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The Experimental Investigation of a Diesel Engine Using Ternary Blends of Algae Biodiesel, Ethanol and Diesel Fuels

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Abstract: Algae are regarded among the most favorable feedstocks for producing sustainable biodiesel and utilizing it in diesel engines. Additionally, ethanol addition further enhanced the performance and reduce greenhouse emission. Algae biodiesel was produced, and an experimental study was performed to understand the diesel engine performance and emissions characteristics using different fuel blends by varying the ratio of diesel, biodiesel, and ethanol, such as D100, B10, B20, B5E5, and B10E10 (where number shows the percentage of the respective fuel). It was found that brake thermal efficiency was reduced by 0.49% and 1.29% for B10 and B20 blends, while the addition of ethanol enhanced the BTE by 0.37% and 1.60% respectively. However, SFC increases by 1.45%, 2.14%, 3.18%, and 3.78% respectively for B10, B20, B5E5, and B10E10 with respect to diesel fuel. Combustion characteristics were increased with increasing concentration of biodiesel and ethanol addition. Particulate matter, smoke emissions, and CO_2 were slightly reduced by 3%, 4%, and 0.18%, respectively, while NOx emissions were increased by 26% for B10 blended fuel as compared to diesel fuel. Further addition of 5% (volume) ethanol in B5 fuel reduced particulate matter, smoke emissions, and CO_2 emissions by 26.4%, 22%, and 23% respectively. Among the tested blends (B10, B20, B5E5, and B10E10), ethanol blended fuel was found to be more promising due to its higher combustion and performance and to have lower emissions to diesel fuel.

Keywords: algae; diesel; biodiesel; ethanol; diesel engine; performance; emission

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1. Introduction

The use of fossil fuels, which are the primary transportation fuels in emerging nations, has increased due to rapid population expansion and industrialization. It is virtually guaranteed that fossil fuels will contribute to around 60% of the expansion in energy, accounting for over 80% of the global energy supply by 2035. This circumstance is predicted to persist in the future [1]. India ranks third in crude oil consumption despite ranking twenty-first in crude oil production. There is a huge difference between oil consumption to oil production. These crude oil imbalances suggest that India is heavily reliant on crude oil imports [2]. Similarly, India, Japan, European Union nations, South Asian countries, and African countries rely heavily on crude oil imports from other countries. These crude oils are used in different sectors for power and electricity, such as transportation, industry, electricity generation, etc. [3]. However, the majority of refined crude oil, i.e., petroleum-based fuel, is used in the transportation sector.

The major concerns that must be taken into consideration when utilizing diesel as a fuel in an internal combustion engine (ICE) include rising exhaust gas emissions and the price of crude oil [4]. The health of people is impacted by major polluting gases, such as NOx, carbon monoxide, unburned hydrocarbons, and smoke opacity, which also contribute to environmental pollution [5]. A diesel-powered engine is necessary in today's climate.

However, it significantly adds to air pollution in the atmosphere. Diesel engines pollute the air because they emit high quantities of aromatics and Sulphur [6]. Emissions from fossil-fueled diesel engines include smoke, NOx, CO_2, CO, SO_x, and PM [7]. With over 66% use, the transportation sector is the largest segment responsible for the limitless energy utilisation from conventional fuel.

The continual depletion of conventional fuel, growing costs, and escalating emissions of greenhouse gases have increased the demand for environmentally friendly, cost-effective, and renewable energy that is conducive to lowering greenhouse gas emissions [8,9]. As a result, there is a need to transition energy from fossil derived fuel to alternative fuel. Canabarro et al. (2022) observed that 70% GHG emission were reduced when biofuel used in place of diesel fuel [10]. Finding a sustainable and alternative fuel to replace diesel is essential to address the current problems and halt climate change. Furthermore, the use of biofuels, such as biodiesel, which has lately been deemed a reasonable substitute to fossil fuels, helps to improve combustion and reduce greenhouse emission [11].

Biodiesels have become increasingly popular in recent years because it contains no sulphur, are oxygenated, and have a higher cetane number than fossil diesel. They typically emit fewer exhaust emissions than those of fossil diesel. Biodiesel also has strong lubricity, which helps the moving components of engine. Biodiesel can be derived using different generation feedstock, including 1st, 2nd, and 3rd generation feedstock [12].

Traditionally, first-generation biodiesel was derived from edible biomass, such as vegetable oils, which may substitute the use of fossil fuel burning while simultaneously reducing CO_2 emissions into the environment. However, it was considered that using first-generation fuel sources would cause a food vs. fuel catastrophe. To address this issue, second-generation biofuels were developed using non-edible feedstock such as agricultural waste, wood residual waste, and energy crops. The amount of carbon generated or ingested by second-generation biofuels is either negative or neutral. The fundamental disadvantage of second-generation fuels is their seasonal reliance on raw resources. Algae is a third-generation biofuel that is a viable alternative renewable source for biofuel production that overcomes the disadvantages of first and second-generation biofuels. These advantages have led to a growth in biodiesel production from diverse feedstocks throughout the years [2]. Despite the advantages described previously, there are significant downsides to using biodiesel in diesel or turbine engines alone. Relative to fossil diesel, biodiesel has greater BSFC and NOx emissions along with lower BTE and ITE.

Prabhu et al. (2018) tested biodiesel blends in diesel engines and discovered that it is a preferable alternative to conventional diesel fuel. The compression ratio was varied, and it was found that the performance of biodiesel is fairly close to that of diesel. However, there was decrease in BTE and increase in SFC and NOx emission as compared to diesel fuel [13]. Karthikeyan et al. (2020) conducted experiments in a CI engine utilizing a diesel–Marginatum macroalgae biodiesel blend. These mixes were tested on diesel engines at a constant rotational speed of 1500 rpm under varied loads, including low, partial, and high loads [14]. Subramaniam et al. (2020) performed an experimental study on blend of algal biodiesel and diesel fuel. Among the evaluated test fuel, A_{20} was found to be more similar to diesel in the terms of combustion. It was discovered that using biodiesel fuel resulted in higher thermal efficiency and lower PM, smoke, CO, and HC emissions except for NOx [15]. Kurczynski et al. (2021) derived biodiesel from waste animal fat and tested it in a diesel engine. It was found that biodiesel blend fuel reduced PM, and CO emissions while there was an increase in SFC and NOx [16]. Rajak et al. (2022) and Singh et al. (2022) obtained similar findings using biodiesel blended fuel in a diesel engine [17,18]. Further, the addition of biodiesel in diesel fuel reduces the BTE and increases the SFC of fuel. These challenges can be overcome by adding some oxygenated additives such as ethanol [19]. Karin et al. (2022) performed an experimental study utilizing the ethanol in biodiesel blended fuel. It was found that Ethanol-blended biodiesel fuel can cut smoke emissions [20]. Sathish et al. (2022) utilize the ethanol in Azadirachta indica biodiesel blend to predict the engine behavior. It was found that BTE was increased by 15% for D80B20 blend as compared to B100 fuel [21].

It was found from the literature that biodiesel can reduce the greenhouse gas emission and can easily blended with diesel fuel. However, the addition of biodiesel in diesel fuel lowers the BTE and increases the SFC. Further, the combustion characteristics of diesel biodiesel blended fuel were found to be lower than the diesel fuel. The emission of NOx also increased with an increasing concentration of biodiesel fuel. These limitations of biodiesel blended fuel can be reduced by adding small concentration of ethanol fuel.

The primary goal of this study is to propose an alternative fuel (biodiesel) derived from algae and further preparing binary and ternary blend with addition of diesel and ethanol. The prepared blend was tested, and an investigation was carried out to understand the influence of blended fuel in diesel engine. The idea focuses on the utilisation of sustainable biodiesel production derived from locally available algae. Furthermore, the paper discusses in detail the key design features of biodiesel production, blending procedure, and the experimental assessment in diesel engine using ethanol addition. As a result, current research work helps in closing the information gap in the application of biodiesel blends and ethanol.

The current research work is as follows. Section 2 highlights the algae oil extraction, biodiesel production, blending procedure and ethanol addition, fuel qualities, experimental test setup, its key features, test protocol, and uncertainty analysis. Section 3 summarizes the key findings of the investigation and initiates vital conversations. Section 4 concludes with closing remarks and future prospects on the subject.

2. Materials and Methods

2.1. Raw Materials

The heterogeneous colony of microalgae was gathered from a lake in Bhopal. The other chemicals, such as catalyst, alcohol, n-hexane etc., were purchased from the local supplier in Bhopal. The collected algae were dried in the sunlight around one week and converted into powder form. A Soxhlet extractor was utilized to extract oil from the dried algae, employing n-hexane as the solvent. The transesterification reaction was carried out using a 6:1 methanol to oil ratio, and (0.9% wt.) KOH catalyst (0.9% wt.) at 65 °C for 80 min. The biodiesel and glycerol were separated under typical gravity circumstances. Figure 1 depicts the schematic diagram of biodiesel production from algae.

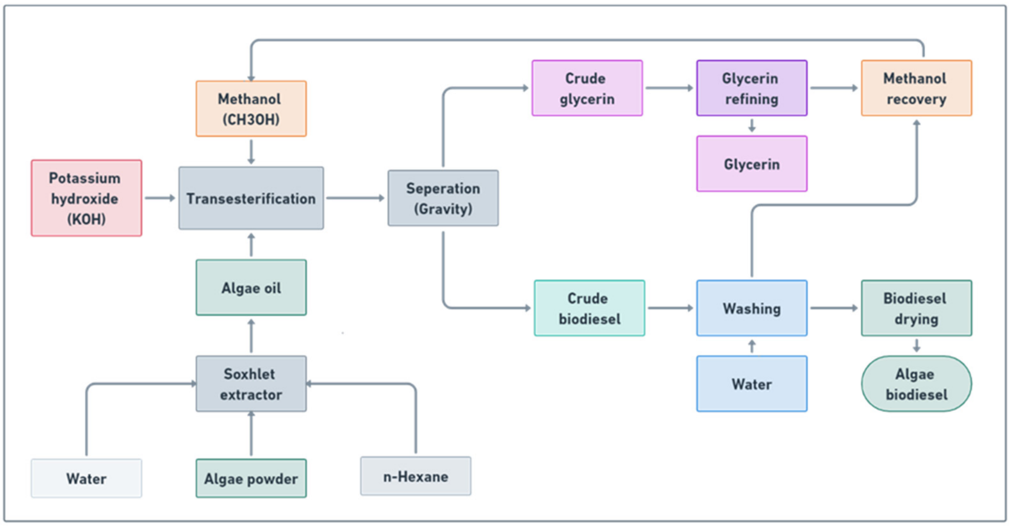

Figure 1. Schematic diagram of biodiesel production from algae.

The physiochemical properties of algae biodiesel were tested according to ASTM standards and listed in Table 1, along with diesel and ethanol fuel.

Table 1. Physicochemical properties of diesel, ethanol and algae biodiesel fuel.

Fuel Properties	Test Method	Ethanol	Diesel	Algae Biodiesel
Carbon (mass%)		52.2	87	78
Hydrogen (mass%)	ASTM D 5291	13.0	12.6	12
Oxygen (mass%)		34.8	0.4	10
Density at 25 °C (kg/m^3)	ASTM D 1298	789	830	871
Viscosity @ 40 °C (mm^2/s)	ASTM D 445	1.2	2.6	5.2
Calorific value (MJ/kg)	ASTM D 240	28.32	42.5	40
Cetane number	-	8	48	52
Auto ignition temperature (°C)	-	365	210	-

2.2. Blend Preparation

Binary and ternary blends are developed and tested against diesel fuel. The blending procedure was carried out using a mechanical mixing approach in which the mixture of algae and diesel was constantly swirled at a speed of 500 rpm for 25 min with a magnetic stirrer at room temperature. Binary blends are represented by the letters BX, while ternary blends are represented as BXEY, where X and Y represent the volume concentration of algae biodiesel and ethanol in diesel fuel. Table 2 lists the key attributes of these blends. All of these blends are thoroughly blended before being analyzed for biofuel homogeneity.

Table 2. Physicochemical properties of diesel, binary and ternary test fuel.

Fuel Blend	Carbon (mass%)	Hydrogen (mass%)	Oxygen (mass%)	Density (kg/m^3)	Viscosity (mm^2/s)	C. Value (MJ/kg)	Cetane Number
D100	87.0	12.6	0.4	830	2.6	42.5	48
B10	86.1	12.5	1.4	834	3.1	42.1	48.4
B20	85.3	12.4	2.3	838	3.5	41.9	48.9
B5E5	75.5	12.6	11.9	829	2.8	41.5	47.8
B10E10	73.9	12.7	13.4	826	2.6	41.1	47.6

2.3. Test Engine

The current experiment was performed on a 3.7 kW direct combustion Kirloskar Model TV 1 diesel engine. A K type thermocouple, standard burette, and an orifice meter were used to monitor the temperature and mass flow rates of fuel and air respectively. An electrical dynamometer was used to load the engine. The emission characteristics, such as CO_2, NOx, and smoke, are measured employing a testo 350 gas analyzer and PM is measured employing air quality device with particle counter (Testo 380). The test engine is fitted with a differential pressure sensor at the air tank section for measurement of the actual volume of air being drawn into the cylinder. Additionally, a Piezo-electric pressure sensor with measurement range of 0–100 bar is fitted for measuring the pressure inside the cylinder.

The data gathering unit signals were synced with the crank angle encoder data. The analogue signal was converted into digital using an analog-to-digital converter and real-time data was analyzed and recorded in data acquisition system. A typical schematic of the test engine is shown in Figure 2. Three repetitions of each experiment were performed, and average data were taken for the computation to assure repeatability.

2.4. Test Procedure

The produced fuel blends are subjected to testing with varying engine loads. To assure the accuracy of the data obtained, the engine is operated on diesel for 10 min before to every investigation. Only after the engine achieved stable equilibrium were the test values recorded. Meanwhile, the stationary multifuel engine is driven at its maximum speed of 1500 revolutions per minute (rpm). The study of different performance metrics, i.e., BTE, ITE, and BSFC, are computed using thermodynamic relations, and the emission characteristics, CO_2, smoke, and NOx, are determined using a testo 380 gas analyzer. The experiment test was carried out at 15.5 compression ratio, 1500 rpm engine speed, adopting various engine loads (25%, 50%, 75%, and 100%) using a 3.7-kW diesel engine.

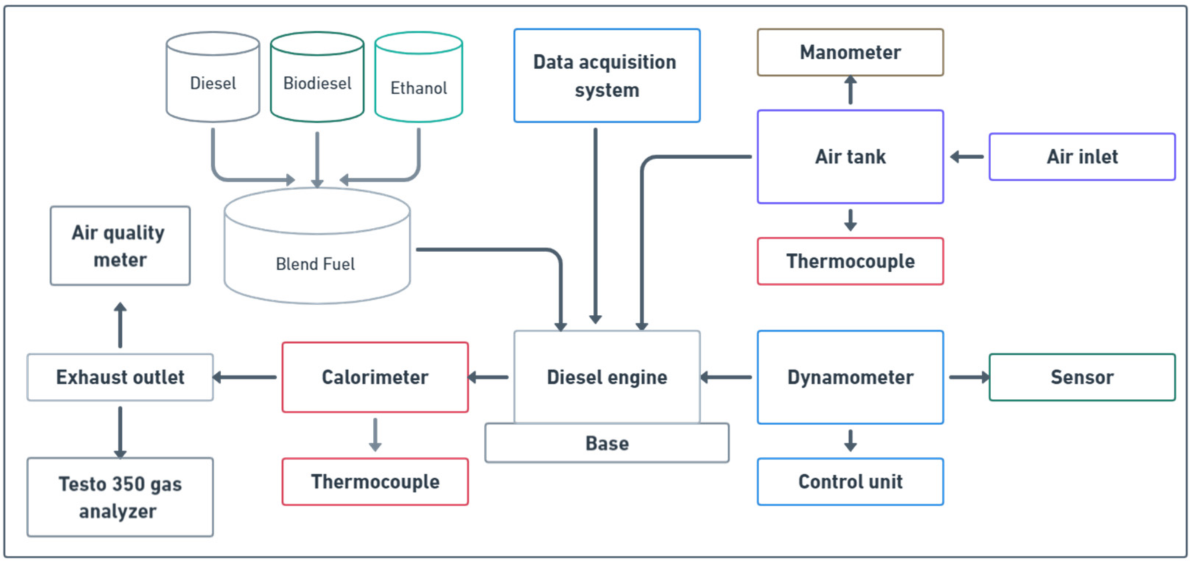

Figure 2. Schematic diagram of test engine and procedures.

2.5. Uncertainty Analysis

Errors and uncertainty occur in experiments due to inadequate observer accuracy, equipment imprecision, and inappropriate instrument calibration. The best accuracy of the experimental results is predicted by examining the number of errors [22]. The real value has been predicted using the mean of repeated observations in uncertainty analysis [23,24]. Table 3 shows the uncertainties of the calculated and measured characteristics. Equation (1) is used to calculate total percentage uncertainty in the experimental setup [25].

$$\text{Percentage uncertainty} = \sqrt[2]{\begin{array}{c}(\text{Brake power})^2 + (\text{SFC})^2 + (\text{Cylinder pressure})^2 + (\text{EGT})^2 + (\text{Smoke})^2 + \\ (\text{PM})^2 + (\text{NOx})^2 + (\text{CO2})^2 + (\text{Time})^2 + (\text{Engine Speed})^2\end{array}} \quad (1)$$

Table 3. Uncertainly error analysis during experiment.

Measure Parameters	Range	Accuracy	Uncertainties
Brake power	-	0.03 kW	±1.0%
SFC	-	±5 g/kW h	±0.8%
Cylinder pressure	1–25 MPa	±10 kPa	±0.5%
EGT	0–1000 °C	±1 °C	±0.25
Smoke	0–100	±1%	±1.0%
NOx	2000–4800 ppm	±20 ppm	±1.0%
CO_2	0–50 vol. %	±0.3 vol.% + 1% of mv (0 to 25 Vol.%) ±0.5 Vol.% + 1.5% of mv (>25 to 50 Vol.%)	±1.25%
PM	0–300 mg/m^3	0.1 mg/m^3	±0.2%
Smoke	0–4800 ppm	±10 ppm	±0.2%
Crank angle encoder	0–720 °CA	± 0.2 °CA b TDC	±0.3%
Time	-	±0.6 s	±0.2%
Engine speed	0–10,000 rpm	±10 rpm	±0.1%

Based on the above Equation (1) the composite uncertainty was found as ±2.39% which was below the permissible limit.

3. Results

3.1. Combustion Characteristics

3.1.1. Cylinder Pressure

Cylinder pressure denotes the highest pressure produced within the combustion chamber, followed by full fuel combustion [26]. Figure 3 depicts the cylinder pressure of various fuel blends at increasing engine load. Biodiesel has a higher cylinder pressure value than conventional diesel due to its higher fuel oxygen molecules, which improved fuel combustion, resulting in an increase in the rate of pressure [27].

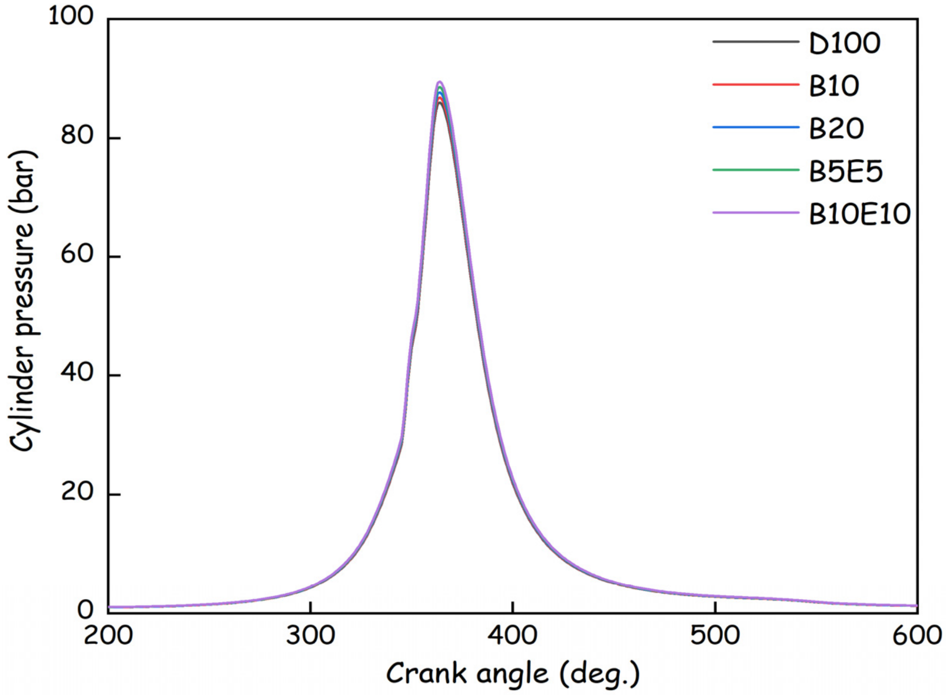

Figure 3. Cylinder pressure against engine load at full load.

Further, ethanol addition in biodiesel blends improve the cylinder pressure and this is particularly noticeable at higher engine load. This can be concluded because of fuel features, e.g., the high autoignition temperature and greater heat of vaporization of ethanol, the pressure of biodiesel combined with ethanol in-cylinder pressure, and the heat release rate is higher than biodiesel [28]. In regard to the increase in cylinder pressure and rate of pressure, the biodiesel blend with ethanol outperforms the biodiesel blend and diesel fuel [29].

3.1.2. Maximum Pressure Rises Rate

The findings of the maximum pressure rise rate are shown in Figure 4 (MPRR). The relationship between MPRR and engine noise and vibration are linear. The pressure increases rate was the greatest at the premixed combustion phase. The MPRR of fuels including ethanol is higher than the MPRR of fuels based on B10, B20, and D100. It rises with the amount of ethanol in the fuels because, at the same injection pressure, the better atomization properties of ethanol-blend fuels with lower viscosity and density result in an increase in the percentage of premixed combustion. These similar results were consistent with the findings of Wai et al. (2022) who conducted their experiment using ethanol and biodiesel fuel [29]. However, it was shown that the MPRR reduced as the biodiesel % grew when it was compared to that of B10, B20 against diesel fuel.

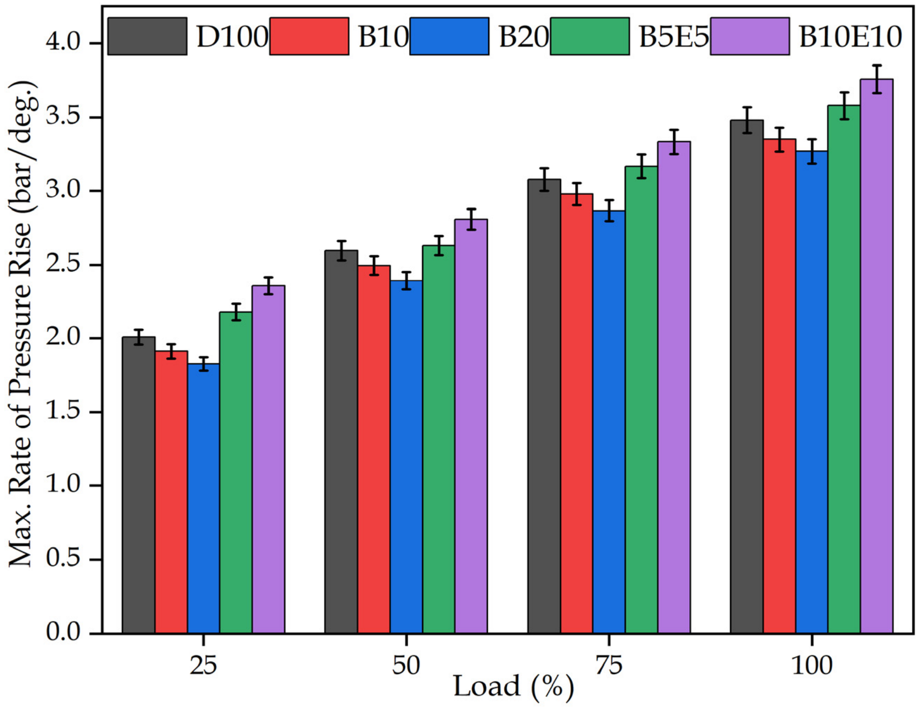

Figure 4. Maximum rate of pressure rise against engine load.

3.1.3. Heat Release Rate

In a diesel engine, the cylinder heat release rate (HRR) is one of the most important combustion factors. The HRR is described as the amount of heat produced by the energy per unit of time. The rate of heat release from a cylinder is determined by the cylinder pressure and peak rising pressure rate [30]. The HRR of algal biodiesel and diesel revealed comparable patterns with regard to crank angle. Figure 5 clearly illustrates that the trajectory for biodiesel has shifted to the left when compared to diesel, indicating that combustion occurs sooner for biodiesel–diesel blends than for base diesel [31].

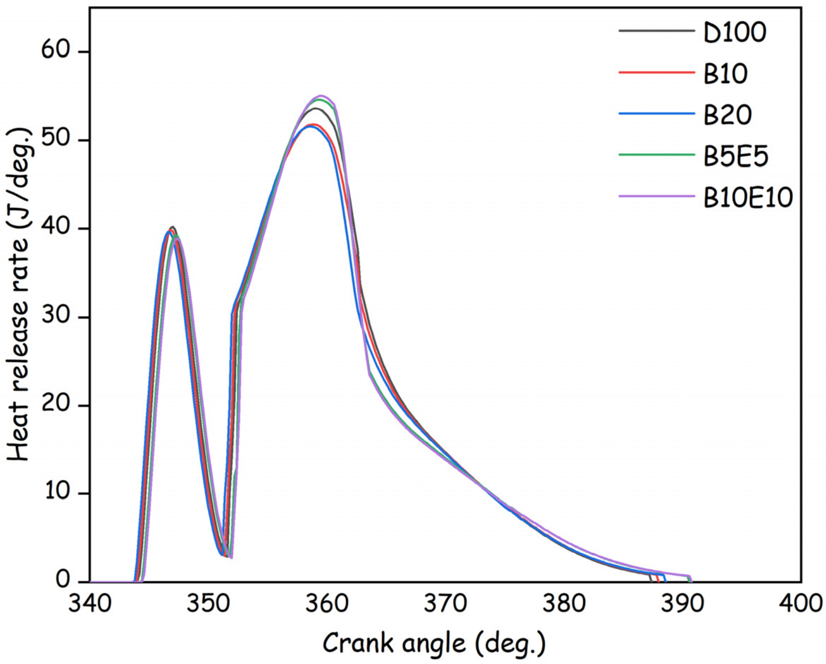

Figure 5. HRR of different fuel blends against crank angle at full load.

HRR was observed to rise with increasing ethanol percentage compared to blended fuel, which might be attributed to the immediate heat release followed by improved mixture preparation during the delay period. The ethanol-blended fuel exhibits the maximum peak of premixed combustion HRR, indicating that a larger proportion of the fuel is burned during the premixed combustion phase. These findings can be validated by previous work, e.g., that of Rajendran et al. (2021) using a ternary blend of isopropyl alcohol, biodiesel, and diesel fuel [32].

3.1.4. Ignition Delay Period (IDP)

In general, the ignition delay is generally referred to as the lag of time between the start of injection of fuel (SOI) to the start of combustion (SOC) upon ignition of the air fuel mixture inside the combustion chamber. The method of calculation involved experimentally finding the time interval between the SOI and SOC. Since the engine is fitted with a data acquisition system, the measurement was performed with ease within the DAQ and the same result was acquired. Ignition delay is a measurement of how quickly a fuel ignites when heated. Because it inhibits premature igniting during the compression stroke, fuel with a comparatively shorter ignition delay is appropriate for diesel engine operations. Figure 6 depicts the IDP of test fuel against increasing engine load for various tested fuels.

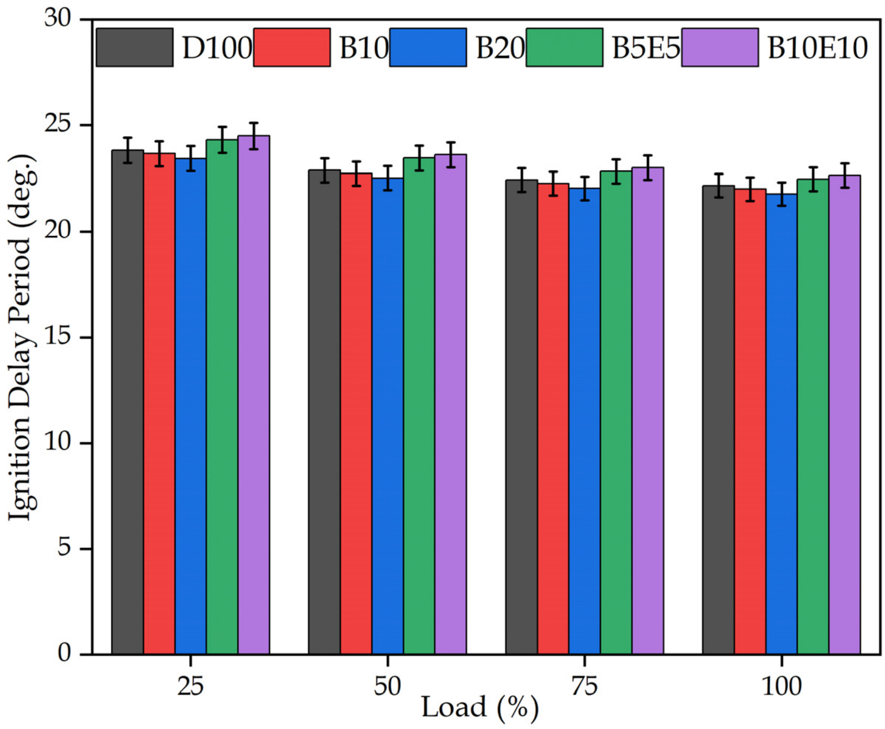

Figure 6. Ignition delay of different fuels against engine load.

It was found that for B10 and B20, ignition delay periods of 0.72% and 1.75% were lower than that of diesel fuel (D100). This can be contributed towards with higher oxygen concentration of biodiesels. Furthermore, the biodiesel has low heat capacity, causing rapid heating and evaporation, reducing the igniting delay [33,34]. However, for the blends of B5E5 and B10E10, ignition delays were 1.35% and 2.17% greater than those of the diesel fuel. It was concluded that adding ethanol in biodiesel blends improved the ignition delay period. The rising tendency may be explained by B5E5 and B10E10 fuels having lower cetane numbers than D100. Because ethanol has a low cetane number, it was concluded that biodiesel ethanol fuel blends had a lower cetane number than diesel fuel (see Table 2). Despite the inability to determine the cetane number for the fuel blends, it was predicted that algae biodiesel and ethanol blends cetane numbers would decline as the ethanol content increased [35].

Furthermore, when engine loads grow, in-cylinder pressure and temperature rise, and numerous activated OH radicals are produced as a result of the addition of ethanol, which play an important part in the fuel ignition stage. Lower cetane numbers have less of an inhibitory influence on ignition. As a result, with large loads, the difference in IDP between biodiesel and ethanol blend fuel mixes lessens [36]. Similar findings were obtained by Chow et al. (2021) when palm biodiesel blend was enriched with ethanol [37].

3.1.5. Combustion Duration

The ignition delay and burn rate of a fuel droplet have the most effects on how long it takes to burn. The length of the burning phase has a considerable impact on how well a combustion-powered engine performs overall and how it emits pollutants. The time from the beginning of combustion to the end of combustion is shown in Figure 7 for each tested fuel. Biodiesel blends had a longer combustion duration than diesel fuel. This might be due to its greater viscosity and reduced volatility, which results in poor combustion and poor atomization, extending the time of ignition [38].

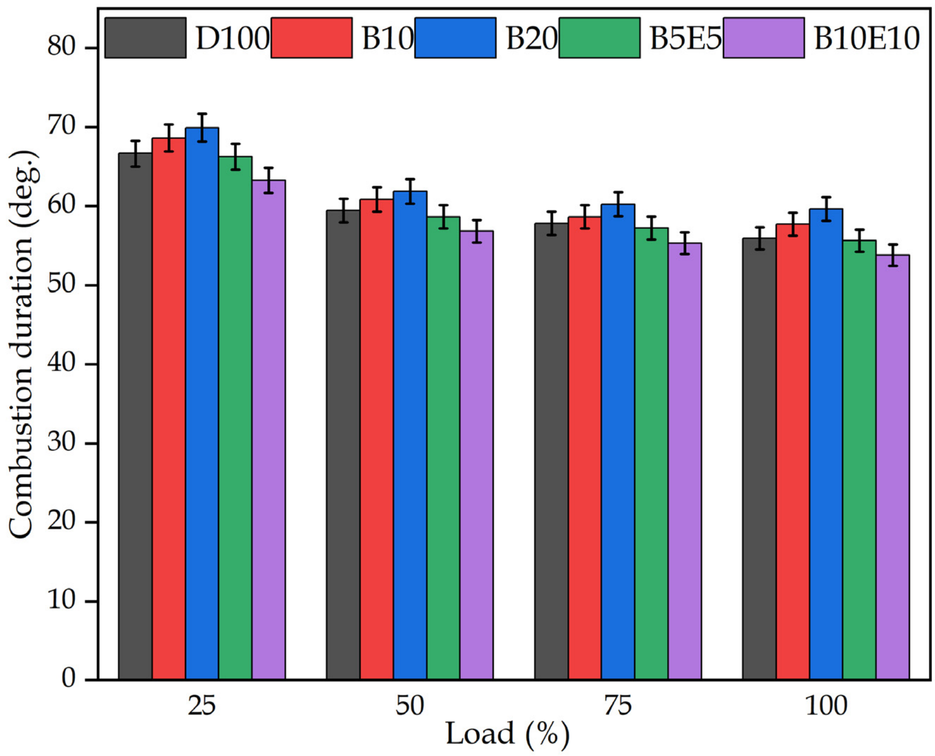

Figure 7. Combustion duration of various fuel blends against engine load.

According to Kuszewski et al. (2019), combustion with more oxygen from intake air or oxygenated fuel has a shorter combustion time because it has less pyrolysis and more oxidation [35]. The combustion duration was seen to steadily decrease from B20 droplet to B5E5 and B10E10 BE30 droplet in Figure 8 As shown in Figure 8, the decreasing trend of combustion duration with increasing ethanol concentration might be explained by the increasing trend of burn-rate constant and higher ignition delay period of ethanol blend biodiesel fuel [37].

3.2. Performance Characteristics

3.2.1. Brake Thermal Efficiency

Brake thermal efficiency (BTE) is defined as the amount of chemical energy in the fuel that is transformed into useable energy.

Figure 8 indicates that when engine load increases, the thermal efficiency of the engine increases for all test fuels. The BTE of D100, B10, B20, B5E5, and B10E10 fuels were 32.37%, 32.21%, 31.95%, 32.49%, and 32.89%, respectively, at full load. As biodiesel blends increase, a significant decline in brake thermal efficiency was observed due to higher density and viscosity, while lower volatility and calorific values of the higher algae biodiesel blend result in impoverished atomization and combustion efficiency [39].

Further addition of ethanol in blended biodiesel fuel improves the BTE at all loads. This can be attributed to the higher oxygen content of ethanol and biodiesel. Thus, the combustion process may be improved, resulting in the increased thermal efficiency of ethanol blended fuel [40].

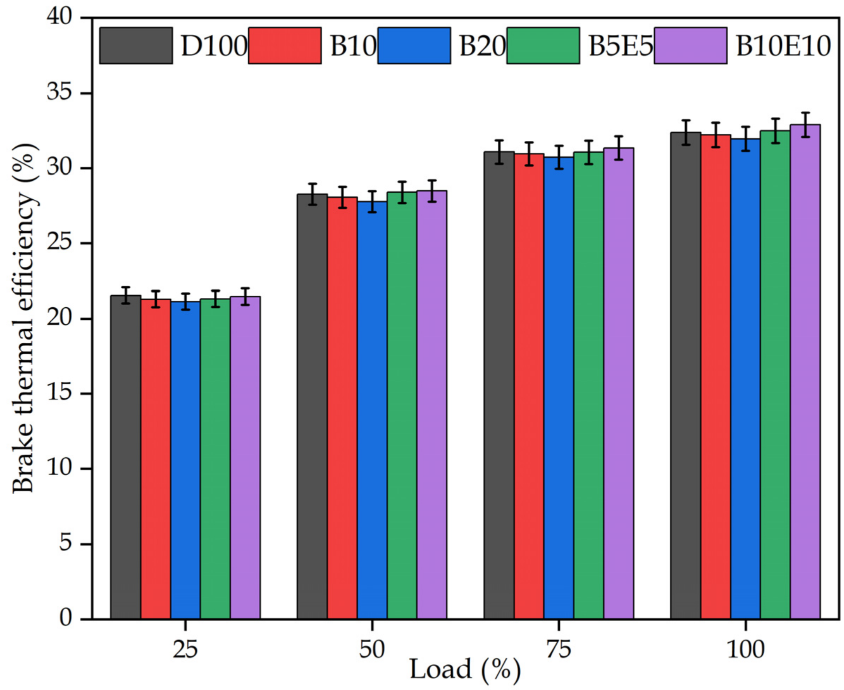

Figure 8. BTE of various fuel blends against engine load.

Ethanol addition also decreases the viscosity and density of the fuel blend and improvements made to the atomization and evaporation of fuel droplets inside the engine cylinder [41]. El-Sheekh et. al. (2022) obtained similar findings using ethanol enriched fuel with blended biodiesel in a diesel engine [42].

3.2.2. Specific Fuel Consumption

Specific fuel consumption (SFC) is used to evaluate engine performance. The ratio of fuel consumption to engine power is known as the SFC and is expressed in kg/kWh. The Figure 9 demonstrates that as engine load increases, the brake specific fuel consumption decreases for every test fuel. The decrease in SFC is evident by the increase in the BTE of the engine, as observed in the above relevant section. B10 and B20 blend fuel had 1.4% and 2.1% higher SFC. However, adding ethanol lowered the SFC by 0.6% and 1.5% for B5E5 and B10E10 fuels as compared to diesel fuel.

Due to a higher load, the in-cylinder temperature and flow turbulence contribute to appropriate atomization and thorough mixing of fuel, consequently leading to a faster combustion efficiency [43]. The ethanol addition in biodiesel blended fuel further reduced the SFC. The decreased specific fuel consumption of ethanol fuel blends may be owing to their lower viscosity and higher volatility, which boosts the mixing of air/fuel velocity and enhances the combustion process and combustion efficiency [24,44].

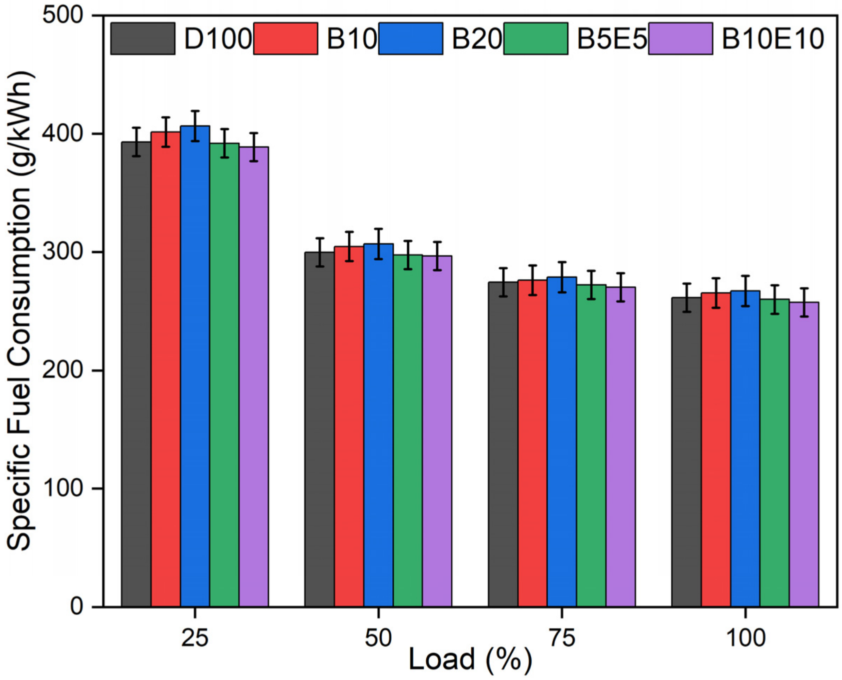

Figure 9. Variation of SFC of various fuel blends against engine load.

3.2.3. Exhaust Gas Temperature (EGT)

The exhaust temperature was determined using a thermocouple mounted on the exhaust pipe, as illustrated in Figure 10. It grows with increasing engine load because at higher load, the engine requires a higher combustion temperature.

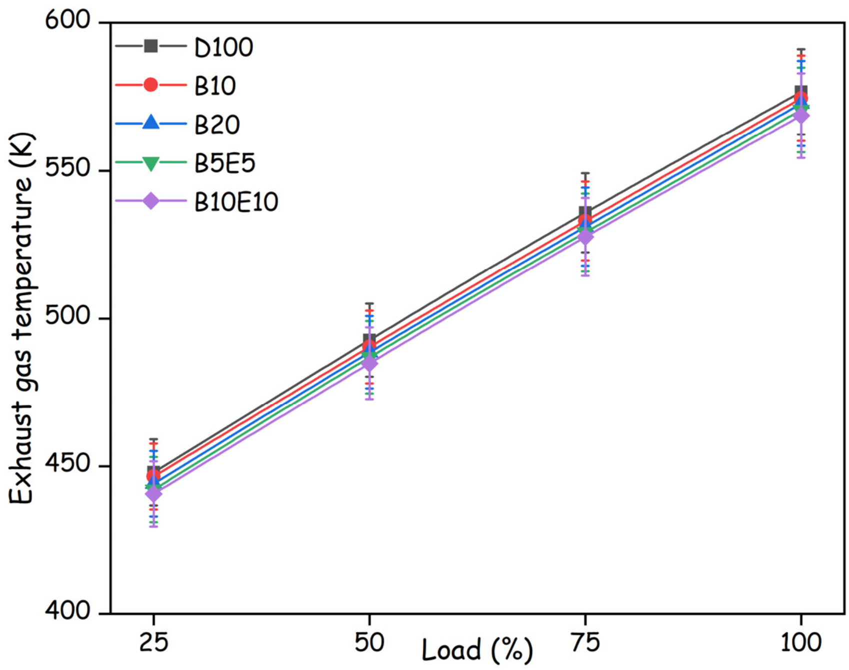

Figure 10. EGT of tested fuel blends against engine load.

It was found that at every engine tested mode, the EGT of ethanol blended fuels is lower than that of biodiesel blended fuel. These results can be validated by other investigations and may corroborate the above-mentioned findings of Thiyagarajan Dabi et al. (2020) [45].

3.3. Emission Characteristics

3.3.1. Carbon Dioxide

The public is concerned about particular carbon dioxide (CO_2) emissions from the transportation and electricity sectors because they have a significant impact on the environment and air quality [46]. Carbon dioxide is a by-product of combustion, which occurs when fuel is completely burned. CO_2 emissions can be reduced in a variety of different ways. The CO_2 emission of tested fuel is depicted in Figure 11 for increasing engine load.

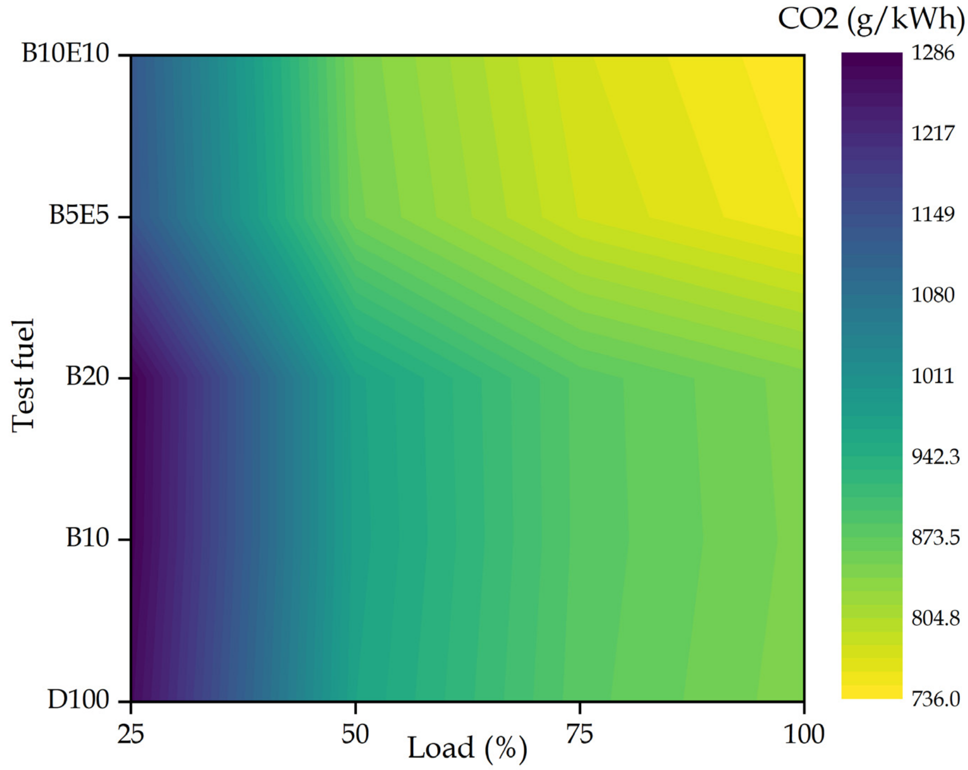

Figure 11. Variation in CO_2 emissions of tested fuel blends against engine loads.

In this current research, emissions were reduced by adding biodiesel and ethanol with diesel fuel [47]. When diesel fuel was used, the CO_2 emission was 843 g/kWh. However, a slight reduction was observed by adding biodiesel. Further, adding ethanol in the binary blend reduced CO_2 emission drastically. CO_2 emission reduced by 11.44% and 12.57% for B5E5 and B5E10 as compared to diesel fuel. However, using biodiesel blended fuel slightly reduced the CO_2 emission 0.18% and 0.56% for B10 and B20 respectively as compared to diesel fuel.

The oxygen emission is inversely proportional to the emission. Since there are more oxygen molecules in ethanol and a smaller propensity for them to develop, ethanol-blend fuels have greater oxygen surpassing capabilities. Further addition of ethanol in blended biodiesel fuel reduced the CO_2 emission in diesel engine due to the reduced carbon content of ethanol. The current research findings can be validated by the previous researcher work as Wai et al. (2022) [48].

3.3.2. Oxides of Nitrogen

Figure 12 depicts the nitrogen oxide emissions from each tested fuel. It really is important to note that increasing combustion temperatures represent a primary factor responsible for the increase in NOx emissions. All of the experiments show that NOx emission increases with increasing engine load for all tested fuels [49].

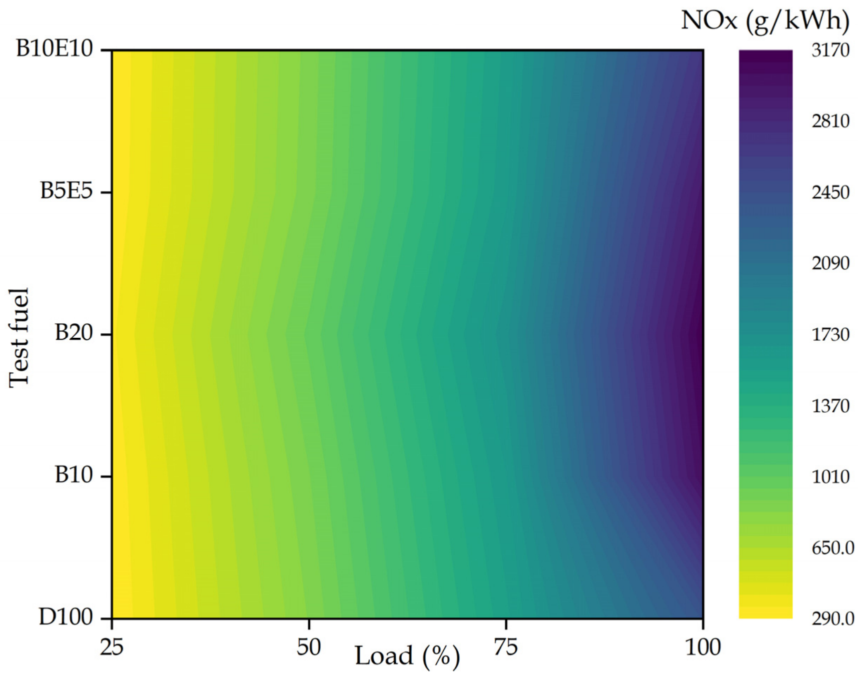

Figure 12. Variation of NOx emissions for tested fuel blends against engine load.

The findings show that as contrasted to pure diesel, the algae biodiesel blend increases NOx emissions. When B10 and B20 used as a fuel NOx emission increased by 26.9%, and 31.7% respectively as compared to diesel. However further addition of ethanol reduced NOx emission by 6.5% and 14.6%, respectively, as compared to B20 blend fuel. This is due to the high latent heat of ethanol vaporization, which causes a substantial quantity of heat to be absorbed inside the combustion chamber, thus lowering the combustion temperature. NOx generation is thus limited in this manner. Another reason for reducing NOx emission due to the substantial fall in EGT as the increasing ethanol content into the blended fuel [42]. Ortega et. al. (2021) found a similar pattern in NOx emission when ethanol is used with the blend of palm and sunflower oil [50]. Similarly, Wojs et al. (2019) found that increasing the concentration of ethanol in biodiesel blended fuel further reduces the NOx emission [51].

3.3.3. Smoke Emission

Smoke is produced as a result of oxygen deficiency and poor combustion of a hydrocarbon. The investigation discovered that the intensity was highly depending on engine load. The higher the engine load in a single cylinder engine, the greater the smoke intensity due to increased fuel supply for burning [52].

The engine load, fuel viscosity, flame velocity, progression of oxidation, and temperature of combustion all these parameters influence smoke emission. Figure 13 depicts the smoke emission of tested fuel at increasing engine load. It was found that the intensity of smoke emission increases with increasing engine load. The highest smoke emission was observed for diesel fuel. The smoke emission reduced by 3.4%, 5%, 22.9%, and 23.7% for B10, B20, B5E5, and B10E10, respectively, as compared to diesel fuel.

Furthermore, with increasing the percentage of algae biodiesel and ethanol added in the blended fuel, smoke emissions fall across the board. This is due to the lower cetane number of biodiesel and ethanol than that of diesel, resulting in a longer flame retardation time and more complete fuel mixing [53]. The decreased viscosity of ethanol and biodiesel promotes evaporation and atomization of the fuel, allowing it to burn more completely. Furthermore, the greater oxygen concentration of ethanol and biodiesel enhances full burning of the fuel and can expedite soot oxidation [54]. Similar findings were obtained by Zhang et. al. (2022) with the experiment performed using a blend of biodiesel and ethanol [55].

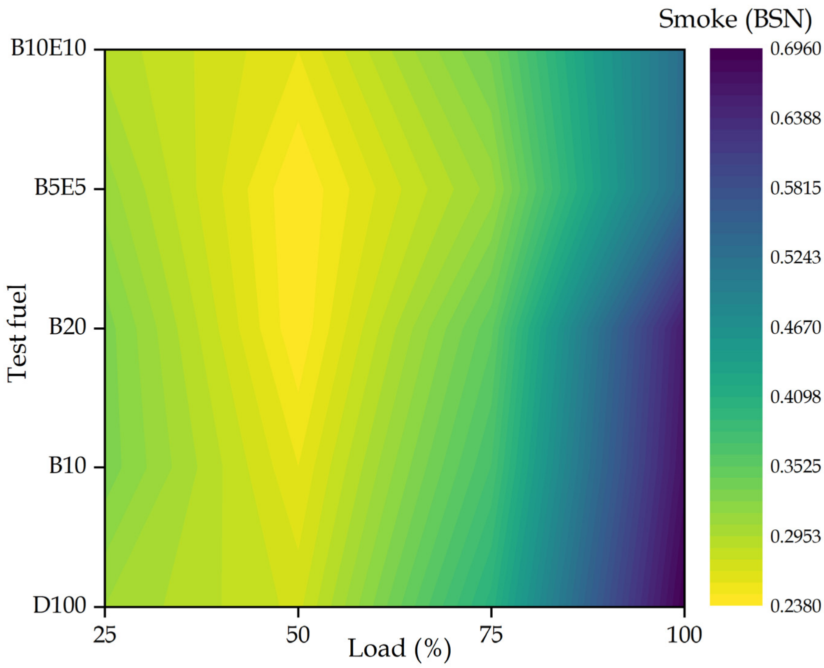

Figure 13. Variation in the smoke emissions of tested fuel blends against engine load.

3.3.4. Particulate Matter

Particulate matter emissions, which represent a significant risk to public health, are a serious concern in the operation of modern diesel engines. Engine fueling with FAME pure biodiesel or mixes containing diesel fuel reduces the amount of dangerous particulate matter in the internal combustion engine exhaust, similar to carbon dioxide emissions and smoke emission [44]. Figure 14 depicts the PM emission of tested fuel at increasing engine load. The maximum pm was observed for diesel fuel. PM reduced by 3% and 26% for B10 and B5E5, respectively, as compared to diesel fuel. It can be concluded from Figure 14 that PM emissions decrease with increasing engine load for all test fuels. Further, it was found that increasing the biodiesel and ethanol concentration reduces the harmful PM emission. This is due the fact of biodiesel and ethanol has higher oxygen concentration.

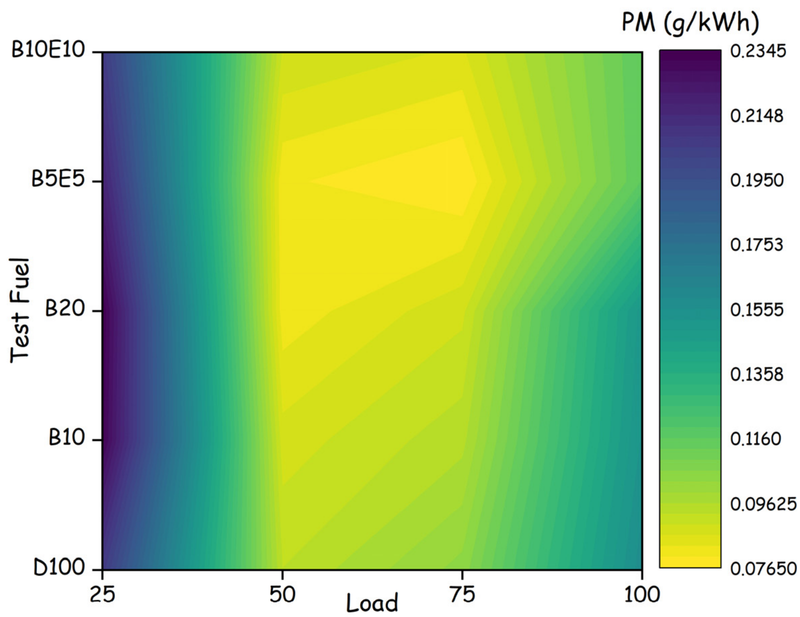

Figure 14. Variation in PM emissions of tested fuel blends against engine load.

The presence of oxygen in the fuel also affects PM, and the amount of oxygen inside the fuel lowers PM emissions after burning. The current study findings agree with literature, as observed by Mofijur et al. (2019) [56].

4. Conclusions

Algae oil is extracted and biodiesel derived using transesterification in the laboratory. Binary and ternary blends are prepared as per ASTM Standard. Blended fuel is tested and combustion, performance, and emission characteristics are examined using a diesel engine. Major findings of this research work concluded based on the current study:

- Algae oil is extracted using n-Hexane solvent and biodiesel produced employing 6:1 methanol to oil ratio, and (0.9% wt.) KOH catalyst (0.9% wt.) at 65 °C for 80 min. The maximum 91% biodiesel yield was obtained employing the transesterification method.
- Binary (B10 and B20) and ternary (B5E5, B10E10) blends of test fuels were prepared using diesel, biodiesel, and ethanol and tested using a diesel engine.
- The diesel-biodiesel and ethanol blends had higher cylinder pressure and heat release rate as compared to diesel fuel. It was found that cylinder pressure increased by 1%, 2%, 3%, and 4% and peak heat release rate reduced by 3.41% and 4.04% and increased by 1.69%, and 2.23% for B10, B20, B5E5, and B10E10 respectively as compared to diesel fuel.
- BTE was found lower while SFC was found higher for algae biodiesel and diesel blends due to their lower heating value and a higher percentage of oxygen as compared to diesel fuel. However, adding ethanol concentration increases the BTE and lowers the SFC of ethanol blended fuel as compared to diesel fuel.
- BTE was reduced by 0.49% and 1.29% for B10 and B20 blends while BTE was increased by 0.37% and 1.60% respectively. However, SFC increases by 1.45%, 2.14%, 3.18%, and 3.78% respectively for B10, B20, B5E5, and B10E10 with respect to diesel fuel.
- The emission characteristics, including NOx, CO_2, PM, and smoke, have been studied at different load employing binary and ternary blended fuels. PM, smoke, and CO_2 emission were decreased for all the biodiesel blends while NOx increased as compared to diesel fuel when the biodiesel blend was used as compared to diesel fuel.
- Ethanol is added in biodiesel blend fuel to reduce the greenhouse gas emission. The addition of ethanol further reduces the emission of PM, smoke, CO_2, and NOx emission as compared to diesel fuel.

Algae can be used to produce sustainable biodiesel. Adding ethanol in biodiesel blends derived from algae proved to be a dependable solution for promoting a feasible and cost-effective fuel operating mode while retaining adequate thermal performance. Furthermore, ethanol presented excellent results in terms of emissions reduction, which encourages the notion of sustainable and clean operation in diesel engines. Future research should incorporate new technologies, such as waste heat recovery systems, which enhance fuel economy and lessen the environmental effect of diesel engines.

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