European Journal of Sustainable Development Research
2026, 10(1), em0355
e-ISSN: 2542-4742
https://www.ejosdr.com/

MODESTUM

Review Article

OPEN ACCESS

Effect of injection parameters on compression ignition engines: A review of methyl ester oil applications

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Citation: H, H., Venu, H., Pasha, Y., G L, A. K., & Rama Krishnaiah, K. (2026). Effect of injection parameters on compression ignition engines: A review of methyl ester oil applications. *European Journal of Sustainable Development Research, 10*(1), em0355. https://doi.org/10.29333/ejosdr/17495

ARTICLE INFO

Received: 17 Dec. 2024

Accepted: 07 Nov. 2025

ABSTRACT

This comprehensive review examines biodiesel as a viable substitute for conventional diesel fuel in internal combustion engines, highlighting its environmental benefits such as reduced emissions. Despite these advantages, the review acknowledges technical challenges and environmental concerns. It discusses advancements in biodiesel production, especially the one-step transesterification process, and explores the efficiency and emissions profiles of various biodiesel blends in generator engines. The review analyzes the effects of injection timing (IT) and nozzle geometry on biodiesel spray characteristics, with a focus on diesel engines equipped with common rail direct injection systems. It investigates the influence of nozzle geometry, injection pressure, and bowl geometry on engine emissions and performance, emphasizing the role of IT and pressure in regulating engine behavior. While recognizing biodiesel's potential as a renewable and biodegradable alternative, the review stresses the need for ongoing research to overcome technical limitations and address environmental concerns, aiming to fully realize biodiesel's potential as a sustainable energy source.

Keywords: energy consumption, fuels, biodiesel, engine performance, injection parameters

INTRODUCTION

The primary aim of this review is to investigate the influence of biodiesel, specifically methyl ester oils, as a renewable alternative fuel in compression ignition (CI) engines. With growing global interest in biodiesel due to its environmental and economic benefits, it is crucial to understand how engine operating parameters, particularly injection timing (IT) and injection pressure (IP), affect biodiesel performance. These parameters significantly influence combustion efficiency, engine performance, and emissions, which are key factors for enhancing the viability of biodiesel as a sustainable alternative to fossil fuels. This review will synthesize recent research on biodiesel's impact on engine efficiency, emissions, and performance, with a special focus on optimizing injection parameters. By addressing the technical challenges associated with biodiesel, this review aims to bridge the gap between biodiesel production and engine optimization, offering a comprehensive analysis of the effects of injection parameters on engine performance.

The energy consumption of a nation serves as a pivotal indicator of its economic and social development, intimately tied to both the gross domestic product and the per capita income of its populace (International Monetary Fund, 2018). Research findings have underscored the direct correlation between greenhouse gas emissions and a nation's level of economic development, emphasizing the adverse impact of industrialization on global warming (Abe et al., 2016). Notably, conventional oil maintains its prominence as a key energy source, holding the foremost position, closely followed by natural gas, as revealed in a comprehensive research report (Newell et al., 2019).

Projections for the year 2040 indicate that fossil fuels will continue to dominate energy consumption, constituting 78 percent of the total, despite the accelerated growth of non-conventional energy sources. The transportation sector is poised to lead the surge in fossil fuel and liquid fuel consumption, contributing to 62 percent of the overall increase in energy consumption during this period. Concurrently, the chemical industry is expected to witness a substantial uptick in energy consumption (Conti et al., 2016).

The transportation sector emerges as the primary consumer of energy, outpacing other industries, largely propelled by the proliferation of vehicle ownership and consequent end-use demands. This surge in demand, particularly for diesel, is projected to escalate from 69.4 million metric tonnes in 2015 to approximately 88 million metric tonnes by 2021. According to current projections, demand is expected to exceed 120 million metric tonnes by 2030 if present trends continue (Ministry of New and Renewable Energy, 2024). India, ranking as the third-largest importer of crude oil, follows the United States and China in the oil and gas industry reports (Impedia, 2025). Forecasts predict a significant expansion in India's automobile industry, projecting an increase from one million to twenty million by 2030, thereby positioning the nation as the third-largest in the world for automobile sales production. Amidst this, renewable energy sources gain prominence due to their lower emissions and the promise of a more secure energy supply. In addition to alleviating the strain on the nation's oil import expenditures, these initiatives carry the potential to stabilize the country's power requirements.

Biodiesel's impact on engine performance is influenced by various factors, including fuel properties and engine operating conditions. The performance of biodiesel in CI engines is highly dependent on factors such as IT and IP, which regulate fuel atomization, combustion efficiency, and emission levels. Therefore, it is essential to understand how these parameters interact with biodiesel's unique characteristics, such as its higher viscosity and oxygen content, which can influence the combustion process. By optimizing injection parameters, it is possible to enhance biodiesel's efficiency and reduce harmful emissions. This review, therefore, links the biodiesel section with engine processing by examining how precise control of injection parameters can mitigate biodiesel's inherent limitations while enhancing engine performance.

Optimizing IT and IP is critical to improving the performance of biodiesel-powered CI engines. Studies have demonstrated that advancing the IT can improve brake thermal efficiency (BTE) by enhancing combustion characteristics, such as quicker ignition and better air-fuel mixing. For instance, research by Mendonca et al. (2021) indicates that advancing the IT of waste cooking oil biodiesel by 3 degrees leads to a 5% increase in BTE and a reduction in carbon monoxide (CO) emissions due to more complete combustion. Similarly, increasing IP has been shown to improve fuel atomization, leading to more efficient combustion and a reduction in smoke opacity and hydrocarbon (HC) emissions. Mendonca et al. (2021) showed that increasing the IP from 200 bar to 240 bar resulted in a 10% improvement in BTE while also reducing specific fuel consumption (SFC) by 8%, though it slightly increased nitrogen oxides (NOx) emissions. Therefore, optimizing both IT and pressure can significantly improve fuel efficiency by ensuring better combustion of biodiesel, reducing unburned fuel and particulate emissions, and enhancing engine power output.

The IT can improve by advancing it slightly to promote earlier fuel ignition, which helps to improve combustion efficiency, reduce ignition delay, and enhance fuel-air mixing. Similarly, optimizing IP by increasing it can improve fuel atomization, leading to better combustion and reduced unburned fuel. Both adjustments contribute to higher BTE and lower SFC, thereby improving fuel efficiency. Literature supports these improvements; for instance, studies have

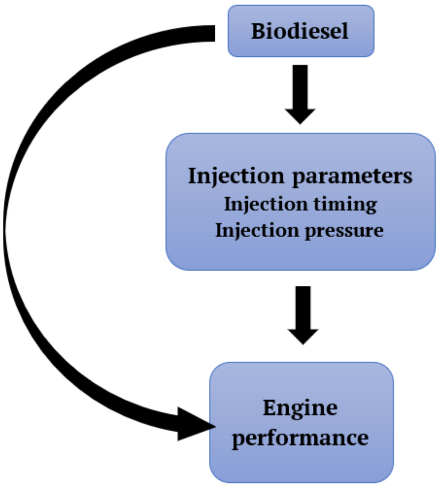

Figure 1. Conceptual framework (Source: Authors' own elaboration)

shown that advancing IT by a few degrees can improve BTE by 5-10%, while increasing IP from 200 bar to 240 bar has resulted in a 7% increase in BTE and a 5% reduction in SFC. These findings highlight the critical role of optimizing IT and IP in maximizing biodiesel engine performance and efficiency.

Figure 1 provides a conceptual framework to visualize the relationships between biodiesel properties, injection parameters, and engine performance. This framework will guide the discussions in this review, illustrating how these factors interconnect and influence engine performance metrics such as BTE, emissions, and combustion characteristics.

Engine Performance

The performance of a diesel engine is typically evaluated through several key parameters, which provide insight into the efficiency, power output, and environmental impact of the engine. These parameters are crucial for assessing the viability of alternative fuels such as biodiesel. The primary indicators of engine performance include BTE, SFC, emissions, peak pressure, heat release rate (HRR), and torque. Below are the definitions and methods for calculating these performance metrics.

Brake thermal efficiency

BTE is a measure of how effectively the engine converts the energy from fuel into mechanical energy. It is one of the most important parameters for evaluating engine performance, especially when using alternative fuels. The formula for calculating BTE as follows:

$$BTE = \frac{BP}{Energy\ input\ to\ engine} \times 100, \tag{1}$$

where BP is the break power that is usable power output from the engine, measured by a dynamometer and energy input is determined by the calorific value of the fuel and the mass flow rate of the fuel into the engine.

Specific fuel consumption

SFC is an efficiency indicator, representing the amount of fuel consumed per unit of power output. It reflects how much fuel is needed to produce a certain amount of power. The formula for calculating SFC is:

$$SFC = \frac{Fuel\ flow\ rate}{BP}, \quad (2)$$

where fuel flow rate is the mass of fuel consumed per unit of time and BP is the power output of the engine.

Lower SFC values are indicative of higher engine efficiency, as less fuel is required to generate a given amount of power.

Emissions evaluation

Emissions are a critical parameter for assessing the environmental impact of an engine. They are typically measured using exhaust gas analyzers, and the following emissions are commonly evaluated:

1. CO: A toxic gas produced from incomplete combustion.
2. Carbon dioxide (CO_2): A greenhouse gas that contributes to global warming.
3. NOx: Pollutants responsible for smog and acid rain.
4. HC: Unburned fuel that contributes to air pollution.

Each of these emissions is measured under various operating conditions to compare the environmental impact of biodiesel vs. conventional diesel fuel.

Peak pressure and heat release rate

Peak pressure refers to the highest pressure within the cylinder during the combustion process and is a good indicator of combustion quality. Higher peak pressures generally correspond to more efficient combustion. The HRR measures the rate at which fuel energy is released during combustion and is calculated from the pressure data over time. The HRR is significant because it reflects the efficiency of the combustion process.

Torque and power output

Engine torque and power output are direct indicators of engine performance, reflecting the engine's ability to do useful work. Torque is the rotational force produced by the engine, while power output is the rate at which work is done. These are typically measured using a dynamometer.

Effect of injection parameters on engine performance

The evaluation of engine performance when using biodiesel (methyl ester oil) depends heavily on various engine operating parameters, particularly IT and IP. These parameters influence fuel atomization, combustion efficiency, and emission levels. Optimizing these parameters is critical for improving the performance of biodiesel-powered engines and achieving a balance between engine efficiency and environmental sustainability. The following sections of this review examine how these parameters interact with biodiesel and impact engine performance.

BIODIESEL

Biodiesel has gained significant attention in recent years due to its numerous advantages. Firstly, biodiesel is environmentally friendly as it is derived from plant-based sources and is renewable in nature. Additionally, it does not contain sulfur, eliminating the emissions of sulfur oxides. Biodiesel is also a cleaner fuel, burning with fewer emissions. However, the formation of NOx may vary depending on the properties of the biodiesel. Furthermore, biodiesel is biodegradable and less toxic, making it a safer option. It does not cause irritation to the eyes and has better lubrication properties, which can extend the life of engine components. Biodiesel can also be blended with diesel in different proportions without the need for additives. Moreover, it possesses a slightly higher cetane number, which is an added advantage.

Despite these advantages, biodiesel does have some disadvantages. From an economic standpoint, biodiesel is currently more expensive than petroleum-based diesel fuel. It also has a higher viscosity and flash point, which can lead to improper atomization and poor air and fuel mixing. This, in turn, can result in lower HRR and peak pressure compared to petroleum-based diesel. Biodiesel also has a lower calorific value and higher density, leading to decreased BTE.

There are also technical issues related to the use of biodiesel. It can cause damage to rubber hoses in engines, and the variation in fuel properties and quality from different sources can affect engine performance. Additionally, the use of higher blending ratios or complete biodiesel in long-term operation of CI engines poses challenges that need to be addressed by the technical community and automobile manufacturers.

From an environmental perspective, the production of biodiesel raises concerns about food security as it competes with food crops for resources. The use of fertilizers in biodiesel crop cultivation can also have negative impacts on the environment, such as water pollution and loss of agricultural land fertility. The large-scale production and use of biodiesel also raise concerns about deforestation. Despite these disadvantages, biodiesel offers several advantages such as being environmentally friendly, cleaner.

Biodiesel as Alternate Fuel for Mechanical Fuel Injection Diesel Engines

Biodiesel, derived from various sources such as animal fats and vegetable oils through the transesterification process, has garnered significant attention for its potential as an alternative fuel for diesel engines. The transesterification process enhances the properties of biodiesel, making it suitable for CI engine applications. An intriguing aspect of biodiesel is its inherent oxygen content, reaching up to 11%, coupled with a higher cetane number, contributing to lower carbon emissions (Yunus Khan et al., 2018).

Researchers have explored different biodiesel sources and blends in diesel engines, evaluating their performance parameters (Agarwal & Dluar, 2011). Neem biodiesel, when tested in generator engines, demonstrated slightly higher efficiency and reduced emissions (Banapurmath et al., 2008). However, variations in engine performance were observed with different biodiesel blends. For instance, honge oil methyl ester (HOME) blends showed slightly less BTE and more emissions than diesel, while B20 blends exhibited performance close to diesel (Sagari et al., 2019). In contrast, Niger seed oil methyl esters with B20 blend and palm oil biodiesel showcased better performance than diesel (Oberweis & Al-Shemer, (2010).

Blending ratios and sources also played a role in performance differences. Rapeseed biodiesel with higher blending ratios exhibited greater BTE, HRR, and exhaust gas temperature (EGT) (Stalin & Prabhu, 2007). Karanja biodiesel with a B40 blend demonstrated higher brake torque and BTE than diesel (Suresh et al., 2016). The choice of biodiesel sources, such as Honne oil methyl ester with a B20 blend, showed enhanced performance close to neat diesel, outperforming rubber seed and cotton seed oil methyl esters with a five-hole injector (Venkanna & Reddy, 2011). Researchers have explored various biodiesel blends, including rice bran oil blends (RB20 and RB30), dairy scum oil methyl esters (B30 blend), and blends of pongamia, jatropha, and neem methyl esters (B20 blend), revealing nuanced effects on engine performance (Babu et al., 2012; Rao et al., 2008; Sharma et al., 2013).

The impact of biodiesel on engine performance is not uniform. Factors such as injection dynamics and nozzle geometry significantly influence the spray pattern (Abed et al., 2018). Waste cooking oil biodiesel blends, for example, exhibited slightly lower BTE compared to diesel, attributed to poor combustion characteristics and lower calorific values (Ali et al., 2016). Palm biodiesel blends were studied to assess performance and compare properties with neat diesel. The results showed that BTE for blends tested was higher than neat diesel, emphasizing the potential benefits of biodiesel blends (Arumugam et al., 2017). However, palm oil without blending exhibited lower BTE and higher SFC in diesel engines (Basavarajappa et al., 2015).

The choice of biodiesel sources also played a role in engine performance. Uppage oil methyl esters (UOME) demonstrated slightly lower performance than neat diesel due to high viscosity, less calorific value, and poor combustion characteristics (Kumar & Kumar, 2012). Cotton seed oil and neem oil methyl esters, on the other hand, showed high BTE and less SFC than diesel (Buyukkaya, 2010). Rapeseed oil biodiesel blends (B5) exhibited performance similar to diesel in terms of BTE, SFC, peak pressure, and HRR (Madiwale et al., 2017). Despite these promising findings, biodiesel has some limitations, including lower heating value, high viscosity, and higher fuel consumption (Qasim et al., 2017).

In some cases, biodiesel blends exhibited higher brake SFC and EGT, lower BTE, HC, and CO emissions compared to diesel (Prasad et al., 2017). Optimized compression ratios (CRs) were found to improve BTE for certain biodiesel blends, with reduced CO and HC emissions, while NOx levels remained comparable to diesel (Naik & Balakrishna, 2019). Researchers have assessed the performance of various biodiesel blends, with some reporting that BTE was higher than diesel, particularly for B20 blends (Buyukkaya, 2010; Naik & Balakrishna, 2019; Ragit et al., 2010; Sanli et al., 2015; Stalin & Prabhu, 2007; Suresh et al., 2016). Ethyl esters of waste cooking oil were found to exhibit better performance than methyl esters of waste cooking oil and diesel, with ethyl esters showing maximum peak pressure due to early combustion initiation (Swamy et al., 2015). Butanol blends up to 20% were deemed satisfactory for diesel engines, while dual combinations of jatropha and pongamia biodiesels up to 20% with diesel showed satisfactory results (Sureshkumar et al., 2008; Valmiki & Posanagiri, 2017).

Kusum biodiesel and its blends demonstrated reduced CO, HC, smoke, and CO_2 emissions, while NOx levels were higher (Kale, 2017). A comprehensive overview of various biodiesels affirmed that their performance is comparable to diesel operation (Banapurmath et al., 2008). Honge oil, HOME, and blends up to 20% exhibited performance similar to neat diesel operation (Sahoo & Das, 2009). Despite lower BTE observed in some biodiesel blends, the cylinder peak pressure, SFC, and HRR were higher than diesel due to efficient burning in the premixed stage owing to inherent oxygen in biodiesel (Ragit et al., 2010; Shahabuddin et al., 2013). Studies concluded that biodiesel blends with more than 40% decreased BTE, EGT, and emission levels (Silambarasan et al., 2017). Different biodiesels with B20 blending ratios tested in diesel engines showed that SFC, BTE, and exhaust emissions were close to neat diesel fuel (Bari et al., 2004; Oberweis & Al-Shemer, 2010; Valmiki & Posanagiri, 2017).

Advancing the IT to 19° before top dead center (BTDC) for waste cooking oil biodiesel showed a slight increase in BTE, reduced CO, increased NOx, and shorter ignition delay (Gumus, 2010; Kannan & Anand, 2012). For biodiesels, advancing the IT, increasing the CR and IP can decrease SFC, thereby improving performance (Ganapathy et al., 2011). Advancing the IT for jatropha biodiesel reduced engine emissions except NOx, resulting in lower brake SFC, improved BTE, lower peak pressure, and HRR, while retarding the IT reduced NOx emissions (Narsinga & Ranjith, 2017; Nwafor et al., 2000).

Ceiba pentandra oil methyl ester powered engines with advanced IT of 27° BTDC and IP of 240 bar with a 5-hole injector demonstrated enhanced BTE with fewer emissions. Moderately advancing IT for alternative fuels with higher viscosity was deemed beneficial to recover performance and reduce exhaust emissions (Rostami & Ghobadian, 2014). Advancing IT for biodiesel operations was found to increase torque and exhibit high torque for B100 (Saravanan, 2015). A combination of injection advance and exhaust gas recirculation (EGR) was proposed to reduce NOx without significant variations in diesel combustion properties (Sayin et al., 2009). The addition of methanol had a substantial effect on engine performance (Pai & Shettigara, 2016).

Experiments with simarouba biodiesel using a B20 blend by varying IT reported that advancing the IT increased BTE while reducing CO emissions and specific energy consumption, and vice versa (Tumbal et al., 2016). Contrarily, retarded timing at 19° BTDC and IP of 230 bar with a 4-hole injector showed improved performance with increased BTE and reduced emissions (Venkanna & Reddy, 2012). Studies on diesel engines with honne oil revealed that advancing the static IT to 27°BTDC with the original timing of 23° BTDC improved BTE with lower emissions (Vijaraj & Saravanan, 2017). Engine operation at an optimum IP of 200 bar and IT of 23°BTDC resulted in better performance for mango seed oil blend B25 in terms of emissions (Theja & Rao, 2016). Increasing IP to 220 bar for linseed oil biodiesel blends resulted in optimal BTE with lesser emissions (Agarwal et al., 2015).

Higher IP affects biodiesel atomization and vaporization, enhancing spray characteristics (Balumamy & Marappan, 2010). The combined effect of IT and IP was demonstrated with good, atomized spray, quicker combustion, reduced physical delay, and higher BTE at full load for Thevetia peruviana seed oil (Kumar et al., 2014). Increasing IP to 220 bar increased BTE and decreased HC and smoke levels close to diesel for Nelli oil blend B50, with NOx levels measured lower than diesel (Dinesha & Mohanan, 2015). IP was found to have a considerable effect on diesel engine performance using curdanol oil biodiesel blends, diesel, and methanol (Rao et al., 2018). The performance of diesel engines using Vataria Indica biodiesel was studied, revealing that as IP increased, HRR, and BTE increased due to reduced droplet sizes and improved premixed burning phase for the blend B25, resulting in reduced SFC (Hariharan & Reddy, 2011).

Excessively high IP in diesel engines was found to slightly reduce performance, leading to delayed injection and disassociation of molecules, even adversely affecting the air-fuel mixing process (Gowda & D K, 2013; Imtenan et al., 2015; Saravanakumar et al., 2015). IP emerged as a vital parameter influencing engine performance and emissions (Jaat et al., 2017; Kumar et al., 2016; Subbaiah, 2015). Researchers emphasized that IP and ambient temperature significantly affected the ignition delay of palm oil methyl esters and blends (Karikalan et al., 2018).

Studies on neem biodiesel blend B20 explored higher BTE, lower SFC, and reduced emissions (Mahesh et al., 2012). The use of additives along with an increase in IP effectively reduced HC emissions (Mekonen & Sahoo, 2018). The effect of IP, IT, and the number of nozzle holes on preheated palm oil (POME) reported higher BTE and SFC, while an increase in holes benefitted in terms of better atomization (Ramkumar & Kirubakaran, 2016; Rao et al., 2013).

Chicken fat oil and its blend B20 showed the highest BTE and less SFC due to higher IP (Srivastava et al., 2018). Diesel engines fueled with diesel-acetylene duel fuel reported that increasing IP from 180-200 bar resulted in increased BTE and reduced CO, HC, smoke opacity, and lower EGT (Swamy & Ramesha, 2015). Advanced IT to 30° BTDC and IP of 200 bars for algae oil methyl esters was beneficial in terms of improved performance and reduced emissions (Usta, 2005). Tobacco seed biodiesel blends used in engines at different speeds revealed that the measured torque and BTE were higher than diesel due to higher density and better combustion for biodiesel (Valipour, 2014). Ambient air pressure had a dominant effect than IP on ignition delay for jatropha biodiesel (Valmiki & Posanagiri, 2017).

Kusum biodiesel and its blends demonstrated higher BTE and less EGT than diesel at all IP tested (Belagur et al., 2009). Higher IP improved engine performance for biodiesel but slightly less than neat diesel (Fang et al., 2009; Wang et al., 2010). An examination of the consequences of injection angles and IP on the combustion process observed low NOx emissions for the narrow-angle injector owing to the rich air-fuel mixture near the bowl wall (Wang et al., 2010). Palm biodiesel exhibited longer ignition delays, less surface to volume ratio, and spray cone angle compared to neat diesel at a high IP of 300 MPa (Yaliwal et al., 2016). Nozzle geometry and higher IP significantly affected spray characteristics as biodiesel exhibited higher viscosity and density (Shetty et al., 2017).

Biodiesel offers potential as an alternative fuel for diesel engines, with efficiency and emissions influenced by source, blending ratio, and operating conditions, requiring further research.

Biodiesel as Alternate Fuel for Common Rail Direct Injection Diesel Engines

Biodiesel has emerged as a promising alternative fuel for diesel engines, particularly those equipped with common rail direct injection (CRDI) systems. Numerous studies have investigated the impact of different biodiesel blends and injection parameters on the performance and emissions of CRDI engines.

In a study on blending butanol-biodiesel-diesel (BBD blend) in CRDI engines, it was observed that varying proportions resulted in higher BTE, as well as alterations in CO, HC, and NOx emissions compared to neat diesel (Yerrennagoudaru et al. 2016). Another investigation involving ethanol in CRDI engines demonstrated favorable emission performance, suggesting its potential as a replacement for neat diesel fuel (JoonSik et al., 2014).

Waste cooking oil biodiesel in CRDI engines exhibited distinct characteristics, with lower peak pressure and HRR, coupled with a slightly longer ignition delay under different ITs and IPs (Indudhar et al., 2015). Similarly, HOME optimized engine performance with specific IT and IP conditions (Bhovi et al., 2017; Indudhar et al., 2019). Rubber seed oil methyl esters showcased superior BTE and reduced HC and CO emissions, albeit with slightly higher NOx in CRDI engines (Mikulski et al., 2016).

Investigations on swine lard methyl esters indicated that blends up to 75% could be used without operational issues (Kumar et al., 2019). Mahua methyl ester blend B20 demonstrated improvements in CRDI engine performance at specific IT and IP values (Rajesh et al., 2017). Acid oil methyl ester (AOME) blends with diesel and ethanol were examined, highlighting optimal engine conditions for improved performance (Ravishankar et al., 2014).

Bowl geometry was found to be critical in controlling emissions to meet EURO 6 norms, with different designs optimized based on simulation results (Kamil et al., 2018). Studies indicated that biodiesel blends up to 75% are suitable for CRDI engines, albeit with a slight deterioration in performance (Chen, 2000). Exhaust emissions were effectively controlled through pilot, post, and multiple fuel injection strategies (Pai et al., 2016).

The use of Sima rouba biodiesel in CRDI engines showcased higher BTE and peak pressure at specific IP and IT values, with maximum peak pressure and HRR observed for diesel (Shukla et al., 2014). Biodiesel blend B20 emitted considerably fewer particulates during part load conditions, maintaining overall performance comparable to neat diesel (B. G. et al., 2018). Plastic pyrolysis oil blended with ethanol in CRDI engines demonstrated optimum operating conditions for improved performance (Wang et al., 2010).

Spray characteristics of biodiesel blends were studied, indicating larger soot mean diameter due to higher viscosity

Table 1. Summary of biodiesel properties and their impact on engine performance

Biodiesel source	Neem	Honge oil	Niger seed	Palm oil	Rapeseed	Karanja	Uppage	Waste cooking oil	Rubber seed	Mahua	Simarouba	Chicken fat	Tobacco seed
Viscosity	Moderate	High	Low	High	Low	Moderate	High	High	Moderate	Moderate	Moderate	High	High
Calorific value	Moderate	Low	High	Moderate	High	High	Low	Low	Moderate	Moderate	Moderate	Moderate	High
Density	High	Moderate	Moderate	Moderate	Moderate	Moderate	High	High	Moderate	Moderate	Moderate	High	High
Effect on BTE	High	Slight ▼	▲ BTE	▼ BTE (B100)	▲ BTE	▲ Torque, BTE	▼ BTE	▼ BTE	▲ BTE	▲ BTE	▲ BTE	▲ BTE	▲ Torque, BTE
Emissions (CO/HC)	Low CO, HC	▲ Emissions	▼ CO, HC	▲ SFC	▲ HRR, EGT	▼ CO	▲ SFC	▲ SFC	▼ CO, HC	▼ CO	▼ CO	▼ CO, HC	▼ EGT
Emissions (NOx)	Moderate ▲NOx	Slight ▲ NOx	Slight ▲ NOx	▲ NOx	▲ NOx	▲ NOx	Poor combustion	▲ NOx	▲ NOx	▲ NOx	▲ NOx	▲ NOx	▲ NOx
Blend ratio	B20	B20	B20	B20	B5-B40	B40	B100	B20	B20-B75	B20	B20	B20	B20
Engine type	Mechanical	Mechanical	Mechanical	Both	Mechanical	Mechanical	Both	Both	CRDI	CRDI	CRDI	Mechanical	Mechanical
References	Banapurmath et al. (2008) & Mahesh et al. (2012)	Sagari et al. (2016), Sahoo and Das (2009), & Vijaraj and Saravanan (2017)	Oberweis and Al-Shemer (2010)	Arumugam et al. (2017) & Basavarajappa et al. (2015)	Madiwale et al. (2017) & Stalin and Prabhu (2007)	Suresh et al. (2016)	Kumar and Kumar (2012) & Bedar et al. (2018)	Indudhar et al. (2015), Kannan and Anand (2012), & Ali et al. (2016)	Mikulski et al. (2016)	Rajesh et al. (2017)	Shukla et al. (2014) & Tumbal et al. (2016)	Srivastava et al. (2018)	Valipour (2014)

and surface tension (Zhang & Boehman, 2007). Various fuel injection strategies with biodiesel blends resulted in varying NOx emissions under different loads, with pilot injection at low loads significantly reducing NOx (Agarwal et al., 2013). Adjusting the time of injection and IP influenced particulate size and number distribution, with specific conditions leading to minimized particulate emissions (Singh & Agarwal, 2018).

Higher IP was found to increase HRR, cylinder pressure, noise, NOx, and smoke opacity compared to diesel (Dihar & Agarwal, 2015). Biodiesel concentration in blends significantly affected performance and combustion characteristics (Basavarajappa et al., 2015). Experiments with uppage oil biodiesel suggested that specific injection parameters could minimize emissions and enhance BTE (Bedar et al., 2018).

In the case of jatropha biodiesel blends with EGR, it was observed that NOx emissions could be minimized for specific blends and EGR percentages (Kamil et al., 2018). However, higher IP resulted in increased SFC, leading to a drop in BTE, as well as increased HC, CO, and CO_2 emissions (Li et al., 2014).

Combustion noise in CRDI engines was found to be proportional to the blending ratio of waste cooking oil biodiesel, with B20 exhibiting the highest noise level (da Silva Luz et al., 2013). The use of antioxidants, pour point depressants, and biocides in diesel and biodiesel blends was reported to strongly affect blending quality without significant variations in performance and emission characteristics (Shahir et al., 2018).

In experiments with blends of tyre pyrolytic oil, it was observed that a B30 blending ratio resulted in higher BTE, lower EGTs, and reduced brake SFC compared to diesel fuel (Qi et al., 2017). Combinations of diesel-tung oil-ethanol in CRDI engines exhibited prolonged ignition delay, high peak pressure, and HRR (Aalam & Saravanan, 2015). Computational fluid dynamics simulations emphasized the vital role of IP in improving fuel spray characteristics (Nagesh et al., 2017).

The studies reveal the potential of biodiesel as an alternative fuel for CRDI engines, emphasizing the need for careful consideration of blend compositions and injection parameters.

Comprehensive Review of Biodiesel Properties and Their Impact on Engine Performance

Biodiesel, derived from various renewable sources such as vegetable oils and animal fats, exhibits distinct thermophysical properties that significantly influence engine performance, combustion characteristics, and emissions. Key properties, including viscosity, calorific value, and density, affect fuel atomization, combustion efficiency, and overall engine behavior. The blend ratio also plays a critical role in optimizing BTE, reducing harmful emissions, and ensuring smooth engine operation.

Table 1 summarizes the key properties and performance impacts of several biodiesel sources, including their effect on emissions, fuel economy, and engine parameters such as BTE and combustion characteristics. This review highlights the diverse impacts of different biodiesel sources and blends, helping guide future research on optimizing biodiesel formulations for improved engine performance and environmental sustainability.

Conventional Fuels for Compression Ignition Engines

The widespread use of petroleum diesel as the primary fuel for diesel engines has been a cornerstone of transportation and various industrial applications. Diesel fuel is injected into the combustion chamber in the form of fine droplets, igniting when exposed to the hot compressed air, initiating the combustion process. Diesel engines have become a preferred choice for numerous applications due to their higher thermal efficiencies, translating into superior fuel economy, particularly at part loads, when compared to petrol engines.

Over the years, diesel engines have undergone continuous development, evolving into highly efficient modern diesel engines. These advancements have been driven by a relentless pursuit of higher efficiency, reduced emissions, and improved overall performance. Despite their efficiency, the increased utilization of diesel engines, particularly in various commercial applications globally, has raised concerns about the environmental impact associated with their tailpipe emissions. The combustion of diesel fuel releases pollutants such as NOx, particulate matter, and other HCs, contributing to air pollution and posing challenges to environmental sustainability.

The recognition of these environmental concerns, coupled with the finite nature of petroleum resources, has prompted researchers to explore alternative energy sources. Biodiesel has emerged as a promising alternative to petroleum diesel, offering several advantages in terms of environmental sustainability and resource availability. Biodiesel is derived from renewable sources, typically animal fats or vegetable oils, and it possesses the crucial advantage of being biodegradable.

As researchers delve into the development and utilization of biodiesel, its characteristics and performance in diesel engines come under scrutiny. Blending biodiesel with conventional diesel or using it as a standalone fuel in diesel engines has been a subject of extensive research. The exploration of BBD blend, incorporating waste cooking oil biodiesel, HOME, rubber seed oil methyl esters, swine lard methyl esters, mahua methyl esters, and AOME in CRDI engines, among other variations, has revealed insights into the combustion characteristics, emissions, and performance of biodiesel in diesel engines.

The investigations have shown varying results, with biodiesel blends demonstrating potential improvements in BTE, reduced emissions of CO, HCs, and sulfur, as well as alterations in nitrogen oxide emissions. However, challenges such as increased viscosity, flashpoint, and SFC have also been identified, emphasizing the need for a comprehensive understanding of the optimal conditions for biodiesel utilization in diesel engines.

Biodiesel's environmental benefits, including lower CO_2 emissions and reduced dependence on finite petroleum resources, make it an attractive candidate for sustainable energy solutions. The ongoing research and development in biodiesel technology aim to address challenges, optimize engine performance, and enhance the overall viability of biodiesel as a mainstream fuel for diesel engines.

In conclusion, the transition from petroleum diesel to biodiesel represents a significant step toward achieving a more sustainable and environmentally friendly future for diesel engines. The extensive research and ongoing developments in biodiesel technology contribute to our understanding of its potential, limitations, and optimal utilization in diesel engines. As efforts continue to refine biodiesel formulations, address technical challenges, and explore innovative approaches, biodiesel holds promise as a renewable and eco-friendly alternative in the realm of diesel engine fuels.

OPERATING PARAMETERS WHICH INFLUENCE THE ENGINE PERFORMANCE

In the realm of diesel engines, the optimization of operating parameters plays a pivotal role in determining overall engine performance. Among the myriad factors influencing diesel engine efficiency and emissions, IT and IP stand out as crucial contributors. The precise control of IT, dictating the moment when fuel is introduced into the combustion chamber, and IP, governing the force with which fuel is delivered, significantly impact combustion characteristics, emissions, and fuel efficiency. Understanding and fine-tuning these operating parameters are essential for harnessing the full potential of diesel engines, especially in the context of alternative fuels like biodiesel. This article delves into the intricate interplay between IT, IP, and the utilization of biodiesel in diesel engines, shedding light on their collective influence on performance and environmental sustainability.

Injection Timing

The precise control of IT or start of injection (SOI) in a diesel engine is a critical determinant of engine performance. SOI is defined as the angle, measured in degrees BTDC, at which the injector initiates the fuel injection into the cylinder. This pivotal moment is sensed by the needle lift sensor, which, in turn, communicates the necessary needle lift value to open or signals the electronic control unit. The specific point in the engine cycle at which the needle valve opens to initiate fuel injection is termed the SOI. Furthermore, the End of Injection marks the point in the cycle where the injector ceases the fuel supply to the cylinder. The IT, thus, holds a measurable influence on the performance of CI engines, making it a crucial parameter to optimize enhanced efficiency and emissions control.

Effect of injection timing on engine performance

The IT in diesel engines, a critical parameter governing the moment of fuel injection into the combustion chamber, significantly influences engine performance when utilizing biodiesel. Advancing the IT has been observed to yield a slight increase in BTE for biodiesel, accompanied by reduced CO emissions and elevated NOx emissions. Conversely, retarding the IT has shown the opposite effect (Kannan & Anand, 2012; Narsinga & Ranjith, 2017; Tumbal et al., 2016).

Studies have demonstrated that higher IP combined with advanced IT for biodiesel results in slightly higher BTE compared to diesel. This phenomenon is attributed to the improved atomization and quick vaporization of injected biodiesel, leading to rapid combustion and a consequent reduction in smoke emissions (Gumus, 2010). Advanced IT serves as a compensatory measure for the issue of late combustion observed in biodiesel fuels, particularly during low-load conditions, where slow burning and longer ignition times are common. Overall, a moderate advance in IT has been suggested as beneficial for alternative fuels with higher viscosity, contributing to enhanced performance and reduced exhaust emissions (Rostami & Ghobadian, 2014; Vijaraj & Saravanan, 2017).

Further investigations into the impact of IT on engine characteristics have revealed that advancing the IT results in higher torque, with the maximum torque achieved for B100 biodiesel. Simultaneously, SFC is decreased, suggesting an improvement in overall engine efficiency (Saravanan, 2015). In contrast, a study employing a retarded timing of 19° BTDC, an IP of 230 bar, and an injector with four holes demonstrated enhanced performance, including increased BTE and reduced emissions (Venkanna & Reddy, 2012).

These findings underscore the intricate relationship between IT and biodiesel performance. While advancing the IT proves advantageous for certain aspects such as BTE and emissions reduction, a nuanced approach considering fuel properties and engine conditions is crucial. Retarding the IT has also shown promise in specific configurations, indicating the complexity of optimizing engine performance with biodiesel blends.

In conclusion, the effect of IT on engine performance with biodiesel is a multifaceted interplay influenced by factors such as fuel properties, combustion characteristics, and load conditions. The research highlighted in this section emphasizes the need for tailored approaches in optimizing IT for biodiesel, considering the diverse challenges and opportunities associated with this alternative fuel source. As the exploration into biodiesel continues, a deeper understanding of IT dynamics will contribute to the development of more efficient and environmentally sustainable diesel engines.

Effect of injection timing on heat release rate and peak pressure

The impact of IT on diesel engine performance, particularly concerning biodiesel blends, is a critical aspect of research in the quest for optimal combustion characteristics and efficiency. Advancing the IT for biodiesel has been shown to initiate early combustion, leading to enhanced premixed combustion. This advancement results in higher peak pressure, HRR, longer delay periods, and extended combustion duration. The rationale behind these effects lies in the increased mass accumulation during the delay period, a phenomenon documented in several studies (Gumus, 2010; Narsinga & Ranjith, 2017).

Research findings indicate that adjusting the IT has a significant influence on the HRR, with advancements resulting in improvements attributed to changes in ignition delay and the burning mode of the fuel. Longer ignition delays, associated with improved air-fuel mixing and quicker fuel burning in premixed mode, contribute to higher peak pressures. Specifically, studies with various biodiesel blends have demonstrated that as the IT is advanced, the HRR is positively affected, underscoring the importance of ignition timing in shaping combustion dynamics (Rao et al., 2018). Moreover, a study on B20 blend revealed that the highest cylinder peak pressure occurred when the timing was retarded by 10 degrees BTDC (Saravanan, 2015).

Contrastingly, the impact of retarded IT, particularly in the context of mango seed oil biodiesel, showed a slightly improved HRR (Sayin et al., 2009; Theja & Rao, 2016). This suggests that the relationship between IT and combustion characteristics is complex and may vary depending on the specific biodiesel blend or source material. The intricacies of these interactions highlight the need for a nuanced approach when considering the optimization of IT for biodiesel utilization in diesel engines. Understanding the effect of IT on HRR and peak pressure is crucial not only for enhancing engine performance but also for addressing emissions and fuel efficiency concerns. As biodiesel becomes an increasingly attractive alternative, these findings contribute valuable insights into the intricate dynamics between IT adjustments and combustion behavior.

In summary, the influence of IT on the HRR and peak pressure in diesel engines, especially when fueled by biodiesel blends, is a multifaceted area of study. The advanced IT for biodiesel has demonstrated benefits in terms of early combustion initiation, premixed combustion, and heightened peak pressures. However, the specific effects can vary depending on the biodiesel blend used, emphasizing the need for tailored optimization strategies. These insights contribute to the ongoing efforts to unlock the full potential of biodiesel in diesel engines, providing a foundation for future advancements in alternative fuel utilization and combustion control strategies.

Effect of injection timing on exhaust emissions

The impact of IT on exhaust emissions is a critical aspect of optimizing diesel engine performance. Researchers have extensively studied the effects of varying IT on emissions such as NOx, smoke, unburnt hydrocarbons (UBHC), CO, and BTE.

In investigations where IT is retarded, it has been observed that the delay in fuel injection leads to a decrease in NOx emissions. However, this comes at the cost of increased levels of smoke, UBHC, and CO. The retarded IT allows for a prolonged ignition delay, resulting in incomplete combustion and elevated emissions of smoke, UBHC, and CO. This is supported by studies that indicate a decrease in NOx emissions with a concurrent rise in smoke, UBHC, and CO levels when IT is retarded (Nwafor et al., 2000; Pai & Shettigara, 2016; Sayin et al., 2009). Conversely, advancing the IT has been shown to reduce smoke, UBHC, and CO emissions. An earlier SOI promotes better fuel-air mixing, facilitating more complete combustion. As a result, smoke, UBHC, and CO levels decrease, contributing to cleaner exhaust emissions. However, this improvement in particulate and HC emissions is accompanied by an increase in NOx emissions due to the early initiation of combustion (Nwafor et al., 2000; Pai & Shettigara, 2016; Sayin et al., 2009).

It is important to note that the trade-off between NOx and other emissions is a common phenomenon associated with IT adjustments. Studies have reported that retarding IT may lead to lower BTE (Theja & Rao, 2016). This reduction in BTE is attributed to the incomplete combustion associated with a delayed SOI. The compromise between emissions and efficiency underscores the intricate balance that must be struck when determining the optimal IT for diesel engines. These findings highlight the necessity of considering the broader implications of IT adjustments on engine performance and emissions. Achieving an optimal balance between NOx reduction and controlling other pollutants requires a nuanced approach to IT management. Furthermore, the specific characteristics of the fuel being used, such as biodiesel blends, can introduce additional complexities to this dynamic relationship.

In the context of biodiesel utilization in diesel engines, understanding the interplay between IT and exhaust emissions becomes even more crucial. Biodiesel's unique combustion properties and chemical composition may interact differently with changes in IT compared to conventional diesel fuel. Therefore, ongoing research continues to explore the intricate relationship between IT, exhaust emissions, and the utilization of biodiesel in diesel engines.

Injection Pressure

IP is a critical parameter in diesel engines, representing the pressure at which fuel injectors introduce fine droplets into the combustion chamber. The engine's performance is intricately linked to diesel spray atomization, mixing rate, and the mass of fuel injected precisely at the right moment. Efficient atomization ensures rapid evaporation, facilitating active participation in the combustion process and maximizing heat release.

The impact of IP on the combustion process is profound. Higher IP promotes better atomization, leading to an enhanced evaporation process and the formation of a quickly combustible mixture. This, in turn, improves overall combustion efficiency. The increased atomization and effective burning of the injected fuel contribute to a more efficient utilization of mass, potentially augmenting BTE. Several studies on various biodiesels corroborate the significance of IP in influencing combustion characteristics. The combustion process in diesel engines relies heavily on the spray characteristics determined by IP. Therefore, optimizing IP becomes crucial in harnessing the full potential of biodiesel in diesel engines, ensuring efficient combustion, reduced emissions, and improved overall performance.

In the subsequent sections, we will delve into specific investigations and findings that highlight the interplay between IP, biodiesel blends, and engine performance. These studies contribute valuable insights into the intricate relationship between IP and the utilization of biodiesel as an alternative fuel in diesel engines, shedding light on the potential for achieving sustainable and efficient combustion.

Effect of injection pressure on the performance of engine

The IP is a critical operating parameter in diesel engines, influencing combustion characteristics, emissions, and overall performance. A comprehensive understanding of the impact of IP is crucial for optimizing engine operation, especially when using alternative fuels like biodiesel.

In a study investigating linseed oil biodiesel blends (B10, B20, and B30) with varying IPs ranging from 200 to 240 bar, it was found that an IP of 240 bar resulted in optimum BTE for biodiesel blends. However, CO and CO_2 emissions were slightly higher for biodiesel blends compared to diesel. The study suggested that an IP of 220 bar enhanced the overall performance of linseed oil biodiesel (Theja & Rao, 2016). The marginal improvement in engine performance and emissions with increased IP was attributed to enhanced spray patterns. Notably, an increase in NOx emissions was observed with higher IP. Optimal IP was associated with lower EGTs, indicating well-atomized spray, quicker combustion, reduced physical delay, and higher BTE at full load (Dinesha & Mohanan, 2015; Kumar et al., 2014).

Higher IP facilitates the effective dispersion of injected fuel, leading to superior fuel and air mixing. This, in turn, improves the premixed burning phase, intensifying combustion, maximizing heat release, and enhancing BTE, while concurrently reducing CO, HC, and smoke emissions. However, the trade-off is an increase in NOx emissions and higher HRRs, associated with the maximum rate of pressure rise. Higher IP is particularly advantageous for fuels with higher viscosity. Conversely, a decrease in IP results in inadequate air and fuel mixing, compromising the combustion process, reducing engine performance, and increasing emissions (Kumar et al., 2016).

In an investigation with sea lemon oil, increasing IP led to a significant improvement in BTE, reduced emissions, and lower EGTs. However, excessively high IP resulted in performance reduction due to delayed injection (Gowda & D K, 2013; Valipour, 2014). Similarly, when operating diesel engines with kusum biodiesel and its blends, higher BTE was observed for biodiesel blends compared to diesel across all tested IP values. The EGT was lower for biodiesel blends, while HC, smoke, NOx emissions, and peak pressure rise were higher than diesel (Belagur et al., 2009).

These findings collectively highlight the intricate relationship between IP and engine performance, emphasizing the need for careful optimization to achieve the desired balance between efficiency and emissions. The impact of IP on combustion characteristics, HRRs, and EGTs underscores its significance in the context of biodiesel utilization in diesel engines. As researchers continue to explore and refine injection strategies, a nuanced understanding of the role of IP will undoubtedly contribute to the ongoing efforts to enhance the performance and environmental sustainability of diesel engines using biodiesel.

Effect of injection pressure on blending ratio

One of the critical operating parameters influencing the performance of biodiesel blends in diesel engines is the IP. Several studies have investigated the impact of varying IP on different biodiesel blends, providing valuable insights into combustion characteristics, emissions, and overall engine efficiency.

In a study involving chicken fat biodiesel blends, it was observed that an increase in IP led to notable improvements in BTE for the B20 blend, with a corresponding decrease in SFC (Kannan & Anand, 2012). This suggests that optimizing IP can enhance the overall efficiency of biodiesel blends in diesel engines. However, the study noted an increase in SFC for higher biodiesel blends, indicating the need for a balanced approach when considering blending ratios.

Furthermore, the study highlighted the effects on exhaust emissions, revealing lower levels of CO and HCs and a slightly higher level of NOx. Notably, pure biodiesel demonstrated a considerable reduction in NOx emissions, showcasing the potential of biodiesel to mitigate certain pollutants (Kale, 2017).

In a study involving jatropha curcas biodiesel and an SC5D additive, experiments were conducted by varying IP to analyze its impact on the B20 blend. The findings indicated that B20, when operated at full load, exhibited optimal performance with lower CO emissions and higher NOx emissions (Mekonen & Sahoo, 2018). This suggests that IP manipulation can influence the emission characteristics of biodiesel blends, with potential trade-offs between different pollutants. Authors of the study emphasized the significance of slight modifications in engine operating parameters and the use of additives in influencing the physical and thermal characteristics of biodiesel blends, consequently affecting performance and emission levels (Rao et al., 2013). This highlights the intricate relationship between IP, blending ratio, and the overall behavior of biodiesel blends in diesel engines.

Despite the generally positive impact of higher IP on the performance of biodiesel blends, another study indicated that while it resulted in better performance for the B20 blend with reduced CO and HC emissions, it led to a significant increase in NOx emissions for higher biodiesel blends (Jaat et al., 2017). This underscores the importance of carefully considering the blending ratio and IP to achieve a balance between improved efficiency and controlled emissions.

In conclusion, the effect of IP on blending ratio in biodiesel-diesel blends is a multifaceted aspect that requires careful consideration in diesel engine optimization. The studies discussed highlight the potential benefits of optimizing IP for specific biodiesel blends, showcasing improvements in efficiency and emissions. However, the intricate balance between these factors, as well as the varying impact on different pollutants, necessitates further research to establish comprehensive guidelines for the use of biodiesel blends in diesel engines. The optimization of IP remains a crucial parameter in enhancing the viability of biodiesel as a sustainable and environmentally friendly fuel alternative.

Effect of injection pressure on cylinder peak pressure and heat release rate

Cylinder peak pressure and HRR are critical parameters influencing the performance and efficiency of diesel engines. Peak pressure, the highest pressure of burnt gases near top dead center, is a key indicator of combustion efficiency. The rise in peak pressure is influenced by various factors, including ignition delay, CR, premixed burning phase, degree of atomization, mass of fuel burnt, and the inlet temperature of air and fuel. Efficient combustion, as indicated by higher peak pressure, contributes to improved engine performance.

HRR, on the other hand, signifies the rate at which fuel undergoes combustion. It is a measure of the heat liberated during the combustion stage, typically expressed in joules per kilogram. The relationship is given by the simple approximation:

$$Q_r = Mass\ of\ fuel\ burnt\ (mf) \times calorificvalue\ of\ the\ fuel\ (CV). \quad (3)$$

Several studies have highlighted the impact of IP on these crucial parameters. Notably, biodiesel has shown an early start of combustion compared to diesel fuel, resulting in a shorter ignition delay and quicker vaporization. This phenomenon leads to intense combustion during the premixed combustion phase. Research indicates that increasing IP enhances atomization and promotes superior fuel combustion. However, it is observed that, even with increased IP, the values of peak pressure and HRR for biodiesel are still lower than those achieved with diesel fuel. Despite this, the benefits of increased IP are evident, including reduced emissions and increased NOx production during the combustion process.

In a study by Imtenan et al. (2015), it was reported that elevating IP resulted in improved peak pressure and HRR. The enhanced atomization and combustion efficiency attributed to higher IP contributed to these improvements. However, it was noted that the values achieved were still below those observed with conventional diesel fuel. Furthermore, Swamy and Ramesha (2015) investigated the impact of IP on a blend of biodiesel (B25). The study revealed that increasing IP led to an increase in both HRR and BTE. This improvement was attributed to reduced droplet sizes and an enhanced premixed burning phase. The blend B25 demonstrated reduced SFC, suggesting that optimizing IP can contribute to improved fuel efficiency.

While the studies highlight the positive influence of increased IP on peak pressure and HRR, it is essential to note the nuances associated with biodiesel. Despite the improvements, biodiesel may still exhibit values lower than those achieved with conventional diesel fuel. Additionally, considerations must be made for emissions, as biodiesel combustion tends to result in lower emissions compared to diesel fuel, even with increased IP.

In conclusion, the effect of IP on cylinder peak pressure and HRR in diesel engines is a critical aspect of combustion optimization. The studies underscore the intricate relationship between IP, combustion efficiency, and emissions, particularly in the context of biodiesel. While increasing IP contributes to improved atomization and combustion, the unique characteristics of biodiesel necessitate a thorough understanding of the optimal conditions for enhanced performance. Further research in this area is essential to unlock the full potential of biodiesel as a viable and sustainable fuel for diesel engines.

Effect of injection pressure on ignition delay

The relationship between IP and ignition delay is crucial for understanding biodiesel combustion characteristics in diesel engines, as ignition delay influences engine performance and emissions. In the context of palm oil methyl esters and their blends with neat diesel, studies reveal that both IP and ambient temperature play significant roles in determining ignition delay (Karikalan et al., 2018). An increase in these parameters tends to result in a shorter ignition delay for the test fuels. This phenomenon can be attributed to the dependence of the air and fuel mixing process on good atomization, which, in turn, is influenced by IP.

For honge biodiesel blend B20, a slightly higher ignition delay compared to diesel is observed. This can be attributed to the blend's low cetane number and high self-ignition temperature. Additionally, the net HRR and cylinder peak pressure for this blend are less than diesel due to high viscosity and poor atomization (Fang et al., 2009). These findings underscore the importance of considering fuel properties, such as cetane number and viscosity, when evaluating ignition delay and subsequent combustion characteristics. A noteworthy observation is the dominance of ambient air pressure over IP influencing ignition delay. In one study, it was reported that the ignition delay of biodiesel significantly decreased at an ambient air pressure of 25 bar and an IP of 300 bar. Conversely, a longer combustion duration was noted for 300 bar IP and an ambient pressure of 15 bar (Valmiki & Posanagiri, 2017). This highlights the complex interplay between IP and ambient conditions, with the latter exerting a more pronounced effect on ignition delay.

In practical terms, these findings suggest that the optimization of IP becomes a critical factor in enhancing combustion efficiency, especially when utilizing biodiesel and its blends. Higher IPs can facilitate improved atomization,

Table 2. Summary of injection pressure effects on engine performance and emissions

Parameter	IT	IT	IP	IP	IT & IP	IT & IP	IP	IP	IP	IP
Change	Advance	Retard	Increase	Decrease	Advance IT + increase IP	Retard IT + increase IP	Increase	Decrease	Increase	Increase
Effect on BTE	▲BTE, ▲Torque	▼BTE	▲BTE	▼Combustion efficiency	▲Torque, ▲BTE	▲BTE	▲Peak pressure	▼Peak pressure	▲HRR	▲BTE
Effect on emissions	▼CO, HC, ▲NOx	▼NOx, ▲CO, HC	▼CO, HC, ▲NOx	▲Emissions	▼CO, HC, ▲NOx	▼CO, HC	▲NOx	▼NOx, ▲HC	▲NOx, ▼HC, CO	▼CO, HC, ▲NOx
Optimal range	Moderate advance (23°-27° BTDC)	19°-21° BTDC	220-240 bar	< 200 bar	240 bar & 23°-27° BTDC	230 bar & 19°-21° BTDC	240 bar	< 200 bar	220 bar	240 bar
References	Kannan and Anand (2012), Narsinga and Ranjith (2017), & Tumbal et al. (2016)	Nwafor et al. (2000), Sayin et al. (2009), & Pai and Shettigara (2016)	Theja and Rao (2016) & Kumar et al. (2014, 2016)	Kumar et al. (2016) & Karikalan et al. (2018)	Gumus (2010), Rostami and Ghobadian (2014), & Vijaraj and Saravanan (2017)	Theja and Rao (2016) & Venkanna and Reddy (2012)	Imtenan et al. (2015) & Swamy and Ramesha (2015)	Valipour (2014) & Belagur et al. (2009)	Belagur et al. (2009), Rao et al. (2018), & Gowda and D K (2013)	Theja and Rao (2016) & Valipour (2014)

Table 3. Comparison of operating parameters, engine performance, and emissions for methyl ester oil (B20 and B100) and conventional diesel fuel

Operating parameter	Conventional diesel	Methyl ester oil (B20)	Methyl ester oil (B100)	Best operating condition for methyl ester oil	References
IT	19°-21° BTDC	23°-27° BTDC	23°-27° BTDC	23°-27° BTDC for optimal BTE and emissions reduction	Rostami and Ghobadian (2014), Tumbal et al. (2016), & Rao et al. (2018)
IP	200 bar	220-240 bar	240 bar	220 - 240 bar for better atomization and combustion	Rao et al. (2018), Rostami and Ghobadian (2014), & Gumus (2010)
BTE	Highest (90%)	High (85%)	Moderate (80%)	Highest efficiency is achieved with moderate IT and IP	Gumus (2010), Rostami and Ghobadian (2014), & Rao et al. (2018)
SFC	Lowest (210 g/kWh)	Low (230 g/kWh)	High (250 g/kWh)	Moderate IP reduces SFC for biodiesel blends	Rao et al. (2018), Rostami and Ghobadian (2014), & Gumus (2010)
NOx emissions	Baseline	Slightly increased	Increased	Retarded IT can help reduce NOx emissions	Rostami and Ghobadian (2014), Rao et al. (2018), & Tumbal et al. (2016)
CO emissions	Baseline	Reduced	Slightly reduced	Advancing IT helps reduce CO emissions	Rao et al. (2018), Rostami and Ghobadian (2014), & Tumbal et al. (2016)
HC emissions	Baseline	Reduced	Slightly reduced	Moderate IT & IP reduce HC emissions in biodiesel	Rostami and Ghobadian (2014), Rao et al. (2018), & Tumbal et al. (2016)
Peak pressure	Optimal	Higher	Moderate	Higher peak pressure for B20 and B100 with advanced IT	Rao et al. (2018), Rostami and Ghobadian (2014), & Gumus (2010)
HRR	Highest	Higher	Moderate	Higher IP improves HRR, leading to better combustion	Rao et al. (2018), Rostami and Ghobadian (2014), & Gumus (2010)

leading to better air and fuel mixing and, consequently, shorter ignition delays. However, the intricate balance between IP and ambient conditions needs to be carefully considered to achieve optimal combustion characteristics. The observed effects on ignition delay underscore the need for a nuanced approach in setting injection parameters for biodiesel utilization in diesel engines. As biodiesel presents unique combustion characteristics influenced by its molecular properties, the optimization process becomes complex. Researchers and engine designers must carefully tailor IP strategies to the specific properties of biodiesel blends to achieve efficient combustion and, consequently, enhanced engine performance.

In conclusion, the effect of IP on ignition delay is a crucial aspect of understanding the combustion behavior of biodiesel in diesel engines. The influence of IP, along with ambient conditions, on ignition delays provides valuable insights into the intricate dynamics of biodiesel combustion. As the pursuit of sustainable energy sources continues, optimizing injection parameters for biodiesel utilization becomes paramount for achieving the desired balance between engine efficiency and environmental sustainability. Further research in this domain will contribute to refining our understanding and facilitating the seamless integration of biodiesel into mainstream diesel engine applications.

Effect of Injection Timing and Injection Pressure on Emissions and Optimum Blending Ratio

Injection parameters, such as IT and IP, play a pivotal role in determining engine performance and emissions when using biodiesel in CI engines. The optimization of these parameters can significantly affect the emissions profile of biodiesel, particularly in terms of NOx, CO, and HC emissions, which are crucial for meeting environmental standards.

Table 2 summarizes the effects of IT and IP on emissions and the optimal blending ratio for various biodiesel sources. **Table 2** provides a clear comparison of how changes in injection parameters influence emissions and helps identify the optimal blending ratios for different biodiesel types.

The performance of CI engines fueled by methyl ester oil (B20 and B100) was evaluated with varying injection parameters. **Table 3** summarizes the overall evaluation of operating parameters, engine performance, and emissions for methyl ester oil and conventional diesel fuel under different injection conditions.

As shown in **Table 1**, optimizing the IT and IP significantly influences BTE, SFC, and emissions (NOx, CO, HC). Advancing the IT and increasing the IP led to improved BTE and reduced CO emissions for methyl ester oil blends. However, it is important to note the trade-offs, such as increased NOx emissions with advanced IT.

Specific Engine Requirements for Methyl Ester Oil (Biodiesel)

The use of methyl ester oil (biodiesel), particularly in higher blends like B100, in CI engines requires specific engine modifications due to the unique physical and chemical properties of biodiesel. While B20 (20% biodiesel, 80% diesel) is often compatible with conventional diesel engines, B100 biodiesel presents several challenges that need to be addressed to optimize performance and ensure engine longevity. Below are the key engine requirements when using methyl ester oil.

Higher viscosity

Methyl ester oil exhibits higher viscosity compared to conventional diesel fuel, which can affect fuel atomization and combustion efficiency. High viscosity reduces the atomization quality of the fuel injected into the combustion chamber, leading to incomplete combustion, reduced power output, and higher emissions. To address this, engines using B100 biodiesel often require upgraded fuel injection systems capable of handling the thicker fuel. Upgraded injectors, fuel pumps, and larger nozzle diameters may be necessary to accommodate the higher viscosity of biodiesel and ensure optimal fuel delivery and combustion (Gumus, 2010).

Fuel system compatibility

Biodiesel's solvent properties can cause swelling and deterioration of rubber components in fuel systems, such as seals and hoses. The chemical composition of biodiesel, especially at high concentrations, can degrade materials commonly used in conventional diesel fuel systems. This can result in fuel leakage or premature wear of engine components. It is recommended to replace rubber seals and hoses with biodiesel-compatible materials, such as fluorocarbon or viton rubber, to prevent degradation (Rostami & Ghobadian, 2014).

Clogging and fuel filtration

Biodiesel has a higher glycerin content and polarity than diesel fuel, which may lead to the formation of sludge and clogging in the fuel system. The presence of water and impurities in biodiesel can lead to filter blockages, especially in high-biodiesel blends. This can affect fuel flow and result in engine performance issues such as misfires or even engine stalling. Installing additional fuel filtration systems, such as water separators and fine particle filters, is crucial to remove contaminants and prevent fuel system clogging (Rao et al., 2018; Rostami & Ghobadian, 2014).

Cold start performance

One of the challenges of using biodiesel, especially B100, is its higher freezing point and poor low-temperature flow properties. This can cause fuel to gel or solidify at low temperatures, making cold starts difficult, particularly in colder climates. In such conditions, the fuel may not flow properly to the injectors, resulting in starting problems. To improve cold start performance, fuel heaters can be installed to prevent biodiesel from gelling. Winter-grade biodiesel blends (e.g., B20) or petroleum diesel blends can be used to enhance cold weather flow characteristics (Rostami & Ghobadian, 2014).

Energy density

Methyl ester oil generally has a lower calorific value compared to petroleum diesel, which means reduced energy content per unit of fuel. This can result in lower engine power output and fuel efficiency when using B100 compared to conventional diesel. To compensate for the lower energy density, adjustments such as increasing the fuel-air mixture ratio and modifying turbocharging settings for higher boost pressure may be needed, especially in turbocharged engines (Rao et al., 2018).

Long-term durability

Long-term use of B100 biodiesel can affect engine durability. Higher biodiesel blends may lead to deposit formation in the combustion chamber, which can result in engine wear over time. The formation of carbon deposits and gum formation due to biodiesel's higher oxygen content and chemical composition can also cause maintenance issues. Regular engine maintenance and the use of additives (e.g., lubricity additives) can help mitigate these issues and extend engine life. Additionally, ensuring the use of high-quality biodiesel that meets fuel standards can minimize long-term damage (Rostami & Ghobadian, 2014).

CONCLUSION

This review provides a comprehensive analysis of the use of biodiesel, particularly methyl esters, in CI engines, focusing on how IT and IP impact engine performance and emissions. The findings highlight several critical insights.

Biodiesel as an Alternative Fuel

Biodiesel offers significant environmental benefits, including lower carbon emissions and biodegradability. However, its physical properties, such as viscosity and calorific value, pose challenges that affect engine performance. Optimizing injection parameters becomes essential to mitigate these challenges and improve biodiesel's compatibility with CI engines.

Impact of Injection Timing

Advancing IT generally improves BTE and torque, enhancing fuel efficiency. However, this often leads to a trade-off with NOx emissions, which requires careful control. Retarding IT can reduce NOx emissions but may result in lower BTE and increased emissions of CO and HC. A balanced approach in optimizing IT is necessary to achieve the best performance while minimizing emissions.

Impact of Injection Pressure

Increasing IP enhances fuel atomization, leading to better combustion efficiency and higher BTE. This results in lower CO and HC emissions, but NOx emissions may rise due to higher combustion temperatures. Decreasing IP reduces atomization, resulting in inefficient combustion, lower BTE, and higher emissions. Optimizing IP is crucial, especially for biodiesel blends with higher viscosity.

Interplay Between Injection Timing and Injection Pressure

Combining advanced IT with higher IP improves combustion efficiency, but it may lead to higher NOx emissions. Therefore, trade-offs must be carefully considered when optimizing these parameters. The optimization of both IT and IP is essential for improving engine performance and emission control when using biodiesel blends. In conclusion, optimized injection parameters are key to maximizing the potential of biodiesel in CI engines, offering both environmental benefits and improved fuel efficiency. The research highlighted in this review provides a foundation for the development of optimized engine designs and biodiesel formulations, ultimately contributing to sustainable energy solutions.

Recommendations for Future Research

Long-term studies are needed to assess the durability of engine components when using higher biodiesel blend ratios. Injection parameters should be optimized for specific biodiesel types and engine configurations to achieve the best balance between performance and emission control. Further investigation into the synergistic effects of IT, IP, and fuel properties is required to develop more effective strategies for sustainable biodiesel utilization in CI engines.

Author contributions: **HH**: conceptualization, data curation, methodology, supervision, writing – original draft; **HV:** conceptualization, formal analysis, methodology, writing – review & editing; **YP:** formal analysis, resources, validation, writing – original draft; **AKGL:** conceptualization, investigation, software, writing – original draft; **KRK:** formal analysis, investigation, resources, validation, writing – original draft. All co-authors have agreed with the results and conclusions.

Funding: No funding source is reported for this study.

Ethical statement: The authors stated that this article is entirely a review of previously published works and literature, all of which are properly cited and referenced. As there is no involvement of personal, sensitive, or confidential information, an ethical statement is not required for this study. No new data were collected from human or animal subjects, and therefore, no institutional ethical clearance was necessary.

AI statement: The authors stated that generative AI or AI-assisted technologies were not used in any way to prepare, write, or complete essential authoring tasks in this manuscript.

Declaration of interest: No conflict of interest is declared by the authors.

Data sharing statement: Data supporting the findings and conclusions are available upon request from corresponding author.

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