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RESEARCH ARTICLE

Comparative review of low-emission biodiesel blends for marine diesel engines, performance and emission impacts

K. Sunil Kumar[1,*], Sathish Kumar Kumaravel[2], Devikala S.[3], Ganapathy G.[4], Kala Raja Mohan[5]

[1]Department of Mechanical Engineering, Saveetha School of Engineering, Saveetha Institute of Medical and Technical Sciences, Chennai, Tamil Nadu, 602105, India
[2]Department of Mathematics, Vel Tech Rangarajan Dr. Sagunthala R and D Institute of Science and Technology, 600062, India
[3]Department of Electrical and Electronics Engineering, Saveetha School of Engineering, Saveetha Institute of Medical and Technical Sciences, Chennai, Tamil Nadu, 602105, India
[4]Department of Mathematics, RMD Engineering College, Kavaraipettai, 601206, India
[5]Department of Mathematics, Panimalar Engineering College, Chennai, 600123, India

Abstract

This study examines the latest trends in the development of biodiesel blends for marine propulsion engines, with the goal of making our oceans cleaner and more sustainable. In this study, we examine various biofuels, including rapeseed, pyrolysis, olive, soybean, waste cooking, jatropha, sunflower, transformer, and palm biodiesel, by testing them in a four-stroke marine diesel engine. One of the primary challenges in the fuel industry is the high levels of pollutants emitted by diesel engines, which can have a negative impact on human health. Our objective is to present the methods used to develop these eco-friendly biodiesel blends. We also examine key performance metrics, such as brake thermal efficiency, fuel consumption, and combustion characteristics (heat-release rates and cylinder pressures), for various biodiesels in marine engines. The use of innovative additives in these biofuels is notable because it confers multiple benefits. Our findings show that all biodiesel blends tested help reduce harmful emissions such as carbon monoxide(CO),hydrocarbons(HC),carbon dioxide (CO_2), and nitrogen oxides (NOx), when compared to traditional diesel fuel. This improvement is due to the favorable physical properties of these blends, which not only meet ASTM standards but also fulfill all requirements for diesel fuel.

Keywords: Marine biofuels, brake thermal efficiency, emissions, marine diesel engine, heat release rate

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1. Introduction

The challenge of controlling diesel-powered engine emissions in the marine industry remains significant. The main challenge in developing marine propulsion systems, from single-cylinder internal combustion engines to multiple-cylinder engines, has been the steady rise in continuous emissions [1]. Principal emissions of the diesel propulsion engines are nitrogen oxides (NOx), carbon dioxide (CO2), carbon monoxide (CO), and hydrocarbons [2,3]. Recent research indicates that NOX particulates emitted by engine exhaust are particularly toxic to marine life. In response to such issues, the International Maritime Organisation (IMO) created MARPOL Annex VI in 1997, which established limits on the amount of air pollutants, such as sulfur oxides (SOx), nitrogen oxides (NOx), and particulate matter (PM), that vessels may discharge into the environment. The Marine Environmental Protection Committee made the same proposals to amend Annex VI to enhance pollution controls in anticipation of technological developments in the same year. This was replaced by the new Annex VI, which came into force that year with stricter regulations and the creation of Emission Control Areas (ECAs) where pollutants were restricted. At present, ECAs are developed in the Baltic Sea (SOx), the North Sea (SOx), North America (NOx and SOx),

*Corresponding Author
E-mail Adress: sunilkumarkresearcher@gmail.com
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and the US Caribbean Sea, including the waters surrounding Puerto Rico and the US Virgin Islands. More ECAs will be appointed in the near future, with locations in the Mexican Caribbean, the Adriatic Sea, and the Japanese coast. Moreover, IMO has established Tier II and Tier III emission standards to further regulate ship emissions within these controlled zones.

Recent studies by [4,5] indicate that 60 per cent of NOx emissions from marine diesel engines are known to affect sea-living organisms, especially skin cancer. Almost 43.2 per cent of CO2 emissions can affect the nervous system; even low levels of HC and CO can increase the risk of lung cancer. Therefore, scholars have sought to apply a traditional multicylinder marine diesel low-weight propulsion engine without making dramatic adjustments [6]. Thus, Various researchers have tried to adapt the traditional marine diesel engine into a multicylinder lightweight propulsion engine without applying any coating to the engine cylinder and related parts. Some disadvantages still remain throughout the analysis, such as additional engine component alterations based on engine materials, which may result in detartrating the piston cylinder and exposing it to various operating conditions [7]. Therefore, the researchers tried to employ other fuels, substitute regular diesel with additives and without. The researcher [8] tested jatropha blends in marine diesel engines without the nano catalyst and found that the engine's thermal efficiency decreased by 4.5 per cent compared to when using diesel. It is further observed that the specific fuel consumption increases with the same blend, reaching 0.24 kg/kWh, which is almost 20.2 per cent higher than that of diesel. With such variables in place, it is also evident that we need to seek ways to minimise pollution by developing and introducing more mitigation technologies. It has the potential to improve the vessel's gas economy and the combustion system [9,10]. In corporate residual electric power systems, some recent residual heat removal networks will be planned and utilised, and will hold significant importance for the future development of the maritime sector [11]. This research paper will examine the various types of biofuels utilised in the marine sector and contrast their performance, combustion, and emissions with those of standard diesel.

The multidisciplinary nature of the research and the complex interplay among the controlled variables can lead to inconsistent investigations of ethanol and nanoparticles. Since you are a specialist in the production of biodiesel blends containing micro-additives, you will see variation in results for fuel efficiency, emissions, and longevity. The differences in the nature of nano-additives, including particle size, dispersion stability, and surface structure, can have a considerable effect on catalyst levels and combustion rates. Moreover, biofuels derived from mango gummi-gutta, rapeseed, soy sauce, or even unconventional sources such as waste milk can yield different interactions when used with nanotechnology. Variations in engine test standards, combustion and monitoring techniques may lead to conflicting results on emissions and performance. The optimal levels of additives are controversial, with some research pointing to greater effectiveness, whereas others report reduced effectiveness or adverse impacts, including injection blockage. Assessments of the life cycle of ethanol can also vary depending on factors such as emissions, toxicity, and durability. Studies focusing on the beneficial impact of nano-additives can receive greater attention, potentially leading to an inaccurate understanding of their actual effects.

Methodological limitations in studies of ethanol use with nanoscale particles in various motors may severely affect the accuracy of the findings. The inability to ensure consistency in their research is known to many researchers. The following are some of the major limitations: The studies mostly compare biodiesel-nano mixtures across different classes of vehicles, including compression-ignition (CI) and spark-ignition (SI) engines, and at varying rates of expansion. This complicates the comparison between the two types. Moreover, the inconsistency between performance and environmental results may be due to variations in injection timing, energy atomization, and ignition characteristics.

The methodologies used for testing lack standardized procedures for stabilizing nanoscale particles in biofuel mixtures. Differences in mixing processes, laser dissemination strategies, and warehousing conditions lead to differences in fuel quality [59]. Some studies do not address oxidation stability or the long-term decomposition of nano-enhanced biodiesel mixtures. The methods for measuring exhaust gases and pollutants vary, which affects NOx and particulate emissions. Numerous reports highlight immediate engine responses but overlook long-term outcomes, including reduced fuel consumption, lower fuel tank volume, and minimal particle pollution. The study of the effects of nano-additives on the resilience and long lifespan of vehicles is scarce. This paper will introduce the performance of biofuels using nano additives to young researchers in the marine engines industry and the significant benefits available to engine performance and emission characteristics. This paper seeks to establish the lowest emissions of the different biofuels and their weaknesses compared to diesel engines [60,61].

1.1. Biofuel generations

They are classified into various biofuels based on their origin, manufacturing process, and chemical composition. First-generation biofuels, derived using consumable commodities such as maize, ethyl sucrose alcohol, and soybeans, fuel. Biofuels of the second generation: Biofuels based on non-consumable material, such as cellulosic alcohol, waste vegetable oils and diesel. Third-generation renewables are produced by algae and microorganisms, such as algal biofuels and biohydrogen. Fourth-generation biofuels focus on carbon capture, advanced biotech approaches, and transgenic microalgae for ethanol production. Biofuels are flexible - the fuel is called bioethanol, and decomposition oil. Liquid renewable sources: Bio gas, Bio Syngas, Bio hydrogen. Timber granules: Timber farming by-products, torrefied feedstock. The corresponding amount of energy, alcohol-derived energies, a solvent the corresponding number of Ester-derived energies, Hydrocarbon-derived fuels and Gas-derived fuels.

1.2. Marine propulsion engines

The section has been utilised to provide information to assist in selecting and developing waste heat recycling technology and systems that will aid in reducing emissions. It is about a standard high-speed diesel engine used in the sea. This type of engine can be a two-stroke or four-stroke motor and can be used for propulsion or as part of the energy generation. The reprocessed statistics from the engine link database [12] serve as the source for the analysis. Due to accessibility considerations, the analysis was performed over the period from 1972 to February this year. It has been made in two types based on engine power.

The section has been used to provide information to support the selection and development of waste heat recycling technology and systems that will help reduce emissions. It deals with standard high-speed diesel engines used at sea. Such engines may be two- or four-stroke motors and are used for propulsion or to assist in generating energy. It is analyzed using reprocessed statistics from the engine link database [12]. The analysis was conducted within a time frame from 1972 to February this year to account for accessibility. It has been released into two categories based on engine strength. Figure 1 is a summary of the various marine propulsion systems that are used in the shipping industry. Diesel engines still account for 33.3% of the world's engines. Other sources of power on various types of ships include gas turbines, steam engines, and diesel engines, among others. Interestingly, alternative fuels currently constitute 11.1 per cent of ship propulsion techniques, indicating that ship owners have increasingly been interested in reducing fuel expenses and other adverse environmental effects [57].

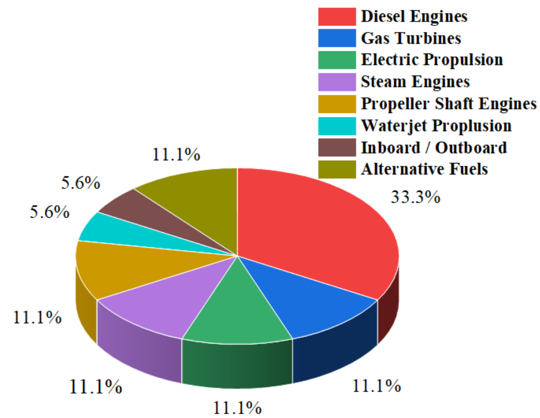

Figure 1. Types of marine propulsion engines

Table 1. CO_2 emissions statistics in the marine engines industry

SNO	Year	Global %	CO_2 Total Shipping (millions of tonnes)	CO_2 International Shipping (millions of tonnes)	Global in %	Global CO_2 (millions of tonnes)
1	2007	3.3	1121	903	2.6	34089
2	2008	3.3	1157	940	2.6	35597
3	2009	3.2	1100	890	2.4	34500
4	2010	3.3	1200	950	2.2	36000
5	2011	3.4	1250	980	2.1	37000
6	2012	3.4	1300	1000	2.2	38000
7	2013	3.1	1320	1100	2.4	38110
8	2014	3.4	1340	1110	2.6	39122
9	2015	3.3	1350	1120	2.8	40112
10	2016	3.4	1360	1130	3.1	41222
11	2017	3.8	1380	1140	3.2	44322
12	2018	4.1	1400	1240	3.4	43212
13	2019	4.2	1420	1340	3.6	44112

Table 1 represents the Statistics of typical CO_2 emissions across the globe in the field of the marine industry, and Table 2 represents IMO regulations concerning the particulates of NO_X emissions in the field of the Marine Industry that are generated by marine diesel engines.

Table 2. NO_X limitations by IMO regulations

SNO	IMO Tier	Year	NOx g/kWh N < 140 rpm	NOx g/kWh 120 N < 1990 rpm	NOx g/kWh N > 2000 rpm
1	I	2000	17.0	$46 \times N^{-0.3}$	9.9
2	II	2011	14.4	$45\times N^{-0.4}$	8.7
3	III	2016	3.4	$10 \times N^{-0.4}$	1.89

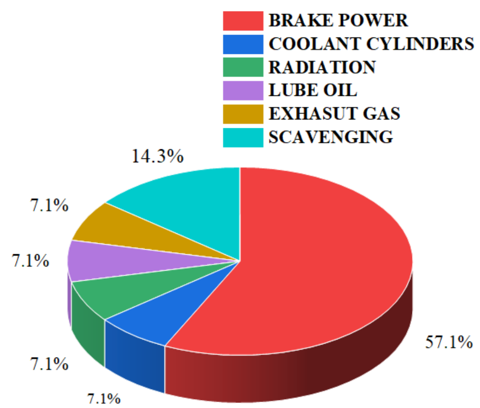

Figure 2. Low-speed marine engines strategy

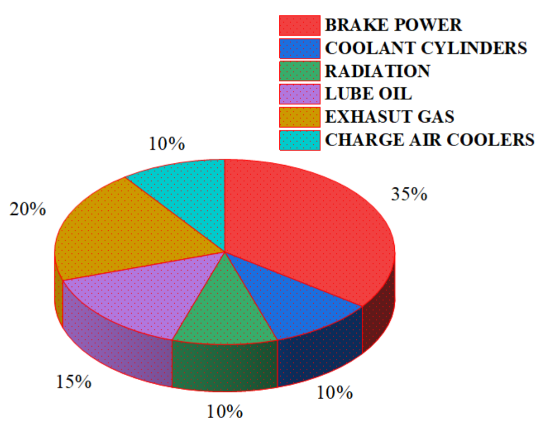

Figure 3. Medium speed engines strategy

The 200-1000 kW power range as shown in Figure 2 is common for smaller boat engine services or generator sets that use large-output outboard drives. By contrast, the category above 1 MW as shown in figure 3 features propeller algorithms used by large ships and marine generator sets for secondary energy generation. At the lowest power level, engine logs reveal that the application of Selective catalytic reduction (SCR) technology tends to meet third-party emissions requirements set by the International Maritime Organisation. But many engines (88.6) do not have emission-reduction technologies. The most popular type of fuel is petroleum (65.7%), which is explained by the fact that outboard motors are included in the number of recreational small vessels, and small inboard generators are included in the total data. The main emissions compliance regulations are the International Maritime Organisation Tier I -III standards, EU Stage II, US Pre-SI Second Stage, US SI Phases 1-2, and the US Stages II-III. The majority of motors are manufactured (62.9%), but a small portion is turbocharged.

Table 3. Marine engines two stroke and four stroke propulsion heat data

SNO	Source and Sink	Two-Stroke	Four-Stroke
1	Charge Air Cooler Cooling Circuit	26–37°C	29- 38°C
2	Sea Water (Heat sink)	-4 to +41°C	-6 to +42°C
3	Engine Room Air	41-46°C	42-46°C
4	Lube Oil Circuit	61–76°C	66–81°C
5	Cooling Water Jacket Temperature	82–92°C	83–96°C
6	Exhaust Gas Temperature After Turbine	252–301°C	302–510°C

2. Biodiesel as reduced emissions and marine engines progress in biofuels

Table 3 presents the heat data for two- and four-stroke marine propulsion systems, and Table 4 presents the effects of biodiesel blends on Marine diesel engines regarding engine performance, combustion, and Emission analysis. Considering recent research and trials on biofuels and Biodiesel, many of the largest Marine engine manufacturers in the world are turning their attention to biofuels and Biodiesel. Since the 1900s, Wartsila, a producer of underwater turbines based in Helsinki, Finland, has been using renewable energy sources. Its efforts began in 2000, and a series of renewable energy tests, such as palm and olive oil, was initiated. They have petrol or other vegetable-based oils in their engines [22]. These trials were carried out. A series of tests to confirm the standing of the manufacturer's 6L 32 engines at the Vaasa Engineering Laboratory, Finland. The first manufacturer's power station was built in Karlberg, Germany, in 2003, using Biodiesel. Afterwards, research into biofuel has improved significantly compared to when the company participated in 2015, as it has been involved with multiple maritime fuel companies to determine the right maritime ethanol to use in its motor. Mann Motor is a multinational manufacturer of engines. In 1994, biofuel. An investigation was conducted by them. Using different biofuel feeds to determine the most appropriate energy to drive their engine. The first test of Biodiesel was in 2006. The study was carried out in the Danish city of Copenhagen on the two-stroke low-speed engines. In 2007, another important step towards palm biofuel was taken when Men Diesel entered into a contract with palm biofuel [23]. Man Diesel offers a variety of marine engines that have proven to be well-suited for biodiesel without modification. Medium-speed engine shipper Rolls-Royce said it had no experience in using ethanol in its vehicles. Nevertheless, biofuel should generally be compatible with nautical propulsion systems. Authorities will be paying particular attention to this alternative fuel shortly, due to some of the buyers' demands. Cummins, another producer of boat engines located in America, also has many years of experience in biodiesel management. The company has conducted research on shuttle turbines that shows there are no immediate problems with using biofuels. [24].

Table 4. Effects of biofuels on marine engines

SNO	Biofuel Used	Engine Type	Performance Parameters	↓ Emissions	Reference
1	Rapeseed Oil	Marine Engine	BTE ↑ 8.73% BSFC ↓ 29.46	CO -13.30% CO_2 - 11.5% HC-7.60% NO_X-8.1%	[13]
2	Palm Oil	Marine Engine	BTE ↓ 9.6% BSFC ↑ 4.34	CO-4.9% CO_2 - 12.7% HC -11.1% NO_X -4.2%	[14]
3	Transformer oil	Marine Engine	BTE ↑12.02% BSFC ↓ 10.1%	CO-11.3% CO_2 -10.3% HC-14.6% NO_X-16.2%	[15]
4	Sunflower Oil	Marine Engine	BTE ↑ 2.1% BSFC ↓ 29.41%	CO-10.81% CO_2 - 10.7% HC-12% NO_X-11.6%	[16]
5	Waste Cooking Oil	Marine Engine	BTE ↑ 3.92% BSFC ↓ 7.42%	CO-13.30% CO_2 -11.9% HC-10.7% NO_X-9.8%	[17]
6	Juliforia oil	Marine Engine	BTE ↑ 6.9 % BSFC ↓ 5.2%	CO -11.8 % CO_2 - 11.1 % HC-11.2% NO_X-10.6%	[18]
7	Olive oil	Marine Engine	BTE ↑ 8.73 % BSFC ↓ 35.5%	CO-9.4% CO_2 9.1% HC-15.2% NO_X-9.8%	[19]
8	Waste pyrolysis oil	Marine Engine	BTE ↑ 5.74 % BSFC ↓ 16.2%	CO-11.3% CO_2 -11.1% HC-9.7% NO_X-9.7%	[20]
9	Soya bean Oil	Marine Engine	BTE ↑ 4.44 % BSFC ↓ 15.2%	CO- 13.81% CO_2 - 11.5% HC-14.8% NO_X-15.7%	[21]

Table 5. Blend approval of different Marine Engines

SNO	Biodiesel Standards	Blend Approval	Company Brand	References
1	ASTM D6751/EN 14214	5–20%	Yanmar	[25]
2	EN 14214	7–30%	Volvo Penta	[26]
3	ASTM D6751	10-100%	Fairbanks Morse	[27]
4	ASTM D6751	5 –20%	Detroit Diesel	[28]
5	EN 14214	10- 100%	Wärtsilä	[29]
6	ASTM D6751/EN 14214	10-30%	Caterpillar	[30]
7	DIN EN 14214	10- 100%	MAN Diesel	[31]
8	ASTM D6751/EN 14214	5 - 20%	Cummins	[32]

Table 6. ASTM Standards of marine blends and automotive blends

S NO	Property	Biodiesel EN14214	Marine diesel ISO 8217	Automotive diesel EN590
1	Flashpoint	> 125	> 62	> 55
2	Ash content, %	< 0.02	< 0.01	< 0.01
3	Sulphur, ppm	< 11	< 200,010	< 352
4	Water content, ppm	< 510	< 310	< 210
5	Calorific value, MJ/kg	37.5	43	44
6	Cetane no.	> 52	37	> 52
7	Acid no. (TAN)	< 0.4	< 2.6	< 0.4
8	Viscosity/40 °C, cSt	3.6–5.1	< 12	2.1–4.6
9	Density/15 °C, kg/m^3	861–910	< 910	825–847

Table 5 shows the craft approvals for different marine engine brands, including Yanmar, Volvo Penta, Fairbanks Morse, Detroit Diesel, Wärtsilä, Caterpillar, MAN Diesel, and Cummins. The table also provides the biodiesel standards and blend approvals of each brand. The low use of blend approvals is mainly due to the fact that exceeding blend limits would result in higher emissions, which in turn can cause serious health conditions in humans, such as lung cancer and asthma, and negatively affect other marine life. It is also important to note that surpassing such limits may cause engine cylinders and other parts to wear out and be damaged more quickly. Overheating disrupts the oxygen supply, leading to partial combustion. This would tend to raise cylinder vibrations, greatly increasing emissions. In difficult situations, engines with high emissions that exceed required standards can be disastrous, causing significant losses to the marine industry.

Yanmar Co. Ltd. is a Japanese manufacturer of nautical engines with a more than a century-long history. The firm has approved the use of B-5 biodiesel as an ingredient in its naval engine product line, provided the biodiesel meets ASTM D6751 or ISO EN14214 standards. Also, certain types of engines can use biofuels up to B20 concentration under certain conditions of use, as declared in Yamar's advisory. For example, Volvo Penta is a Swedish manufacturer of engines since 1907, known as a marine engine supplier, and manufactures engines with power ratings ranging from 10 to 800 horsepower. Volvo Penta can operate with biofuel up to 7 per cent. A combination above 30 per cent can be authorized only on engines produced after January 1, 2012, provided that they meet the requirements of EN 14214 and EN 590. The company insists that users of fuels containing 30 per cent biofuel require proper engine maintenance. This, however, is not the case with the manufacturer's supplemental generators. The company was the first to sell gasoline engines in the country. Once a manufacturer, Fairbanks Morse is currently the top-ranking producer of boating and fixed-power engines. The company enables the use of B100, or 100 per cent biodiesel, in its Contrary Diaphragm Model 38D engine. They assert that biofuels contribute to emission reductions by reducing carbon monoxide and fine particle matter. They also use fish oil biofuels in their rotating engines and medium-speed generating motors. Oakland State College also started using bioenergy B80 in the late 1990s. Barrow Morse Engine has reached another milestone by successfully introducing B100 soybean biodiesel into its engines.

Detroit Diesel, based in Detroit, Michigan, makes heavy-duty engines for use on land and at sea. It paves the way for the use of B5 biodiesel certified by ASTM in specified engine types, namely the DD13, DD15, DD16, and engine models marked with MBE9004000. This applies to engines in the Series Sixty, which were fabricated after 2004, and can run up to 20 per cent of bio-diesel. But engines manufactured before 2004 are not supposed to consume more than 5 per cent biodiesel, as some parts may not be compatible. This contains some foam seals and metals, including bronze, copper, zinc, galvanized iron, and lead. Wartsila has also used palm oil-based biofuel in various outdoor locomotives in Europe, which are mainly used to generate power. The firm has four biofuel generators that have a total capacity of 820 MW. The Wärtsilä 6L 20 power plant can use many different types of biofuels that fulfil Wärtsilä's bioenergy requirements. They have an engine technology that enables them to use various hydrocarbons without disrupting performance.

Only the use of authorized ASTM D6751/EN 14214 biodiesel, as indicated in the engine instructions, is covered by the manufacturer's warranty. Consumers are encouraged to contact engine dealers if they want to use a biodiesel blend exceeding the maximum of 30. MAN Mechanical is involved in the manufacture of large-bore maritime diesel propulsion engines and has specialized in operating large, medium-speed 4-stroke engines on renewable fuels. Such fuels include oil from soybeans, palm oil, sunflower seed oil, edible waste oil, and animal fat. Under their guidelines, MAN permits the use of biofuels in their combustion engines but also imposes restrictions on biodiesel blends, especially those of residual oil or heavy fuel oil. MAN focuses on the utilization of its large, medium-speed engines that operate on B5 fuel (5 per cent biodiesel). Cummins supports using 5 per cent biodiesel in all of its engine models, as long as the blends comply with the requirements defined by ASTM D6751 or EN14214. Biodiesel concentrations as high as 20% (B20) can only be used in limited models that meet the emission standards. The ASTM standards for marine and automotive blends are presented in Table 6.

2.1. Potential challenge as biodiesel in the field of marine industry

Biodiesel has been considered the best alternative fuel for replacing existing marine fuels. It states that using soybean oil as a feedstock is not as preferred as using pure biodiesel or its mixtures, although palm oil, sunflower seeds, and waste oil can also be used as alternatives [33]. The combustion of pollutants from maritime boats can be greatly reduced with the use of pure biodiesel or biodiesel mixtures, with or without modifications to the engine. Some renowned engine makers, namely Caterpillar, Wärtsilä, MAN, and Rolls-Royce, have stated that biodiesel can be used in their boat engines. There are various issues and challenges that may prevent methanol from being utilised in marine engines, along with possible corrective solutions. Possible advantages of biodiesel in the maritime industry.

2.2. Competitiveness in feedstock

Producing biodiesel consumes a significant amount of fuel. Most countries now use edible crops to produce biofuels, such as corn, coconut, palm, and rapeseed oils. The availability of food to the sector is threatened, thereby raising competition in the biodiesel business, since the sector has been dependent on food sources. Further, customers have shifted their attention to alternative channels for recovering ethanol due to the ever-increasing cost of fodder. Some of the new generations of biodiesel are neem, algae and waste oil, which are inedible, and the waste oil is inexpensive. Microalgae are a good choice as a natural, environmentally friendly source of biodiesel. Compared to plants that can produce safflower or soybean, phytoplankton produce between 10 and 20 times the amount of biodiesel but require approximately 100 times less space. In both environments, you will find macroalgae, or large algae that undergo photosynthesis, and microalgae, or very small algae [34]

2.3. Stability of fuel oxidation

It is seen that the stability of fuel oxidation for different biodiesel blends is quite high, due to varying combustion rates and phenomena discussed above. Biofuels require special care because they are likely to be oxidation-sensitive and may deteriorate during long-term storage. Biofuels may be destroyed by oxidative or microbial degradation when exposed to humidity. copper-coloured, bronze-coloured, zinc, tin, and brass are among the ingredients utilised. react immediately and therefore cannot be retained in standard tanks for storage. The development of aluminium substances, sodium chloride, and hydrogel is possible [35].

2.4. Feasibility in production costs

The final price of biodiesel includes the cost of raw materials, the processing costs for cleansing, and manufacturing. Numerous studies have identified that biodiesel raw materials are very expensive, with the high cost of vegetable feedstocks accounting for about 75 per cent of the total production cost [36,37]. It is important to decide to feed properly to reduce manufacturing costs. As an example, alone, it is clear that the price of used cooking oil is two or three times lower than pure vegetable oil. As stated earlier, developing a new process or finding more ways to use less expensive byproducts would help make biodiesel cheaper. The generation of biofuel from agricultural products, such as algae and used oil, has increased by an enormous percentage over the past few years. This innovation has led to better, cheaper biodiesel production. The existence of government incentive programs comprising tax breaks, economic incentives, and low biofuel prices in petroleum products also plays a significant role in reducing the cost of producing biofuels.

3. Marine Diesel Engine

Figure 4. Experimental setup of marine diesel engine [38] permissions from Ain Shams Engineering Journal

Figure 4 illustrates the typical experimental setup used in the marine industry. The engine is cleaned thoroughly before the biodiesel experimentation is conducted, and an uncertainty analysis is performed across three sets of trials to assess the accuracy of the engine parts and associated components and identify potential errors. Table 7 defines Engine specifications. The AVL gas exhaust analyser is utilised in the experimental setup to monitor the different types of gases emitted to the atmosphere with the least possible deviation. Table 8 represents different nanoadditives and their performance.

Table 7. Engine specifications

S NO	Description	Units	Specification
1	Cylinders		6
2	Cycle Type	-	4 Stroke
3	Output of Engine	kW	210
4	Engine mass	kg	900
5	Displacement of piston	Litres	11400
6	Type of Aspiration	-	Turbocharged

Table 8. Dispersion and effects of different nano additives

Biodiesel	Percentage of blends	Nano additive	PPM	Main effect	References
Jatropha	25 20	Al_2O_3 Cerium Oxide	20 90	BTE is increased by 1.23%	[68]
Polanga	25	CeO_2	25	All emissions is reduced by 2%	[69]
Waste Cooking	20	TiO_2	50	Emissions reduced by 10%	[70]
Algae	100	Zno	100	CO and HC emissions are decreased	[71]
Braunii	20	Copper oxide	100	NOx is reduced by 3.4%	[72]

4. Error or uncertainty analysis

Finding positive concordance in the research findings, distinct performance settings, and mistakes requires extensive error-prone studies. An examination of conviction took advantage of the Phillips approach for the spread of unknowns [67]. Tables 9 refers instruments uncertainties and Table 10 refers parameter uncertainty for each device.

Table 9. Instruments uncertainties

Sl. No	Measured Instrument	%Uncertainty
1	Stopwatch	0.24
2	Manometer	0.9
3	Tachometer	0.55
4	Exhaust Gas	0.22
5	Smoke meter	0.9
6	Pressure Transducer	0.5

Table 10. Parameter uncertainty

Sl. No	Parameters	% Uncertainty
1	Oxygen Content	0.25
2	NO_x	0.5
3	CO	0.4
4	UBHC	0.4
5	BTE	1.2
6	Pressure	1.4
7	BSFC	1.1
7	Load	0.9
8	CO_2	0.8

5. Marine engine performance

5.1. Performance and emissions overview

Some biofuels, in addition to their fuel properties, have poor cold-flow characteristics, requiring the use of chemicals to enable seasonal use. The CO_2 emitted during the ignition process is also considered environmentally friendly because it is offset by the CO_2 captured during grain production. Biodiesel generally increases NOx emissions due to higher combustion temperatures, and it requires reduction strategies. The particles emitted by fuels are significantly reduced compared to those from conventional fuels. Biofuels may contain low levels of sulfur, thereby eliminating SO_2. Jatropha biodiesel is a potential alternative fuel which is derived from the seeds of Jatropha curcas. A summary of its efficiency and pollutants is provided below: Jatropha, as well as biodiesel blends (with up to 20 content), have BTE comparable to oil, but larger mixes 50% and above) tend to reduce this effectiveness, especially. High blends increase the consumption of fuel between ten and twenty per cent because of reduced energy density. Jatropha ethanol augments engine oiling, reduces, and enhances durability. Freezing movement similarity.: Like other diesels, the plant ethanol has poor freezing flow properties, requiring the addition of lubricants during seasonal use.CO_2 emissions: Worse than diesel at low temperatures, but better at higher loads because of emissions raised compared to diesel due to poor combustion at higher mixes. The increase in NOx compared to gas requires implementing measures. Lower than with combustible fuel, however, overheated seed ethanol is characterised by high-emitting smoke [62]. Ethanol from sunflowers is now being studied to realise its potential as an alternative to oil-based fuels.

This study examines its effectiveness and greenhouse gas emissions: Sunflower-mixed biodiesel generally shows BTE comparable to diesel, with slight reductions at higher blends. Mixes of safflower and biodiesel, due to their lower energy content, tend to require more fuel than pure biodiesel. Safflower biofuels increase machine friction, reducing corrosion and increasing durability. Just like other renewable fuels, safflower biofuel also has poor cold-flow properties, which require the use of modifiers when used seasonally. Safflower ethanol has a lower carbon footprint than diesel and therefore alleviates the effects of global warming. Less than biodiesel due to the increased combustion ability[65]. NOx greenhouse gases are produced by combustion due to higher oxygen levels, and reducing these levels requires minimisation. Biodiesel mixed with safflower reduces smoke opacity and levels of chemical greenhouse gases, particularly in the presence of ethanol stabilisers. Studies have been carried out on blends of cottonseed oil biodiesel, using various additives to enhance performance and emissions properties. Cottonseed or seed biodiesel blends exhibit higher combustion efficiency when supplemented with chemicals such as cellulose nanotubes (CNTs). Methanol-hemp seed oil enhances engine grease, reduces wear, and extends life. The downside of cottonseed biodiesel is its poor chilli-stability properties, and the use of antioxidants is encouraged to make it work seasonally. Biodiesel made from cottonseed reduces greenhouse gas emissions compared to diesel. Less than diesel due to improved combustion. Higher than propane because of increased oxygenation level; however, antioxidants like CNTs help to mitigate the pollutants of NOx. Ethanol blends derived from cottonseed reduce the visibility of smoke emissions and hydrocarbon emissions [45,46].

5.2. Brake thermal efficiency

The very important parameter that determines the capability of engine brake power, capable of liberating the chemical energy required during the combustion process of a Marine diesel engine, is defined by the term brake thermal efficiency [39]. The brake thermal efficiency of blends such as cotton, jatropha, sunflower, and soya is higher than that of conventional diesel engines due to the higher calorific values of the blends. The maximum brake thermal efficiency for rape seed biodiesel blends is 36.2%, but for diesel it is 30.1%. Rape seed biodiesel leads by 17.21%, superior to diesel blends. This results in superior performance compared to diesel-based fuels. Few researchers have reported that the lowest calorific value is achieved with the palm biodiesel blend, because the higher density of diesel results in the lowest brake thermal efficiency [40].

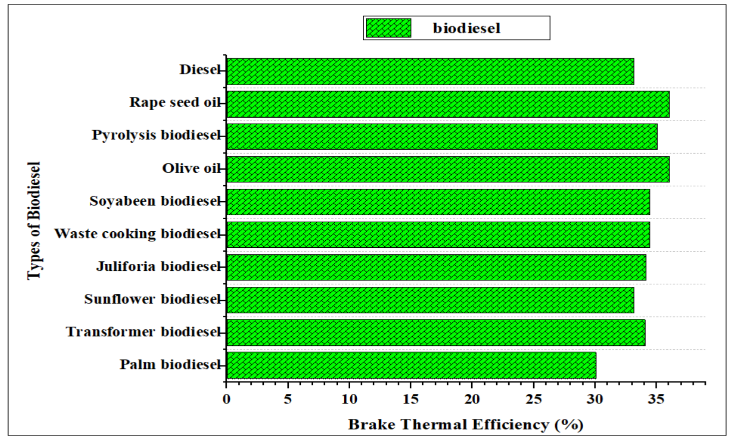

Figure 5. Brake thermal efficiency

Brake Specific Fuel Consumption

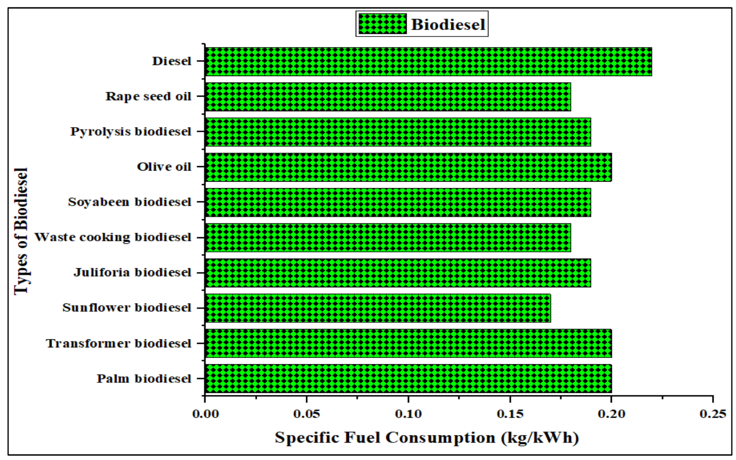

Figure 6. Brake-specific fuel consumption

The lowest amount of fuel consumed per kg/kWh when a marine diesel engine operates at elevated temperatures and pressures is called the brake-specific fuel consumption; Figure 6 shows brake-specific fuel consumption for biofuel tested in marine diesel engines. This term defines the engine's lowest consumption and improved performance, subject to consumption levels [41]. Few researchers reported that the lowest consumption of the blends is achieved at 31.3% compared to diesel, due to their lower density, which results in easier evaporation than diesel. The various potential biodiesel blends such as transformer oil, pyrolysis oil, sunflower oil, jatropha oil, and rapeseed oil have significant effects on marine diesel engines, followed by the very least consumption of fuels at elevated pressures and temperatures at peak loads during the combustion process [42], It is also noted that rapeseed blends offers very low specific fuel consumption followed by 0.18 kg/kWh, which is 33.3% low than diesel.

6. Combustion

6.1. Heat release rate

The rate of heat released during the combustion of fuels under elevated pressure and temperature is called the heat release rate. The HRR is higher for all biodiesel blends than for diesel. The surface tension property plays a vital role in achieving these heat release rates as a function of crank angle. The lowest atomization results in the lowest HRR, leading to poor combustion [43]. Hence, the moderate atomization of biodiesel blends results in the highest atomization with oxygen supply than diesel-based fuels in the marine industry.

6.2. Inline cylinder pressure

The important technical term that defines the amount of pressures required or peak pressures required to accelerate the combustion process is superior and quicker owing to different rotations of crankshafts is called inline cylinder pressures, Usually the inline cylinder pressures for diesel occur above 60 bar, various researchers reported that biodiesel blends operated for marine diesel engines exceeds 60 bar, because of high oxygenated atoms present in the biodiesel blends tends to oxidize, evaporate and form combustion in shorter ignition delay. The longer ignition delay causes the piston and cylinder movements from TDC to BDC to have more elaborate ignition timing,, resulting in poor formation of cylinder pressure [44].

7. Emissions

7.1. Hydrocarbon emissions

The hydrocarbon emissions are distinguished by the development of white, pungent fumes that rush to unburned sources of carbon in case of excess supply of hydrogen molecules. These emissions are a threatening and dangerous one, especially to the elderly, and may also lead to eye diseases. Scientists have discovered that biodiesel blends in marine diesel engines produce lower emissions in parts per million (ppm) than ordinary engines. Figure 7 shows the hydrocarbon emissions of biofuel mixtures and conventional diesel in four-stroke marine diesel engines. The hydrocarbon content in biofuels is much lower than in conventional diesel. Furthermore, the levels of petroleum hydrocarbons in various forms of gasoline differ. Maritime energy is normally comprised of lighter elements of petroleum, which are easily evaporated.

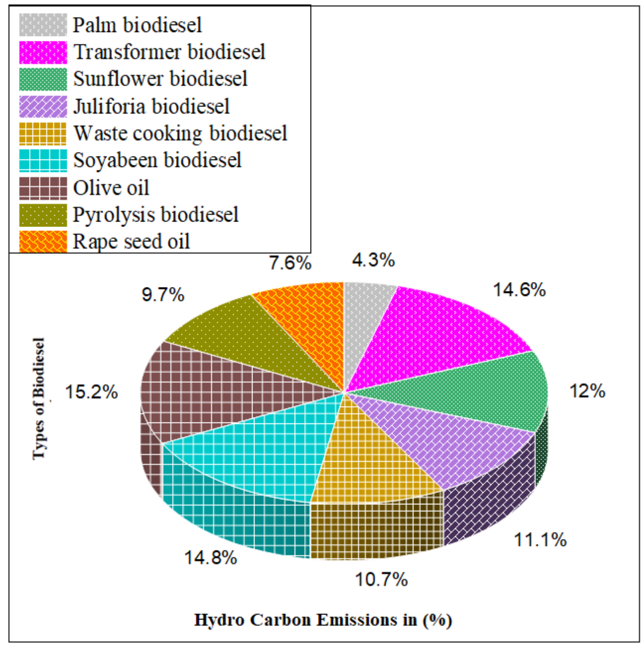

Figure 7. HC emissions of different biofuels and diesel [63] Permissions from Energies

A performance evaluation utilising sunflowers found that a higher proportion of olive oil decreased unprocessed hydrocarbon output across all investigated scenarios. Phthalates in fuels have led to accelerated vaporisation, increased efficiency, and consistent ignition. J The probable cause of this is the different kinds of hydrocarbons. It is more prevalent in heavy gasoline oil than in biofuel. It also reported a drop in vehicle engines. HC components by fourteen per cent to thirty per cent, respectively, while utilising B20 Palm biodiesel. These outcomes can be ascribed to elevated cetane concentrations and oxygenation components in the biodiesel fuels, which enhance the Oxidation of unburned hydrocarbons [47]. The lowest HC emissions are achieved with olive oil, which is 15.2% lower than diesel. The highest cetane number tends to atomise the fuel into a finer spray, rapidly accelerating carbon atoms with hydrogen atoms [48]

7.2. Carbon monoxide emissions

The particulate matter resulting from the incomplete combustion of carbon molecules combined with oxygen molecules under inadequate combustion conditions and excess oxygen supply is termed co-emissions [49]. Figure 8 shows CO emissions from different biofuels tested on marine diesel engines; from the various blends, it is evident that soybean biodiesel blends have the least CO emissions, followed by 13.8% more than diesel. This is due to the property that blends with higher calorific values tend to vaporise more quickly and emit fewer emissions than diesel [50].

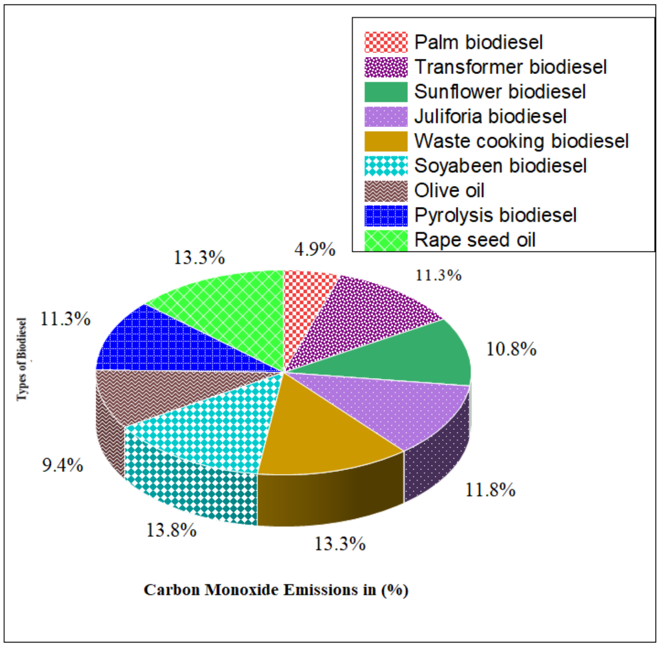

Figure 8. CO Emissions [64] Permissions from ACS omega

7.3. Carbon dioxide emissions

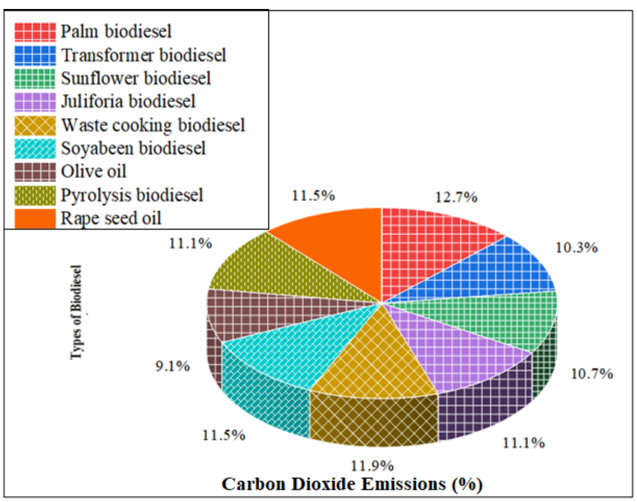

Figure 9. CO_2 Emissions

The unburnt gases that escape into the atmosphere are very harmful to lung cancer and eye disorders, and they result from insufficient combustion of air with carbon molecules [51]. Figure 9 depicts the CO2 emissions caused by the various biodiesel blends utilised in marine diesel engines [52]. Among various researchers investigating different biofuels, palm biodiesel has the lowest CO_2 emissions due to its easier evaporation, atomization, and penetration compared to other blends. Next to palm biodiesel, the CO_2 emissions are lower for waste-cooking biodiesel blends, with 11.9% less than diesel. The reduction in the formation of cooking biodiesel blends is due to the blends' higher surface tensions, which efficiently atomise and have higher calorific values than diesel [53,58].

7.4. Nitrogen emissions

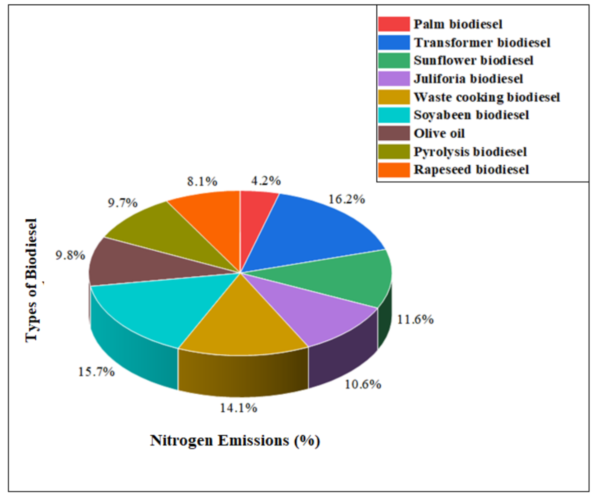

Figure 10. NO_X Emissions [66] Permissions from International Journal of Ambient Energy

Emissions resulting from increased temperatures and reduced oxygen supply under higher pressure are called NOX emissions [54]. Healing these harmful gases results in permanent failure of respiratory organisms. Figure 10 represents the NO_X emissions offered by different blends tested on marine diesel engines. The reduced NOX emissions observed for the soybean biodiesel blends are 15.7% lower than those of diesel. This is due to the good oxidation stability of the soybean blends, owing to lower viscosities and better ignition delays than other blends and diesel [55]. Next to the sunflower oil, the waste cooking properties are better than those of diesel, which is reduced in NOX formations by 14.1% less than diesel. Hence, various studies show that all biodiesel blends produce less NOX than diesel [56]. Therefore, researchers suggested utilising biodiesel blends for future aspects of the marine industry.

8. Conclusion

The research on biodiesel blends in the marine sector and the possible difficulties they pose is thoroughly examined. This study has enabled the realisation that Biodiesel blends have significant potential for enhanced brake thermal efficiency and reduced emissions. Because of the high calorific values of various biofuels, which greatly affect performance, biodiesel blends with higher calorific values have lower fuel consumption than diesel. Another significant property that influences the performance of marine diesel engines powered by biodiesel is that the higher the cetane number and the lower the density, the higher the oxidation rate and hence easier atomization. This makes the engine's operation much smoother than with diesel or other traditional fuels. The utilisation of the marine diesel engine results in the following:

- The highest brake thermal efficiency offered by rape seed biodiesel blends is 36.2, whereas the BTE of diesel is 30.1. Rape seed biodiesel is 17.21 per cent superior to diesel blends. All biodiesel blends have a higher calorific value than diesel.
- Among the biodiesel blends, Rapeseed blends are the only ones with very low consumption compared to diesel, at 0.18 kg/kWh, 33.3% lower than diesel.
- These heat release rates, when subjected to crank angle motion, are heavily dependent on surface tension. Therefore, all biodiesel blends have lower heat release rates than diesel.
- These heat release rates, when subjected to crank angle motion, are heavily dependent on surface tension. Therefore, all the biodiesel blends have lower heat release rates than diesel.
- The inline cylinder pressure is high across all biodiesel blends, due to the high oxygen content, which is likely to oxidise and evaporate, resulting in shorter ignition delay and combustion.
- The lowest HC emissions are obtained when using the Olive oils, it is 15.2 lower than diesel due to the highest cetane number, which tends to atomise the fuel in a fine spray to thrust the carbon atoms with the hydrogen atoms at a very high rate.
- It is well known that soybean biodiesel blends have the lowest CO emissions, at 13.8%, compared to diesel, due to their higher calorific values, which tend to easily vaporise the blend and give lower emissions than diesel.
- The waste-cooking biodiesel blends have the lowest CO2 emissions, 11.9% lower than diesel. The decrease in the formation of cooking biodiesel blends is due to the higher surface tensions of the blends, which facilitate easier atomization and higher calorific values compared to diesel.
- Lower NOX emissions are observed with soybean biodiesel blends, which are 15.7% lower than with diesel. It is because of the observed good oxidation stability of the soybean blends, with low viscosities and delayed ignition compared to diesel and other blends.

Author contributions statement

K. Sunil Kumar – conceptualization and writing - original draft. Sathish Kumar Kumaravel – Review & editing. Devikala S - method, software. Ganapathy G - supervision. Kala Raja Mohan - Formal analysis.

Declaration of interests

The authors have any competing financial or personal interests related to this work.

Data availability statement

The datasets used and or analyzed during the current study are available from the corresponding author on reasonable request.

Declaration of generative AI and AI-assisted technologies in the writing process

The authors would like to thank AI-powered writing tools, such as Grammarly, for their aid in enhancing the linguistic precision, correctness of grammatical structures, and the overall coherence of this article. All content, analysis and conclusions contained in this work are the author's own and are not in any way the work of AI. All content, analytical discussion and conclusions presented in this work are the sole work of the author and have not been generated using AI tools for any purpose other than to enhance the presentation and clarity of the text. The use of AI is aligned with the journal's standards of transparency and ethical guidelines in the authoring process.

Appendices

Al_2O_3	Aluminum Oxide
BTE	Brake thermal efficiency
B100	100% biodiesel
BSFC	Brake-specific fuel consumption
TDC	Top dead Centre
BDC	Bottom dead Centre
CeO_2	Cerium Oxide
ASTM	American Society for Testing and Materials
EU	European union
US	United States
NO_X	Nitrogen oxide
TiO_2	Titanium Oxide
HC	Hydro carbons
CO	Carbon monoxide
CO_2	Carbon dioxide
Zno	Zinc Oxide

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