliant with emission regulations. However, due to the specific preparation methods and feedstocks of these biofuels, their overall share is not significant. Here are some examples. Tarabet et al. conducted an experimental investigation to examine the effect of eucalyptus biofuel and natural gas on performance and emission on a single-cylinder four-stroke air-cooled direct-injection IC engine at different loads. In this dual-fuel combustion mode, natural gas, a low-reactive fuel, was injected into the intake manifold, while eucalyptus biofuel derived from eucalyptus or traditional diesel fuel, both highly reactive, were injected directly into the cylinder. The experimental results demonstrated that in the dual-fuel combustion mode, using biofuel blends as highly reactive fuels led to a reduction in unburned hydrocarbons and CO and CO₂ emissions across all loads compared to those of pure traditional diesel fuel. The reduction in emissions was more pronounced at high engine loads. This effect was primarily attributed to the low LHV of the biofuel and the low hydrogen-to-carbon ratio of natural gas [108]. Al-lwayzy et al. prepared microalgae biofuel derived from *Chlorella Protothecoides* (MCP-B) and blended the biofuel with traditional diesel fuel at volume ratios of B100, B50 and B20. Experiments were then conducted to analyze and evaluate the combustion and emission characteristics of these blends on a four-stroke single-cylinder air-cooled IC engine. The results showed that B100 emitted less CO₂ than traditional diesel fuel, with a 4.2% reduction in CO₂ emission [67]. Tayari et al. prepared biofuels from *Eruca sativa* (ES), waste cooking oil (WCO) and microalgae *Chlorella vulgaris* (MCV) through alkaline-catalyzed esterification. The engine tests were then conducted to assess the combustion and emission characteristics of these biofuels and traditional diesel fuel on a four-stroke single-cylinder IC engine. The experimental results showed that the WCO and ES had higher CO₂ emission than traditional diesel fuel, primarily due to the more complete combustion of these biofuel blends, which facilitated the oxidation of CO. In contrast, MCV biofuels exhibited the opposite trend. Specifically, MCV-B20 had the lowest CO₂ emission, with a 5.3% reduction compared to traditional diesel fuel. This reduction may be attributed to the physicochemical properties of the biofuel [109].

After reviewing a large amount of the related literature, we found that different researchers have varying conclusions regarding CO₂ emission. Some researchers have discovered that using biofuels can simultaneously reduce CO and CO₂ emissions, while others have found that CO emission decreases significantly, but CO₂ emission increases compare to traditional diesel fuel. This section regarding the relevant literature presents

both perspectives. The primary reason for these differences is the varying physicochemical properties of different biofuels.

Some biofuels have a lower carbon-to-hydrogen ratio, which reduce their CO and CO₂ emissions at the source. Even if complete combustion leads to the oxidation of some CO to CO₂, the emission of CO₂ is still lower than that of traditional diesel fuel [33,57,63,85,90]. However, some biofuels have a higher carbon-to-hydrogen ratio, which are generally lower than that of traditional diesel fuel. In these studies, more complete combustion can also lead to the oxidation of CO to CO₂, potentially resulting in higher CO₂ emission compared to traditional diesel fuel [102,105,109].

At the same time, CO and CO₂ have a trade-off relationship and the total amount of carbon elements remains constant. Moreover, based on the previous literature, the researchers also assessed the impact of biofuels on global greenhouse gas emissions through the life cycle of CO₂ emission. They noted that biofuels can reduce CO₂ emission by 50% to 80% compared to traditional diesel fuel. Therefore, in any event, the CO₂ emission of biofuels are greatly reduced from the view of the life cycle circulation of CO₂ [110,111].

The emission characteristics of biofuels are the basis for evaluating whether they can serve as green and clean fuels. From the literature over the past two decades, it is evident that biofuels significantly reduce CO emission, as well as HC and soot emission, which are not listed here due to space constraints. The reduction in CO and HC emissions generally ranges from 30% to 50%, with some studies reporting decreases of around 70%.

NO_x emission, however, tend to increase, with an average rise of 5% to 15%. This is because most biofuels, classified by their raw materials, contain oxygen, leading to more complete combustion compared to traditional diesel fuel. This explains the lower emission of CO and HC, as more complete combustion reduces the formation of these incomplete combustion products. At the same time, the peak combustion temperature is higher, leading to an increase in the formation of NO_x, although the increase is not significant due to the high density and viscosity of biofuels, which helps to limit the in-cylinder temperatures.

Finally, the CO₂ emissions presented by research results show different trends. Some researchers believe that the lower carbon-to-hydrogen ratio of biofuels inherently reduces CO and CO₂ emissions. Others argue that more complete combustion of biofuels oxidizes CO to CO₂, leading to higher CO₂ emission. These differing conclusions ultimately stem from the various physicochemical properties of different biofuels. Biofuels with a lower carbon-to-hydrogen ratio are more likely to exhibit lower CO₂ emission compared to traditional diesel fuel, while those with a higher ratio may show an increase of CO₂ emission due to the oxidation of CO. Overall, the CO₂ emission of biofuels is greatly reduced from the view of the life cycle circulation of CO₂.

5. Conclusions

After discussing the examples of three generations of biofuels and their mixtures with traditional diesel fuel, it is evident that the combustion and emission performance of various biofuels differs. Moreover, experimental results sometimes contradict theoretical expectations, likely due to the differences in the composition and physicochemical properties of biofuels produced from different sources. This review of previous research concludes that while biofuels prepared from different sources exhibit some variations in combustion, performance and emission characteristics, they generally follow similar trends due to the similarities in preparation methods and raw material structures.

- The main factors influencing engine combustion when comparing these three generations of biofuels (categorized by their raw material) with traditional diesel fuel include oxygen content, LHV, cetane number, viscosity and other properties.
- Among the three generations of biofuels classified by raw materials, the first-generation biofuels are primarily made from animal fats or edible plant oils. Producing these biofuels incurs significant costs. Moreover, they compete with food crops for growing space. Second-generation biofuels are mainly produced from non-edible plants or waste oils. Compared to the first generation, these biofuels are less dependent on land

resources, easier to obtain and have lower costs. The third-generation biofuels are primarily made from microalgae oils which have the lowest requirements for growing environments and will not compete with food crops for land resources. However, the third-generation biofuels are more difficult to produce, leading to lower production volumes than the other two generations of biofuels. From the perspective of raw material acquisition, all three generations of biofuels have their own problems.

- Since most of these three generations of biofuels are prepared through esterification, the main components of the resulting biofuels are esters. The LHV of these esters is generally slightly lower than that of traditional diesel fuel, leading to higher fuel consumption when using biofuels or blends of biofuels with traditional diesel fuel to generate the same amount of heat. Typically, this increase in fuel consumption is around 5% to 10% higher than that of traditional diesel fuel. However, there are also cases where the LHV of certain biofuels is higher, depending on the specific nature of the esters.
- Generally, biofuels have higher cetane numbers and oxygen content compared to traditional diesel fuel. This indicates that the combustion performance of most biofuels is typically better than traditional diesel fuel, with lower ID and thermal losses, resulting in higher combustion efficiency.
- Due to the characteristics of biofuels, such as low LHV, high viscosity and high density, the combustion of biofuels or blends of biofuels with traditional diesel fuel can be adversely affected. This ultimately results in lower performance characteristics for most biofuels. For example, their BTE and BP are typically 10–20% lower than those of traditional diesel fuel. Additionally, their CP and HRR are also slightly lower compared to those of traditional diesel fuel. In this respect, the performance of the three generations of biofuels is consistent.
- Due to the high oxygen content in the three generations of biofuels, the peak cylinder temperature during the combustion of biofuels or blends of biofuels with traditional diesel fuel is higher than that of traditional diesel fuel. Additionally, biofuels often contain unsaturated long-chain fatty acids, which can result in NO_x emission of biofuels being more than 10% higher than that of traditional diesel fuel.
- Similarly, the high oxygen content in the three generations of biofuels facilitates the oxidation of unburned CO to CO_2 during combustion, resulting in a significant decrease in CO emission, with reductions often exceeding 30% and even 50%.
- The CO_2 emission of the three generations of biofuels is less consistent. Some researchers suggest that more complete combustion of biofuels leads to the conversion of CO to CO_2 , resulting in a decrease in CO emission and an increase in CO_2 emission. Others argue that the lower carbon-to-hydrogen ratio of biofuels leads to reductions in both CO and CO_2 emissions. In summary, the CO_2 emission from biofuels depends on their inherent properties or feedstock, while it is reduced greatly from the view of the life cycle circulation of CO_2 . Additionally, according to the conclusion of the literature, microalgae biofuels tend to have lower carbon-to-hydrogen ratios and are more likely to exhibit lower CO and CO_2 emissions. Therefore, microalgae biofuels still have an advantage over the other two generations of biofuels.

In conclusion, although algal biofuels offer the best engine performance and emission characteristics, they have low availability and are currently difficult to prepare. The other two generations of biofuels require more or less land resources, but they are more suitable for current use as transition fuels because of their high production volumes.

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