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Biodiesel-Fueled Compression Ignition Engines: Reviewing The Impact Of Feedstock Diversity On Performance And Emissions

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Abstract

With the depletion of fossil fuel reserves, there is a tremendous importance in the search of alternative fuels for automotive engines. These fuels have a number of advantages including renewability, lower emissions, energy security and lower operating costs. Among them algae-based biodiesel has become a good alternative and sustainable resource because of its low sulfur content and about 10% oxygen, which facilitates combustion efficiency. Its higher cetane number also leads to better quality of ignition regardless of the blend ratio. This paper highlights a comparative evaluation of different biodiesel fuels based on the influence of fuels on compression ignition (CI) engine performance and emissions. Key performance parameters such as brake specific fuel consumption (BSFC) and brake thermal efficiency (BTE) are studied as well as emission parameters in terms of carbon monoxide (CO), carbon dioxide (CO2), hydrocarbons (HC), particulate matter (PM) and nitrogen oxides (NOx). Studies have shown that biodiesel and biodiesel blends typically increase BSFC, BTE, and brake power, and decrease CO, CO2, and HC emission. The increase in NOx emissions can be lifted slightly by means of suitable additives. Algae biodiesel has the same performance and properties as conventional diesel and therefore can be used in existing engines with no engine modifications. Future research should be conducted on the optimization of algal biodiesel with additives for better performances and its utilization for sustainable energy applications.

Keywords: *Biodiesel, Performance parameter, Emission parameter, Compression ignition engine, Additives*

1. INTRODUCTION

The conventional energy sources such as coal, fossil fuels, nuclear energy and natural gas are non-renewable and are currently extensively used because of their low cost and high efficiency, but they are major contributors to pollution. Oil, which is referred to as "liquid gold," is used to run aircraft, cars, trains, and ships. In contrast, the renewable energy sources such as solar, wind, bio-energy, and tidal energy are cleaner alternatives (Ang *et al.*, 2022). Compression Ignition (CI) engine transforms the chemical energy in the fuel to heat energy and then mechanical energy. As a result of high performance, fuel efficiency, and low emission for being considered, they are extensively used in power generation, industrial sectors, and agricultural machinery. Diesel engines have high brake thermal efficiency (BTE) and brake power (BP). However, nitrogen oxides (NOx), carbon oxides (CO) and unburned hydrocarbons (UHC) emitted during the diesel combustion are hazardous from environmental and health perspectives. NOx causes acid rain, CO impacts ozone layer, and UHC causes heart diseases (Kesharvani *et al.*, 2023).

In view of the increasing energy demand in the transport and power production sector, the depletion of non-renewable resources and toxic emissions, researchers have been interested in renewable alternatives. Renewable liquid fuels used either in their pure form or as an admixture with diesel fuel provide an economic, environmentally friendly and competitive solution. They are important in order to suppress emissions, to secure energy independence and to make up for the shortage of fuel (Muruganantham, Pandiyan and Sathyamurthy, 2021). Other alternative fuels like methanol and ethanol (alcohol fuels), natural gas (LNG, CNG) and biodiesel

Methanol, ethanol, propanol and butanol are the promising fuels for IC engine owing to their high octane rating, lower emissions and high energy efficiency. Nox emissions and brake thermal efficiency are improved by using methanol as a blend fuel Ethanol, which is a high-octane and low carbon renewable fuel, is an efficient alternative to gasoline in IC engines (Vaidya *et al.*, 2022).

Natural gas, a primary constituent of which is methane (CH4), is a clean and low carbon alternative fuel with a high hydrogen content. Therefore it is generated from renewable resources, such as biogas, which reduces CO and CO2 emissions. In the case of diesel engine, the NG is injected into the intake manifold, which leads to improved air-fuel mixing and reduced fuel consumption compared to pure diesel. With 98.5% methane, NG has high heating value, Octane value, and flame spread rate compared to the gasoline, making it suitable for transportation. Brake specific fuel consumption and NOx was lowered (Bayat and Ghazikhani, 2020).

Biodiesel is a green and renewable alternative to fossil-based fuels which is produced from plants or animals. It has low emissions, ensures energy security and can be used in diesel engines without adjustments. Biodiesel decreases unburnt hydrocarbons, CO and particulates and has a high cetane number, which improves ignition, and is made using processes such as transesterification (Dash *et al.*, 2020). With the absence of sulfur and 10% oxygen content, it burns well and contributes to the improvement of air quality. Despite its renewable and clean nature, biofuel has its limitations such as viscosity, poor cold weather performance, and high NOx emissions. The use of additives such as oxygenates, metal-containing, antioxidants and cetane improver are used to improve the stability, performance and emission control of biodiesel (Yadav, Kumar and Chaudhary, 2020).

Although there are many researchers who have worked on using various types of biodiesel fuels in diesel engines to compare the performance and emission characteristics, there has been a lack of interest in using algal, hybrid, or additive-assisted biodiesels. In order to reduce NOx emission for certain applications, further studies are necessary. In future studies, microalgal biodiesel could be produced, blended and characterised and the impacts of CI engine performance and emission profiles could be investigated with the addition of additives. For this, it is essential that a thorough review is carried out. The aim of this work is to review the effect of diesel fuel blends, alternative fuels and additives on the performance and emission of compression ignition engines.

2. MATERIALS AND METHODS

2.1. Biodiesel feedstock

Biodiesel is a renewable fuel that is produced through the transesterification of lipids such as plant oils, waste oils, animal fats and algae oil. Biodiesel blends (e.g. B5-B20) are intensively used in transportation based on edible and non-edible oils and other feedstocks. Feedstock types influence the quality of biodiesel and thus, they are important factors in blending with petroleum diesel. Biodiesel is a type of biofuel which is a form of energy derived from plant or animal biomass (Anwar, 2021). It is clean, renewable, and is produced from a variety of feedstocks and it is used as an alternative to diesel fuel. The sustainability, cost and environmental impact of production is dependent on the use of a suitable feedstock. Sustainable biodiesel seeks to reduce the negative impact on food production, biodiversity, and land use as well as increase energy efficiency and decrease greenhouse gases (Yaşar, 2020). Research is being done on more sustainable feed sources for biodiesel.

First generation biofuels are made from edible energy crops, sugarcane, corn, wheat, rapeseed and sunflower. Production of these biofuels relies on processes such as fermentation, distillation and transesterification, which have their roots in conventional applications such as brewing alcohol. The ethanol is produced by fermentation of sugar and starch, and biodiesel is produced through the reaction of crops containing oil, alcohol and catalyst (Mat Aron *et al.*, 2020). Biodiesel can be mixed with petroleum diesel to help reduce GHG emissions and dependence on fossil fuel. Whilst promising, first-generation biofuels production has caused concerns regarding food security, food supply and land use (Malode *et al.*, 2022).

Second-generation biofuels are derived from lignocellulosic crops, and plant lignin and cellulose is used to make ethanol. The raw materials used in second-generation biofuels are non-food biomass such as non-edible oil (Jatropha, Karanja, Neem), agricultural residues (straw, bagasse, rice husk), sawdust, animal fat, and other waste materials, which are available in plenty and have less impurity contents like sulfur, nitrogen or metal and are cheap renewable energy sources (Lin and Lu, 2021). Second-generation biofuels have the potential to provide a number of benefits, such as smaller impacts on food production,

increased sustainability, and minimized greenhouse gas emissions through the use of agricultural wastes and other by-products for the production of biofuels (Singh *et al.*, 2021a).
Third generation biofuels, also called algae fuel, are obtained from algae biomass, which can be grown to produce lipids (oils) that are transformed into biodiesel or other biofuels such as gasoline, butanol, propanol, and ethanol. These algae provide much higher yields (around 10 times higher than second generation biofuels) that address most of the major issues of land competition, resource efficiency and greenhouse gas emissions (Chia *et al.*, 2022). Algae is especially promising because of its high oil yield per acre of land, the possibility to be cultivated in places where no other cultivation would be feasible, and the possibility to use a variety of water, such as saline or waste water (Bhatia *et al.*, 2022). Fig. 1 illustrates the classification of biodiesel with respect to its evolution and production.

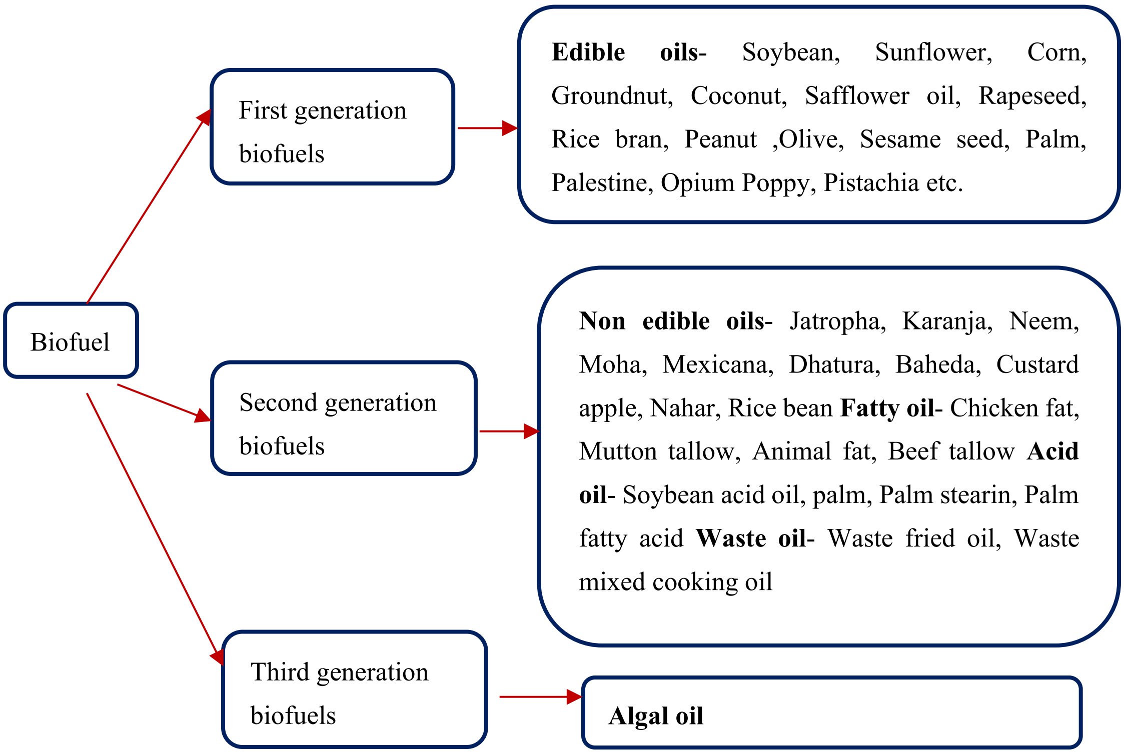

Fig. 1: Biofuel classification as per generation

The conversion of edible oils into biodiesel is not always viable because of a possible shortage of oil. As a result, attention has now shifted to non-edible oil sources like jatropha, karanja, used cooking oil, etc. Moreover, algae oil has recently come up as a promising feedstock for biodiesel production.

2.2. Biodiesel Production Methods

The main objectives of biodiesel production methods are to increase the product yield, optimize the product's fuel properties and minimize the cost of production. High viscosity vegetable oils with limited oxidative stability, specific methods need to be used to convert to biodiesel. There are four main methods: dilution, micro-emulsification, pyrolysis and transesterification (Maheshwari *et al.*, 2022). These methods have been devised in order to solve the difficulties of oil conversion and to produce sustainable biodiesel, and the focus is on the Feasibility of commercial-scale production from an economic point of view.

Dilution Method: It consists of mixing vegetable or animal oils with petroleum diesel (10-40%) to be used in diesel engines. While blending enhances the mobility and thermal energy content (around 80%) of the fuel, it is not possible to use it for oils that show high viscosity, low volatility or unsaturated carbon bonds. Issues such as coking, carbon deposition, and oil ring sticking, and gelling of lubricating oil come up when using 100% vegetable oil (Brahma *et al.*, 2022).

Micro emulsification: In order to mitigate the high viscosity of vegetable oils, short chain alcohols such as methanol, ethanol or butanol are employed for the formation of micro emulsification (Kumar, Sarma and Kumar, 2020). These emulsions have liquid microstructures ranging from 1 to 50 nm. While the presence of alcohols lowers heat value as compared to petroleum diesel, their high latent heat of vaporization helps in reducing nozzle coking by cooling down the combustion chamber (Murray, King and Wyse-Mason, 2021).

Pyrolysis: Pyrolysis is the process of heating vegetable oil, animal fats or triglycerides in an atmosphere devoid of oxygen at high temperatures of 300-1300C. Degradation of long chain compounds to smaller molecules results in biodiesel with acceptable fuel characteristics such as low viscosity, high cetane number and acceptable sulfur content. However, pyrolysis products have undesirable ash content, carbon residues and pour points (Hoang *et al.*, 2021).

Transesterification: Biodiesel is formed in this process by the catalytic reaction of triglycerides in the vegetable oils or fats with alcohol such as methanol or ethanol. The products of the reaction are biodiesel (alkyl esters) and glycerol. The transesterification process produces biodiesel of higher cetane numbers, less emissions and higher combustion efficiency (Kant Bhatia *et al.*, 2021). It is a convenient approach to large-scale production of biodiesel from different feedstocks such as oils from plants, animals and waste vegetable oil (Salaheldeen *et al.*, 2021).

2.3. Algae as biodiesel feedstock

Algae are the microscopic plants that are responsible for transforming carbon dioxide, water and sunlight into biomass, lipids and oxygen through photosynthesis. Algae float on the water surface due to gas from photosynthesis and they are kept in contact by proteins containing silica which keep the cells together (Kumar *et al.*, 2020). Algae are divided into two general groups, microalgae and macroalgae. Macroalgae are multicellular multicellular organisms larger in size and are found in aquatic environments such as ponds, while microalgae are unicellular, microscopic organisms suspended in water, as it is widely known that a common type of macroalgae is seaweed. Microalgae have much higher growth rates than terrestrial plants and have a higher lipid accumulation capacity. Some microalgal strains can contain fatty acids of up to 70% and are therefore very suitable for the production of biodiesel. Algal biomass includes triglycerides, carbohydrates and proteins; the triglycerides give rise to oils that are processed into biodiesel (Chhandama *et al.*, 2021). Crude oil (triglyceride) can be converted to a biodiesel which can be used as a fuel in power generation systems. Among various types of biodiesel feedstocks, microalgae offer unique benefits such as ease of cultivation and oil productivity is a lot higher (in the order of eight to ten times more oil than traditional land-grown crops). Algae is a breakthrough biomass feedstock as it combines rapid growth, high biofuel yield and sustainable carbon sequestration without competing for arable land or food production (Saeed *et al.*, 2021).

As photosynthetic autotrophs algae grow in a range of water bodies such as lakes, rivers and seas. They are important sources of atmospheric oxygen via photosynthesis, the process of using solar energy to combine water and carbon dioxide to form carbohydrates (Wang *et al.*, 2021). The oil yield of microalgae is competitive with other feedstocks used to produce biodiesel, and microalgae require much less land to produce than other feedstocks, making the use of microalgae for biofuel production an attractive option. In terms of CO2 consumption capacity, oil content and low land demands, microalgal oils and their diesel blends are regarded as potential replacements for conventional fuels for compression ignition engines, compared to other feedstocks. Thus, microalgae can be a viable option to solve both the biofuel production and food security problems (Moshood, Nawanir and Mahmud, 2021). Table 1 illustrates various feedstocks for biodiesel according to their source, the oil content, the yield of oil, the productivity and land use.

Table 1: Comparison of various biodiesel feedstocks

Feedstock Source	**Oil Content in seed (% by wt)**	**Oil Yield (L/ha/year)**	**Productivity (kg/ha/year)**	**Use of Land (m^2/kg/year)**
Coconut	60–65%	2,200–2,800	1,900–2,400	4.2–5.3
Rapeseed	40–45%	1,200–1,600	1,000–1,400	7.1–10.0
Sunflower	40–50%	800–1,200	700–1,000	10.0–14.3
Soybean	18–20%	400–600	350–500	20.0–28.6
Corn	3–5%	150–250	135–225	44.4–74.1
Groundnut (Peanut)	45–50%	1,000–1,400	900–1,260	7.9–11.1
Jatropha	30–35%	500–800	400–700	14.3–25.0
Karanja (Pongamia)	30–40%	500–900	450–810	12.3–22.2
Castor	45–55%	600–1,000	540–900	11.1–18.5
Neem	20–30%	300–500	270–450	22.2–37.0
Nahar (Mesua ferrea)	60–70%	200–400	180–360	27.8–55.6
Palm Oil	35–45%	4,000–6,000	3,500–5,400	1.9–2.8

Low oil microalgae	10–20%	10,000–20,000	9,000–18,000	0.56–1.1
Medium oil microalgae	20–30%	20,000–40,000	18,000–36,000	0.28–0.56
High oil microalgae	30–50%	40,000–80,000	36,000–72,000	0.14–0.28

In biomass processing, dehydration, concentration, filtration, and drying are necessary processes to eliminate water content, concentrate the biomass, and reach the desired dryness. Oil production from algae is usually conducted by mechanical methods such as solvent extraction or pressing for the separation of lipids from the algal biomass (Ganesan *et al.*, 2020). The lipids are then transesterified into biodiesel via the chemical reaction with alcohol (methanol or ethanol) in the presence of a catalyst to produce biodiesel and glycerol as by-products that provide a renewable substitute for conventional diesel fuel (Ghedini *et al.*, 2021). Algae are preferred as the biodiesel feedstock for internal combustion engines due to high lipid content, high growth rate and suitability for being grown for non-agricultural land. Biodiesel from algae sources has higher cetane numbers, which can improve engine performance, combustion efficiency and reduce engine knocking. In addition to being sustainable and environmentally friendly compared to traditional fossil fuels, algal cultivation has the potential to compensate for carbon dioxide emissions by having a lower sulfur content (Zahedi *et al.*, 2024).

2.4. Additives

Additives are incorporated in biodiesel for performance, stability and compatibility purposes in engines. While a lot of advantages can be attributed to algae biodiesel, its combustion is still associated with nitrogen oxide (NOx) emissions, which are implicated in air pollution and smog formation (Mofijur *et al.*, 2024). Further, NOx emissions have proven a significant challenge in all compositions of biodiesel. Moreover, under certain circumstances, incomplete combustion of the algae-based biodiesel may lead to the formation of particulate matter and unburned hydrocarbons, which have detrimental effects on air quality and human health (Rangel *et al.*, 2021). In cold weather, algae biodiesel can have some problems, for example, gelling and increased viscosity at low temperatures, resulting in poor engine efficiency and increased emissions. In order to solve these problems, fuel additives are used to enhance the properties of biodiesels. These additives have anti-gelling properties, cold flow properties, and emission reduction while being compatible with existing engine technologies (Loo *et al.*, 2023). Table 2 gives the types of fuel additives, their examples, and properties. Furthermore, the application of additives guarantees better fuel quality and performance, thus solving the specific problems related to the exploitation of the biofuel.

Table 2: Different types of fuel additives, examples and properties

Additives	**Example**	**Properties**	**Ref**
Metal based	Platinum, Cerium, Iron, Barium, Calcium, Manganese, Copper, Alumina, Zinc oxide, Ferro-fluids etc.	Catalyst during combustion, Performance Enhancement, Emissions reduction	(Pullagura *et al.*, 2024)
Oxygenated	Alcohol (ethanol, methanol, butanol and propanol etc.), Ester (dicarboxylic acid ester and acetoacetic esters) and Ether (ethyl tertiary butyl ether methyl-tert butyl ether, disopropyl ether, diethyl ether, dimethyl ether etc.)	Enhances the combustion process of fuel. Improve performance parameters (octane rating)	(Nabi *et al.*, 2024)
Antioxidant	Phenylene diamine, Alkylated phenol antioxidants	It improves the stability of biodiesel. Reduce the cylinder temperature in the combustion process, Reduction in NOx emission	(Rajendran and Ganesan, 2021)
Lubricity improver	Chlorinated paraffins, Sulfurized lard oils, Phosphate esters, Overbased calcium sulfonates	Increase the tribological properties	(El-Sheekh *et al.*, 2023)

Cetane number improver	Di-tertiary-butyl peroxide (DTBP), 2-Ethylhexyl nitrate (EHN)	Decreases Ignition delay Improves cetane index	(Paneerselvam *et al.*, 2021) (Gurusamy *et al.*, 2021)
Ignition boost additives	alkyl nitrates (e.g., amyl nitrate, hexyl nitrate and octyl nitrate)	Decrease ignition delay Decrease noise Reduce the toxic emissions	(Kumar, Pendyala and Gugulothu, 2024)
Nano additives	Copper, Iron, Platinum ,Cerium Oxide, Alumina, Silica, Graphene, Carbon Nanotubes, Titanium Dioxide Nanoparticles	Enhances combustion efficiency Reducing emissions	(Angappamudaliar Palanisamy, Rajangam and Saminathan, 2020)

Table 3 gives a detailed review of combined effects of biodiesel, different fuel additives on engine performance and emission parameters. It points to the factors that affect key outcomes such as the thermal efficiency of the brake, brake-specific fuel consumption, and exhaust emissions. The table also provides a summary of trends observed while working across different studies to find the best combinations to achieve better engine performance and lower emissions.

Table 3 : Review of Biodiesel, Additives, Performance and Emission factors

SN	**Author & year**	**Biodiesel**	**Additives**	**Performance**	**Emission**
1	(Gad and Jayaraj, 2020)	Jatropha	Al2O3, Carbon nanotubes,TiO2	↑ BTE,↓ BSFC	↓ CO (35%), ↓ HC (22%), ↓ Smoke (50%), ↓NOx (52%)
2	(Sakthivadivel *et al.*, 2022)	Neem oil (Azadirachta Indica)	Ethanol, Diethyl ether, alumina	↑ BTE (7.2 %), ↓ BSFC (6.7%)	↓ CO, ↓ HC, ↓ Smoke, ↓NOx (17.5%)
3	(Yesilyurt and Aydin, 2020)	cottonseed oil	Diethyl ether	↓BTE (17.39 %), ↑ BSFC (29.15%)	↑ CO, ↓ HC, ↓ Smoke, ↓NOx
4	(Shrivastava, Thipse and Patil, 2021)	Karanja	Ethanol	↓ BTE (2%), ↑BSFC (3%)	↓ CO (0.029%), ↓ HC, ↓NOx
5	(Kumar Kadian *et al.*, 2022)	Jatropha	Heptanol	↑ BTE (30.1 %), ↓ BSFC	↓ CO, ↓ HC, ↓ Smoke, ↓NOx
6	(Krishania *et al.*, 2020)	Mahua oil methyl ester	Di-ethyl ether	↑ BTE 3%, ↓ BSFC 12.16%	↓ CO (53%), ↓ HC (35%), ↓ Smoke (55%), ↓NOx (7%)
7	(Baweja, Trehan and Kumar, 2021)	Mahua	TiO2	↓ BTE 1.01%, ↓ BSFC	↓ CO (46.54%), ↓ HC (28.4%), ↓ Smoke (6.4%), ↓NOx (2.3%)
8	(Chacko, Rajkumar and Thangaraja, 2021)	Neem oil (Azadirachta Indica)	Ethanol, Diethyl ether, Alumina	↑ BTE (7.2 %), ↓ BSFC (6.7%)	↓ CO, ↓ HC, ↓ Smoke, ↓NOx (17.5%)
9	(Sonachalam, Manieniyan, *et al.*, 2024)	Waste cooking oil	Ethanol, nanoparticles	↑ BTE (3.1 %), ↓ BSFC	↓ CO (37%), ↓ HC (39%), ↓NOx (35%)

				(2.5%)	
10	(Roy *et al.*, 2021)	Castor-Jatropha		↑ BTE (14%), ↓ BSFC (16.7 %)	↓ CO (60%), ↓ HC, ↓NOx (61%)
11	(Jit Sarma *et al.*, 2023)	Mahua	TiO2 nano additive	↓ BTE 1.01%, ↓ BSFC	↓ CO, ↓ HC, ↓ Smoke, ↓NOx
12	(Khan, Kumar Kadian and Sharma, 2023)	Jatropha oil methyl ester-	Heptanol	↑ BTE (3.9 %), ↓ BSFC (12.5%)	↓ CO (57.4%), ↓ HC, ↓ Smoke (91.6%), ↓NOx (13.27%)
13	(Anish *et al.*, 2024)	Nano chloropsis microalgae	alcohol and ZnO	↑ BTE,↓ BSFC	↓ CO, ↓ HC, ↓ Smoke, ↓NOx
14	(Fayad *et al.*, 2024)	Microalgae	TiO2	↑ BTE (4.53%), ↓ BSFC (6.47%)	↓ CO, ↓ HC, ↓ Smoke, ↓NOx (26.48%)
15	(Gavhane *et al.*, 2020)	Soybean	Copper coated Zinc oxide	↑ BTE (16.1 %), ↓ BSFC (18.9%)	↓ CO (34.5%), ↓ HC (24.1), ↓ Smoke (16.8%), ↑NOx
16	(Kaya and Kökkülünk, 2023)	waste frying oil	-	↑ BTE, ↑ BSFC	↓ CO (24.1%), ↓ HC (29.27%), ↓ Smoke (25%), ↓NOx (6.52%)
17	(Sonachalam, Jayaprakash, *et al.*, 2024)	chlorella protothecoides	acetylene gas	↑ BTE,↓ BSFC	↓ CO (15.4%), ↓ HC (8.3%), ↓ Smoke (16.9%), ↓NOx (7%)
18	(Fareed *et al.*, 2024)	waste cooking and castor	-	↓ BTE, ↑ BSFC	↓ CO, ↓ HC, ↓ Smoke, ↑NOx
19	(Selvabharathi, Selvam and Palani, 2022)	Rice bran	Ceria and zirconia	↑ BTE 8%, ↓ BSFC 9%	↓ CO (30%), ↓ HC (19%), ↓NOx (13.3%)
20	(Parida *et al.*, 2020)	Karanja	TiO2	↑ BTE 1.72%, ↑ BSFC 10.71%	↓ CO (21.5%), ↓ HC, ↓NOx (1.54%)
21	(Kesharvani, Verma and Dwivedi, 2023)	Chlorella Protothecoides	-	↓ BTE (1.45%), ↑ BSFC (3.67%)	↓ CO, ↓ HC, ↓ Smoke, ↑NOx
22	(Verma *et al.*, 2023)	Microalgae	Butanol and TiO2 nano-additive	↑ BTE (12 %), ↑ BSFC (5.02 %)	↓ CO, ↓ HC, ↑NOx
23	(Woldetensy, Zeleke and Tibba, 2025)	cotton and castor	-	↓ BTE, ↑ BSFC	↓ CO, ↓ HC, ↑NOx
24	(Christopher selvam, Devarajan and Raja, 2025)	Caesalpinia bonduc oil	-	↑ BTE,↓ BSFC	↓ CO, ↓ HC, ↓ Smoke, ↑NOx

25	(Doppalapudi, Azad and Khan, 2024)	Tucuma and Ungurahui	-	↓ BTE, ↑ BSFC (11.2%)	↑ CO, ↓ HC, ↑NOx
26	(Miriam *et al.*, 2021)	Microalgal	-	↑ BTE (7.3%), ↓ BSFC	↓ CO (35.5%), ↓ HC (59.3%), ↑NOx
27	(Rajak *et al.*, 2020)	Spirulina microalgae,	N-butanol, Diethyl ester, Hydrogen	↑ BTE (0.95%), ↑BSFC (6.4%)	↓ CO, ↓ HC, ↓ Smoke, ↑NOx (21.3%)
28	(Singh *et al.*, 2021b)	Microalgae Spirulina (L.)	-	↑ BTE,↓ BSFC	↓ CO, ↓ HC, ↓ Smoke, ↑NOx
29	(Rahman Adib *et al.*, 2024)	C. cohnii microalgae	-	↑ BTE, ↓ BSFC (2.15%)	↓ CO, ↓ HC, ↑Smoke (6.9%), ↓NOx (8.4%)
30	(Dhairiyasamy and Gabiriel, 2025)	Mahua oil	-	↑ BTE (9.15%), ↓ BSFC (6.23%)	↓ CO (20.35%), ↓ HC (12.28%), ↓ Smoke, ↓NOx (5.36%)
31	(Saravanan and Krishnamoorthy, 2020)	Algae (B20)	Butylated hydroxytoluene anti-oxidants	↑ BTE,↓ BSFC	↓ CO (26%), ↓ HC (40%), ↑ Smoke (29%), ↑NOx (30%)
32	(Subramaniam *et al.*, 2020)	Algae- azolla pinnata	-	↑ BTE (25%), ↑ BSFC (10 %)	↓ CO, ↓ HC (50%), ↓ Smoke (30%), ↓NOx (39%)
33	(Jayabal, 2025)	lychee seed	acetylene	↑ BTE,↓ BSFC	↓ CO, ↓ HC, ↓ Smoke, ↑NOx
34	(Praveen, Lakshmi narayana and Ramanaiah, 2022)	Chlorella vulgaris micro algae	Al2O3 Nano-particles	↑ BTE,↓ BSFC	↓ CO, ↓ HC, ↓NOx
35	(Mohammad *et al.*, 2025)	waste oil	Fe3O4-SiO2	↑ BTE, ↑ BSFC	↓ CO, ↓ Smoke, ↑ NOx
36	(Islam, Rashid and Arefin, 2021)	Algae	-	↑ BTE,↓ BSFC	↓ CO, ↓ HC, ↓ Smoke, ↓NOx
37	(Sathish, Ağbulut, *et al.*, 2024)	calotropis gigantea seed	TiO2, Cr2O3 and SiO2	↑ BTE, ↑ BSFC	↓ CO, ↓ HC, ↓ Smoke, ↑ NOx
38	(Rehman, Kesharvani and Dwivedi, 2023)	Microalgae	-	↓ BTE, ↑ BSFC	↓ CO, ↓ HC, ↓ Smoke (14.16%), ↑ NOx
39	(Taguiling, Manegdeg and Rollon, 2024)	petroleum nut	-	↓ BTE (3.95%), ↑ BSFC	↓ CO, ↓ HC, ↑NOx
40	(Venkatesan *et al.*, 2023)	Algae	-	↑ BTE (14.52%), ↓ BSFC	↓ CO, ↓ HC (32.37%), ↓ Smoke (33.33%), ↓NOx (49%)

41	(Al-Bawwat *et al.*, 2024)	muskmelon seeds	-	↓ BTE (3.24%), ↑ BSFC	↓ CO (31.99%), ↓ HC, ↓ Smoke, ↑NOx (1.03%)
42	(Ariyarit *et al.*, 2024)	castor oil ethyl ester	-	↓ BTE, ↑ BSFC	↓ CO, ↓ HC, ↓ Smoke, ↑NOx
43	(Muniyappan and Krishnaiah, 2024)	mahua	TiO2 nanoparticles, n-heptane	↑ BTE,↓ BSFC	↓ CO, ↓ HC, ↓ Smoke, ↓NOx
44	(Kari, Vanthala and Sagari, 2024)	Mesua ferrea	chromium oxide	↑ BTE (16.58%), ↓ BSFC (0.58%)	↓ CO (31.85%), ↓ HC (22.23%), ↓ Smoke (62.61%), ↓NOx (6.16%)
45	(Muhammad Hammad *et al.*, 2024)	Jatropha curcas	Graphene oxide	↓ BTE (12.5%), ↓ BSFC (16.5%)	↓ CO, ↓ HC (94%), ↓ Smoke, ↓NOx (84.78%)
46	(Gzate *et al.*, 2024)	moringa oleifera seed oil	Diethyl ether	↑ BTE,↓ BSFC	↓ CO, ↓ HC, ↓ Smoke, ↓NOx
47	(Sathish, Giri, *et al.*, 2024)	tamarind seed oil	Al2O3/SiO2 /MgO	↑ BTE,↓ BSFC	↓ CO, ↓ HC, ↓NOx
48	(Hasnain *et al.*, 2024)	soybean	methyl oleate	↓ BTE, ↑ BSFC	↓ CO, ↓ HC, ↑NOx
49	(Prabu, 2024)	Mahua	clove antioxidant	↓ BTE, ↑ BSFC	↓ CO (28%), ↓ HC, ↓ Smoke (9.9%), ↓NOx (8.8%)
50	(Simhadri, Rao and Paswan, 2024)	Mahua	TiO2 nanoparticle	↑ BTE (1.7%), ↑ BSFC	↓ CO, ↓ HC, ↓ Smoke, ↓NOx
51	(Zeleke and Bezabih, 2024)	soybean	moringa leaf, ethanol	↑ BTE (4.4%), ↓ BSFC (4.6%)	↓ CO (20.27%), ↓ HC (8%), ↓ Smoke, ↓NOx (7%)
52	(Abebe Debella *et al.*, 2024)	Prosopis Juliflora	diethyl ether	↓ BTE, ↑BSFC	↓ CO, ↓ HC, ↓ Smoke, ↓NOx
53	(Vellaiyan, 2024)	Cottonseed oil	alcohol	↑ BTE (3.2%), ↓ BSFC (1.4%)	↓ CO (12.8%), ↓ HC (14.3%), ↓NOx
54	(Ooi *et al.*, 2024)	palm-oil	Ethanol, diethyl ether	↑ BTE, ↑ BSFC	↓ CO, ↓ HC, ↓ Smoke, ↓NOx
55	(Ellappan *et al.*, 2024)	Coconut waste cooking oil	Di-ethyl ether	↑ BTE (3 %), ↓ BSFC (2.42%)	↓ CO (11%), ↓ HC (18%), ↓ Smoke (19%), ↓NOx (21.2%)
56	(Behera and Hotta, 2024)	Waste cooking oil	-	↑ BTE (5 %), ↓ BSFC (9.7%)	↑ CO (7%), ↓ HC (25%), ↓ Smoke (7%), ↓NOx (25%)
57	(Divyachandrika *et al.*, 2024)	Jatropha oil	Citrus Limetta peels	↑ BTE (1.2 %), ↓	↓ CO (10.3%), ↓ HC (11%), ↓ Smoke

			as a biocatalyst	BSFC (11%)	(2%), ↓NOx (3%)
58	(Kunchi *et al.*, 2024)	Terminalia bellirica	multi ferrites nanoparticles	↑ BTE,↓ BSFC	↓ CO, ↓ HC, ↓ Smoke, ↑NOx
59	(Bylapudi, Kambagowni and Sagari, 2024)	Madhuca longifolia	ferric chloride and graphene	↑ BTE,↓ BSFC	↓ CO, ↓ HC, ↓ Smoke, ↑NOx
60	(Asokan *et al.*, 2024)	safflower	antioxidants	↑ BTE (1.6 %),↓ BSFC	↓ CO (33.33%), ↓ HC (10%), ↓ Smoke (19.2%), ↓NOx (5%)

3. DISCUSSIONS

3.1. Performance characteristics

3.1.1. Brake thermal efficiency (BTE)

BTE Classified as the efficiency of an engine where the percentage of chemical energy of the fuel consumed is converted to useful brake power. At each engine load the BTE of diesel is better than that of biodiesel. Diesel fuel has more energy content per unit of fuel than biodiesel. The oxygenated nature of biodiesel slightly improves combustion efficiency, but the lower energy density does mean that more fuel must be burnt in order to make the same amount of power, so its brake thermal efficiency is lower. Diesel engines are typically in the range of BTE 30-45% while biodiesel engines fall in the range of 25-40%, 5-10% lower. This slightly lower BTE in biodiesel because of its inherently lower energy content per unit mass and its greater viscosity which makes it difficult for fuel spray to break up into small particles and mix with air unless an engine is specially optimized to run on biodiesel. These together make the energy conversion less efficient than diesel.

Soybean biodiesel has a BTE of 25-38%, which is based on the moderate calorific value and the use of oxygenated combustion, but its low energy density has a higher fuel consumption than diesel. With a BTE of 28-40%, palm biodiesel has such poor viscosity and density, but good cetane number, which can improve the quality of ignition although its energy content is still low. A balanced FAME composition of rapeseed biodiesel (27-38% BTE) stabilizes the combustion but its lower sulfur content only reduces the emission, not the efficiency. Jatropha biodiesel (26-37% BTE) is prone to oxidative instability caused by unsaturated fatty acids, but energy losses can be avoided by optimal injection time. Fats from the repeated frying of the cooking oil cannot be turned into superior quality biodiesel and therefore have a low BTE (24-35%) and have to be blended with diesel (e.g. B20) to enhance performance. Coconut biodiesel has the lowest BTE (22-33%) due to its extremely low heat or calorific value and is best used in blends or in tropical climates to mitigate problems during cold weather flow. Algae-based biodiesel has similar engine performances in the optimized engine (BTE = 30-42%) to that of diesel, thanks to high lipid content, but the scalability and cost of production are barriers to its implementation. B10 and B20 blends have similar or slightly lower BTE than diesel because it has good combustion properties and low emissions. B50 and B100 blends exhibit a noticeable reduction in BTE because of the decrease in the calorific and increase in the fuel consumption. BTE of Palm and Algae biodiesels, on average, is slightly higher than other biofuels because they have a higher cetane number and combustion properties. Waste Cooking Oil (WCO) and Coconut biodiesel had the lowest values of BTE because of their low quality, presence of impurities, and low combustion efficiency.

Cetane boosters are additives that help enhance biodiesel ignition properties, which in turn produce good combustion and reduce engine knocking. As a result, they improve Brake Thermal Efficiency by 2-4% with most biodiesel blends, of which the increase is more apparent in higher biodiesel blends, such as B50 or B100. Ethanol and other oxygenates can help to improve combustion by providing extra oxygen, which helps to promote the burning of the air and fuel mixture. This leads to moderate BTE improvements of 1-3% but exhaustive use leads to energy content reductions which limit the full potential of the improvement. Lubricity enhancers, though not directly working on BTE, play an important part in providing smoother engine running, reduced mechanical friction, which indirectly improves engine performance and stabilizes BTE in the long term. It is worth noting that Palm and Algae blends of biodiesel will have relatively higher BTE values due to improved combustion characteristics, and, in particular, the addition of cetane boosters and oxygenates. On the other hand, adding to biodiesels from soybeans and waste cooking oils may have modest benefits. Cetane boosters provide the greatest BTE improvement especially in blends of higher biodiesel content. Nano-metal particles (e.g. Fe_2O_3, CuO) are generally known to increase BTE by 4-6%, particularly in biodiesels with lesser energy density such as WCO and Jatropha. Carbon nanotubes (CNTs) enhance BTE by 3-5% with the best performance in the blends B50 and B100 of biodiesel. Metal oxide nanoparticles (e.g. TiO_2, Al_2O_3) - Results in 2 - 4% BTE improvement especially for soybean and rapeseed biodiesel blends. Graphene and graphene oxide have the potential to increase BTE by 3-5% particularly in algae and palm biodiesel blends. Overall, though, even though additives can improve combustion efficiency and engine performance quite considerably, they affect BTE differently with different feedstock and blending ratio combinations.

3.1.2. Brake-specific fuel consumption (BSFC)

BSFC is a measure of the amount of fuel used per unit of power output by the engine brakes. Biodiesel have a 5-15% higher BSFC on diesel engines. This disparity Due to its lower energy content as compared to diesel. To generate the same amount of brake power as is produced with diesel, biodiesel engines must burn more fuel mass to overcome the reduced energy density of the biodiesel fuel, which affects its fuel economy figures such as BSFC directly.

Soybean biodiesel has a BSFC 15-25% higher than diesels, because of its lower calorific value and has to make the engine burn more fuel to produce the same power level of diesel. Palm biodiesel has BSFC, as a result it is 10-20% higher than diesel. It has high viscosity which is less efficient atomization then the higher cetane number partially compensate the energy losses. Rapeseed (canola) biodiesel has a BSFC which is 20-25% higher than that of diesel. While the moderate calorific value and higher oxygen content is good for combustion, the engine still needs a high mass of fuel to produce the same power as diesel. Jatropha biodiesel leads to BSFC which increases fuel usage by 20-30% vis-a-vis diesel. Its oxidative instability, which is due to unsaturated fatty acids, as well as its lower energy density are responsible for this higher BSFC. Waste cooking oil biodiesel has BSFC which is 25-35% higher than diesel. The poor quality and impurities of the oil due to repeated frying cause reduced efficiency of combustion which results in impaired fuel economy. Coconut biodiesel has the highest BSFC making it 30-45% higher than diesel. It's incredibly lesser calorific value and additional cold winters fluidity require to significantly burn more fuel to get the same power output as diesel. Algae based biodiesel has BSFC that is 8-20% more than diesel. Its high lipid content (30-50%) leads to an increase in energy density which reduces the BSFC gap with diesel on optimized engines. Lower bio diesel blends (B5-B20) provide a good compromise between efficiency and fuel consumption. Higher blends (B40 and above) lead to a high increase in BSFC due to the reduced energy density of bio-diesel.

Oxygenated additives such as ethanol, methanol and diethyl ether make enhanced combustion more effective, and as a result BSFC is reduced. However, too high a content of oxygen could lead to an increase in fuel consumption because of the reduced energy density. Cetane number improver's compounds like 2-ethylhexyl nitrate improve the ignition quality and thus have a positive effect on the combustion and a slightly lower BSFC. Metal-based additives, Nano-additives containing cerium oxide (CeO_2), iron oxide (Fe_2O_3) and aluminum oxide (Al_2O_3) possess the function of combustion catalysts, which reduce the BSFC by promoting the atomization of the fuel and improving the burning efficiency. Antioxidants and stability improvers help fuel stability and reduce deposits, the effect on BSFC is usually low unless as a result of improving the combustion characteristics indirectly.

3.2. Emission parameter

3.2.1. Carbon monoxide (CO)

Diesel contains less oxygen that results in higher carbon monoxide emission and incomplete burning. Biodiesel also makes CO emissions lower because of its oxygenated nature, which helps to make combustion more efficient. Biodiesel has higher cetane number which improves ignition timing by reducing delay period, so favoring good combustion and reducing CO formation. Biodiesel has a very high potential in lowering CO emissions (10-50%) due to its oxygenated characteristics with the reduction being the highest at B20-B100 blends. The high oxygen content and the improved combustion efficiency makes algae biodiesel one of the best fuels to reduce CO emissions. Higher viscosity biodiesels (palm, waste cooking oil) will produce slightly higher CO at low loads but overall, the use of biodiesel results in cleaner burning compared with diesel. Additives play a large role in improving the CO emission reduction of all biodiesels. Algae biodiesel containing oxygenated additives and nano-additives has the greatest

CO reduction. On the other hand, for biodiesel derived from waste cooking oil and palm oil, the surfactants, emulsifiers and cetane improvers are equally beneficial, as they improve the combustion at low loads. Nano-additives are the most effective when it comes to reducing CO emissions in all types of biodiesels.

3.2.2. Carbon dioxide (CO2)

Diesel emits most CO2 as it is 100% fossil-based and there is no CO2 absorption in its life cycle. Biodiesel is a major source of CO2 emission reduction. Biodiesel from algae has the biggest impact on CO2 reduction as algae contains high concentrations of CO2 during its rapid growth cycle. Soybean and rapeseed biodiesel also have a remarkable reduction in CO2 emissions because of their renewable source and good combustion properties. Palm and Jatropha biodiesel are less efficient in achieving CO2 reduction because of the higher viscosity which, to a small extent, increases fuel consumption. The high CO2 reduction in waste cooking oil biodiesel is because it recycles carbon that is already in the system. Fuel additives can be used to decrease CO2 emissions. Improvement of combustion efficiency by nano-additives leading to reduction of CO2 by 10-20%. Cetane improvers - this is to improve ignition and reduce CO2 by 2-5%. Water-dissolved bio-diesel that has a CO2 reduction of 5-15% by enhancing fuel atomization. Oxygenated additives have either a slightly positive or negative impact on CO2 emissions based on their effect on fuel consumption.

3.2.3. Hydrocarbons (HC)

HC emission is highest because of incomplete burning and less oxygen in diesel fuel. Biodiesel is oxygenated and this improves combustion properties and also results in reduction of HC emissions compared to diesel. Algae biodiesel has the greatest HC reduction (60-80%) because of its high oxygen level and clean burning characteristics. E. Using biodiesel from soybean and rape seed also results in very significant HC emission reduction (40-65%) while that from palm and jatropha is relatively moderate (30-55%) during combustion, attributed to their slightly higher viscosity. Waste cooking oil biodiesel has 50-70% lower HC emissions with pre-oxidized fuel characteristics. Nano-additives seem to be the most effective additives for HC emission reduction (30-50%), followed by cetane improvers (20-40%). The most effective way to reduce HC emissions without antagonizing the combustion efficiency is to use algae biodiesel with nano-additives or cetane improvers.

3.2.4. Nitrogen oxides (NOx)

Nitrogen oxides are major air pollutants that cause smog, acid rain and respiratory illness. Nitrogen oxide (NOx) generation is mainly controlled by the combustion temperature, amount of available oxygen and fuel composition. Biodiesel, due to the higher oxygen content and an improvement in combustion performance, often has a greater NOx emission, when compared to diesel. Biodiesel from algae has the maximum NOx increase (10-20%) because it contains more oxygen and burns more efficiently. Rapeseed and soybean biodiesel also display a large increase (5-18%) due to their higher cetane numbers which ensure rapid combustion. Bio surfactants derived from palm and jatropha, a slightly higher viscosity and a slightly different fatty acid composition were also examined and showed a lower increase in NOx (3-12%). Waste cooking oil biodiesel still increases NOx emissions (5-15%), but this is affected by the degree of oxidation of the fuel. Water-in biodiesel has been found to provide the most NOx reduction (15-30%) on the account of a lower peak combustion temperature. Nano-additives have a great effect in reducing NOx (10-25%) by optimizing combustion and suppressing hot-spot formation. Cetane improvers show reduction of NOx from 5-15% due to promotion of fuel ignition and decrease of peak temperatures. The effect of oxygenated additives depends on their effect on the combustion temperature; slight increases or decreases in NOx emission have been reported.

3.2.5. Particulate Matter (PM)

Particulate Matter (PM) emissions are soot, ash, and unburned hydrocarbons, and cause air pollution, respiratory diseases and decreased engine efficiency. The emission of PM is mainly a function of fuel composition, combustion efficiency and oxygen content. High PM emissions of diesel engines are mainly caused by incomplete burning of fuel and high carbon content. Biodiesel generally reduces PM because of its high contents of oxygen and low aromatic hydrocarbons. Additives also help in reducing PM emissions, improving combustion and fuel properties. Algae biodiesel has the lowest PM emission (60-80% reduction) and produces better fuel combustion. Soybean and rapeseed biodiesel also have a significant effect on PM (40-65%), improving the efficiency of combustion. Palm and Jatropha biodiesel has moderate effect in reduction of PM (30-55%), while the higher viscosity may have an effect on fuel atomization. Waste cooking oil biodiesel reduces PM emissions by up to 70%, because it contains pre-oxidized compounds, which improve ignition. Nano-additives provide the largest PM reduction (30-50%), which act as combustion catalysts. Cetane improvers reduce the PM emissions by 20-40% by reducing the ignition delay and improving combustion. Oxygenated additives lower the PM emission by 10-30% to ensure a better oxidation of the fuel. Water-emulsified biodiesel reduces PM emissions by 15-30% which reduces the combustion due to better fuel dispersion. The use of algae biodiesel containing nano-additives or cetane improvers gives the best opportunity of reducing PM emissions without compromising good combustion efficiency.

4. CONCLUSIONS

This has been extensively reviewed and it has discussed the performance and emission responses of CI engines to the different biodiesel fuels. The main conclusions show that while biodiesel blends tend to result in lower carbon monoxide (CO), hydrocarbons (HC) and particulate matter (PM) emissions, they also result in an increase in the emission levels of nitrogen oxide (NOx). Due to the low calorific value and increased viscosity of biodiesel, typically the brake thermal efficiency and the brake specific fuel consumption of biodiesel blends are lower than those of conventional diesel fuel. Algae derived biodiesel offers an attractive sustainable alternative due to its better yield and lower land use requirements compared to the conventional feed stocks. By improving biodiesel's combustion properties additives assist improve a combustion of overall engine performance and minimize emissions. Oxidative stability and NOx emissions as well as viscosity behavior could be tackled with the help of additives.

Efficiencies can be improved and emissions reduced but more research and development are needed to ensure balanced efficiency gains from biodiesel applications. This study presents opportunities for the optimization of the additive-enhanced biodiesel to be used as a sustainable alternative for enhancing engine performance and reducing harmful emissions. Furthermore, further studies are required to find the best methods to limit NOx emissions down to the minimum, such as the algae-based biodiesel potential as an environmentally friendly and efficient fuel source.

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