J Ther Eng, Vol. 11, No. 1, pp. 215–225, January, 2025

Journal of Thermal Engineering
Web page info: https://jten.yildiz.edu.tr
DOI: 10.14744/thermal.0000914

Research Article

Effect of diethyl ether and isobutanol as fuel additives on the diesel engine attributes fueled with subabul seed biodiesel

K. YAMINI[1], P. S. KISHORE[1,*], V. DHANA RAJU[2]

[1]*Department of Mechanical Engineering, Andhra University, College of Engineering (A), Visakhapatnam, 530003, India*
[2]*Department of Mechanical Engineering, Lakireddy Bali Reddy College of Engineering, Mylavaram, 521230, India*

ARTICLE INFO

Article history
Received: 04 December 2023
Revised: 09 April 2024
Accepted: 09 April 2024

Keywords:
DEE; Engine Characteristics; Isobutanol; Subabul Biodiesel

ABSTRACT

In recent years, biodiesel has emerged as a renewable and eco-friendly alternative to traditional diesel fuel, garnering significant attention. This research investigates the viability of utilizing subabul seed biodiesel in diesel engine applications. The process involves mechanically pressing crude oil from subabul seeds and subsequently extracting subabul seed methyl ester through transesterification. The physical and chemical properties of subabul seed biodiesel are compared with those of diesel. To enhance the performance of the biodiesel, fuel additives such as diethyl ether (DEE) and isobutanol (ISOB) are introduced to a 20% concentration of subabul seed methyl ester (SSME 20) at varying levels. At full load, SSME 20, with the addition of 10% DEE, demonstrates a 7.4% increase in Brake Thermal Efficiency (BTE) compared to SSME 20 alone. Furthermore, emissions from the diesel engine are significantly reduced—hydrocarbon by 24.39%, carbon monoxide by 4.6%, nitrogen oxide by 9.33%, and smoke emissions by 8.84%—compared to conventional diesel fuel. Similarly, the incorporation of 10% isobutanol into SSME 20 results in a 4.71% higher BTE than SSME 20 alone. Engine tailpipe emissions show a noteworthy reduction of 20.73%, 4.12%, 6.42%, and 6.62% for hydrocarbon, carbon monoxide, nitrogen oxide, and smoke, respectively, compared to diesel fuel at full load. The addition of isobutanol and diethyl ether to SSME 20 is found to increase the Heat Release Rate (HRR) over SSME 20 biodiesel. Diesel exhibits the highest HRR at 73.55 J/°CA, followed by SSME 20 with 10% DEE at 72.15 J/°CA, and SSME 20 with 10% isobutanol at 71.85 J/°CA. In conclusion, biodiesel, particularly from subabul seeds, shows promise in reducing greenhouse gas emissions and fostering sustainable energy systems. The blending of subabul biodiesel with fuel additives like DEE and isobutanol positions it as a viable standard fuel for diverse applications such as transportation, agriculture, and electricity generation.

Cite this article as: Yamini K, Kishore PS, Dhana Raju V. Effect of diethyl ether and isobutanol as fuel additives on the diesel engine attributes fueled with subabul seed biodiesel. J Ther Eng 2025;11(1):215–225.

*__Corresponding author.__
*E-mail address: prof.pskishore@andhrauniversity.edu.in

This paper was recommended for publication in revised form by Editor-in-Chief Ahmet Selim Dalkılıç

Published by Yıldız Technical University Press, İstanbul, Turkey

INTRODUCTION

In the modern-day world, depleting conventional energy sources, surging crude oil prices, increasing environmental concerns have necessitated to main focused on the other source of alternative fuels. India imports petroleum products percentage is around 70-80% costing is about 70-80 thousand crores per year as reported by Ashok et al. [1]. The Indian government has recently made a significant decision to incorporate biodiesel derived from non-edible oil seeds into diesel fuel blends. This move highlights the recognition of biodiesel as a promising alternative energy source. By utilizing non-edible oil seeds, the government aims to promote sustainable and environmentally friendly practices in the country's energy sector mentioned by Murugesan et al. [2]. In the past two to three decades, researchers have dedicated significant attention to exploring various feedstocks and production techniques for biodiesel. Studies have demonstrated the successful utilization of biodiesels derived from sources such as corn seed, jatropha, rape seed, mahua seed, tamarind seed, sunflower, and soybean in diesel engines, as reported by Sahoo et al. [3]. Dhana Raju et al. [4] used tamarind seed biodiesel in CI engines and recommended the 20% tamarind biodiesel blend for diesel engine applications. Similarly, Dhana Raju et al. [5] found that TSME20 blend shows the better thermal efficiency as 1.17% higher than diesel fuel and engine exhaust emissions were significantly reduced at full load. Further, the use of fuel additive (NAA) has reduced the smoke density by 29.49%. Dhanasekharan et al. [6] used n-pentanol as fuel additive to the yellow grease oil and performed tests on CI engine and they inferred that BTE was slightly improved and engine emissions were reduced significantly. Yamini et al. [7] observed that DMC10% blend gives the best result in performance parameters and reduce emissions like CO, CO_2, and Smoke at 100% load. Dhana Raju and Kishore [8] investigated the 20% tamarind blend and diesel as base fuel at constant speed and varying load conditions. They found better results with TSME20 and the use of EGR 10% has shown major reduction of NOx emissions.

Kumar et al. [9] explored the effects of blending palm biodiesel with diesel fuel on various aspects of diesel engine performance. The study specifically examined different injection timings and at different EGR rates. Remarkably, the findings unveiled that employing an advanced injection timing in combination with a 10% EGR rate yielded exceptionally promising characteristics for the diesel engine. This innovative approach showcases the potential of palm biodiesel as a positive approach in optimizing engine efficiency and reducing emissions. Das and Lingfa [10] studied different nahar biodiesel blends at standard operating conditions of CI engine, and they found for 10% nahar biodiesel was 1.08% drop in BTE and 5% increment in BSEC at full load. Emission parameters show reduction in hydrocarbons and carbon monoxide at maximum load over base fuel. Table 1 shows the summary of different fuel additives explored in the existing literature [11-16].

Singh et al. [17] analyzed the effect of alcohols in diesel engines. In their observation isopropyl alcohol blends are prepared as 5%,10%,15%,20% on volume basis. Experiments are conducted on single cylinder unmodified diesel engine. The results show that the brake thermal efficiency was increased slightly for the last two blends (15% & 20%). And there was a significant reduction in oxides of nitrogen emissions. The CO_2 % was decreased with an increased percentage of isopropyl alcohol. Atmanli et al. [18] studied ternary blend usage on performance and emissions and impact of a blend using response surface methodology. The results indicated that the blend of diesel-butanol-cotton oil marginally increased BSFC and decreased major exhaust emissions. Karthikeyan et al. [19] reported about use of water hyacinth biodiesel shown reduced BTE and increased BSEC at all load conditions. The authors were concluded that 20WHB+80D (20% water hyacinth biodiesel+ 80% diesel) blend is one of the best alternative feed stocks for diesel engine applications. Reddy et al. [20] focused on exploration of various cord seed biodiesel blends on diesel engine applications. From the results, it was found that CSME20 (20% Corn seed methyl ester) shows increased thermal efficiency and SFC (Specific Fuel Consumption) at maximum load. Prabhu and Venkata Ramanan [21] studied the CI engine fueled with pentanol at various levels like 15%, 20%

Table 1. Effect of fuel additives on the characteristics of diesel engine

Authors	Type of fuel additive	Additive concentration	Findings
Wei et al. [11]	n-pentanol	10%, 20%, 30%	↑BSFC, HRR, UHC, NOx and CO ↓PM concentration
Karabektas and Hosaz [12]	Isobutanol	5%, 10%, 15% and 20%	↑BSFC, HC↓BTE, CO, NOx
Dogan [13]	n-butanol	5%	↑BSFC, BTE, HC↓EGT, SO, NOx, CO
Manickam et al. [14]	DEE	5%, 10%, 15%	↑BTE, CO_2↓BSFC, NOx, CO and SO
Kaimal and Vijayabalan [15]	DEE	5%, 10% and 15%	↑BTE, HC↓CO, NOx and SO
Pandian et al. [16]	DMC	5% and 10%	↓BTE, HC, NOx, CO, and Smoke.

Note:↑indicates increases ↓ indicates decreases.

and 35% respectively. The addition of pentanol has shown improved fuel properties and diesel engine smooth operation results in improved engine performance.

Kumar et al. [22] found that the characteristics of biodiesel can be improved by incorporating additives like oxygenated additives, metal-based additives, antioxidant additives, and cetane number improvers. They concluded that the use of fuel additives is strongly recommended for biodiesels as it enhances combustion parameters. Yesilyurt and Aydin [23] studied the effects of addition of alcoholic additives to biodiesel at different ratios to a diesel engine were examined. Blending is a common practice to enhance the properties of biodiesel and make it more suitable for use in existing diesel engines and infrastructure. Blending isobutanol with biodiesel can help improve the cold flow properties of the biodiesel. Further, isobutanol is more compatible with biodiesel and petroleum diesel than some other alcohols. This compatibility can lead to better stability and less separation in the blended fuel, ensuring a more homogeneous mixture. Isobutanol has a higher energy content per unit volume compared to ethanol. This can be advantageous when blending with biodiesel, as it allows for increased energy density in the final fuel blend.

Saha et al. [24] studied the characteristics of diesel engines operated with waste cooking biodiesel. They performed all the tests on diesel engines at ideal operating conditions. From their results, they inferred that BTE was slightly reduced, and exhaust emissions were drastically reduced by 58.73%, 14.26% and 34.61% of HC, CO and smoke opacity respectively at full load over diesel fuel. Raj et al. [25] examined the characteristics of diesel engine run with Jojoba biodiesel with coir pith gas at different load conditions. They found that significant reductions of NOx and smoke opacity when diesel engine were run in dual fuel mode with producer gas flow rate of 21.69 kg/hr at full load. However, there was marginal increments of HC and CO. Sarkar et al. [26] performed tests on diesel engine using two different nonedible oil along with diesel at ideal operating conditions. From their test results, they inferred that BTE was increased by 2.18% and drastic reduction of smoke emissions by 11.64% at full load for the post injection of biodiesel when compared to diesel. Adhinarayanan et al. [27] examined the use of decanol and Di-n-Butyl Ether as fuel additives for the biodiesel blends and they found enhancement in engine performance and significant reduction in harmful exhaust emissions at full load. Reddy et al. [28] studied the effect of decanol as fuel additive to the mango seed biodiesel and the application of 10% decanol to the MSME20 blend was shown 3.2% increment in BTE when compared to MSME20 blend at full load. Jayabal et al. [29] found the application of combined effect of oxygenated fuel additives have shown drastic reductions in CO, HC and smoke emissions without much loss of engine brake thermal efficiency at full load. Reddy et al. [30] also studied the effect of engine operating conditions like EGR and injection timing to enhance the diesel engine attributes and they found advanced injection timing with 10% EGR has shown improved diesel engine parameters and significant reduction of engine tailpipe emissions.

Mohamad et al. [31] reviewed the effect of Ethanol-gasoline blends on the attributes of diesel engine and found that the use of ethanol in gasoline blends were shown significant reduction of exhaust emissions at full load. Through a comparison of performance, combustion, and emission parameters, it was observed that the presence of DEE in biodiesel blends had a positive impact on engine performance parameters. From the overall detailed existing literature, it is found that 20% blend of different biofuels with diesel can be smoothly operated on diesel engine. Also, this research investigates the impact of diethyl ether (DEE) and isobutanol additives on a 20% blend of subabul seed biodiesel-diesel fuel. The study explores the attributes of a diesel engine, focusing on improved engine performance and reduced harmful emissions resulting from the application of these fuel additives.

MATERIALS AND METHODS

Subabul Biodiesel Preparation and Its Availability

Subabul tree or leucaena leucocephala mainly belongs to southern Mexico and northern central America. This tree also has common names as white lead tree, river tamarind and pearl white etc. Subabul is cultivated in the tropics as a fodder plant and subabul wood is mainly used in paper production industries. For this purpose, hectares of subabul trees are planted in dry waste lands. This tree has white flowers tinged with yellow resembling mimosoid and long pods.

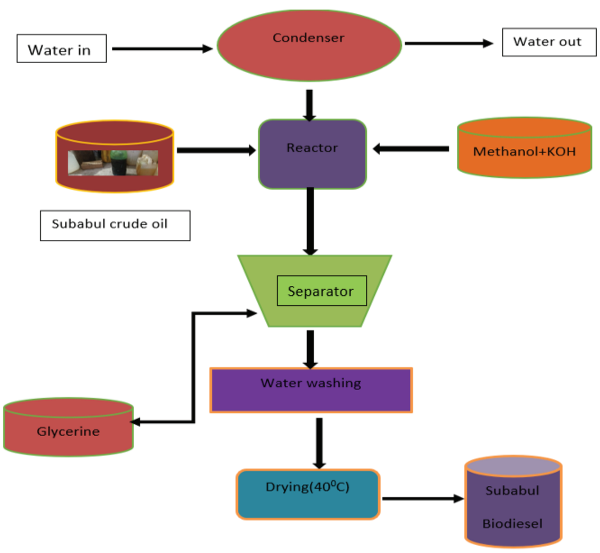

Figure 1. Biodiesel production through transesterification method.

These pods contain the seeds in dark brown shading. It might contain the oil yield as 20-32%. Saturated acids comprise 26-29% and unsaturated acids comprise 71-73%. Subabul seed oil was generally extracted using mechanical pressing operation. The crude or unrefined subabul seed oil has some drawbacks like high density, high viscosity, and unstable nature. So, to overcome these problems transesterification technique is used. In the biodiesel preparation procedure, 1000ml of Leucaena crude oil is combined with 300ml of methanol and 14g of potassium hydroxide (KOH) alkaline catalyst in a container for transesterification, as shown in Figure 1. The process employs KOH as the catalyst, a reaction temperature of 70°C, a response time of 180 minutes, and a stirring speed of 500 rpm. After 24 hours of settling, the final product is transferred to a separating flask where the by-product glycerin separated from the biodiesel, and it is found 90% biodiesel yield is obtained from this technique.

Fuel Additives (or) Ignition Improvers

The test results of SSME10, SSME20 and SSME30 are presented in Table 2. From the base tests, it is noticed that SSME20 demonstrates superior performance and lower engine exhaust emissions. Consequently, SSME20 is selected as the optimal blend. Fuel additives, such as dimethyl carbonate, diethyl ether, dimethyl ether, dimethoxymethane, 1-pentanol, isobutanol, decanal, octanol, dimethoxy propane, methanol, and ethanol, have been utilized by researchers (Ashok et al. [1]; Dhana Raju et al. [8]; Manickam et al. [14]) to improve fuel characteristics and reduce emissions. In this study, diethyl ether (DEE) and isobutanol are chosen as fuel additives for the optimum blend, with their properties outlined in Table 3.

Experimental Setup

The experiments were conducted on a Kirloskar agriculture diesel engine loaded with the use of eddy current dynamometer (Fig. 2). Tests were performed at a constant speed with varying load conditions (0%, 25%, 50%, 75%, and 100%). Calibrated instruments were used, and the fuel's mass flow rate was determined through glass tube measurements. Each test was repeated at least three times for accuracy. The data acquisition system recorded combustion data (heat release rate, cylinder pressure, ignition delay), exhaust parameters (CO, HC, NOx emissions), and performance parameters (BTE, BSFC). Smoke intensity

Table 4. Specifications of test apparatus

Engine type	Kirloskar TAF1, Diesel engine
Engine power/Speed	4.4kW/1500 rpm
Stroke	110 mm
Diameter	87.5 mm
Displacement Volume	661 CC
Compression Ratio	17.5:1
Injection Timing	23° BTDC
Orifice diameter	20 mm
Injection pressure	220 bar
Type of injection	Direct injection

Table 2. Experimental results of a subabul seed biodiesel blend

Fuel	Performance		Combustion		Emissions			
	BTE (%)	BSFC (kg/kWh)	Pressure (bar)	HRR (J/deg)	CO (%)	HC (ppm)	NOx (ppm)	SO (%)
Diesel	33.92	0.24	68.68	73.55	0.218	82	2024	69
SSME10	30.03	0.29	64.85	69.42	0.307	72	1951	68
SSME 20	30.68	0.28	65.95	70.13	0.231	77	2131	67
SSME 30	29.21	0.30	63.63	68.98	0.331	74	1905	70

Table 3. Fuel properties of diesel, fuel additives and subabul biodiesel

Properties	Diesel	SSME	SSME20	DEE	Iso-butanol
Calorific value(kJ/kg)	42,500	37227	41,554	33,900	33,000
Specific gravity	0.830	0.875	0.840	0.718	0.810
Kinematic viscosity(cst)	3.05	3.64	2.64	0.23	0.25
Flash Point (°C)	56	85	62	34	35
Fire Point (°C)	62	92	76	38	39
Cetane number	49	53	51	125	22
Stoichiometric ratio	15:1	14:1	13:1	9:1	12:1

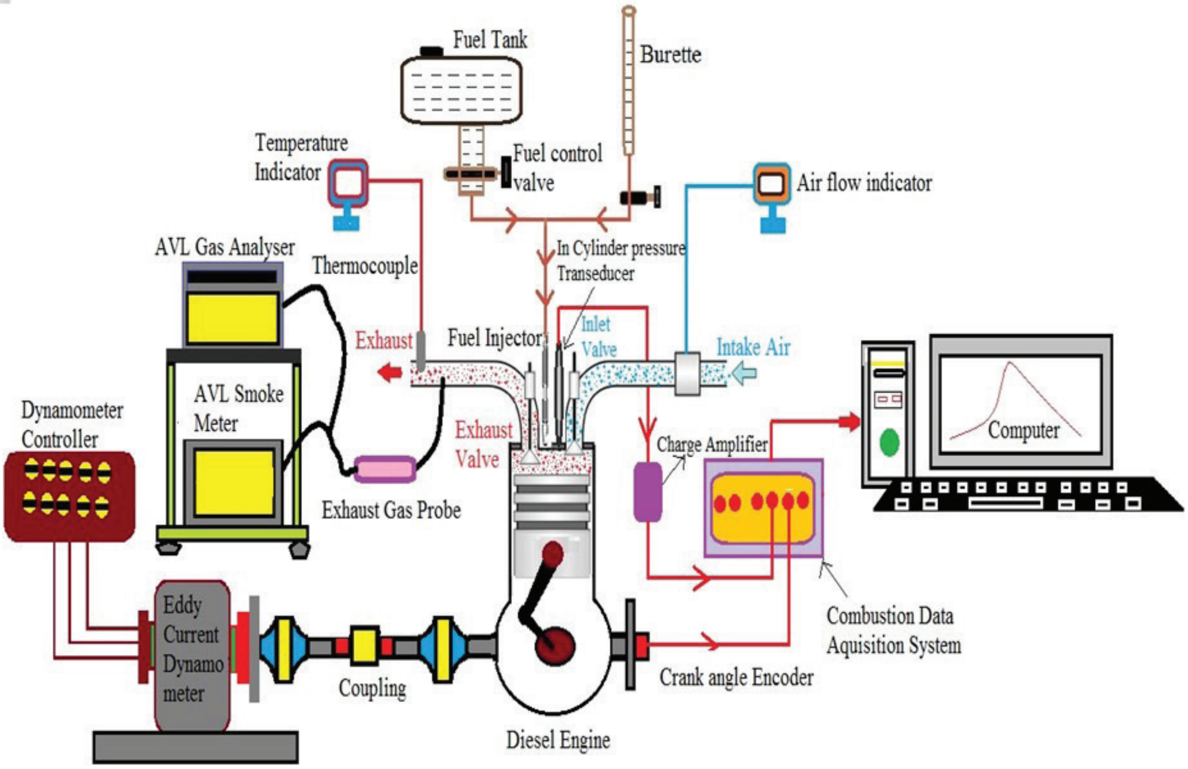

Figure 2. Schematic view of experimental engine setup.

was measured using a smoke meter, and an AVL multi-gas analyser was used for exhaust emissions. See Table 4 for the specifications of the diesel engine test rig.

Uncertainty analysis

Uncertainty analysis was conducted to enhance the accuracy of the experiment by addressing errors and deviations that may arise from changes in the atmospheric conditions. Prior to the experiment, thorough calibration of the test engine and all relevant devices was performed. Investigating uncertainty analysis is crucial for obtaining more precise and accurate readings. Table 5 presents the uncertainty, accuracy, and range of used instruments in this study. The overall uncertainty of the net experimental investigation is 2.15% and it is well within acceptable limit. The equation (1) for the uncertainty of the overall experimental test, incorporating the square root method suggested by Holman [32], can be rewritten as follows:

$$\begin{aligned}\Delta &= \sqrt{(BTE)^2+(BSFC)^2+(CP)^2+(HRR)^2+(CO)^2+(HC)^2+(NOx)^2+(SO)^2}\\ &= \sqrt{(0.25)^2+(0.5)^2+(1)^2+(1)^2+(0.1)^2+(0.2)^2+(1)^2+(1)^2}\\ &= \pm\,\mathbf{2.15}\end{aligned} \tag{1}$$

Table 5. Uncertainty, accuracy, and range of various instruments

Instrument	Measurement	Range	Accuracy	Uncertainty
AVL DI Gas444Five Gas Analyzer	CO	0 to15% vol	±0.01%	±0.1%
	HC	0 to 20000ppm	±10ppm	±0.2%
	CO_2	0 to 20%vol	±5%	±0.5%
	O_2	0 to 25% vol	±0.1%	±0.5%
	NO_X	0 to 5000ppm	±50ppm	±1%
AVL 415 Smoke Meter	Smoke	0-100	±1%	±1%
Pressure Transducer	Pressure	0-100 bar	±0.1bar	±0.2%
Angle encoder	Crank angle	0-720°	±1%	±0.2%
Data acquisition system	Combustion data	12 bit	±0.01bit	±0.1%
Temperature indicator	Temperature	0-900°C	±1°C	±0.2%

RESULTS AND DISCUSSION

Brake Thermal Efficiency

Figure 3 depicts the variation in BTE for different tested fuels of diesel and blends of subabul seed methyl ester (SSME) with DEE and isobutanol additives. BTE is influenced by fuel properties, engine design, and operating parameters, representing the engine's ability to convert fuel energy into useful power. Biodiesel typically exhibits slightly lower BTE than diesel due to its lower energy content. Brake thermal efficiency is measured by using the following equation.

$$BTE = \frac{BP}{mf*CV}*100 \tag{2}$$

Where BP =Brake power in kW
m_f= Mass of fuel consumption in kg/s
CV= Calorific value in kJ/kg.

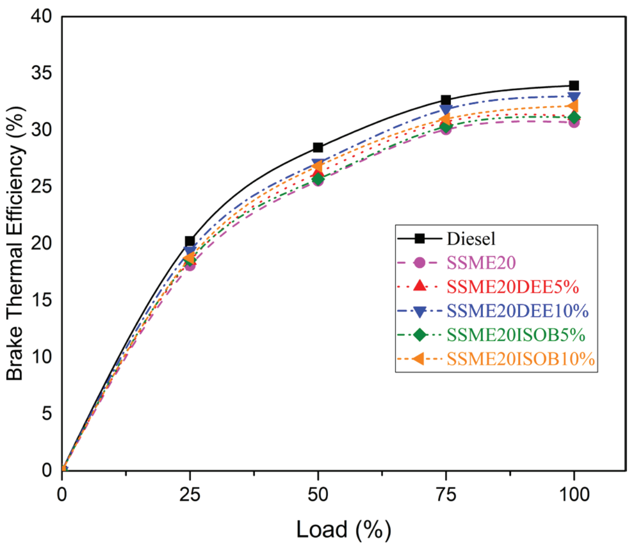

Figure 3. Variation of brake thermal efficiency with engine load.

The tested fuels, namely diesel, SSME 20, SSME 20 DEE 5%, SSME 20 DEE 10%, SSME 20 ISOB 5%, and SSME 20 ISOB 10%, demonstrate BTE values of 33.92%, 30.68%, 31.24%, 32.98%, 31.13%, and 32.15% at full load. Diesel fuel consistently exhibits higher BTE compared to SSME blends. However, the use of alcohol additives improved BTE when blended with SSME 20. Specifically, adding 10% DEE and 10% ISOB to the SSME 20 blend increases BTE by 7.4% and 4.71%, respectively, at full load, compared to the SSME 20 blend alone. This improvement can be attributed to the additives' better cetane number, increased oxygen availability, and improved combustion characteristics resulting from their enhanced volatile nature. Kumar et al. [9] reported that BTE of palm biodiesel was marginally lower than diesel fuel due to its lower net energy content. Diesel fuel has shown higher BTE than biodiesel blend because of higher heating value and these results were close confirmed with findings were reported by the Markov et al. [33]. Brake thermal efficiency follows a similar pattern for the examined fuels at all load conditions. Fuel additives can significantly influence both the chemical kinetics and thermodynamics of the combustion process. Fuel additives can alter the rates at which chemical reactions occur during combustion. They may act as catalysts, speeding up reactions or inhibitors, slowing them down. For example, some additives promote more complete combustion by accelerating the oxidation of fuel molecules. Additives can affect the initiation of combustion reactions. They may lower the activation energy required for ignition, making combustion easier to initiate under various conditions. Additives can prevent the formation of deposits on engine surfaces by modifying the chemical pathways that lead to deposit formation. This can improve engine efficiency and longevity.

Brake Specific Fuel Consumption

The amount of fuel used per unit power generation is well known as BSFC. Figure 4 illustrates the changes in BSFC values with engine load for the examined fuels. Biodiesel generally exhibits slightly higher BSFC because lower heating value. The tested fuels, including diesel, SSME 20, SSME 20 DEE 5%, SSME 20 DEE 10%, SSME 20 ISOB 5%, and SSME 20 ISOB 10%, demonstrate BSFC values of 0.24 kg/kWh, 0.30 kg/kWh, 0.26 kg/kWh, 0.25 kg/kWh, 0.28 kg/kWh, and 0.27 kg/kWh at full load. Among the biodiesel blends, SSME 20 DEE 10% and SSME 20 ISOB 10% display higher BSFC compared to other fuel samples. It's important to note that while biodiesel may have a slightly higher BSFC compared to petroleum diesel; it offers other benefits such as reduced emissions, renewable source, and potential for improved lubricity. These results were close conformity with the results reported by Dhana Raju and Kishore [8].

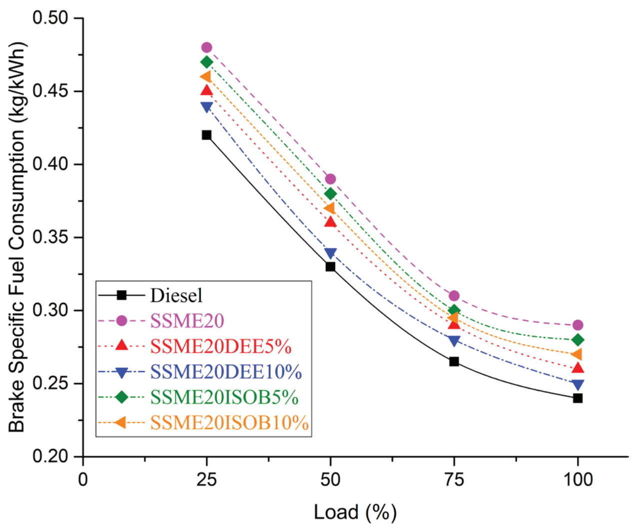

Figure 4. BSFC variation with engine load.

In-cylinder Pressure

The change of cylinder pressure with different crank angle for the subabul seed biodiesel blends with DEE and isobutanol additives is presented in Figure 5. The cylinder pressure in a diesel engine using biodiesel blend with fuel additives would depend on various factors, including the blend ratio, type, and concentration of additives in the biodiesel blend. When fuel additive like DEE and isobutanol blended with biodiesel, it can increase the cylinder pressure due to its higher cetane number and oxygen content. Biodiesel typically has a higher cetane number than diesel, which refers to its ignition quality. Higher cetane numbers can lead to shorter ignition delays and faster combustion, resulting in higher peak cylinder pressures. The in-cylinder pressure values at full load for diesel, SSME20, SSME20 with 5% DEE, SSME20 with 10% DEE, SSME20 with 5% isobutanol, and SSME20 with 10% isobutanol are 68.68 bar, 65.95 bar, 66.46 bar, 67.71 bar, 66.18 bar, and 66.45 bar, respectively. Diethyl ether has a high cetane number and can improve the ignition quality of diesel fuel, potentially leading to more efficient combustion. When fuel additives like isobutanol or diethyl ether are added to SSME20 blend, it can enhance the overall combustion process by reducing the ignition delay. The application of DEE has shown reduction in the ignition delay, diethyl ether can promote more rapid and efficient combustion, leading to higher cylinder pressures.

Heat Release Rate

The amount of heat released in the ignition process in the engine cylinder is referred as HRR. It represents the rate at which the fuel-air mixture burns and releases energy. In a diesel engine, the heat release rate is typically characterized by a distinct shape known as the heat release rate curve. Figure 6 illustrates how the heat release rate changes over the course of the combustion process. Fuel additives can influence the thermodynamics of combustion by altering the energy released during the process. Some additives enhance the energy density of the fuel, leading to higher combustion temperatures and pressures, while others may reduce energy losses through improved combustion efficiency. Additives can modify the heat release profile during combustion, affecting factors such as flame propagation speed and combustion stability. This can result in smoother and more controlled combustion, reducing the likelihood of engine knock or detonation. Fuel additives may influence the temperature distribution within the combustion chamber. By altering combustion kinetics, they can affect peak temperatures and temperature gradients, which in turn impact emission levels and engine performance.

From the 1st law of thermodynamics, the HRR is determined by using equation (3) as presented below.

$$\frac{dQ}{d\theta} = \left(\frac{\gamma}{\gamma} - 1\right)P\left(\frac{dV}{d\theta}\right) + \left(\frac{1}{\gamma} - 1\right)V(\mathrm{dP/d}\theta) \qquad (3)$$

Here $\frac{dQ}{d\theta}$ represents the HRR in J/ degree CA,
P represents the in-cylinder pressure in bars
γ indicates the specific heat ratio
V indicates the volume of combustion chamber in m^3
θ represents the crank angle in degrees.

HRR is highly affected by many factors like fuel properties, design of combustion chamber, and overall engine operating conditions. It consists of distinct phases including ignition delay, premixed combustion, controlled combustion, and afterburning. The presence of fuel additives can enhance combustion by reducing ignition delay and improving overall efficiency. Additionally, they can promote faster flame propagation, resulting in accelerated combustion. At full load, the heat release rate values for diesel, SSME20, SSME20 with 5% DEE, SSME20 with 10% DEE, SSME20 with 5% isobutanol, and SSME20 with 10%

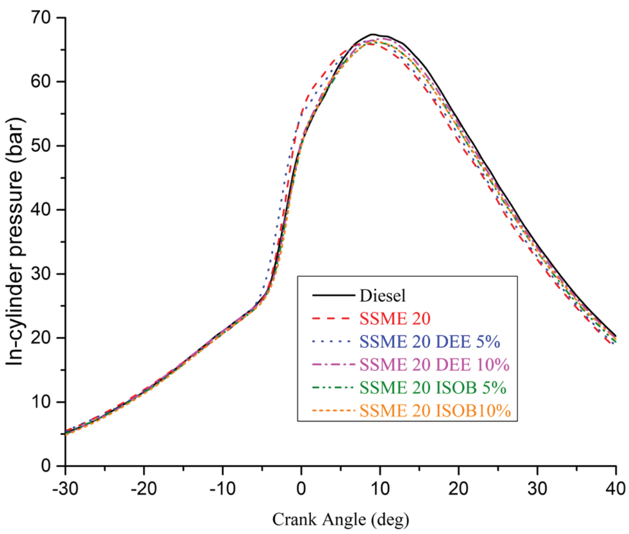

Figure 5. In-cylinder pressure variation with crank angle.

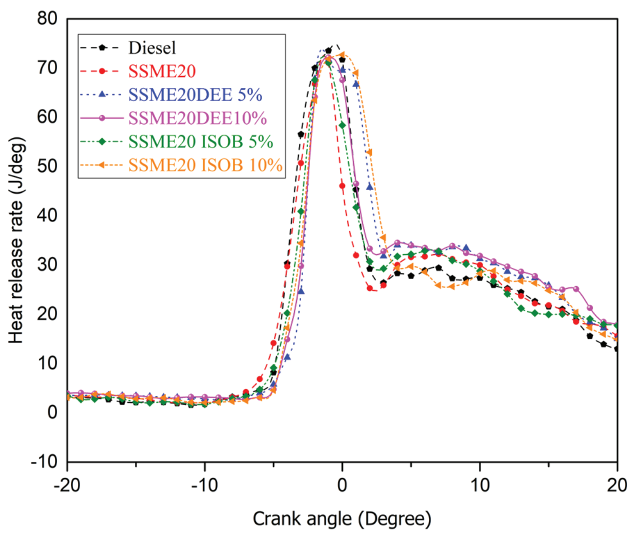

Figure 6. Variation of HRR with crank angle.

isobutanol were 73.55 J/⁰CA, 71.03 J/⁰CA, 71.68 J/⁰CA, 72.15 J/⁰CA, 71.18 J/⁰CA, and 71.85 J/⁰CA, respectively. The use of DEE & isobutanol to the SSME20 biodiesel blend resulted in higher heat release rates compared to the baseline SSME20 blend. From the test results, diesel is found to have a more heat release rate of 73.55 J/⁰CA followed by SSME 20 DEE 10% with 72.15 J/⁰CA and SSME 20 ISOB 10% 71.85 J/⁰CA. The main reason for increase in heat release rate is due to addition of fuel additives improve atomization and vaporization of the fuel can result in more efficient combustion.

Exhaust Emissions

Hydrocarbon emissions

Figure 7 indicates the changes in HC emissions with engine load. Incomplete combustion or inefficient fuel-air mixing can lead to higher hydrocarbon emissions. Unburned or partially burned fuel molecules can be released into the exhaust gases. These unburned hydrocarbons are typically in the form of alkanes and alkenes. Other hydrocarbon compounds, such as aromatic hydrocarbons and polycyclic aromatic hydrocarbons can also be present in the exhaust emissions. The composition and quantity of hydrocarbons emitted from a diesel engine depend on several factors, including fuel quality, combustion efficiency, and the engine design. The hydrocarbon (HC) emissions at full load for diesel, SSME20, SSME20 with 5% DEE, SSME20 with 10% DEE, SSME20 with 5% isobutanol, and SSME20 with 10% isobutanol are 82 ppm, 77 ppm, 71 ppm, 62 ppm, 74 ppm, and 65 ppm, respectively. The addition of fuel additives resulted in reduced hydrocarbon emissions for the subabul seed biodiesel blend. The use of 10% DEE and isobutanol 10% to the SSME20 blend is shown 24.39% and 20.73% at 100% load.

Carbon monoxide

The variation of CO emissions with engine load is shown in Figure 8. CO emissions in a diesel engine are primarily caused by incomplete fuel combustion, influenced by factors such as air/fuel ratio, combustion chamber design, fuel quality, engine temperature, speed, and load. At full load, the CO emission values for diesel, SSME20, SSME20 with 5% DEE, SSME20 with 10% DEE, SSME20 with 5% isobutanol, and SSME20 with 10% isobutanol were 0.218%, 0.231%, 0.225%, 0.208%, 0.218%, and 0.209%, respectively. The addition of fuel additives resulted in reduced CO emissions. Specifically, the inclusion of 10% DEE and 10% isobutanol to the SSME20 blend led to reductions of 4.6% and 4.12% of carbon monoxide emission at 100% load respectively, compared to diesel fuel. Furthermore, these additions resulted in reductions of 9.95% and 9.51% in CO emissions over SSME20. The additional oxygen can enhance combustion and facilitate more complete fuel oxidation, potentially leading to lower CO emissions. The presence of oxygenated additives promoted better fuel atomization, faster and more complete combustion can be achieved, resulting in reduced CO emissions reported by Kumar et al. [22].

Nitrogen oxides

Controlling NOx emissions from diesel engines is a significant challenge. Engine design, optimization of the combustion process, and after-treatment technologies are commonly employed to mitigate NOx emissions. Nitrogen oxides (NOx) are formed in a diesel engine due to a combination of thermal and fuel-related mechanisms. The main factors contributing to the NOx formation from the diesel engine are high combustion temperature and oxygen availability. Some fuel additives, such as combustion catalysts can optimize the combustion process in a diesel

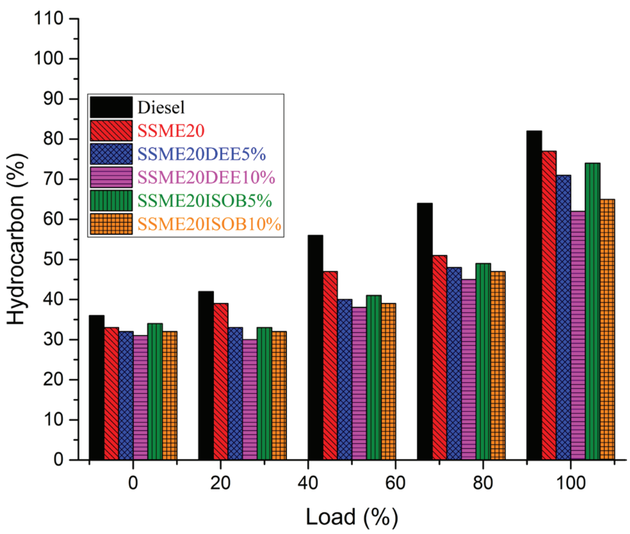

Figure 7. HC emission variation with engine load.

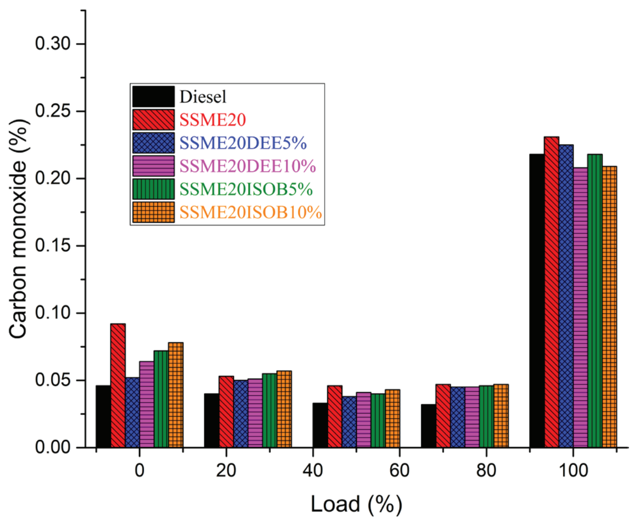

Figure 8. Carbon monoxide emissions variation with engine load.

engine. By promoting better fuel atomization, faster and more complete combustion can be achieved, resulting in reduced NOx emissions. The NOx emission values at full load for diesel, SSME20, SSME20 with 5% DEE, SSME20 with 10% DEE, SSME20 with 5% isobutanol, and SSME20 with 10% isobutanol are as follows: 2024ppm, 2131ppm, 1895ppm, 1835ppm, 1967ppm, and 1894ppm, respectively. The presence of alcohol additives in the SSME20 blend resulted in lower NOx emissions compared to diesel fuel and SSME20 biodiesel blend. Specifically, the inclusion of 10% DEE and 10% isobutanol in the SSME20 blend led to reductions of 9.33% and 6.42% in NOx emissions over diesel. Moreover, these additions resulted in reductions of 13.89% and 11.12% in NOx emissions over the SSME20 at 100% load (Fig. 9).

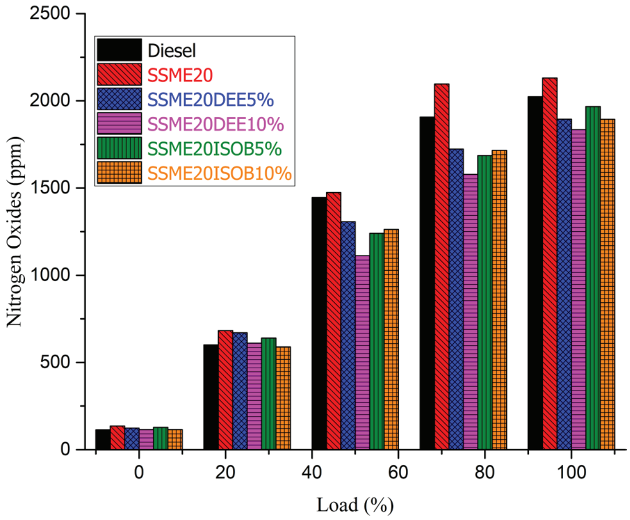

Figure 9. NOx emissions variation with engine load.

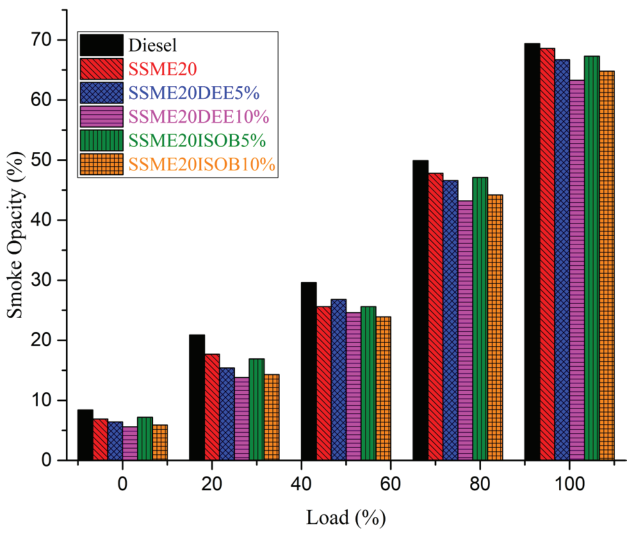

Figure 10. Smoke opacity variation with engine load.

Smoke opacity

The changes in smoke density with engine load as indicated in Figure 10. Biodiesel typically has better combustion properties compared to conventional diesel fuel. Biodiesel also has better oxygen content, promoting more complete combustion. Enhanced combustion efficiency can result in reduced smoke opacity emissions. From the results at 100% load, smoke intensity values of diesel, SSME20, SSME20 DEE5%, SSME20 DEE10%, SSME20 ISOB 5%, AND SSME20 ISOB 10% are 69.4%, 67.6%, 66.7%, 63.3%, 67.3% and 64.8% respectively. The use of fuel additives is shown to have a drastic reduction of smoke emissions. It is inferred that smoke opacity is reduced by 8.84% and 6.62% respectively for the SSME20 DEE10% and SSME20 ISOB 10% over base fuel at 100% load. The smoke emissions are reduced due to the additive's ability to improve combustion efficiency and optimize the combustion process.

CONCLUSION

This experimental investigation is mainly focused on the effect of oxygenated fuel additives like diethyl ether (DEE) and isobutanol, at two different levels (5% and 10%) to a blend of SSME (referred to as SSME20). The following are the major conclusions presented from this research work.

- The use of 10% DEE and 10% isobutanol to the SSME20 blend resulted in a 7.4% and 4.71% enhancement in BTE at 100% load. However, these values are slightly lower than those achieved with diesel fuel.
- DEE and isobutanol improved heat release rates compared to SSME20, but diesel had the highest rate, followed by SSME20 with 10% DEE and 10% isobutanol.
- Compared to diesel fuel, the SSME20 with 10% DEE achieved significant reductions in major emissions. At full load, hydrocarbons (HC) decreased by 24.39%, carbon monoxide (CO) decreased by 4.6%, nitrogen oxides (NOx) decreased by 9.33%, and smoke opacity decreased by 8.84%.
- Similarly, the use of 10% isobutanol in the SSME20 blend resulted in a significant reduction in major emissions: 20.73% for HC, 4.12% for CO, 6.42% for NOx, and 6.62% for smoke opacity when contrasted with diesel fuel.

The findings indicate that adding DEE and isobutanol to the SSME20 blend can enhance engine performance and decrease emissions. However, diesel fuel retains superior characteristics in certain aspects.

Future Scope

- To investigate the diverse attributes of diesel engine with different piston bowl geometries.
- To study the performance, combustion and emission characteristics of diesel engine operating under various compression ratios, injection pressure, injection timings and exhaust gas recirculation.

- To explore the tribological characteristics of diesel engine operated with subabul biodiesel.
- To examine the effect of nanoparticles on the characteristics of diesel engine operated with SSME20 biodiesel blend.

NOMENCLATURE

SSME	Subabul Seed Methyl Ester
BTE	Brake Thermal Efficiency
BSFC	Brake Specific Fuel Consumption
HRR	Heat Release Rate
CP	Cylinder Pressure
CO	Carbon monoxide
HC	Hydrocarbons
NO_X	Nitrogen Oxides
SO	Smoke Opacity
ID	Ignition Delay
CO_2	Carbon dioxide
SSME 20	20% Subabul Seed Methyl Ester+ 80% Diesel
SSME 20 DEE 5	SSME 20 with Di Ethyl Ether 5%
SSME 20 DEE 10	SSME 20 with Di Ethyl Ether 10%
SSME 20 ISOB 5	SSME 20 with Isobutanol 5%
SSME 20 ISOB 10	SSME 20 with Isobutanol 10%
EGT	Exhaust Gas Temperature
BSEC	Brake Specific Energy Consumption
WHB	Water Hyacinth Biodiesel
TSME	Tamarind seed methyl ester
CSME	Corn seed methyl ester
NAA	N Amyl Alcohol
MSME	Mango seed methyl ester

AUTHORSHIP CONTRIBUTIONS

Authors equally contributed to this work.

DATA AVAILABILITY STATEMENT

The authors confirm that the data that supports the findings of this study are available within the article. Raw data that support the finding of this study are available from the corresponding author, upon reasonable request.

CONFLICT OF INTEREST

The authors declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

ETHICS

There are no ethical issues with the publication of this manuscript.

REFERENCES

[1] Ashok B, Raj RT, Nanthagopal K, Krishnan R, Subbarao R. Lemon peel oil–a novel renewable alternative energy source for a diesel engine. Energy Convers Manage 2017;139:110–121. [CrossRef]

[2] Murugesan A, Umarani C, Subramanian R, Nedunchezhian N. Bio-diesel as an alternative fuel for diesel engines—A review. Renew Sustain Energy Rev 2009;13:653–662. [CrossRef]

[3] Sahoo PK, Das LM, Babu MKG, Arora P, Singh VP, Kumar NR, et al. Comparative evaluation of performance and emission characteristics of jatropha, karanja and polanga based biodiesel as fuel in a tractor engine. Fuel 2009;88:1698–707. [CrossRef]

[4] Dhana Raju V, Kishore PS, Nanthagopal K, Ashok B. An experimental study on the effect of nanoparticles with novel tamarind seed methyl ester for diesel engine applications. Eur J Sustain Dev Res 2018;164:655–666. [CrossRef]

[5] Dhana Raju V, Kishore PS, Yamini K. Experimental studies on four-stroke diesel engine fuelled with tamarind seed oil as a potential alternative fuel sustainable green environment. Eur J Sustain Dev Res 2018;2:1–10. [CrossRef]

[6] Dhanasekaran R, Krishnamoorthy V, Rana D, Saravanan S, Nagendran A, Kumar BR. A sustainable and eco-friendly fueling approach for direct-injection diesel engines using restaurant yellow grease and n-pentanol in blends with diesel fuel. Fuel 2017;193:419–431. [CrossRef]

[7] Yamini K, Dhana Raju V, Kishore PS. Experimental investigation on diesel engine using DMC as a fuel additive tamarind seed oil methyl ester. Int Res J Eng Technol 2017;4:1372–1379.

[8] Dhana Raju V, Kishore PS. Effect of exhaust gas recirculation on performance and emission characteristics of a diesel engine fuelled with tamarind biodiesel. Int J Ambient Energy 2019;40:624–633. [CrossRef]

[9] Kumar AN, Kishore PS, Raju KB, Kasianantham N, Bragadeshwaran A. Engine parameter optimization of palm oil biodiesel as alternate fuel in CI engine. Environ Sci Pollut Res 2019;26:6652–6676. [CrossRef]

[10] Dash SK, Lingfa D. Performance evaluation of ahar oil-diesel blends in a single-cylinder direct injection diesel engine. Int J Green Energy 2018;15:400–405. [CrossRef]

[11] Wei L, Cheung CS, Huang Z. Effect of n-pentanol addition on the combustion, performance, and emission characteristics of a direct-injection diesel engine. Energy 2014;70:172–180. [CrossRef]

[12] Karabektas M, Hosoz M. Performance and emission characteristics of a diesel engine using isobutanol diesel fuel blends. Renew Energy 2009;34:1554–1559. [CrossRef]

[13] Dogan O. The influence of n-butanol/diesel fuel blends utilization on a small diesel engine performance and emissions. Fuel 2011;90:2467–2472. [CrossRef]
[14] Manickam AR, Rajan K, Manoharan N, Kumar KRS. Experimental analysis of a diesel engine fuelled with biodiesel blend using diethyl ether as fuel additives. Int J Eng Technol 2014;6:2412–2420.
[15] Kaimal KV, Vijayabalan P. An investigation on the effects of using DEE additive in a DI diesel engine fuelled with waste plastic oil. Fuel 2016;;180:90–96. [CrossRef]
[16] Pandian M, Sivapirakasam SP, Udayakumar M. Investigations on emission characteristics of the pongamia biodiesel-diesel blend fuelled twin-cylinder compression ignition direct injection engine using exhaust gas recirculation methodology and dimethyl carbonate as additive. J Renew Sustain Energy 2010;2:043110. [CrossRef]
[17] Singh AK, Mishra C, Vibhanshu V, Kumar N. Performance evaluation and emission studies of a single-cylinder diesel engine fuelled with isopropyl alcohol and diesel. SAE Tech Paper 2013;2013-01-1132. [CrossRef]
[18] Atmanli A, Yüksel B, Ileri E, Karaoglan AD. Response surface methodology-based optimization of diesel-n-butanol ecotton oil ternary blend ratios to improve engine performance and exhaust emission characteristics. Energy Convers Manage 2015;90:383–394. [CrossRef]
[19] Karthikeyan A, Venu H, Jayaprabhakar J, Dhana Raju V, Subramani L, Prabhu A, et al. Novel water hyacinth biodiesel as a potential alternative fuel for existing unmodified diesel engine: Performance, combustion and emission characteristics. Energy 2019;179:295–305. [CrossRef]
[20] Reddy ERK, Lakshmi YS, Dhana Raju V, Rao KA, Kumar MH, Reddy SR. Assessment of performance, combustion and emission characteristics of the diesel engine powered with corn biodiesel blends. Int J Ambient Energy 2019;43:435–443. [CrossRef]
[21] Prabhu A, Venkata Ramanan M. Emission and performance analysis of pentanol-diesel blends in unmodified diesel engine. Int J Ambient Energy 2020;41:699–702. [CrossRef]
[22] Kumar NA, Kishore PS, Brahma Raju K, Nanthagopal K, Ashok B. Experimental study on engine parameters variation in CRDI engine fuelled with palm biodiesel. Fuel 2020;276:1–13. [CrossRef]
[23] Yesilyurt MK, Aydin M. Experimental investigation on the performance, combustion and exhaust emission characteristics of a compression-ignition engine fueled with cottonseed oil biodiesel/diethyl ether/diesel fuel blends. Energy Convers Manage 2020;205:112355. [CrossRef]
[24] Saha R, Dixit A, Verma A, Singh A, Chakrabothy G, Rout C, Nayak B. Performance and emission characteristics of a diesel engine using waste cooking biodiesel blends. Int J Energy Clean Environ 2022;23:77–88. [CrossRef]
[25] Raj Y, Sinha N, Swain S, Harshwardhan A, Bhardwaj H, Chakraborthy D, Nayak B. Performance of a dual-fuel diesel engine fuelled with jojoba biodiesel with coir pith gas. Int J Energy Clean Environ 2022;23:17–27. [CrossRef]
[26] Sarkar S, Verma R, Baksi S, Mukherjee A, Shandilya S, Anubhawi A, Nayak B. Effect of post-mixed biodiesel fuels on performance and emission characteristics of a diesel engine. Int J Energy Clean Environ 2022;23:65–75. [CrossRef]
[27] Adhinarayanan R, Ramakrishnan A, Kaliyaperumal G, De Poures MV, Babu RK, Damodharan D. Comparative analysis on the effect of 1-decanol and di-n-butyl ether as additive with diesel/LDPE blends in compression ignition engine. Energy Sources Part A 2020;1–18. [CrossRef]
[28] Rami Reddy S, Murali G, Dhana Raju V. Influence of decanol as fuel additive on the diverse characteristics of the diesel engine powered with mango seed biodiesel blend. Int J Amb Energy 2020;43:2875–2888. [CrossRef]
[29] Jayabal R, Thangavelu L, Subramani S. Combined effect of oxygenated additives, injection timing and EGR on combustion, performance and emission characteristics of a CRDI diesel engine powered by sapota biodiesel/diesel blends. Fuel 2020;276:118020. [CrossRef]
[30] Rami Reddy S, Murali G, Shaik AA, Dhana Raju V, Sreekara Reddy MB. Experimental evaluation of diesel engine powered with waste mango seed biodiesel at different injection timings and EGR rates. Fuel 2021;285:119047. [CrossRef]
[31] Mohamad B, Szepesi GL, Bollo B. Effect of ethanol-gasoline fuel blends on the exhaust emissions and characteristics of SI engines. In: Jármai K, Bolló B, editors. Vehicle and Automotive Engineering. Cham: Springer; 2018. pp. 23–30. [CrossRef]
[32] Holman JP. Experimental Methods for Engineers. New York: McGraw-Hill; 2012.
[33] Markov VA, Kamaltdinov VG, Zykov SA, Sa B. Optimization of the composition of blended biodiesel fuels with additives of vegetable oils. Int J Energy Clean Environ 2019;20:303–319. [CrossRef]