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Review Article

A comprehensive review on the use of biodiesel for diesel engines

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Abstract. Fossil fuels are the main source of energy for transportation operations around the world. However, fossil fuels cause extremely negative impacts on the environment, as well as uneven distribution across countries, increasing energy insecurity. Biodiesel is one of the potential and feasible options in recent years to solve energy problems. Biodiesel is a renewable, low-carbon fuel source that is increasingly being used as a replacement for traditional fossil fuels, particularly in diesel engines. Biodiesel has several potential benefits such as reducing greenhouse gas emissions, improving air quality, and energy independence. However, there are also several challenges associated with the use of biodiesel including the compatibility of biodiesel with existing engine technologies and infrastructure as well as the cost of production, which can vary depending on factors such as location, climate, and competing uses for the feedstocks. Meanwhile, studies aimed at comprehensively assessing the impact of biodiesel on engine power, performance, and emissions are lacking. This becomes a major barrier to the dissemination of this potential energy source. Therefore, this study will provide a comprehensive view of the physicochemical properties of biodiesel that affect the performance and emission properties of the engine, as well as discuss the difficulties and opportunities of this potential fuel source.

Keywords: Biodiesel; physicochemical properties; engine performance; emissions characteristics; blended fuel; nano-additives.

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1. Introduction

Fossil fuel reserves include areas where the existence of fossil fuels is "proven, probable, or possible" to approach and extract (Speight, 2011). There are obvious differences between reserve and resource. While all reserves are resources, the reverse does not happen. Resources become reserves when two conditions are met: (i) - they must be discovered and recorded, (ii) - the economic feasibility of being able to access and extract mineral resources. Therefore, though there are many calculations about how much time humanity has left before fossil fuel reserves are exhausted, most of the calculations are inaccurate when it is common to consider only "proven, probable, or possible" reserves while the number of resources that exist is still unexplored (Perera and Nadeau, 2022; Plantinga and Scholtens, 2021). With technology in the field of resource extraction increasingly developed, more and more resources are discovered as well as the ability to exploit reserves that were previously unexploitable is also improving. That is good news when in the short term, the problem of running out of fuel is not a threat (Shafiee and Topal, 2009). However, the nature of these resources is still non-renewable, not to mention the number of actual resources being able to become reserves is unknown. On the other hand, despite the increasingly developed technologies that help machines operate more efficiently and smoothly, directly helping to improve energy efficiency, the world's resource consumption is increasing every year and there is no sign of a decline (Martins *et al.*, 2018; Peters *et al.*, 2017). Therefore, their depletion is inevitable. Research to find and shift to renewable resources is essential and helps humanity best prepare before any serious energy crisis can occur.

Energy has always been a burning issue throughout the development of mankind. Along with the population explosion, the demand for energy of each individual also increases, making energy is never enough even though newly invented technology has helped people increasingly exploit and create more energy from different sources (Pham *et al.*, 2023). Transport is an important industry in every economy (Hoang *et al.*, 2022a). They not only serve the travel needs of people but also play a lifeline role in the supply chain, especially in the current period of globalization (Nguyen and Bui, 2021; Rudzki *et al.*, 2022). Most of the energy supplied to the transportation industry comes from fossil fuel sources such as gasoline or diesel (Fernández et al., 2020; Serbin et al., 2021). Even so, the misuse of fossil fuels can create negative impacts on society (Stelmasiak *et al.*, 2017; Yang *et al.*, 2019). Energy consumption is an important economic driver fueling growth and prosperity

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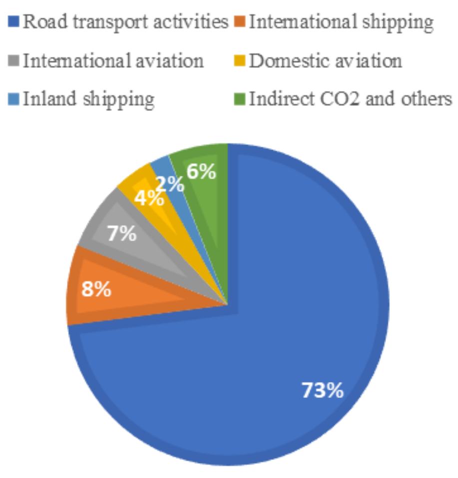

Fig. 1. Contribution of GHG emissions in the transport industry in 2018 (Lamb *et al.*, 2021)

(Venugopal *et al.,* 2023). Recent decades have observed exceptional growth in global energy demand with forecasts predicting a steady increase in the coming years as countries around the world continue on their paths of economic development. Since it was first invented, internal combustion engines have played an important role in propelling societies forward in both the literal and metaphorical senses of the world (Balasubramanian *et al.*, 2022; Sharma *et al.,* 2023).

Today, the internal combustion engine model is one of the most common heat engines installed among vehicles, production machinery, and manufacturing equipment. Due to the better energy conversion efficiency and cheaper fuel costs, the diesel engine is often favored over the gasoline counterpart as the main power source in electric generators, machinery, and equipment that are used in various sectors including construction, agriculture, and heavy industry, as well as among road vehicles and maritime transport fleets (Hoang and Pham, 2019; Lamas *et al.*, 2015). One of the biggest drawbacks of diesel engines is the significant amounts of air pollutants emitted during the combustion process. With the common application of diesel engines worldwide, this negative impact on the environment is only further exacerbated by the annual increase in the number of passenger vehicles. High-density urban areas are often subjected to hazardous air quality conditions due to the heavy city traffic which has become a fairly common occurrence (Hoang *et al.*, 2021a). As a proportion of the urban population in countries around the world continues to grow, environmental and health impacts caused by poor air quality present a major challenge to today's government leaders (Bakır *et al.*, 2022. On the other hand, the urgent need for alternative sources of energy that could potentially replace traditional fossil fuels has become increasingly apparent. According to a study by Lamb *et al.* (Lamb *et al.*, 2021), the total GHG emissions from transport operations worldwide were about 8.5 $GtCO_2eq$ in 2018, accounting for about 14% of total emissions. Among them, emissions from road transport activities account for a staggering 73% of the industry's emissions. Figure 1 shows the contribution of GHG emissions in the transport industry in 2018 (Lamb *et al.*, 2021). With the characteristics of being able to be used flexibly for short distances and only having to bear a small load when compared to aircraft and ships, along with a densely located and easily accessible distribution and repair facility, the application of alternative fuel sources in road traffic is not only easier but also much safer than changing fuel sources for aviation or ships. In addition, since it accounts for the majority of the industry's emissions, being able to successfully use environmentally friendly fuel sources in road transport will rapidly reduce emissions in the transportation industry. Therefore, research on alternative fuels for cars and motorcycles is of the utmost interest and development. Another serious problem is the uneven distribution of fossil fuel deposits around the world, this leads to energy insecurity in these resource-deficient countries. According to the latest statistics in 2022, only the ten countries possessing the largest oil reserves in the world account for more than 85% of the total oil reserves of the whole world ("Oil Reserves by Country 2022," n.d.). For the above reasons, researchers have been making great efforts to find a fuel that can be widely used to replace fossil fuels. Among them, biodiesel is considered to be one of the most suitable and potential alternatives (Nguyen and Vu, 2019; Prabhu *et al.*, 2023).

Four generations of biodiesel have been researched and developed depending on the raw materials used for production (Singh *et al.*, 2019). While first-generation biodiesel uses edible resources like rapeseed oil, palm oil, and soybean oil for production, second and third-generation biodiesel uses non-edible resources (Goh *et al.*, 2022). *Jatropha curcas*, rubber seed, or neem oil are commonly used to produce second-generation biodiesel (Singh *et al.*, 2020), while animal fat and waste cooking oil are the main sources of third-generation biodiesel (N *et al.*, 2023; Hadiyanto *et al.*, 2018). In addition, algae are usually used for synthesizing fourth-generation biodiesel (Jeyakumar *et al.*, 2022; Maroušek *et al.,* 2023b). The difference between the second, third, and fourth-generation biodiesel is that the third and fourth-generation use more economically optimal raw materials as well as do not depend on the seasonal characteristics of the crop, and do not affect the food chain and use the land for cultivation (Sakthivel *et al.*, 2018). Usually, food crops such as rapeseed, soybean, sunflower, safflower, palm, coconut, and animal fats, etc. are processed and it is converted into biodiesel. These biodiesels are obtained and are named 1st generation biofuels as this was the earliest alternative idea in the production of biodiesel. Still, various types of research have been carried out and many found that biodiesel production can also be done by the processing of non-food crops and novel starch like jatropha, pongamia, mahua, pine, nerium, and *Calophyllum inophyllum*, etc. These biodiesels obtained are named as 2nd generation biofuels as this was taken as the next initiative in the production of biofuels. Many improvements were found in 2nd generation biofuels when comparing them with the 1st generation biofuels in terms of performance, combustion, and emission characteristics of the diesel engine. But the availability of these 1st and 2nd generation biofuels is limited. For large-scale production of biodiesel from algae in countries like India, Vietnam, etc. is available in plenty among various water reserves. Hence, the yielding of biofuel from the micro-algae feedstock seems to be better than the other feedstocks in the ASEAN countries. Therefore, biodiesel is renewable energy with extremely diverse production materials and can be found in every country (Silviana *et al.*, 2022; Zullaikah *et al.*, 2021; Hadiyanto *et al.*, 2016). Figure 2 shows the main sources of biodiesel production ("Global biodiesel production is increasing - Renewable Carbon News," n.d.). It can be seen that biodiesel production sources are extremely diverse, and it should be noted that these are statistics on commercialized biodiesel sources when the percentage of edible sources still accounts for a fairly high proportion. Meanwhile, in recent years, advances in the field of fuels have helped researchers to propose more efficient and less socially harmful sources of biodiesel production (Kolakoti *et al.*, 2022;

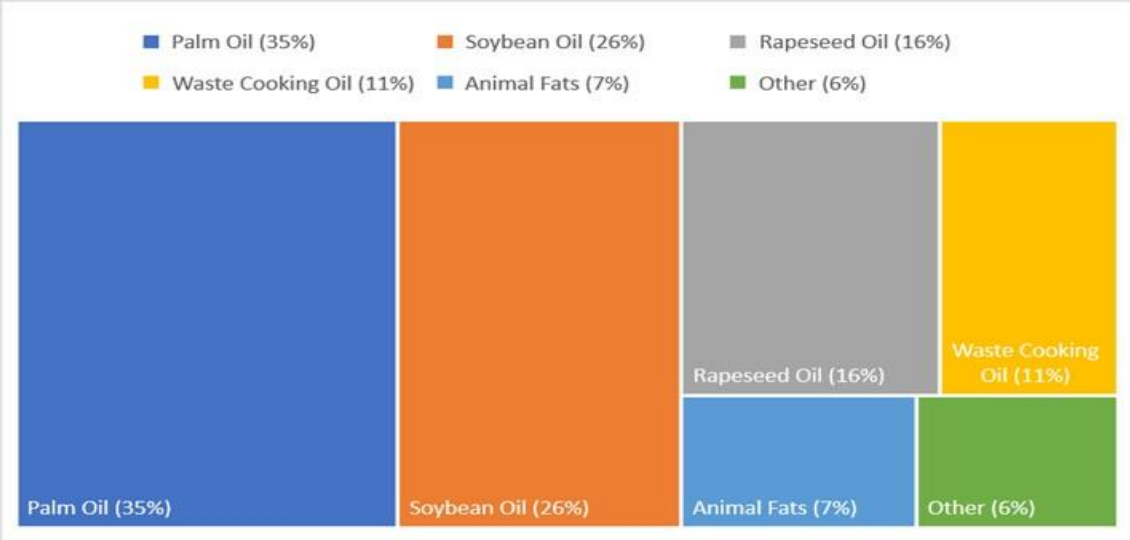

Fig. 2. Main sources of biodiesel production (Sarin, 2012)

Widayat *et al.*, 2023). However, it is necessary to have a comprehensive review of the use of biodiesel for diesel engines. This study will focus on analyzing the properties of biodiesel and their influence on engine performance and emissions. In addition, the study also discusses challenges and provides the latest methods to solve outstanding problems.

2. Biodiesel properties

With the main purpose to replace mineral diesel in the internal combustion engine itself, biodiesel's physical and chemical properties have many similarities with diesel. These similar properties make the blending of biodiesel easy, as well as the use of biodiesel does not require the engine to be seriously modified. However, differences are still present and need to be analyzed to understand their effects before being widely used. Table 1 shows the important properties of some common biodiesel compared to diesel (Ayhan *et al.,* 2020; Dinesha *et al.*, 2019; Hoang *et al.*, 2021b; Jafari *et al.*, 2019; Nagaraja *et al.*, 2012; Nayak *et al.*, 2021). This section will focus on analyzing each fuel's characteristics and comparing it to diesel fuel.

2.1. Kinematic viscosity

Viscosity is one of the most important fuel parameters that every fuel research must consider first. Viscosity represents the ability of the fuel to flow and this parameter will directly affect how the fuel injection system works. From the data in Table 1, it can be seen that the viscosity of biodiesel is higher than diesel oil. Especially, kinematic viscosity will greatly affect performance and even cause engine damage if operating at low temperatures. This is the main reason for the obstacles when using biodiesel in engines that operate in low-temperature environments and can only be used as a secondary fuel to blend with diesel if there are no suitable engine modifications (Hoang, 2021a). The reason for the high kinematic viscosity of biodiesel is because of their high chemical structure and molecular weight. The suitable viscosity range according to ASTM D445 is 1.9–6.0 mm^2/s and according to EN ISO 3104 is 3.5–5.0 mm^2/s (Balat, 2011; Balat and Balat, 2010). The viscosity of biodiesel is still in the area of satisfying the above standards, but when applied to each specific engine, it should be considered very carefully.

2.2. Density

Density is the weight per unit volume, density of the fuel is also a highly significant factor since it has been associated with other characteristics of fuel like the cetane number and heating value (Tesfa *et al.*, 2010). Besides, based on density, engineers can measure and design the fuel tank and the amount of fuel in the system (Alptekin and Canakci, 2008). There is not much of a density difference between diesel and biodiesel although the density of biodiesel tends to be slightly higher than that of diesel.

Table 1
Physicochemical properties of diesel fuel and some popular biodiesel

Fuel properties	Diesel fuel	Palm oil methyl ester (POME)	Corn oil methyl ester (COME)	Coconut biodiesel	Waste cooking oil biodiesel	Honge oil methyl ester (HOME)	Rice bran oil-based biodiesel (RBO)	Fish oil biodiesel (FBD)
Kinematic viscosity (cSt)	3.18	4.5	4.3	4.82	4.36	4.7	4.68	4.91
Density (kg/m³)	839.0	870.0	870-880	860.0	890.0	890.0	892	877
Lower heating value (MJ/kg)	44.8	37	39.6	37.2	38.8	38.9	42.2	41
Cetane number	40-55	56.5	>55	58.6	53.4	54	63.8	59
Flashpoint (°C)	68	178	>100	150 to 170	175.4	210	183	156
Pour point (°C)	-7	-5 to -10	-10 to -15	5 to 12	0 to -5	-3 to -12	-11	5
Cloud point (°C)	-10 to 6	5 to 10	-5 to -10	9 to 14	-3	0 to -9	-10	9
Oxygen content (%)	0	11.26	10.96	11.54	11	11.3	10-12	9.3

Besides density, relative density, which is the density of the component compared to the density of water, is also an important parameter of the fuel to compute flow and viscosity characteristics, convert mass to volume, and assess the homogeneity of biodiesel tanks.

2.3. Calorific value or lower heating value

Calorific value (CV) or lower heating value (LHV) is a measure of the amount of heat generated from the full combustion of a hydrocarbon not accounting for the heat contained in combustion products if not returned to pre-combustion temperature. CV is the real energy content and is also an important parameter for estimating the design parameters of the combustion process (Giakoumis and Sarakatsanis, 2018; Kumar *et al*., 2013). The CV of diesel is approximately 12% higher on a weight basis when compared to biodiesel, which also means diesel fuel has higher energy content than biodiesel. However, biodiesel has a slightly higher density than diesel, so the CV of diesel is only about 8% higher than biodiesel on a volume basis (Ozcanli *et al*., 2013).

2.4. Cetane number

The cetane number (CN) shows the ability of the fuel to auto-ignite quickly after being injected. The higher the cetane number, the shorter the time between the start of fuel injection into the combustion chamber and the ignition process. The higher the cetane number, the better the ignition quality of the fuel (Karmakar *et al*., 2010; Lapuerta *et al.,* 2008). This is one of the extremely important indicators in choosing the right fuel for the engine. In the table, it can be seen that the cetane number of diesel is slightly lower than that of biodiesel. The advantages of having a higher cetane number in biodiesel are manifold. These include shorter ignition delay, lower NO_x emissions, and a decreased incidence of knocking during the combustion process (Godiganur *et al*., 2010; Kumar and Kumar, 2010; Reyes and Sepúlveda, 2006).

2.5. Flash point, Cloud point, and Pour point

The temperature at which a fuel will catch fire when exposed to a flame or a spark is known as its flash point. Flashpoint varies inversely with the fuel's volatility. The flash point is a significant property that pertains to the combustibility characteristics of liquids (Mejía *et al.,* 2013). The flash point values of methyl esters derived from vegetable oil are considerably lower compared to the flash point values of the original vegetable oils. Moreover, as the quantity of residual alcohol increases, the flash point of these methyl esters decreases (Černoch *et al*., 2010). It can be seen in the flash point of biodiesel that is much higher than that of diesel, which will make it safer to handle, store, and transport fuel.

The cloud point is the temperature at which wax crystals first become visible when the fuel is cooled, whereas the pour point of a liquid is the temperature below which the liquid loses its flow characteristics. It is defined as the minimum temperature at which the oil can pour down from a beaker (Lopes *et al.,* 2008). These indicators are very important especially when the engine has to work at low temperatures. Unsuitable cloud point and pour point fuels can cause the fuel to solidify and clog the vehicle's fuel system and filters, directly affect engine performance, and cause long-term engine damage.

2.6. Oxygen content

One of the biggest differences between biodiesel and diesel fuel is the oxygen content (Coşofreţ *et al*., 2016). While the oxygen content of diesel is very low or even absent, biodiesel is an oxygen-rich fuel. Oxygen content in biodiesel is about 10 to 12% weight depending on the type of biodiesel. The oxygen content in biodiesel will help fuel burn cleaner and significantly reduce the number of unburned hydrocarbons (UHC).

2.7. Stability of oxidation

The stability of oxidation in fuels refers to their resistance to oxidative reactions, which can lead to the formation of harmful by products, degradation of the fuel quality, and potential engine performance issues. The stability of oxidation is particularly important for hydrocarbon-based fuels like gasoline and diesel. The oxidative stability of biodiesel fuel is influenced by the number of bis-allylic sites present in unsaturated biodiesel compounds. Factors such as the biodiesel's age, the composition of fatty acid methyl esters, and storage conditions contribute to biodiesel's oxidation stability (Rajamohan *et al.,* 2022). Due to its molecular structure, biodiesel fuels are more susceptible to oxidative degradation compared to fossil diesel fuels. ASTM D6751 and EN-14214 are two standards for evaluating the oxidation stability of fuels. While the minimum requirement for oxidation stability at 110°C with ASTM D6751 standard is 3 hours, the EN-14214 standard is stricter when it comes to the requirement that the fuel maintains 6 hours under similar conditions. Nevertheless, biodiesel in its pure form, derived from various feedstocks, typically fails to meet this requirement (Sakthivel *et al*., 2018). Therefore, some additives are often added to biodiesel to enhance its stability of oxidation.

3. Effects of biodiesel on combustion, performance, and emissions characteristics of the engine

With the above properties, the direct use of biodiesel on the engine is feasible, but its effects on the engine need to be comprehensively evaluated. Therefore, a lot of research has been done recently to study different aspects of engines using biodiesel as well as improve both its performance and emission characteristics. This section will present a comprehensive perspective on the above problem. Limits and opportunities of potential biodiesel fuel sources will also be mentioned and discussed.

3.1. Effects of biodiesel on combustion characteristics

To better understand the effect of biodiesel on the engine, it is necessary to analyze the combustion process. The most important parameters in combustion analysis are ignition delay (ID), heat release rate (HRR), and pressure rise rate (PRR) which are commonly calculated and measured. Table 2 shows the newest finding on engine combustion characteristics as well as performance. All the data is collected when the engine is operating at 100% load if the engine load is not specified. The trends of increasing or decreasing the above parameters when compared with diesel-only engines can be predicted in theory based on the physicochemical properties of biodiesel (Sharma *et al*., 2022).

The parameters of the engine are most closely related to each other, and changing one parameter will affect all the other

Table 2
Effects of biodiesel on engine performance and combustion

Biodiesel	Ratio	Engine performance			Engine characteristic			Ref
		BSFC	BTE	EGT	Ignition delay (°CA)	Heat release rate (J/°CA)	Pressure rise rate (MPa/°CA)	
Jatropha oil methyl ester	B20, B40, B60, B80, B100	-	↓ 10%, 12%, 18%, 24% and 33 % for B20, B40, B60, B80 and B100 at 75% load	-	-	↓ 4%, 6%, 8%, 10% and 11% for B20, B40, B60, B80 and B100 at 75% load	↓ 3%, 4%, 6%, 7% and 8.5% for B20, B40, B60, B80 and B100 at 75% load	(Gad et al., 2021)
Jatropha Oil	B20, B40, B60, B80, B100	↑ 4%, 7%, 9%, 10%, 14% for B20, B40, B60, B80, B100	↓ 5%, 7%, 8%, 9%, 11% for B20, B40, B60, B80, B100	↑ 1%, 3%, 4%, 5.5% and 6% for B20, B40, B60, B80, B100	↓ 2.5%, 3%, 3%, 7% and 8% for B20, B40, B60, B80, B100	↓ 4% for B100	↓ 6%, 10%, 10%, 13% and 14% for B20, B40, B60, B80, B100	(Rao et al., 2007)
Jatropha oil	B20	-	↓ 5%	-	↑ 5%	↓ 9%	↓ 13%	(Deepanraj et al., 2017)
Karanja oil	B20	-	↓ 5.2%	-	↑ 11%	↓ 12.5%	↓ 15%	(Deepanraj et al., 2017)
Waste cooking oil	B100	↑ 13%	↑ 5%	-	-	↓ 7.8%	↓ 6.5%	(An et al., 2013)
Waste cooking oil	B20, B40, B60, B80, B100	↑ 16%, 19%, 32%, 35% and 45% for B20, B40, B60, B80, B100	↓ 16%, 22%, 32%, 32% and 47% for B20, B40, B60, B80, B100	-	↓ 10%, 19%, 28%, 37% and 46% for B20, B40, B60, B80, B100	↓ 3%, 5%, 7%, 9% and 11% for B20, B40, B60, B80, B100	↓ 3%, 5%, 7%, 8% and 9% for B20, B40, B60, B80, B100	(Mohamed et al., 2020)
Canola oil and Safflower oil	B100	↑ 10%	-	-	↑ 1.5%	↑ Insignificant	↑ Insignificant	(Alptekin, 2017)
Soybean	B10, B20, B50, B100	↑ 2%, 4%, 7% and 9% for B10, B20, B50, B100	-	-	↓ with the increase of biodiesel in the mixture	↓ insignificant	↑ Insignificant	(Özener et al., 2014)
Soybean	B30, B50, B80, B100	↑ 7%, 8%, 10% and 12% for B30, B50, B80, B100	↓ insignificant	-	-	↓ insignificant at 90% load	↓ 2.5% B100 at 90% load	(Qi et al., 2010)
Rapeseed oil	B5, B20, B70, B100	↑ 2.5%, 3%, 5.5% and 7.5% for B5, B20, B70, B100	↑ insignificant	↑ 3% for B100	↓ 9.7%, 17%, 30% and 48% for B5, B20, B70, B100	↓ 5.4%, 8,4%, 12% and 16% for B5, B20, B70, B100	↓ 3%, 3.8%, 4,2% and 5% for B5, B20, B70, B100	(Buyukkaya, 2010)
Fish oil	B20, B40, B60, B80, B100	-	↑ 4% for B20 ↓ 1.5%, 9.8%, 11% and 13.5% for B40, B60, B80, B100	↑ 2%, 3%, 4% and 5% for B40, B60, B80, B100	↓ with the increase of biodiesel in the mixture	↓ 2.5%, 12%, 14%, 18% and 22% for B20, B40, B60, B80, B100	↓ 4.5%, 12%, 12%, 23% and 30% for B20, B40, B60, B80, B100	(Gnanasekaran et al., 2016)
Fish oil	B20, B40, B60, B80, B100	-	↑ 3.7% for B20, ↓ 1.8%, 6.4%, 11.3% and 12.4% for B40, B60, B80, B100	↑ 0.4%, 2.4%, 2.1%, 1.1% and 3.3% for B20, B40, B60, B80, B100	↓ 2.2%, 2.5%, 4%, 15%, 24% for B20, B40, B60, B80, B100	↓ 2.8%, 12.2%, 20%, 22.5% and 24,5% for B20, B40, B60, B80, B100	↓ 8.6%, 19%, 24.8%, 47% and 71% for B20, B40, B60, B80, B100	(Sakthivel et al., 2014)
Rice Bran oil	B20	-	↓ 3.45%	↑ 7.8125%	↓ 6.7%	↑ 17.6%	↑ 13.7%	(Dhamodaran et al., 2017)
Neem oil	B20	-	↓ 10.34%	↑ 5.65%	↓ 14.2%	↑ 12.5%	↑ 8.5%	(Dhamodaran et al., 2017)

parameters (Tuan Hoang *et al.*, 2021). Although it is possible to predict the trend of the parameters, it is still necessary to perform specific simulations or experiments to accurately determine the effect of the fuel on the engine because any small change can have a bigger impact in the long run, not to mention that most internal combustion engines degrade in efficiency and fail very quickly at the end of their life.

Ignition delay (ID) is the period between the start of fuel injection and the start of combustion (SOC) and is usually shown by the crank angle (°CA) (Saravanan *et al.*, 2014). During this time, the fuel is atomized and mixed with air, and then the heat generated by compression raises the temperature and pressure of the fuel-air mixture until it reaches its ignition point (Aldhaidhawi *et al.*, 2017; Pham and Cao, 2023). Once this temperature is reached, the fuel starts to burn rapidly, releasing energy to drive the engine. Biodiesel helps to reduce ID and this trend becomes more obvious as the proportion of biodiesel in fuel increases (Allen *et al.*, 2013). This is explained by two main reasons: the oxygen content and the cetane number of the fuel. Biodiesel becomes more combustible due to the increased presence of oxygen in the fuel mixture, which also assists in breaking down larger fatty acids in biodiesel into smaller molecules, resulting in the production of a greater number of volatile substances (Singh *et al.*, 2021). In addition, the cetane number is often inversely related to the ignition delay time and the cetane number of biodiesel is usually higher than that of diesel (Bittle *et al.*, 2010). Therefore, it is not surprising that many studies in Table 2 have shown that increasing the ratio of biodiesel in the fuel will decrease the ignition delay. This is an advantage of biodiesel since with a shorter ID, the fuel will have more time to burn, leading to more complete combustion within the engine cylinder (Agarwal *et al.*, 2013; Bednarski *et al.,* 2019). This makes it possible for the engine to take advantage of more of the potential energy generated from the fuel and thus also reduce the power loss represented by the exhaust gases, such as smoke, particulate matter, or unburnt hydrocarbon. However, a very short ignition delay may cause a knock or excessive pressure rise, leading to engine damage. Therefore, understanding the properties of different types of diesel engines will help manufacturers recommend suitable biodiesel or its ratio in the mixture of fuel.

Heat release rate (HRR) has an extremely close relationship with ignition delay. The HRR of a diesel engine is a measure of the amount of heat energy released by the combustion process in the engine cylinder over time (Kaya and Kökkülünk, 2020). The ignition delay affects the heat release rate because it determines the timing and duration of the combustion process. Given the lower calorific value (CV) of biodiesel but a shorter ignition delay (ID), it is not difficult to see that the heat release rate of an engine using either biodiesel fuel or a biodiesel-diesel fuel mixture will be significantly reduced compared to engines using only diesel. Besides, the fact that biodiesel has a higher kinematic viscosity and density than diesel is also another important factor that reduces the HRR of the engine (Shahabuddin *et al.*, 2013). It is easy to see that a higher HRR will help the engine produce better fuel energy, and biodiesel makes the HRR of the engine lower, which significantly affects engine performance. Pressure rise rate (PRR) is another important factor to control the performance and durability of the engine (Wei *et al.*, 2018). Although the pressure rise rate of the engine at a low load increases more rapidly when using biodiesel, a similar trend does not occur at a high load. Temperature and pressure are two interrelated quantities that exhibit a direct proportionality. Additionally, diesel fuel

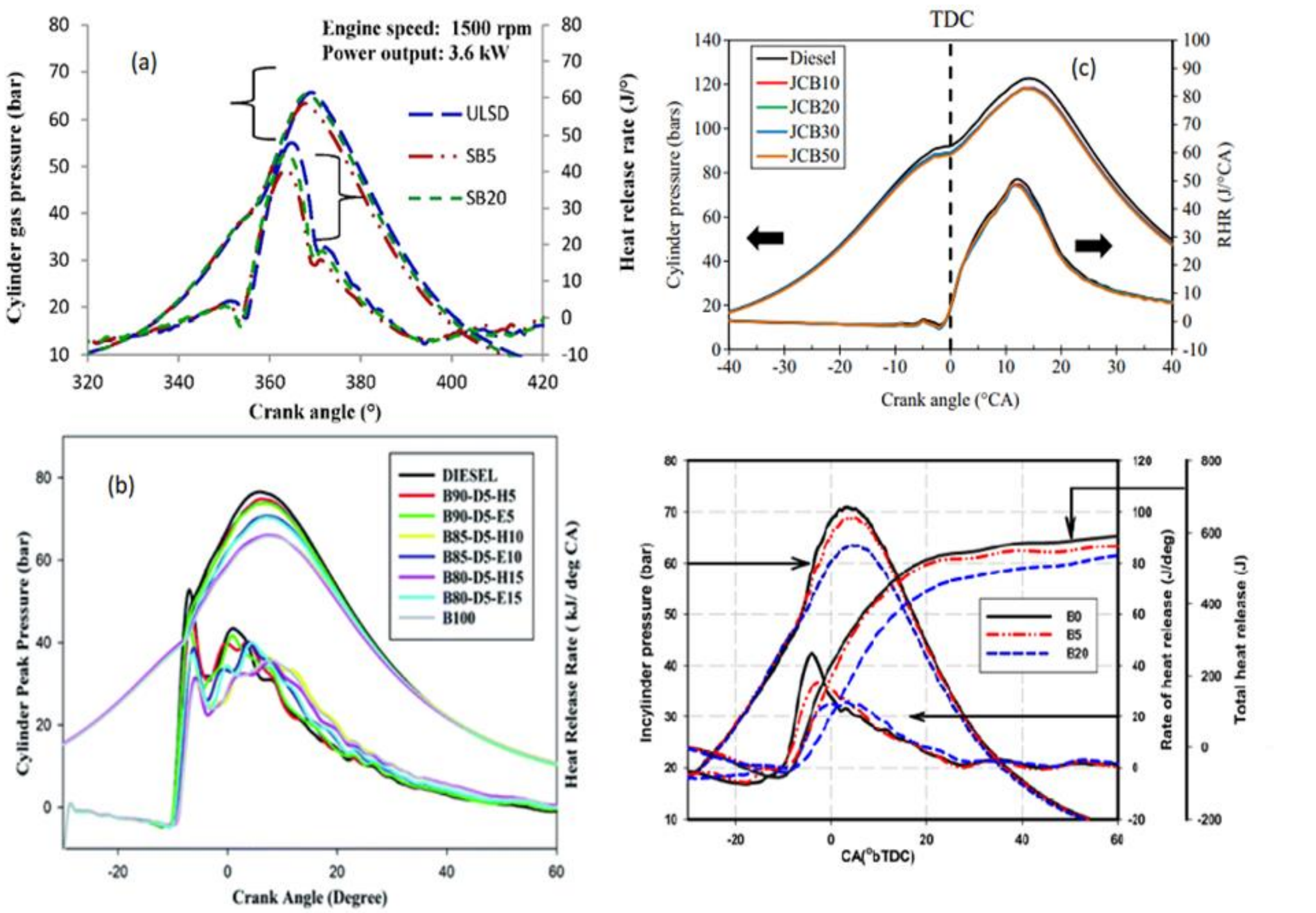

Fig. 3. The different between cylinder gas pressure and heat release rate with the crank angle of diesel fuel and different biodiesels (Ramalingam and Mahalakshmi, 2020; Seraç *et al.*, 2020; Silitonga et al., 2017; Zarrinkolah and Hosseini, 2022)(a) soybean-based biodiesel (b) *Moringa oleifera* biodiesel (c) *Jatropha curcas* biodiesel (d) sunflower methyl ester biodiesel

generally possesses greater energy density than biodiesel (Bergthorson and Thomson, 2015; Elkelawy *et al.*, 2019). Therefore, under heavier loads, engines running on biodiesel tend to experience a slower increase in pressure rate and consequently, the peak pressure is also lower compared to when using diesel fuel (Tamilselvan *et al.,* 2017). Figure 3 shows the difference between cylinder gas pressure and heat release rate with the crank angle of diesel fuel and different biodiesels (Ramalingam and Mahalakshmi, 2020; Seraç *et al.*, 2020; Silitonga *et al.,* 2017; Zarrinkolah and Hosseini, 2022). The difference is not too large to require serious modifications to the engine, however, to avoid affecting the power experience that people are used to with diesel engines, many measures are still proposed by researchers which will be clarified in the next section.

3.2. Effects of biodiesel on engine performance

With the effects on the engine characteristics recorded above, biodiesel surely has effects on engine performance. Common parameters used to evaluate engine performance include Brake-specific fuel consumption (BSFC), brake thermal efficiency (BTE), and exhaust gas temperature (EGT). While brake-specific fuel consumption (BSFC) and brake thermal efficiency (BTE) are intended to help comprehensively evaluate the engine's ability to generate power as well as fuel consumption, exhaust gas temperature (EGT) provide valuable information about the combustion efficiency, the state of the engine components, and the overall health of the engine (Sivaramakrishnan and Ravikumar, 2014). Monitoring and controlling these parameters is crucial to prevent damage to the engine and its components. It also helps optimize the performance, efficiency, and durability of the engine while also ensuring compliance with emission regulations.

BSFC is a measure of the fuel efficiency of an engine. It is defined as the amount of fuel consumed per unit of power produced by the engine and it also expresses the proportion of fuel mass used by the engine relative to the amount of braking power it generates. BSFC of engines using biodiesel will increase significantly. This is explained by BSFC having a close relationship with the viscosity, density, and especially the calorific value of the fuel (A.V.S.L *et al.*, 2021). Usually, the lower the calorific value, the higher the BSFC will be. Meanwhile, higher viscosity and density of fuel can also increase the BSFC because they can increase the friction between the fuel and the engine components, resulting in more energy losses due to friction. This, in turn, can cause the engine to work harder and consume more fuel to produce the same amount of power output, leading to a higher BSFC value. Additionally, higher viscosity and density can also cause the fuel to atomize less effectively, leading to incomplete combustion and further increasing fuel consumption and BSFC (Kathirvelu *et al.*, 2017; Temizer *et al.,* 2020). However, if biodiesel is used as a fuel blend with diesel fuel in small proportions, typically less than 20% of the fuel density, the BSFC is recorded to be insignificant (Canakci and Van Gerpen, 2003; Pullagura *et al.*, 2023) In theory, changing the compress ratio appropriately will improve the BSFC for all fuels, however, the efficiency when changing the compress ratio on biodiesel engines is noted to be much better than diesel engines (Suresh *et al.*, 2018). With high compression ratios, biodiesel is reported to have lower volatility and higher kinematic viscosity, which directly improves engine performance. Figure 4a compares the fuel consumption of some biodiesel with diesel. Some exceptions like Argemone biodiesel or home oil-based biodiesel have significantly improved BSFC. These fuel sources are said to be extremely potent, and more research is needed to understand this phenomenon. In general, although the BSFC of the engine depends a lot on many different parameters such as engine type, engine operating conditions, fuel injection pressure (FIP), the fuel injection method, and so on, biodiesel will always tend to increase BSFC under the same operating conditions if compared with diesel.

Meanwhile, brake thermal efficiency (BTE) is a measure of the efficiency of an engine in converting the energy contained

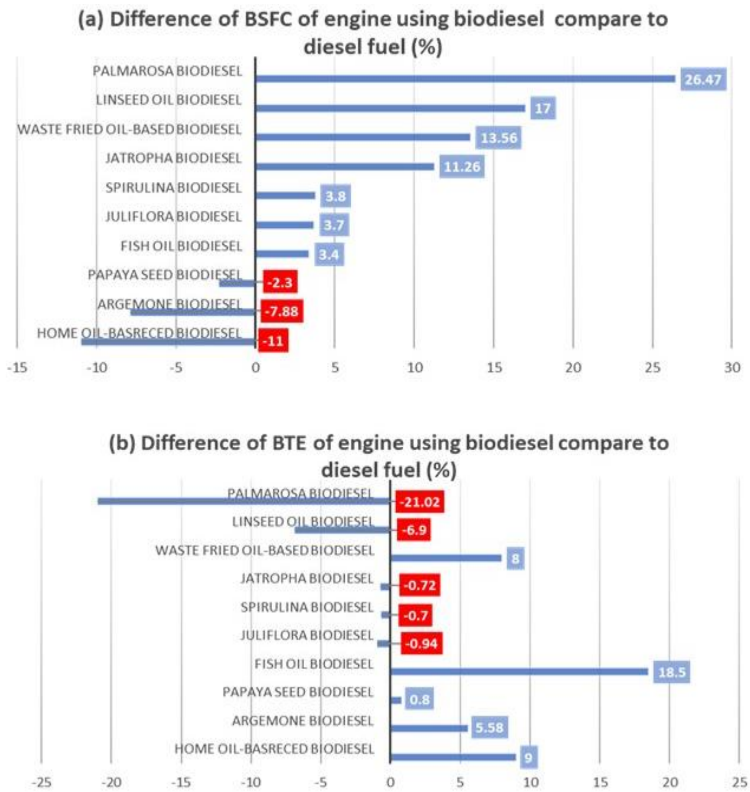

Fig. 4. Comparison of engine performance using biodiesel and diesel; (a) difference of BSFC (b) difference of BTE

in the fuel into useful work. It is defined as the ratio of the engine's brake power output to the energy content of the fuel consumption by the engine. The poor vaporization characteristics of biodiesel make the engine tend to use a lot of energy to produce useful work, which causes the BTE of the biodiesel engine to be significantly reduced at low engine speed and load ranges (Karthikeyan *et al.*, 2020). However, at higher engine loads and speeds, where the vaporization of the fuel is also smoother, the oxygen content in the component helps the fuel to burn more cleanly, reducing the loss of useful power (Jindal *et al.*, 2010). Both the BSFC and BTE of the engine are significantly affected by the difficulty of vaporization of biodiesel, especially in the low load ranges of the engine (Agarwal *et al.*, 2017). Researchers have proposed an extremely effective method to solve the above problem is adding an amount of alcohol to the fuel. The amount of alcohol with the characteristic of having low viscosity and density will reduce the overall viscosity and density of the fuel (Veza *et al.*, 2022), making it easier for vaporization to occur, thereby improving the efficiency of the engine (Duraisamy *et al.*, 2021; Padhee and Raheman, 2015; Truong *et al.*, 2021). Blends of biodiesel with ethanol or methanol have been reported to significantly improve BTE over diesel fuel regardless of operating conditions, in which biodiesel alone shows weakness (EL-Seesy *et al.*, 2021; Venu and Madhavan, 2017). However, the ratio between biodiesel and alcohol content needs to be studied and calculated carefully because an excessive alcohol ratio will cause a cooling effect due to the high latent heat of the vaporization of alcohol (Erdiwansyah *et al.*, 2019; Yilmaz *et al.,* 2016). This will in turn reduce the BTE. It can be seen that the relationship between the physicochemical properties of the fuel and the BTE of the engine is not quite linear and it is necessary to find the optimal points to help the engine operate more smoothly. Figure 4b shows the comparison between the brake thermal efficiency of some biodiesel with diesel fuel (Riyadi *et al.*, 2023). Diesel engines have a continuous development history to exploit and make the most of the energy produced from diesel fuel. When changing diesel with biodiesel, regardless of the change in their composition and chemical properties as mentioned above immediately affect the performance of the engine, both negative and positive effects (Nagarajan *et al.*, 2022). However, the negative effects are more obvious. Data in Table 2 shows recent research on the effect of biodiesel on engine performance and emission characteristics. Most biodiesel reduces engine performance, as shown by increasing BSFC and decreasing BTE (Dubey *et al.*, 2022; More *et al.,* 2020; Perumal and Ilangkumaran, 2018). The use of biodiesel as the main fuel without any improvement in fuel or engine characteristics has been proven both theoretically and experimentally to reduce the performance of the engine significantly. However, when using biodiesel fuel as a second fuel source to mix with diesel fuel, the engine has minimized its power loss. Many studies have shown that the 20% biodiesel blending ratio (B20) is the optimal fuel ratio for the engine when the changes in BTE and BSFC are insignificant (Canakci and Van Gerpen, 2003; Jindal *et al.*, 2010; Lue *et al.*, 2001).

Exhaust gas temperature (EGT) is another parameter that also needs to be paid attention to when analyzing the combustion of an engine. During low engine loads, the exhaust gas temperature (EGT) tends to be lower due to reduced fuel consumption and subsequent lower heat production. Conversely, at high engine loads, the EGT typically rises as a result of increased fuel combustion and the generation of greater heat (Mehta *et al.*, 2010; Uyumaz *et al.*, 2014). Heat is also a type of energy produced by combustion, so a higher exhaust gas temperature also means that combustion produces more energy. However, this is wasted energy that is not useful for engine operating processes. The cause of higher exhaust gas temperature can also come from incomplete combustion leading to a significant amount of unburned particles in the exhaust gas. Besides, too high exhaust gas temperature will put pressure on machine parts such as the pistons, valves, and exhaust system, reducing their durability and causing damage if continued for a long time. Usually, the EGT of a diesel engine can range from 300°C to 700°C or even higher, depending on the operating conditions and characteristics of the fuel. However, the recognition of the trend of the EGT trend of biodiesel engines is not unanimous. Some studies recorded a decrease in EGT (Ghazali *et al.*, 2015; Kegl, 2011; Shrivastava *et al.*, 2019) while others noted an increase in EGT (Abed *et al.,* 2018; Kerihuel *et al.,* 2005). However, the trend of increasing EGT is more recognized by many studies. In the case of a decrease in EGT, the phenomenon is explained that biodiesel has a higher oxygen content and a lower carbon-to-hydrogen ratio than diesel fuel as well as its lower heating value (LHV), which can lead to more complete combustion and less unburned fuel in the exhaust gases (Al-lwayzy and Yusaf, 2017; Haşimoğlu *et al.*, 2008; Yilmaz *et al.*, 2014). Conversely, the higher viscosity of methyl esters, leading to inadequate fuel atomization and vaporization, can account for the delayed combustion of injected fuel. This delayed burning process elucidates the rise in exhaust gas temperature (EGT) in the engine (Yilmaz *et al.*, 2014; Yilmaz and Atmanli, 2017).

3.3. Effects of biodiesel on emissions characteristics

In the opposite direction, unlike creating negative effects on engine performance, biodiesel has always been known as a fuel source to help reduce emissions. Biodiesel is an oxygenated fuel with a more complete combustion process, leading to significantly improved emission parameters (Elkelawy *et al.*, 2021). Table 3 shows recent research about the effects of biodiesel on emission characteristics and compounds.

All the data is collected when the engine is operating at 100% load if the engine load is not specified. Most studies show that the use of biodiesel significantly reduces UHC and CO (Ahmad and Saini, 2022; Joy *et al.*, 2018; Vellaiyan and Partheeban, 2018). The unburnt hydrocarbons (UHC) as the name suggests are the result of incomplete combustion of the fuel in the engine. The term "UHC" refers to all varieties of hydrocarbon compounds produced by an engine, but which cannot be assessed separately. As a result, depending on their makeup, they are categorized and referred to as UHC emissions comparable to C1, C3, or C6. When the air-fuel ratio is either too rich or too low for auto-ignition, UHC emissions take place and the combination cannot sustain a flame or ignite automatically (Mofijur *et al.*, 2016). The fact that biodiesel has a significantly higher oxygen content than diesel fuel, and the cetane number of biodiesel is also slightly higher than diesel fuel; thus biodiesel could help the combustion process be more complete. This directly reduces the amount of UHC formed (Abed *et al.*, 2019; E *et al.*, 2017). Interestingly, mixing a small amount of alcohol as mentioned above to improve engine performance also reduces the amount of UHC. This makes the solution of mixing alcohols of particular attention to researchers. A similar problem occurs with CO emissions because CO is the result of fuel combustion under bad conditions such as a lack of oxygen or improper air-to-fuel ratio (Kim *et al.*, 2018). Therefore, the presence of oxygen in the composition of biodiesel also helps to reduce CO formation significantly by creating conditions for CO emissions to be able to convert into CO_2,

Table 3
Effects of biodiesel on emission characteristics

Blended fuel	Ratio	Emission performance				Ref
		UHC	CO	NOx	Smoke	
Rice Bran methyl ester	B20	↓ 10.5%	-	↑ 16%	↓ 10%	(Jayaprabakar and Karthikeyan, 2016)
	B10D90, B20D80, B50D50, B100	↔ for B20. ↑ 30%, 18%, 33% for B10, B50, B100	↑ 20% for B10 ↔ for B50 ↓ 40% and 20% for B20 and B100	↔ for B10, B20 ↑ 6.25% and 9.2% for B50, B100	↓ 27% and 33% for B10, B20 ↑ 2% for B50, B100	(Shah, 2015)
Jatropha methyl ester	B10, B20	↓ 2.5% and 10.3% for B10, B20	↓ 20% and 29% for B10, B20	↑ 3.1% and 6.3% for B10, B20	-	(Mofijur et al., 2013)
	B20	↓ 28.6%	↓ 45%	↑ 9.3%	-	(Kumar and Sharma, 2016)
	B20, B100	↓	↓ 34% and 50% for B20, B100	↑ 12.8% and 57% for B20, B100	-	(Kathirvelu et al., 2017)
Fish oil methyl ester	B20, B100	↓	↓ 25% and 47% for B20, B100	↑ 13.2 and 29% for B20, B100	-	(Kathirvelu et al., 2017)
Moringa methyl ester	B20	↓ 28.6%	↓ 30%	↑ 9.3%	-	(Kumar and Sharma, 2016)
Rapeseed methyl ester	B25, B50, B75, B100	↓ 15.4%, 26.7%, 32.2% and 42.1% for B25, B50, B75 and B100	↓ 7.6%, 22.7%, 30.4%, 35.4% for B25, B50, B75 and B100	↑ 14.4%, 21.6%, 28.5% and 32.9% for B25, B50, B75 and B100	↑ 5.6% for B25 and 10.3% for B100	(Raman et al., 2019)
Palm methyl ester	B20, B40, B60, B100	↑ 14%, 43% for B60, B100 ↑ 100% for B40 and B20	↔ for B100 ↑ 10% for B60, B20 ↑ 22 % for B40	↓ insignificantly for B20, B40 ↓ 7% and 16% for B60, B100	-	(Iqbal et al., 2013)
	B20	↓ 38%	↓ 14%	↑ 37%	↓ 11.7%	(Rosha et al., 2019)
	B20D80	↓ 42.8%	↓ 50%	↑ 1.6%	-	(Kumar and Sharma, 2016)
	B30, B100	↓ 18.26% for B30 ↑ 30% for B100	-	↑ 2.3% for B30	-	(Verma and Sharma, 2015)
Soybean methyl ester	B30, B50, B70	↓ 1.83%, 2.94%, 4.18% for B30, B50 and B70	↓ 15.02%, 33.81%, and 30.73% for B30, B50 and B70	↑ 4.28%, 5.52%, 11.9% for B30, B50 and B70	↓ 5.4%, 18.02%, 34.09% for B30, B50 and B70	(Elkelawy et al., 2019)
Coconut methyl ester	B30	↑ 31.21%	-	↑ 3.8%	-	(Verma and Sharma, 2015)
Cottonseed methyl ester	B5, B10, B20	↓ 16.2%, 41% and 47% for B5, B10, B20	↓ 40%, 68% and 76% for B5, B10, B20	-	-	(Sinha and Murugavelh, 2016)
Waste cooking methyl ester	B20, B50	↓ 25%, 27% for B20, B50	↓ 10.7%, 32.1% for B20, B50	↑ 18%, 41% for B20, B50	-	(El-Adawy et al., 2013)
Juliflora methyl ester	B20, B30, B40, B100	↓ 6%, 9%, 13% and 17% for B20, B30, B40, B100	↔ for B20, B40 ↑ 7% for B30 ↓ 3.8% for B100	↓ 1.6%, 1.4%, 1,1% for B20, B30, B40 ↑ 0.6% for B100	↓ 11.7%, 4.4% for B20, B30 ↑ 10.3%, 14% for B40 and B100	(Asokan et al., 2019)

leading to a significant reduction in CO emissions (Abed *et al.*, 2018). However, one major difference between UHC and CO is that mixing a small amount of alcohol can significantly increase the amount of CO. Specifically, the amount of CO was reported to have increased by 39.95%, 38.83%, and 12.6% for propanol, butanol, and pentanol, respectively (Uyumaz, 2018; Zhang *et al*., 2022). Figures 5a and Figure 5b show a comparison of the UHC and CO emissions of engines using biodiesel with diesel fuel and the similarity in their trends is shown clearly when most biodiesel will reduce UHC and CO emissions except in some special cases.

On the contrary, the availability of oxygen in the biodiesel composition will increase NO_x emissions, which is a typical trade-off relationship in most combustion fuel studies (Duraisamy *et al*., 2021; Manigandan *et al.,* 2020). Nitrogen oxides (NO_x) are the most hazardous pollutants generated by engines and are dependent on factors such as the combustion temperature and the length of time it is exposed to a high-temperature environment (above 1400°C), the chemical composition of the fuel, and the availability of oxygen in these high-temperature areas (Appavu *et al*., 2021). The cause of NO_x emissions when using biodiesel increases can be explained by the earlier combustion of the fuel in the combustion chamber along with the improved combustion process in both quality and speed, causing the 87 in the combustion chamber to rise, thereby enhancing the formation of NO_x (Chen *et al.,* 2018; Mirhashemi and Sadrnia, 2020). In the combustion chamber equipped with electronic injectors, unsaturated biodiesel with higher iodine value is also the main cause of the increase in NO_x emissions (Mofijur *et al.,* 2019). The same phenomenon does not occur with the engine with a common rail direct injection system. All the above signs indicate that the increase in NO_x emissions of the engine is bound by many causes, however, their relationship has not been interesting and clarified by many studies (Rathinam *et al.,* 2018; Varatharajan and Cheralathan, 2012; Zare *et al*., 2021). Not many studies have documented a reduction in NO_x emissions as shown in Table 3 and in those cases, it is explained that the lower heating value of biodiesel compared to diesel fuel and lower ID, which forces hot gases to stay in the combustion chamber at high temperature to generate less NO_x. Figure 5c compares the NO_x emission of different biodiesel to diesel fuel. In addition, the alcohols once again show a suitable fit and have a very important role in turning biodiesel into a more user-friendly fuel as the addition of longer chain alcohols will reduce NO_x emissions by approximately 27.44%, 19.27%, and 15.05% for pentanol, butanol and propanol compared with a 50% biodiesel blend (Uyumaz, 2018).

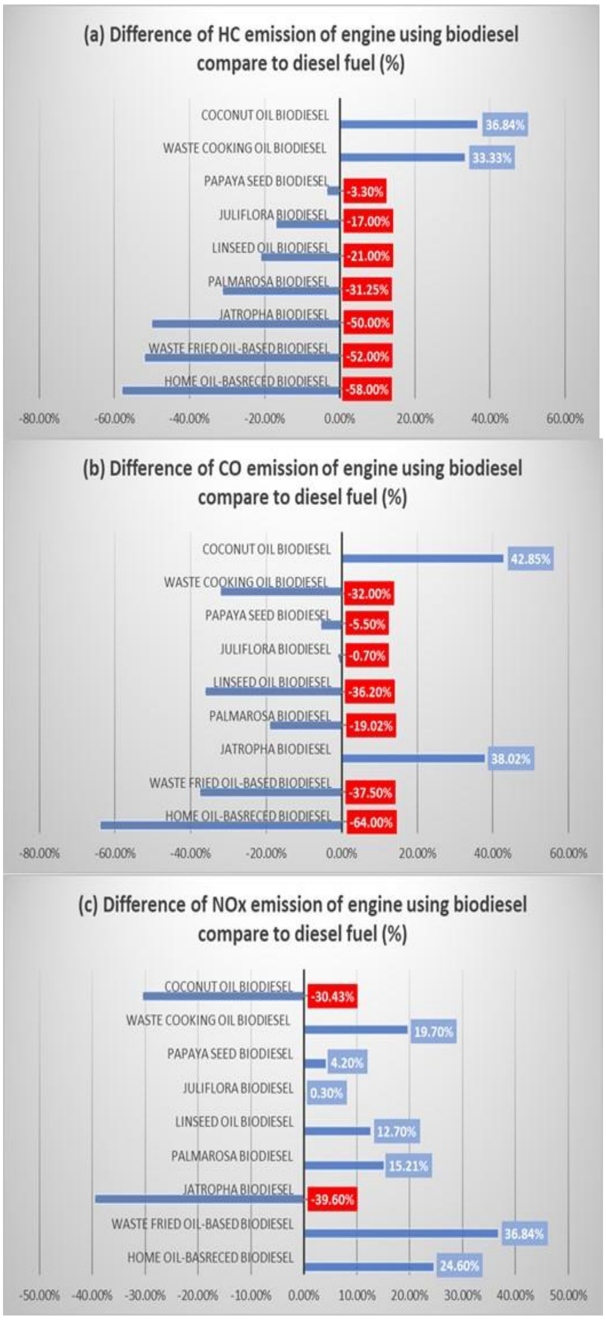

Fig. 2. Comparison of emission from the engine using biodiesel and diesel; (a) difference of HC emission (b) difference of CO emission (c) difference of NOx emission

It is undeniable that biodiesel will increase NO_x emissions, the overall emissions are still significantly reduced, and biodiesel is still widely considered by researchers as a much cleaner energy source than diesel fuel. Therefore, instead of completely using biodiesel in an internal combustion engine, using biodiesel as a secondary fuel source to blend to help overcome the inherent weaknesses of diesel while still being able to partly avoid depending on them is a much more potential approach. Although it is difficult to find a type of biodiesel that, after blending with diesel oil, can improve all aspects of engine performance as well as reduce all types of emissions, there are three important issues to be aware of when using this method: (i) engine performance should not necessarily be improved, but should focus on reducing emissions, (ii) biodiesel improvement studies are still being carried out and biodiesel applications will be more and more perfect in the future and (iii) fuel blending will help reduce consumption as well as ensure energy security for many countries. Of course, the higher the efficiency of the engine, the better, however, the internal combustion engine has been in common use for a long time and the efficiency of the internal combustion engine has thus been widely accepted. As long as the fuels used do not reduce engine performance or do not significantly reduce it, it is acceptable. In other words, the priority when researching fuel blends should be to help reduce emissions rather than improve engine performance. With this approach, the disadvantages of diesel oil cannot be completely overcome but will be improved and also easier to use. Furthermore, finding a fuel source that can be mixed with diesel will greatly reduce the need for diesel. This has not been able to completely solve the burning problems of diesel fuel, but it will help countries lacking oil reserves reduce pressure on energy and also give humanity more time to find a solution to the problem. Besides, this method is considered one of the extremely simple, economical, and proactive methods to solve fuel and emissions problems in the short term. The physicochemical properties of diesel and biodiesel can vary significantly, and these differences can impact their

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Table 4.
Nanoparticle approaches in improving engine performance and emission characteristics

Biodiesel	Nanoparticles	Engine Performance		Emission Performance				Ref
		BSFC (or SFC)	BTE	HC	CO	NOx	Smoke	
Jatropha	CeO_2 particles (40ppm and 80ppm)	-	↑ insignificant	↓ 16.7%, 38.9 % for 40ppm and 80ppm CeO2	↓ 21%, 40% for 40ppm and 80ppm CeO2	↓ 7%, 21% for 40ppm and 80ppm CeO2	-	(Sajith et al., 2010)
	CO_3O_4 particles	↓ 2%	↑ 0.6% at 50% load	↓ 83% at 75% load	↓ 50% at 75% load	↓ 47% at 75% load	-	(Ganesh and Gowrishankar, 2011)
	Al-Mg particles	↓ 1%	↑ 0.2% at 50% load	↓ 70% at 50% load	↓ 66% at 50% load	↓ 20% at 50% load	-	(Ganesh and Gowrishankar, 2011)
	Al_2O_3 particles (50ppm)	↓ 13.5%	↑ 12%	↓ 13.3%	↓ 40%	↓ 20.8%	↓ 13.4%	(Basha and Anand, 2013)
	TiO_2	↓ 5%	-	↑ 6%	↓ 20%	↔	↑ 21%	(Venu and Madhavan, 2016)
	ZrO_2	↔	-	↔	↓ 20%	↔	↓ 21%	(Venu and Madhavan, 2016)
Mustard	TiO_2 nanofluid (100 and 200ppm)	-	-	↓ 3%, 4.2% for 100ppm and 200ppm	↓ 8%, 13% for 100ppm and 200ppm	↓ insignificant	↓ 6,7%, 16.7% for 100ppm and 200ppm	(Yuvarajan et al., 2018)
Poultry litter	Al_2O_3 particles	-	↓ 6.7%	↓ 25.4%	↓ 28.5%	↓ 4.4%	↑ 1%	(Ramesh et al., 2018)
Neem	Carbon nanotubes	↓	↑ 3.43%	↓ 8.15 %	↓ 11.77 %	↓ 4.67 %	↓ 5.74 %	(Gnanasikamani et al., 2015)
Calophyllum inophyllum	TiO_2 particles	↓ 13.8%	↑ 3.1%	↓ 12%	↓ 23%	↑ insignificant	↓ 7.7%	(Praveen et al., 2018)
Caulerpa racemosa	Iron II and Iron III nanofluid	-	-	↓ 11.2%	↓ 8.9%	↓ 10%	↓ 10.3%	(Karthikeyan and Prathima, 2016)
Mahua	CuO	-	↑ insignificant	↔	↓ 33%	↑ insignificant	↓ 12.5%	(Chandrasekaran et al., 2016)
Neem	Carbon nanotubes (50ppm and 100ppm)	-	-	↓ 5.1% and 6.7% for 50ppm and 100ppm	↓ 2% and 5.8% for 50ppm and 100ppm	↓ 6.3% and 9.2% for 50ppm and 100ppm	↓ 6.3% and 7.8% for 50ppm and 100ppm	(Ramakrishnan et al., 2019)

However, by carefully adjusting the fuel mix ratio, it is possible to resolve these differences and achieve a desirable balance between the properties of the two fuels and help the engine operate smoothly with high efficiency.

In the efforts to help overcome the remaining weaknesses of biodiesel, researchers have applied many different technologies and have achieved remarkable achievements in recent years. One of the recent approaches of researchers is to use nanoparticles additives (Hoang, 2021b; Kandasamy and Sundararaj, 2018; Pradeep and Senthilkumar, 2021; Rameshbabu and Senthilkumar, 2021; Sathish *et al.*, 2023). Applications of nanoparticles are diverse such as nano metal-based particles such as cerium oxide (Kumar *et al.*, 2019; Shaisundaram *et al.*, 2021), titan oxide (Nanthagopal et al., 2017; Sunil *et al.*, 2021), zinc oxide (Javed *et al.*, 2016; Vali *et al.*, 2022), copper oxide (Kalaimurugan et al., 2019; Rozina *et al.*, 2022), carbon-based nanoparticles (Murugesan *et al.*, 2022), nanofluids (Kannan *et al.*, 2011; Khalife *et al.*, 2017; Shaafi *et al.,* 2015). Nanoparticles can be used as additives in diesel and biodiesel to increase surface area to volume ratio as well as increase catalytic activity in nano-size metal oxides and metals (Hoang *et al.,* 2022b). Nano additives directly improve engine combustion by improving heat transfer, catalytic activity, and air fuel mixing rate (Karthikeyan *et al.*, 2017; Tomar and Kumar, 2020). Table 4 shows the comparison between with and without nano-additives on engine performance and emission characteristics. The data shows that using nano additives or nanofluid significantly reduces emissions such as HC, CO, and smoke, especially in some research, the results show that nanotechnology can even reduce NO_x emissions, which solves the trade-off problem of emissions in the combustion process of the engine. Regarding the engine performance, many studies also show an improvement in BSFC and BTE of engines powered by nanoparticles-included fuels although it does not completely solve the problem. Besides, because nanoparticles are used as a catalyst in the combustion process, their shelf life and performance will be maintained for a long time if there are no problems such as poisoning or thermal degradation, leading to deactivation. This will make the cost of applying nano additives not too high, but the effect is extremely stable. However, studies aimed at comprehensively assessing the potential of this method are very limited. Therefore, it is necessary to have a comprehensive assessment of the use of nanoparticles for blending with biodiesel.

4. Challenges and opportunities

With the ever-increasing energy demand and political instability directly affecting the supply stability of fossil fuels, the development and utilization of biodiesel becomes more relevant than ever (Coşofreţ *et al.*, 2016). The diversity in production inputs, coupled with the fact that it has been shown to significantly reduce greenhouse gas emissions, which has been a sore point in recent years, creates extremely favorable conditions for biodiesel to compete with fossil fuel sources. Unlike traditional fossil fuels, biodiesel can be produced domestically, reducing the need for foreign oil imports. This can also help to stimulate local economies by creating jobs in the production and distribution of biodiesel.

Another opportunity for biodiesel is its potential to reduce greenhouse gas emissions. Biodiesel is considered a low-carbon fuel, meaning that it produces fewer greenhouse gas emissions than traditional fossil fuels (Semwal *et al.*, 2022). This can help countries and companies meet their emissions reduction targets and contribute to global efforts to combat climate change (Babatunde *et al.*, 2022). Additionally, biodiesel can be used in a wide range of applications, including transportation, heating, and electricity generation. This versatility makes biodiesel a flexible and adaptable fuel source that can meet a variety of energy needs. However, like any new technology or industry, biodiesel faces both challenges and opportunities.

One of the primary challenges of biodiesel is its cost, while the production of biodiesel has become more efficient and cost-effective in recent years, it is still more expensive than traditional fossil fuels (Maroušek *et al.*, 2023a; Meira *et al.*, 2015). This is partly due to the higher cost of feedstocks, such as soybean oil, which is used to produce biodiesel. Additionally, the cost of production equipment, infrastructure, and transportation can also be higher than traditional fossil fuel production (Kumar *et al.*, 2021). However, according to many researchers, the cost of raw materials, especially biomass feedstock, accounts for most of the financial structure (Apostolakou *et al.*, 2009). Therefore, finding cheap fuel will greatly improve profits. To solve the above problem, the use of biomass sources to convert into biodiesel must be considered carefully. One potential approach not only to reducing the cost of biodiesel production but also improving other environmental issues is by utilizing biomass sources derived from by-products and waste products from production and living activities (Baldia *et al.*, 2023; Sung *et al.*, 2021; Vani *et al.,* 2022). However, they are still in the early stages of development and are not yet widely available or cost-effective.

Secondly, biodiesel can hurt engine performance in cold weather conditions (Rochelle and Najafi, 2019). This makes the use of biodiesel at certain times of the year or in some countries with cold climates extremely unsuitable. Biodiesel has a higher cloud point and pours point than petroleum diesel, which means that it solidifies at a higher temperature, making it challenging

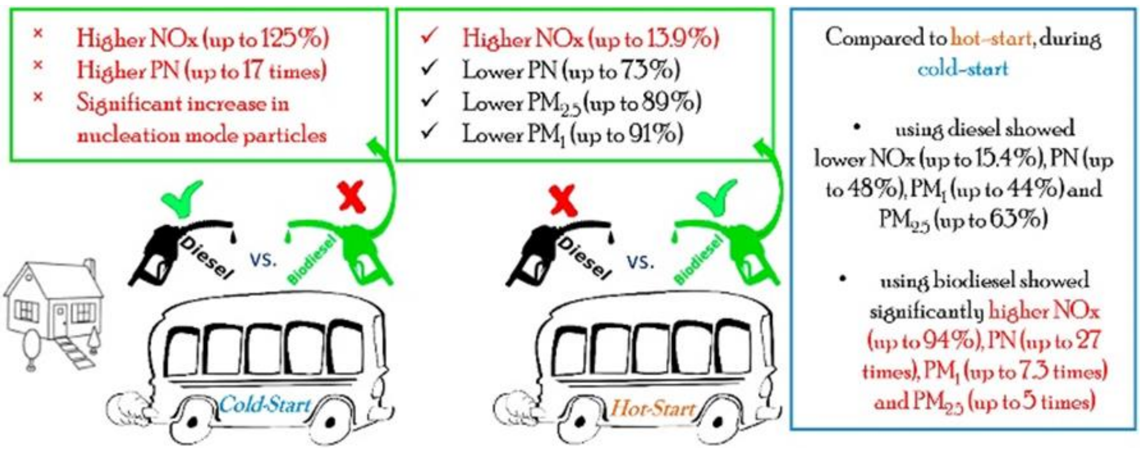

Fig. 3. Comparison between diesel and biodiesel in different start temperatures (Zare *et al.*, 2017)

to use in low-temperature conditions (Sani *et al*., 2018; Su *et al*., 2021). This can result in engine starting problems and fuel filter clogging, which can affect engine performance and reliability (Nursyairah *et al*., 2022). Many studies have been done to evaluate the performance of biodiesel engines at low temperatures and most of the results show difficulty in cold-start the engine (Hadi *et al*., 2023; Yubaidah, 2023). Besides, biodiesel that has solidified or thickened due to cold weather may not properly atomize and mix with air in the combustion chamber, resulting in incomplete combustion and reduced engine performance (Chaichan *et al*., 2020; Clenci *et al*., 2016; Jiaqiang *et al*., 2019). Figure 6 compares the advantages and disadvantages of biodiesel and diesel in cold-start and hot-start (Zare *et al.,* 2017). It can be seen that the use of biodiesel at low temperatures completely loses the natural advantages of this fuel. This is a research direction that needs to receive a lot of attention to make it possible to use biodiesel in different weather and temperature conditions.

Besides improving engine performance and reducing emissions, another problem for the long-term and widespread use of biodiesel that needs to be analyzed and evaluated is the possibility of engine damage (Dharma *et al*., 2023). Engine performance and emission index are parameters that only show the immediate suitability of biodiesel. In case the use of biodiesel causes the engine to degrade quickly, biodiesel is very unlikely to be considered a sustainable alternative fuel source. One of the criteria to evaluate the suitability of the fuel, in the long run, is the degree of deposit formation of the fuel when used in the engine (Zhang *et al*., 2020). Some studies have shown that biodiesel has poor atomization and low evaporation, which leads to larger fuel droplets as well as the heterogeneity of the fuel mixture, which directly increases the possibility of deposit formation (Liaquat *et al*., 2014). However, the three most important causes of scale formation are thought to be temperature, nozzle geometry, and fuel composition (Leedham *et al*., 2004). Birgel *et al.* (Birgel *et al*., 2011) experimented with the deposit formation on the injector using different fuels, and the results were shown in Figure 7. It can be seen clearly with the naked eye that biodiesel significantly increases the amount of deposit formation on the injector (Hoang and Le, 2019). This is still a challenge with efforts to bring biodiesel into widespread use. Many researchers propose several solutions to try to limit the formation of deposits. Mulyono *et al.* (Mulyono *et al*., 2018) used the hydrotreating method and got some positive results. The results show that the formation and growth of scale are slower in hydrotreated vegetable oil than in biodiesel. Besides, the above phenomenon can be partly solved by improving the parameters of biodiesel. Biodiesel has high viscosity, while fuel with high viscosity requires a longer ignition delay because the fuel droplets take longer to vaporize, which makes scale formation more likely to occur (Emiroğlu, 2019). Although there are many theoretical studies explaining the cause for the formation of biodiesel scale, the solutions to solve this phenomenon are still very limited. This also could be a potential direction for biodiesel fuel researchers

Another aspect that needs to be considered in the long term is the engine corrosion of biodiesel. The corrosive potential of biodiesel is rated as much higher than that of diesel because of its high oxygen content (Fazal *et al*., 2012; Hoang *et al*., 2020). In addition, the biodiesel production process can generate impurities such as free fatty acids, glycerol, and metal catalyst residues. If not handled properly, these impurities can participate in reactions that corrode metals. Fazal *et al.* (Fazal *et al*., 2010) observed corrosion rate of palm oil biodiesel with copper, and aluminium is 0.586 and 0.202 mils per year (mpy) while for diesel, the corrosion rate is only 0.3 mpy and 0.15 mpy respectively. In another study, Saravana Kannan Thangavelu *et. al* also reported a higher corrosion rate when blending biodiesel into diesel. Specifically, B20D75E5 (20% biodiesel, 75% diesel, and 5% ethanol) and B20D70E10 (20% biodiesel, 70% diesel, and 10% ethanol) have a corrosion rate of 0.1572 and 0.1817 mpy respectively while diesel has a corrosion rate of only 0.1572 and 0.1817 mpy, respectively. 0.0523 mpy (Thangavelu *et al*., 2016). This is a significant increase when just mixing 20% biodiesel into the fuel, but it increases the corrosion rate by more than 3 times. This is considered a serious problem because it not only reduces engine performance but also causes engine damage, directly increases warranty and repair costs, or even raises a big question mark to safety concerns. These are all major obstacles to the widespread dissemination of biodiesel and require research to come up with optimal solutions.

With its enormous potential but still underappreciated today by businesses and citizens, the role of government in promoting and supporting this fuel is more widespread is indispensable. Policies for biodiesel around the world vary widely, depending on factors such as government priorities, energy security goals, and environmental concerns (Austin *et al*., 2022). Some countries have implemented ambitious targets for biodiesel production and use, while others have been slower to adopt this renewable fuel source. In Europe, Renewable Energy Directive has set a target of 14% renewable energy in transportation by 2030, which includes the use of biodiesel (Long *et al.,* 2021). Many European countries have implemented mandatory biodiesel blending policies, with blending ratios ranging from 7% to 20% (Chong *et al*., 2021). For example, in Germany, diesel fuel must contain a minimum of 7% biodiesel, while in France the mandatory blend is 8.5%. In the United States, the federal government has implemented a Renewable

Fig. 4. The optical investigation for deposit formation level evaluation on injectors (a) new nozzle, (b) diesel fuel, (c) BD30, (d) BD100 (Birgel *et al*., 2011)

Fuel Standard program, which requires a certain volume of renewable fuel to be blended into gasoline and diesel fuel. Biodiesel is included as a renewable fuel under the RFS, and the program has helped to promote the growth of the domestic biodiesel industry. In addition, some states, such as California, have implemented low-carbon fuel standards that incentivize the use of biodiesel and other low-carbon fuels. In South America, Brazil is a leading producer and user of biodiesel, with a mandatory blending policy that requires all diesel fuel to contain at least 13% biodiesel (de Souza *et al.,* 2022). Argentina and Colombia have also implemented mandatory blending policies, with blending ratios of 10% and 8%, respectively (Canabarro *et al.*, 2023). In Asia, several countries have implemented biodiesel policies to promote renewable energy and reduce dependence on imported fossil fuels. For example, Indonesia has set a target of 30% renewable energy in transportation by 2025, with biodiesel playing a key role in achieving this goal (Kharina *et al.*, 2016). Malaysia has also implemented a biodiesel blending policy, with a mandatory blend of 10% (Zulqarnain *et al.*, 2020). Overall, biodiesel policies around the world are evolving as governments seek to promote sustainable energy sources and reduce their reliance on fossil fuels. While the specifics of these policies vary widely, they all aim to promote the growth of the biodiesel industry and reduce greenhouse gas emissions from transportation.

5. Conclusions

The study presents the important properties of biodiesel and updates the latest research to improve engine performance and reduce emissions when using biodiesel. It can be seen that, with its physicochemical properties, biodiesel improves the engine's emission indicators significantly, however, operational issues such as performance or durability of the engine have become a problem that scientists are trying to resolve. Completely independent use of biodiesel without engine modifications is theoretically possible but is a huge minus point for both engine performance and operating costs. The use of biodiesel as a fuel mixed with diesel fuel will be more reasonable at present. Besides, to fully realize the opportunities of biodiesel, several steps need to be taken. One of the most important is to continue to invest in research and development to improve the efficiency and cost-effectiveness of biodiesel production. This includes developing new feedstocks and production methods, as well as improving the efficiency of existing production processes. In addition, social policies such as tax incentives, subsidies, and mandates that require a certain percentage of transportation fuel to be made from renewable sources are also necessary to support the commercialization of biodiesel. This also will help to educate the public and raise awareness about the benefits of biodiesel. Success in utilizing the fullest potential of biodiesel will relieve pressure on energy issues in many countries, setting the stage for sustainable development.

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