International Journal of Engineering Research and Development

DOI: 10.29137/ijerad.1535731

Volume:17 Issue:02 Pages:330-348 July/2025

Research Article

Evaluation of Diesel-Hazelnut Oil Biodiesel-Butanol Triple Fuel Blends as a Potential Alternative Fuel in an Unmodified Diesel Engine

Ümit Yüce [1], Melih Can Saydam [1], Batuhan Altundağ [1], Zeki Yılbaşı [2*], Hayri Yaman [1]

[1]Kırıkkale University, 71452, Kırıkkale, TÜRKİYE
[2]Yozgat Bozok University, 66200, Yozgat, TÜRKİYE

Received: 21/08/2024 **Accepted**: 22/11/2024 **Published Online:** 15/07/2025
Final Version: 01/07/2025

Abstract
This study examined diesel-hazelnut oil biodiesel-butanol triple blends as alternative fuels. Hazelnut oil was converted to biodiesel using transesterification and blended with diesel and butanol at various ratios. Engine performance parameters like brake-specific fuel consumption (BSFC), brake thermal efficiency (BTE) and exhaust gas temperature (EGT) were analyzed. Emissions of NOx, smoke-opacity, HC, CO_2, and CO were also measured. Fuel consumption increased slightly with more butanol due to its lower energy density, but BTE remained stable. EGT decreased for blends containing butanol due to factors like latent heat and oxygen content. CO and HC emissions were significantly reduced by up to 32% and 23%, respectively, for the highest butanol blend due to increased oxygen. NOx emissions were also reduced in comparison to diesel, with reductions up to 21%, likely due to lower combustion temperatures. Smoke opacity decreased between 13 and 69% for blends versus diesel. Overall, study demonstrated that these triple-blends can be utilized as an alternative fuel in unmodified diesel engines. The blends performed comparably to diesel efficiency while lowering most exhaust emissions. However, further testing under different operating conditions is needed to validate the long-term impacts.

Key Words
Hazelnut oil, Biodiesel, Butanol, Performance, Emission characteristics

**** Responsible Author:** zekiyilbasi@gmail.com*

Nomenclature

B20	80% diesel fuel and 20% HOB
B20Bt5	75% diesel fuel, 20% HOB and 5% butanol
B20Bt10	70% diesel fuel, 20% HOB and 10% butanol
B20Bt15	65% diesel fuel, 20% HOB and 15% butanol
BSEC	Brake-specific energy consumption
BSFC	brake-specific fuel consumption
bTDC	before top dead-center
BTE	brake thermal efficiency
CI	compression-ignition
CO	carbon monoxide
CO_2	carbon dioxide
D100	diesel fuel
EGT	exhaust gas temperature
FFA	free fatty acid
GHG	greenhouse gas
$C_4H_{10}O$	butanol
HC	hydrocarbons
HOB	hazelnut oil biodiesel
KOH	potassium hydroxide
NOx	nitrogen oxides
OH	oxidation of the hydroxyl radical
ppm	particles per million
R	dependent factor
w_n	uncertainty of the independent variable
w_R	uncertainty value
x_n	function of the independent variable

1. Introduction

The energy crisis is a global challenge that affects the economic and environmental sustainability of nations. It stems from the imbalance between the supply and demand of energy, which depends on various factors such as population growth, industrialization, urbanization, and climate change. Developing countries, in particular, face a high demand for energy due to their rapid economic and social development. However, the majority of the energy supply in the world is still based on fossil resources, like natural gas, oil, and coal, which have been widely utilized for transportation and industrial purposes for decades (Garg et al., 2023). The over-abundant and indiscriminate utilization of fossil fuels has resulted in the exhaustion of non-renewable resources, and it has also stirred up violent environmental problems like greenhouse gas (GHG) emissions, air pollution, and global warming (Raza Abbasi et al., 2022; Yoro & Daramola, 2020). Therefore, there is an urgent need to explore and adopt alternative and renewable fuels, which are derived from sources that are not dependent on fossil fuels and have lower environmental impacts (Bonenkamp et al., 2020).

Biodiesel fuels are renewable and biodegradable fuels acquired from biological sources like animal fats, vegetable oils, or recycled greases (Yilbaşi et al., 2022). They made up of long-chain fatty acid esters that can be blended with conventional diesel fuel in any ratio (Yesilyurt & Aydin, 2020). Biodiesel fuels offer a range of benefits compared to fossil fuels, including lower GHG gas emissions, less air pollution, greater energy security and better engine lubricity. Biodiesel fuels can be obtained from various feedstocks using different production methods. The most common method is transesterification, which involves reacting animal fats or vegetable oils with an alcohol (usually ethanol/methanol) to produce biodiesel and glycerol in the absence of a catalyst (usually potassium/sodium hydroxide) (Mathew et al., 2021). Other methods include micro-emulsion, dilution, and pyrolysis, which are less widely used but may have some benefits in terms of cost, quality, or performance (Nayab et al., 2022). Among the feedstocks, there are many options for obtaining biodiesel, ranging from non-edible to edible oils, from agricultural to microbial sources, and from fresh to waste materials (Singh et al., 2020). Some examples of biodiesel raw materials are soybean, rapeseed, palm, jatropha, algae, waste cooking oil, and animal fats (Krishnan et al., 2023). The choice of raw material depends on various factors, like cost, availability, yield, quality, and environmental impact. Biodiesel fuels have the potential to replace or supplement fossil fuels in the transportation sector, as they are compatible with most diesel engines and can decrease the dependence on imported oil. Biodiesel fuels are also environmentally friendly, as they are non-toxic, non-explosive, and sulfur-free and can lower the emissions of nitrogen oxides (NOx), hydrocarbons (HC), particulate matter, and carbon monoxide (CO). However, biodiesel fuels also have some limitations, like higher viscosity and density, lower energy content, higher pour and cloud points, and higher oxidation and corrosion tendencies than diesel fuel (Hassan et al., 2022). These properties may affect the engine performance, fuel injection, combustion, and emission characteristics of biodiesel fuels. Therefore, the utilization of biodiesel fuels in compression-ignition (CI) engines requires careful consideration of the engine design, fuel quality, and operating conditions. Some studies have reported that neat biodiesel (100% biodiesel) could be introduced into CI engines with no grand changes, as long as the fuel meets the required standards and specifications. Other research has shown that to get better engine performance and emission results when using neat biodiesel, some changes may need to be made (Altarazi et al., 2022). These include changing the timing, pressure, and size of the fuel injectors, as well as the compression ratio and intake air temperature, and adding additives or blending the biodiesel with other fuels. In general, the optimal use of biodiesel fuels depends on the engine type, fuel source, production method, and blend ratio and requires further research and development to address the existing challenges and opportunities (Kattimani et al., 2020; Kumar et al., 2019; Venu et al., 2019).

Hazelnut (*Corylus colurna* L.), which is an important agricultural crop, is called "fındık" in Türkiye (İslam et al., 2023). It is also called filbert, cobnut, or hazel around the world. It is relatively tolerant of drought conditions (Hicks, 2022). Hazelnut production in Türkiye takes first in the global (Temizyurek-Arslan, 2023). Despite hazelnut oil having a high potency as an essential cooking oil supply for Türkiye, it is not widely depleted by people. Consequently, it may be assessed in several domains. The plant height of the hazel tree can reach up to 10 meters, while its root depth may be 1-2 meters depending on the soil type (Paradinas et al., 2022). Hazelnut kernels have an oil content of around 60% (Celenk et al., 2020).

In Scopus, a globally used database containing the largest collection of peer-reviewed literature, including citations and abstracts, documents containing the keywords hazelnut oil and biodiesel were scanned within the "Article Title, Abstract, and Keywords" option. According to these search results, only 41 articles related to hazelnut oil biodiesel (HOB) were found in the database, and only 14 of them were determined to include engine performance and emissions (Scopus, 2024). In these studies, only engine performance and emissions of HOB-diesel fuel mixes were tested, and fuel additive additions such as butanol, methanol, ethanol, etc. were not investigated. Compared with diesel fuel and pure HOB, engine power, torque, and BTE generally decreased at different rates, and BSFC increased. When emission comparisons were evaluated, CO_2, CO, unburned HC, and smoke emissions were less than diesel fuel, while NO_X emissions were perceptibly larger.

In addition to biodiesel, the engines can also run on alcohol-mixed fuels (Yilmaz et al., 2023). In the early 21st century, the use of diesel and alcohol mixtures, including ethanol, methanol, and butanol, has become a common dual-fuel mode. Nevertheless, the cost of alcohol is more than that of diesel fuel derived from petroleum. Therefore, in the past, the utilization of alcohol in CI engines was not a preferred option. According to recent studies, alcohols have the potential to play an key role in the process of finding replacements for petroleum-based fuels, which are on the verge of running out for the foreseeable future. In this regard, legal guidelines have been put in place to encourage the utilization of alcohol in engines, and they have been backed by different incentives (Oloyede et al., 2023; Usmani et al., 2023).

Butanol stands out as a superior biofuel to ethanol due to its higher energy density, lower attraction to water, compatibility with existing fuel infrastructure, reduced corrosiveness, and better blending capabilities (Swamy et al., 2023; Zhao et al., 2023; Zhao et al., 2020). Additionally, its diesel-like properties, like a higher cetane number, similar combustion and emission characteristics, lower heat of vaporization, and suitable density-viscosity values, make it a promising alternative to diesel (Thakkar et al., 2021; Tipanluisa et al., 2022). These attributes not only enhance butanol's potential as a bridge between fossil fuels and renewable energy sources but also highlight the need for further research to optimize its production and ensure its economic feasibility as a future energy solution. The information provided in the previous paragraph about butanol is accurate based on current scientific knowledge and research. Butanol is indeed a 4-carbon alcohol with the chemical formula $C_4H_{10}O$. Additionally, butanol has a higher cetane number and energy content in comparison to ethanol, making it a suitable alternative fuel (Abrar et al., 2023). These properties are well-documented in scientific literature and support the utilization of butanol as a potential biofuel in CI engines (Mahla et al., 2020; Sahu & Shukla, 2022; Şimşek, 2020).

Diesel-biodiesel-methanol and ethanol fuel mixes have been the subject of many studies. However, adding butanol to diesel-biodiesel fuel blends as a fuel additive for CI engines has not been studied very much. Some of these studies are given in the following sentences. Mohammad et al., (2023) investigated the performance and emission characteristics of a one-cylinder, 4-stroke, air cooled CI engine fueled on blends of diesel fuel with biodiesel produced from waste cooking oil and butanol. They tested fuels containing 20% biodiesel with 80% diesel (D80B20), 10% biodiesel-10% butanol-80% diesel (D80B10BU10), and 15% biodiesel-15% butanol-70% diesel (D70B15BU15). The experiments were conducted at a fixed speed of 2250 rpm across particular engine loads ranging from 4-10 kW. The results stated that BTE was reduced for all fuel mixes compared to diesel, with triple-mix fuels having lower efficiency. BSFC increased for the blends relative to diesel. EGT were lower for the blends due to their lower energy content and butanol's higher heat of vaporization. CO and HC decreased for the blends, while CO_2 increased in comparison to diesel. NOx emissions decreased for the triple blends but increased slightly for the D80B20 blend. It was concluded that waste cooking oil biodiesel could be utilized with butanol as a viable diesel fuel alternative with potential emissions benefits. Asokan & Prabu (2023) investigated the effect of n-butanol on cottonseed oil biodiesel and its mixtures with diesel fuel on the performance, emissions, and combustion of a single-cylinder CI engine. Biodiesel was created from cottonseed oil through a transesterification process. The fuels included D100, B20, B30, B40, B100, BN20, BN30 and BN40, where N represents addition of n-butanol. Experiments were conducted at a constant speed of 1500 rpm and varying loads. Results indicated that BSFC increased and BTE decreased for biodiesel blends in comparison to diesel. HC and CO emissions cut down on with biodiesel and further decreased with the adding of n-butanol. NOx increased for biodiesel blends but reduced with n-butanol addition. It has been found that cotton seed oil biodiesel with n-butanol is a better fuel alternative in terms of performance and emissions compared to biodiesel and diesel. Thiruselvam et al. (2023) examined emissions and performance direct injection CI engine operated on mixes of Delonix regia biodiesel with n-butanol and EGR. Biodiesel had manufactured from Delonix regia oil through transesterification. Test fuels included DRB10+D90, DRB10+BUT10+D80, DRB10+BUT20+D70, DRB20+D80, and DRB20+D80+EGR10. Experiments were conducted at a fixed speed of 1500 rpm with varying loads. The findings showed that the DRB10+BUT20+D70 blend reduced both BSFC and BTE by 11.19% and 2.62% respectively compared to diesel. Smoke and CO emissions decreased with biodiesel and were further reduced with n-butanol addition. NOx reduced with EGR. It was concluded that Delonix regia biodiesel with n-butanol and EGR improves performance and reduces most emissions in comparison to diesel and biodiesel. Fernández-Rodríguez et al. (2021) reviewed studies on the utilization of biobutanol mixes in diesel engines. Biobutanol could be manufactured through lignocellulosic feedstocks via fermentation and has 60% less GHG emissions than diesel. Butanol properties like density, viscosity, heating value, lubricity, and miscibility make it more suitable than ethanol for diesel blending. Studies found butanol-diesel mixes up to 40% butanol content could be run in CI engines without changes. Particulate emissions were reduced for blends up to 16% butanol content while THC increased for higher butanol content. CO and NOx emission trends varied between studies. It was concluded that biobutanol has the feasibility of reducing life-cycle emissions when blended with diesel in engines without modifications.

Recent literature research shows that many studies have investigated the exhaust emissions and engine performance of butanol, biodiesel, and diesel ternary mixes on CI engines. On the sidelines, no study has been found in the literature examining a ternary mixture of hazelnut biodiesel in these ternary fuel mixtures. In addition, it was noticed that very scarce studies were produced on the application of butanol, one of the higher alcohols, as a fuel additive in CI engines. Moreover, to the best of the authors' awareness, there has been no works in literature on the addition of butanol to HOB or HOB-diesel fuel mixtures. This motivated experimental investigation aims to examine how diesel-HOB-butanol mixes impact the exhaust emissions and engine performance of a CI engine. Biodiesel-diesel fuel (20% HOB) was mixed with butanol (4-carbons) at 5%, 10%, and 15% (by volume) to make B20Bt5, B20Bt10, and B20Bt15 test fuels matching this plan. Hazelnut oil was processed to biodiesel utilizing a transesterification procedure. A naturally-aspirated, 4-stroke, water-cooled, one-cylinder CI engine operating at 1500 rpm at fixed engine speed was used to test the fuel samples at four different engine loads: 25%, 50%, 75%, and 100%. As covered in several other relevant investigations, the experimental outcomes were contrasted with baseline diesel fuel.

2. Material and Methods

2.1. Material and chemicals

Convenience and accessibility of availability had a role in the selection of the materials and reagents. Hazelnut oil was bought from a commercial firm in Kırıkkale, Türkiye, and utilized as a feedstock in the synthesis of biodiesel in this research. The fossil-based diesel fuel that is sold was acquired from a plant in the same city, and its fuel qualities satisfy EN 590 standards. The alcohol used to produce biodiesel, methanol (99.5%), originated from Sigma-Aldrich Chemical Company. The catalyst utilized in the process was potassium hydroxide (KOH), which was obtained from Tekkim Chemical Company. Because all chemicals were of the quality of analytical reagents, they were utilized just as supplied, requiring no purification. The supplier of the 125 mm quality-filter paper was S&H Labware in Ankara, Türkiye.

2.2. Biodiesel produced with hazelnut oil

In this research, hazelnut oil biodiesel has been generated using the transesterification process, which is often used in the literature. However, a number of factors, catalyst concentration and type, reaction temperature and time, including free fatty acid (FFA), water content, alcohol ratio and type, etc., affected the transesterification reaction. The following paragraphs provide a comprehensive explanation of the rationale for the levels of selected parameters.

The transesterification is primarily influenced by the water content and FFA quantity in the oil, both of which have a negative effect. Water content has a greater impact on reducing biodiesel yield during transesterification compared to FFA. Increased water quantity in the oil could result in saponification, an incomplete reaction, and decreased ester yield (Yesilyurt et al., 2020). Moreover, the separation of glycerol becomes challenging during saponification, resulting in lower biodiesel yields (Jariah et al., 2021). The FFA content of the oil used in biodiesel production should not exceed 0.06% (Elgharbawy et al., 2021). Increased levels of FFAs in the raw material result in higher catalyst use during the reaction, leading to a reduction in biodiesel production owing to saponification. Consequently, rather than using a direct transesterification method, several researchers have suggested utilizing a two-step approach that includes esterification and transesterification. Regrettably, the production cost of HOB was seen to be costly than the price of diesel. The potential of HOB was assessed for further examination. Figure 1 provides a concise depiction of the flowchart illustrating the process of biodiesel generation derived from hazelnut oil. In addition, Figure 2 presents an image of the produced hazelnut oil biodiesel in a screw cap bottle.

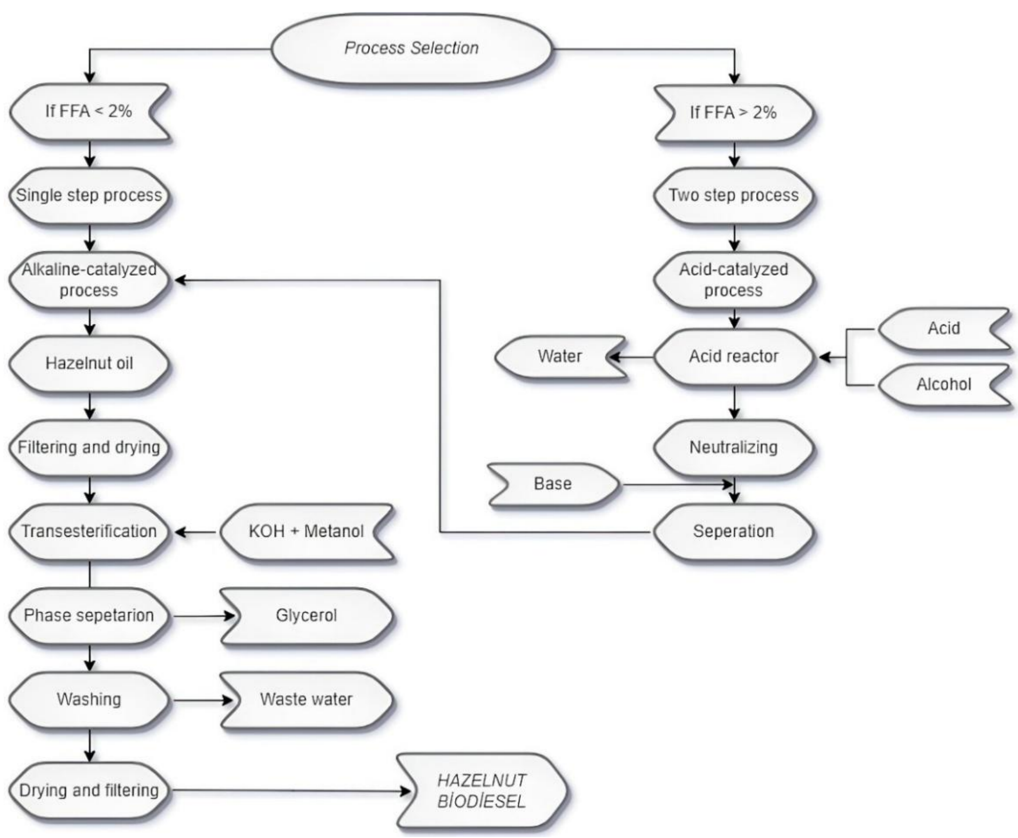

Figure 1. Steps involved in selecting a process and producing biodiesel

Figure 2. Hazelnut oil biodiesel in a screw-capped bottle

2.3. Preparing binary and ternary fuel mixtures

This experiment employed diesel fuel, HOB, and butanol to produce test fuels for the purpose of testing. The test fuels were created utilizing a standard beaker made of glass with a capacity of ±0.5 ml. The splash mixing technique, being the most cost-effective option, was used due to its widespread preference. Various percentages of butanol were combined with HOB and diesel fuel while maintaining a consistent biodiesel content of 20% throughout all blends. The fuel mixtures were produced by combining butanol at concentrations of 5%, 10%, and 15% with diesel fuel at concentrations of 75%, 70%, and 65%, respectively. Furthermore, a binary mixture consisting of B20 (80% diesel fuel and 20% HOB) has been formulated. The ternary fuel mixes' experimental outcomes were contrasted with those of B20 and D100. Also, several important physicochemical properties of the test fuel samples are listed in Table 1. Before testing phase, test fuels were kept for a full day at room temperature in a dark, airtight glass container. As a result, there was no phase separation seen in the mixes.

Table 1. Some of the significant physical and chemical characteristics of the test fuel samples

Property	D100	B100	Butanol	B20	B20Bt5	B20Bt10	B20Bt15
Density at 15 °C (kg/m^3)	820	882	808.14	832.4	831.81	831.21	830.62
Cetane number (-)	53.5	51.2	17.32	53.04	51.23	49.42	47.61
Kinematic viscosity at 40 °C (mm^2/s)	2.745	4.936	2.678	3.183	3.180	3.177	3.173
Calorific value (kJ/kg)	43,200	40,208	35,033	42,302	42,193	41,785	41,377
Flash point (°C)	60	169	35	81.8	80.55	79.3	78.05
Water content (ppm)	36.457	469.23	298.00	123.01	136.09	149.17	162.24
Copper strip corrosion (3 h at 50°C)	1A	1A	1A	1A	1A	1A	1A
pH (-)	8.235	7.174	6.709	8.023	7.947	7.870	7.794
Cloud point (°C)	-8	-6.2	-115	-20.5	-13	-18.3	-23.7
Cold filter plugging point (°C)	-23.5	-8.6	-	-	-	-	-
Pour point (°C)	-35	-14.3	-90	-30.9	-33.6	-36.4	-39.1

2.4. Experimental configuration

The current study involved engine testing in a test set-up CI engine model TV1 of the Kirloskar brand and an exhaust emission device model MOD 2210 of the Bilsa brand. Figure 3 depicts a simplified spectacle of the test setup. Table 2 displays the important properties of the diesel engine.

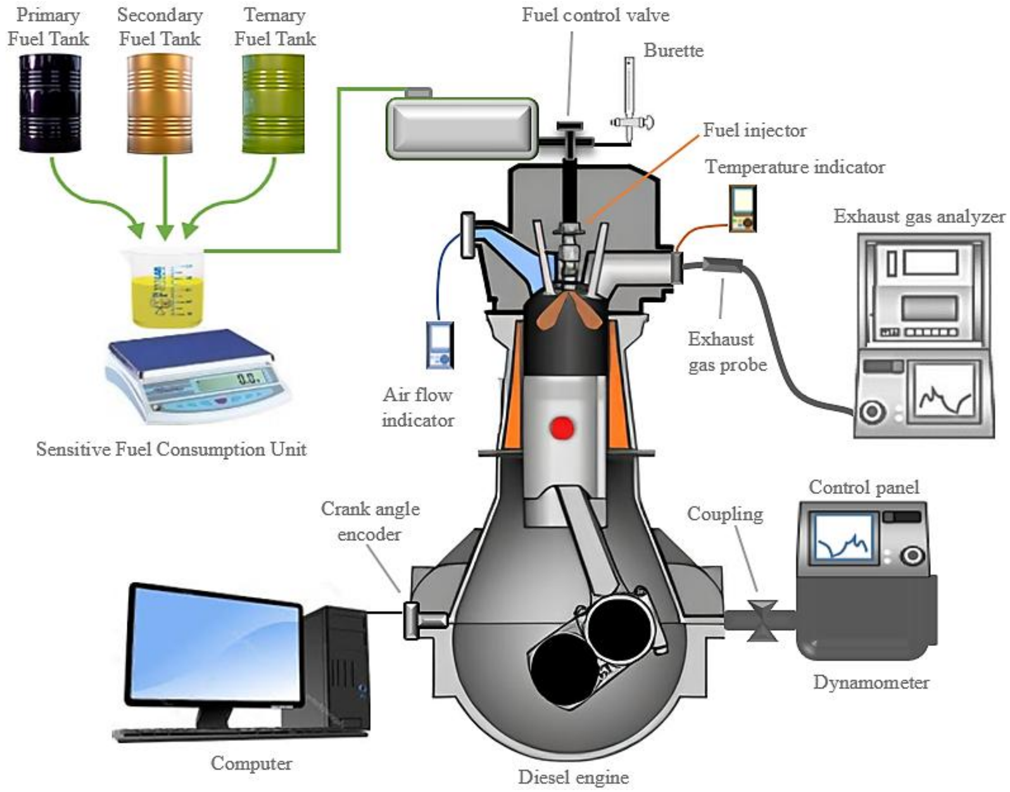

Figure 3. A simplified appearance of the test setup

Table 2. Significant properties of the CI engine

Item	Specification
Valve system	Two valves
Fuel injection type	Direct-injection
Fuel type	Multi-fuel
Compression ratio	18/1
Number of injector nozzles	4
Opening pressure of the nozzle	200 bar
Rated engine power	5.2 kW
Stroke length	110.00 mm
Bore diameter	87.50 mm
Displacement	661.45 cc
Fuel injection timing	23^o bTDC

Smoke opacity and exhaust emission values were gauged with the aid of an exhaust emission device that can be viewed and printed on the monitor. To obtain exhaust gas measurement data, the measurement probes of the device are placed in exhaust pipe. In order to mitigate potential inaccuracies, exhaust gas measurement probes were calibrated using standard gas samples prior to conducting experiments. Table 3 lists the technique information of the exhaust gas analyzer. A Abustek Fr Block model K thermocouple was utilized to show the EGT readings. This type of thermocouple can be connected to the experimental setup's control panel unit and can measure temperatures between 0 and 1200 °C. The amount of fuel consumed were calculated with the help of a stopwatch and an electronic precision balance.

Table 3. Technical data of the opasimeter and exhaust gas analyzer

Variables	Units	Interval	Accuracy
NO_X	ppm	0-5000	±1
O_2	%	0-25	±0.01
HC	ppm	0-10000	±1
CO_2	%	0-19.99	±0.001
CO	%	0-10	±0.001
Smoke opacity	1/m	0-10	±1%
Operating temperature	ºC	5-40	±0.01%

2.5. Uncertainty Analysis

Understanding the intricacies of experimental measurements and accurately calculating performance parameters is crucial for achieving precision. Various parameters, such as test planning, observation, reading, environmental conditions, calibration, and equipment selection, can influence the emergence of errors and uncertainties. Performing an uncertainty analysis is called for to demonstrate precision of trial outcomes. The formula shown in Equation 1 was used to calculate the uncertainties (Holman, 2021).

$$w_R = \left[\left(\frac{\partial R}{\partial x_1} w_1\right)^2 + \left(\frac{\partial R}{\partial x_2} w_2\right)^2 + \cdots + \left(\frac{\partial R}{\partial x_n} w_n\right)^2\right]^{1/2} \quad (1)$$

In the above equation, the uncertainty value of the outcomes is denoted as w_R, while the uncertainty of the independent variables, is represented by w_1, w_2, …, w_n. x_1, x_2, x_3, …, x_n is a function of the independent variables and R is the dependent factor. The uncertainty analysis for the equipment used was computed according to Equation 1 and the uncertainty values are listed in Table 4 below.

Table 4. Uncertainty values of several crucial parameters

No	Parameter	Measuring range	Accuracy	Uncertainty (%)
1	Brake thermal efficiency	-	-	±1.69
2	Mass of the fuel consumption	-	-	±1.55
3	Unburned HC	0-10000 ppm	±1 ppm	±1.39
4	Exhaust gas temperature	-	±0.1 °C	±1.00
5	CO	0-10% vol.	±0.001%	±0.90
6	CO_2	0-19.99% vol.	±0.001%	±0.76
7	Brake power	0-5.2 kW	±0.3 kW	±0.67
8	O_2	0-25% vol.	±0.01%	±0.67
9	NO_X	0-5000 ppm	±1 ppm	±0.67

3. Results and Discussion

3.1. Engine Performance

The study focused on three-in-one mixes of diesel-butanol-HOB fuel and contrasted them with a two-in-one mix of diesel and biodiesel fuel. Exhaust emissions, including NOx, smoke opacity, HC, CO_2, and CO, and engine performance characteristics, including BTE, BSEC, BSFC, and EGT, were analyzed at 25%, 50%, 75%, and 100% engine loads.

3.1.1. Brake-specific fuel consumption

BSFC offers a means of comparing fuel consumption at a certain moment with power generated by a diesel engine. Fuel economy and efficiency are crucial factors to consider when selecting fuel for a CI engine (Gao et al., 2020). It is expected that BSFC value will decrease if fuel consumption decreases at a certain power level. The fuel mixes' specific fuel consumption behaves similarly and has comparable magnitude values, as seen in Figure 4. A progressive decline in BSFC values was seen as load rose. The BSFC value of D100 fuel was reduced by about 24.61% when the load rose from 25% to 50%, by about 27.8% when the load rose to 75%, and by about 29.8% when the load rose to 100%. Conversely, as the engine load rose, the efficiency of combustion improved, resulting in a decrease in BSFC values. This can be referred to the longer duration needed for combustion, enhanced turbulence within cylinder, and regular dispersal of the air/fuel mixture within cylinder (Hamid et al., 2018).

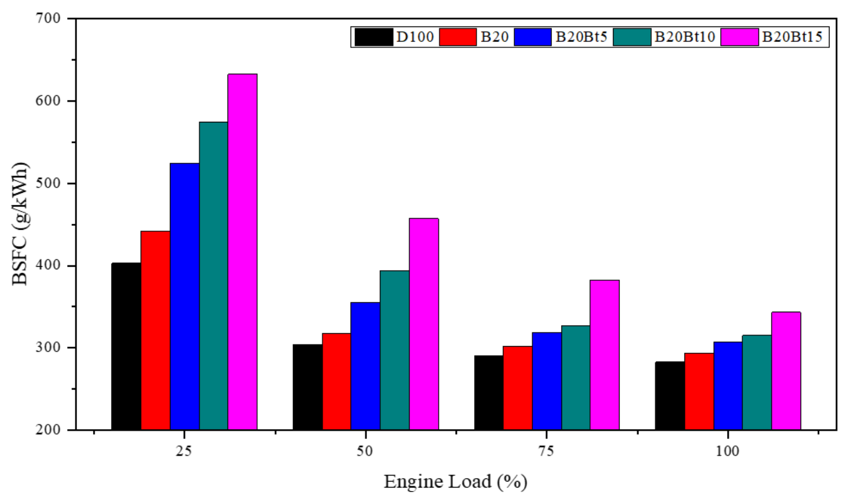

Figure 4. Change of BSFC results based on the engine load

The fueling of B20 fuel resulted in a more pronounced enhancement in BSFC with each increasing load, in contrast to utilization of D100. That is mainly B20 fuel has a lower caloric content, necessitating a bigger amount of fuel to sustain the same load condition. The fact that it provided peak BSFC results for all-load levels of the lowest-ranking fuels in terms of energy content, B20Bt15, and B20Bt10, further supports this argument. Furthermore, it was comprehended that the involvement of butanol in the B20 combination caused in an augmentation of the BSFC. That is because butanol has a lower heating value and cetane number than B20. This means that it takes a longer ignition delay and burning time (Örs et al., 2020; Yesilyurt, 2020; Zhang et al., 2022). Consequently, this has a negative effect on performance and combustion efficiency. The BSFC values show a positive correlation with the alcohol concentration in combinations that include alcohol. The lower cetane number and calorific value of butanol in comparison to diesel and HOB result in an increased fuel need to achieve equivalent engine power at every engine load, thereby impacting the BSFC. It is also known that alcohols have higher latent temperatures of vaporization, which means that evaporation process would happen more slowly in fuels containing butanol. Therefore, combustion will worsen, and hence BSFC will increase.

3.1.2. Brake-specific energy consumption

BSEC refers to quantification of energy acquired from fuel consumption within a one-hour timeframe, divided by the effective power generated by the engine. There exists a directly correlation within BSEC values of the fuel samples and BSFC values. Figure 5 displays the BSEC graph of five types of fuels that were evaluated in this research under varying engine loads. The reduction in BSEC as engine load rises is primarily due to improved thermal efficiency at higher loads. At a higher load, a motor generally operates closer to its ideal efficiency point. Thus, a larger portion of the fuel energy contributes to the generation of useful work. As a result, a decreasing trend in BSEC is observed, meaning that fuel efficiency increases (Zangana et al., 2023). The rise in alcohol concentration in the ternary mixes led to a drop in calorific values, resulting in a rise in the BSEC. The fuels B20Bt15 and B20Bt10 exhibited the greatest BSEC values, while their lower calorific values were found to be 26.20 MJ/kWh and 24.16 MJ/kWh, respectively, at a load of 25%. When lowest BSEC values for each fuel were determined to be at full load, these values were computed as 12.52 MJ/kWh, 12.72 MJ/kWh, 13.09 MJ/kWh, 13.25 MJ/kWh, and 14.22 MJ/kWh for D100, B20, B20Bt5, B20Bt10, and B20Bt15 fuels, respectively. It is considered possible that a rise in the cetane number resulted in a decrease in the ignition delay time. As a consequence of this phenomenon, the fuels were unable to adequately blend with the air, leading to reduced flammability caused by the heterogeneous mix and an increase in energy demand (Liu et al., 2014).

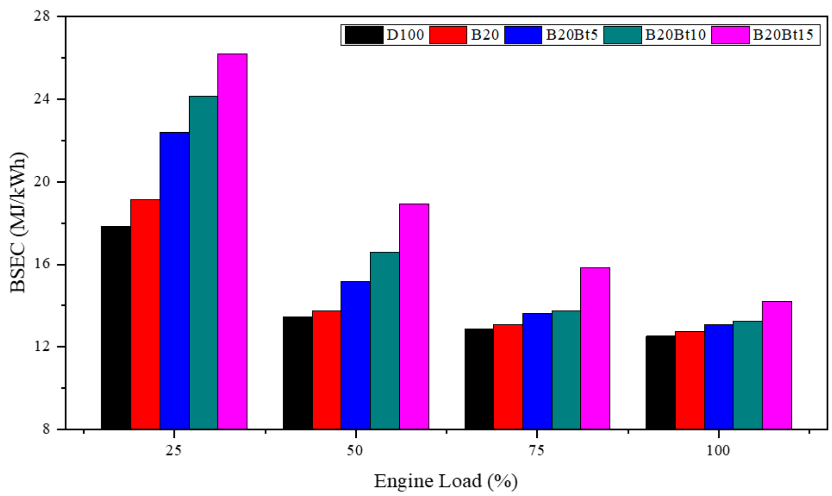

Figure 5. Change of BSEC results based on the engine load

3.1.3. Brake thermal efficiency

BTE is the measure of the proportion of the engine's effective power output relative to thermal energy provided by fuel delivered into combustion chamber (Deepanraj et al., 2022). Optimal BTE corresponds with peak engine torque. Enhanced combustion efficiency, coupled with improved volumetric efficiency and elevated engine load, leads to a decrease in BSFC and an augmentation of engine torque (Baek et al., 2021). Figure 6 illustrates the variation in BTE values across different engine loads for all fuels that were evaluated. Across the range of fuels tested, D100 exhibited better BTE. The B20 blend was perceived to yield less BTE compared to D100, attributed to its reduced energy content and the increased density and viscosity it possesses (Ahmad et al., 2023). It has been known that adding butanol to B20 fuel lowers the energy content of the mixture and the BTEs. This is because cetane numbers and heating values of the fuels go down and the latent heat of vaporization goes up. The BTE outputs exhibited a further decline as the quantity of butanol added increased, indicating a deterioration in the characteristics of the fuel mixes. The highest BTE values of ternary mixtures containing alcohol were computed as 27.50%, 27.16%, and 25.32% for B20Bt5, B20Bt10, and B20Bt15, respectively, at full load.

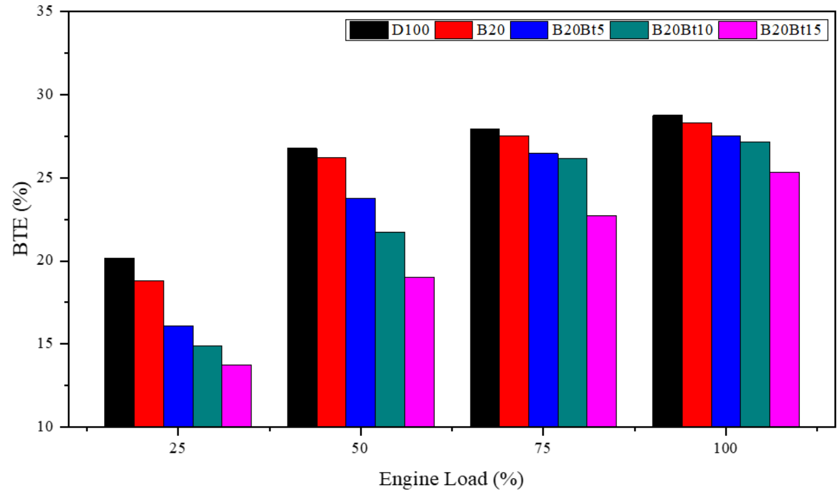

Figure 6. Change of BTE results based on the engine load

3.1.4. Exhaust gas temperature

EGT is a significant indicator, providing insights into the combustion process's quality (Ağbulut et al., 2020). Exhaust gas content is a crucial element which significantly reveals the change in emissions. Figure 7 illustrates the fluctuation of EGT amounts for biodiesel, diesel, and other in relation to engine load. A comparison was made between the EGT values of reference D100 and triple fuels containing B20 and butanol. It has been observed when EGT values of triple blends are fewer compared with B20 and D100. The EGT results of alcohol-containing fuels at maximum load decreased as the amount of alcohol in the fuel rose. This is the same for other loads. The measured values for D100, B20, B20Bt5, B20Bt10, and B20Bt15 were 507.05 °C, 505.95 °C, 504.03 °C, 501.89 °C, and 493.00 °C, respectively. Every engine load is ranked similarly. This idea was based on the probability that the latent heat of vaporization, cetane number, and oxygen content had a bigger impact than the heating value. Due to the enhanced cooling impact of alcohols as the alcohol concentration increases, it can be concluded fuel blend with 15% butanol had the lowest EGT (Truong et al., 2021).

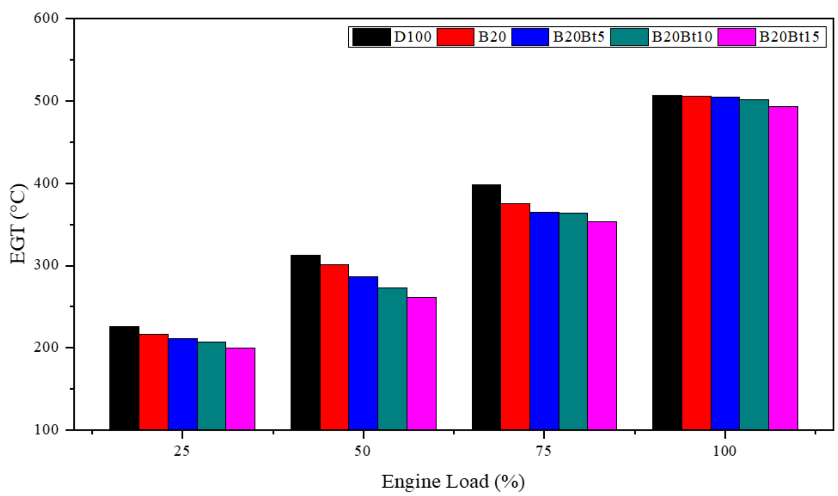

Figure 7. Change of EGT results based on the engine load

3.2. Exhaust emissions characteristics

3.2.1. NO_X emissions

Nitrogen, which typically remains unreactive under normal circumstances, makes up about 78 percent of air. The NO_X consists of a major quantity of NO and a small quantity of NO_2. Often, other NO_X, like NO_3, N_2O_5, and N_2O, are not taken into account. In addition, NO_X emissions are classified as a detrimental and undesirable byproduct. Understanding the mechanism of NOX formation is crucial for effectively reducing these emissions. Within the existing body of literature, various processes have been identified to elucidate the process of NO_X generation along the way in the combustion of diesel fuel. The Fenimore and Zeldovich processes are widely acknowledged as viable models for both biodiesel combustion and diesel combustion (Alagumalai et al., 2022).

There are three main factors that frequently have an impact on the generation of thermal NOx: (i) elevated charge temperature; (ii) increased oxygen concentration; and (ii) duration allocated for reactions to occur (Satsangi & Tiwari, 2018). Figure 8 illustrates the variation in NOx emissions of D100, B20, B20Bt5, B20Bt10, and B20Bt15 with engine load. As previously stated, there is a noticeable increase in NOx emissions exceeding a temperature of 1700 K in the combustion chamber. Moreover, the levels of NO_X also increase as the duration of the mixes' residence time increases at higher temperatures (Veza et al., 2023).

The NO_X emissions were assessed, and it was seen that all of the tested fuels exhibited an upward trend in relation to the engine load. This could be ascribed to the rise in engine load consistently leading to a rise in cylinder temperature. The verification of this may be conducted using EGT findings, as seen in Figure 7. A reduction of the NO_X emissions of ternary fuel mixtures containing B20 and butanol was observed compared to the D100 reference fuel. Furthermore, it was noted as butanol added to the diesel fuel-HOB mixture resulted in a greater decrease of NO_X emissions. The evaluation of impact of including butanol in the diesel-HOB mix on the generation of NO_X revealed a steady reduction in NO_X emissions. Notably, the average decline in NO_X emissions for B20Bt5, B20Bt10, and B20Bt15 was 11.87%, 16.73%, and 21.28%, respectively, as compared to the D100 fuel mix. A similar situation was seen in the comparison with B20 fuel, albeit at lower rates, and NO_X emissions reduction by an average of 7.02%, 12.14%, and 16.95%, respectively.

The decrease in temperature of remaining gases within combustion chamber may be attributed to many phenomena, on condition that the elevated latent heat of evaporation, the low heating value, and the high oxygen content present in alcohols. Consequently, it induces a decrease in temperature, preventing the reaction between oxygen and nitrogen atoms. As a result, the production of NOx was reduced. Moreover, the reduced viscosity and density of alcohols in comparison to biodiesel and diesel fuels have a direct impact on the final temperature of the combustion period. The test findings were consistent with the majority of previous investigations done by other researchers using higher alcohol concentrations (Bhanu Teja et al., 2023; Devarajan et al., 2022).

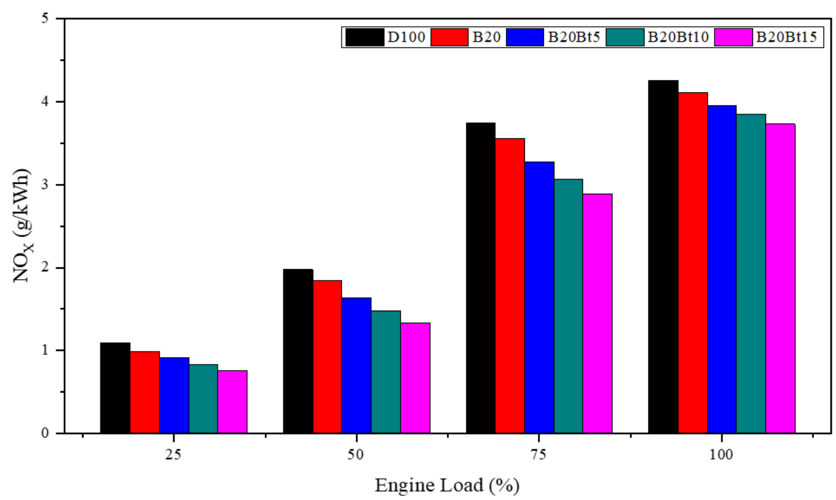

Figure 8. The NOx results of the fuels based on the engine load

3.2.2. HC emission

Lower oxidation reactions and incomplete combustion processes are the major causes of HC emissions. The following factors might be at play: (i) very poor/rich air-fuel proportions within the combustion chamber; (ii) heat loss to cold areas on the walls of the cylinders; and (iii) flames extinguishing in these locations (Yesilyurt et al., 2018; Yilmaz et al., 2017). Similar patterns are also seen in HC emissions and CO emissions. Figure 9 depicts the change in HC emissions from fuels with the engine load. Both CO and HC emissions of B20 fuel were determined to be less than those of D100. The highest concentration of HC emissions was detected while the engine was operating at a load of 100%. The B20 had an average decrease of 7.67% in HC emissions in comparison to D100. Furthermore, the additive of butanol into the diesel-biodiesel resulted in a significant reduction in HC emissions. Xiao et al. (2020) note that HC emissions intensify under higher engine loads owing to increased mass of injected fuel and quenching effect. The outcomes of the current study were coherent with previous studies conducted on alcohol-added fuels, indicating a high level of satisfaction.

Some studies in the literature revealed that ternary blends, which have a higher alcohol content, exhibited higher levels of HC emissions levels than D100 (Yilmaz & Davis, 2016; Wei et al., 2018). Nevertheless, it is evident from Figure 9 that the incorporation of butanol into biodiesel-diesel combinations resulted in a decrease in HC emissions. In comparison with D100, the HC emissions of B20Bt5, B20Bt10, and B20Bt15 exhibited an average reduction of 10.86%, 16.61%, and 23.00%, respectively. Additionally, rates of 3.46%, 9.69%, and 16.61% were identified in relation to the B20 fuel mix. Devarajan et al. (2022) reports that the supplementation of butanol to the test fuel rose the availability of oxygen, which ensured a reduction in HC emissions under all loading states. It is also stated that maximum HC emissions were achieved at full load and were measured as 57 ppm for diesel and 49 ppm and 46 ppm for fuels containing 5% and 10% butanol, respectively.

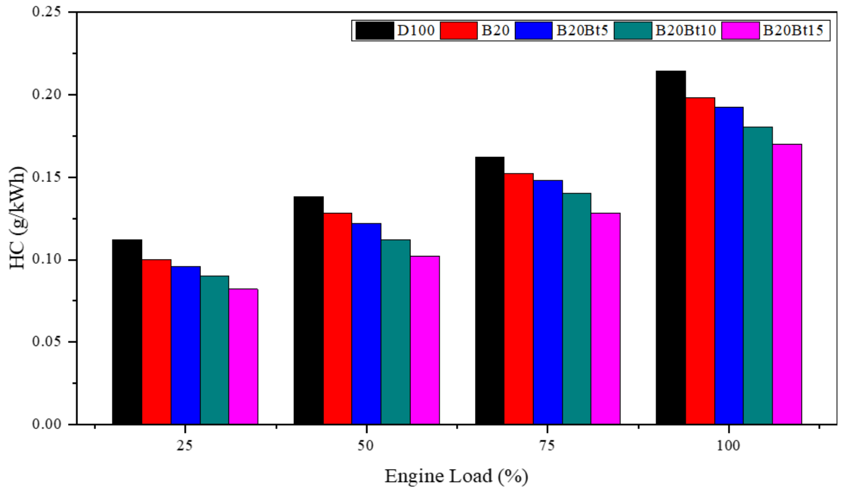

Figure 9. The HC results of the fuels based on the engine load

3.2.3. CO_2 emission

CO_2 emissions are widely recognized as the primary driver of global warming, exerting a substantial influence on the GHG gas effects inside the Earth's atmosphere (Zhang et al., 2023). It may also be a significant factor in the development of ozone and serious public health issues (Arias et al., 2022). However, some scholars have emphasized that the plants effectively capture and utilize all of the CO_2 emissions resulting from the burning of biodiesel, in conjunction with the essential process of photosynthesis (Tucki et al., 2020; Mourad et al., 2021; Thiyagarajan et al., 2021). The monitoring of CO_2 emissions is a crucial aspect that may provide insights into the extent of full combustion in the cylinder. Consequently, an increased amount of oxygen in the cylinder has the potential to generate excellent combustion. Providing a sufficiently large number of oxygen molecules are available inside the combustion chamber, CO will undergo conversion into CO_2 emissions due to the oxidation of the hydroxyl radical (OH), which is considered a crucial characteristic (Viswanathan & Paulraj, 2023).

Figure 10 illustrates the CO_2 emission ranges for various test fuels while maintaining varied engine loads and a constant engine speed of 1500 rpm. Upon analysis of Figure 10, it was seen that the greatest engine speed corresponded to the largest CO_2 levels. Furthermore, the concurrent rise in engine load ensured a reciprocal increase in CO_2 emissions across all tested fuels. Because the binary and ternary mixes' structures included more oxygen than necessary to achieve full combustion, their CO_2 emissions were greater than those of D100. The average CO_2 emissions of D100, B20, B20Bt5, B20Bt10, and B20Bt15 were determined to be at 306.798 g/kWh, 330.710 g/kWh, 344.690 g/kWh, 365.079 g/kWh, and 382.296 g/kWh, respectively. At an engine load of 100%, the B20Bt15 fuel blend exhibited a peak CO_2 emission of 489.227 g/kWh. This value was determined to be 15.56% more than that of the D100 and 10.95% greater than that of the B20. The enhanced evaporation of the fuel could be related to reduced kinematic viscosity and density of ternary mixtures, causing a constant rise in CO_2 emissions.

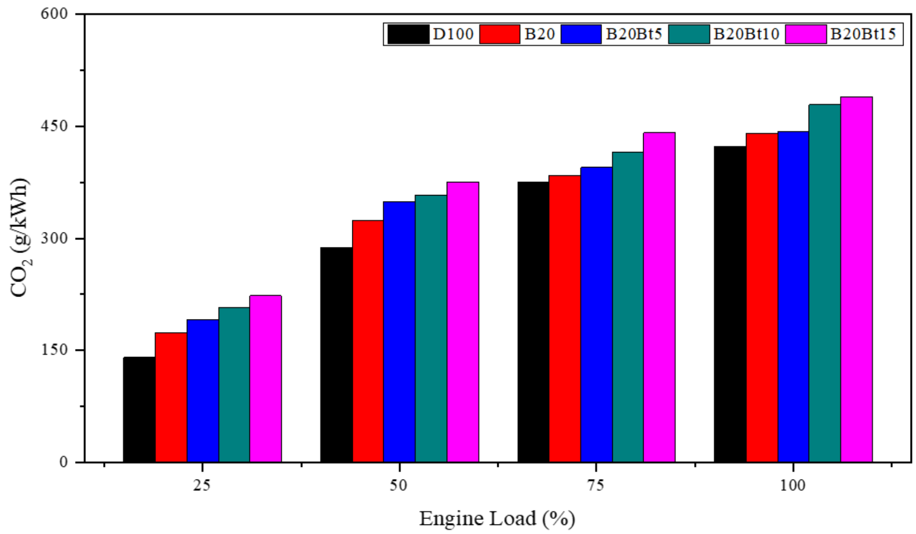

Figure 10. The CO_2 results of the fuels based on the engine load

3.2.4. CO emission

Figure 11 plot the change of CO emission levels of every fuel sample with engine load. Upon evaluating Figure 11 based on engine load, it was clearly understood that the CO emissions of test fuels exhibited lower values as engine load decreased. Nevertheless, the maximum engine load resulted in the most significant CO emissions for every fuel sample. The mean CO emissions of B20, B20Bt5, B20Bt10, and B20Bt15 have decreased on average by 8.55%, 19.08%, 24.07%, and 32.30%, respectively, in comparison to the D100 results. The introduction of butanol to the diesel-biodiesel fuel mix appeared to result in a noticeable reduction in CO emissions, mostly ascribed to the existence of oxygen in alcohol structure. CO emissions serve as a measure of the chemical energy that is going down the drain through exhaust emissions. Moreover, the existence of CO emissions in the exhaust emissions may indicate an inadequate combustion procedure inside the cylinder. The primary factor contributing to this phenomenon is a deficiency in the oxygen concentration inside the combustion chamber. A higher concentration of oxygen molecules in the medium may result in the production of CO_2 emissions rather than CO emissions. Hence, the quantity of oxygen has a critical role to play in preventing the production of CO emissions as part of exhaust emissions.

Although biodiesel fuels as well as alcohols contain oxygen in their chemical bonds, it is not present in diesel fuel. Consequently, it can be indicated that the utilization of oxygenated fuels in CI engines will provide a smaller quantity of CO emissions. Additionally, it is guessed that the surplus quantity of oxygen will react with carbon atoms, resulting in the release of CO_2 emissions in the exhaust. It is also known that alcohols have fewer carbon atoms in their composition and thus produce fewer CO emissions. Upon analysis of the results from the present research, it was seen that the B20 fuel mix showed reduced CO emissions, while the alcohol-added fuel mixtures showed even lower CO emissions over diesel fuel. Devarajan et al. (2022) stated that CO emissions in B20, B100, B20-5Bu, B20-10Bu, and B20-15Bu were reduced by 10%, 20%, 25%, 40%, and 45%, respectively, compared to the reference fuel, diesel.

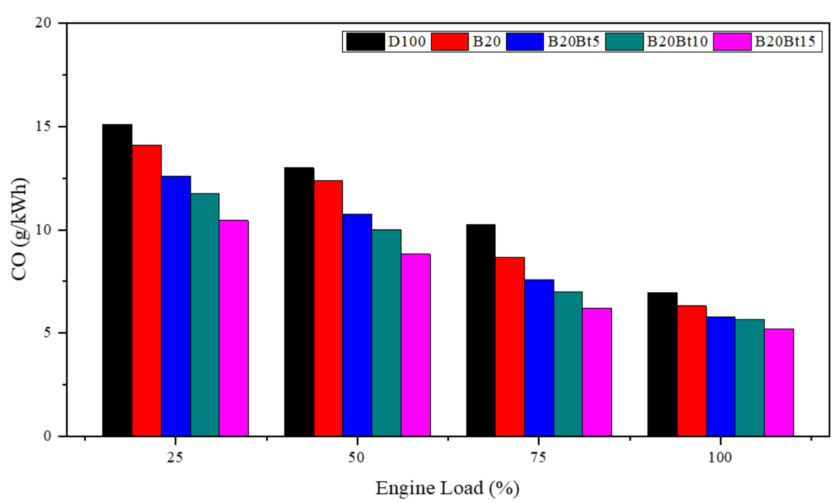

Figure 11. The CO results of the fuels based on the engine load

3.2.5. Smoke opacity

Smoke opacity emerges as a fundamental problem when emissions from diesel engines are evaluated. Smoke is an undesirable combustion product that consists of as a consequence of poor combustion of fuel in diesel engines (Selvan et al., 2022). The production of smoke opacity in the exhaust was a result of the poor combustion of carbon and HC particles in the mixes (Yusuf et al., 2023). The current investigation included the assessment of smoke emissions for all tested fuels using an opacimeter. Figure 12 shows how the amount of smoke changed for D100, B20, and ternary blends as the engine load changed. There was a small rise in the smoke-opacity results of fuels as the engine load rose. Additionally, it was observed that the smoke opacity of B20 fuel had a decreased visual appearance in comparison to diesel fuel under each engine load operating states. The study determined that mean smoke opacities of D100 and B20 were about 0.713 1/m and 0.610 1/m, respectively.

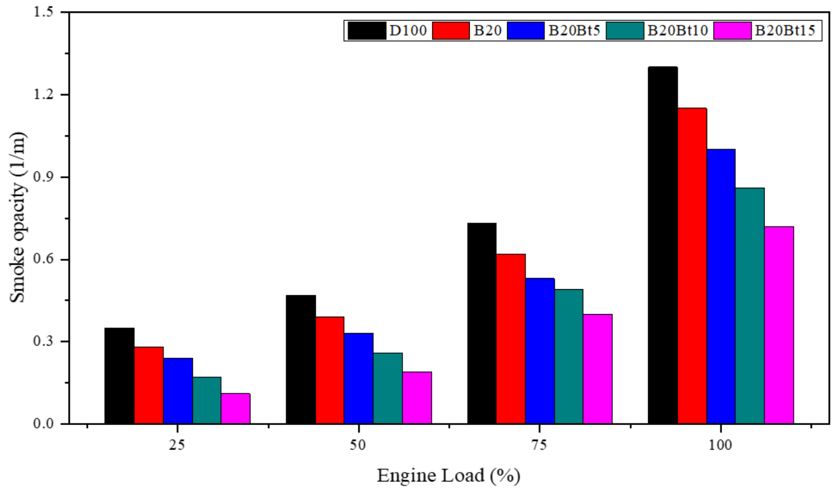

Figure 12. The smoke opacity results of the fuels based on the engine load

The smoke-opacity averages of triple mixtures consisting of B20Bt5, B20Bt10, and B20Bt15 were measured as 0.508 1/m, 0.445 1/m, and 0.335 1/m, respectively. It is worth noting that there is a noticeable correlation between the percentage rise of butanol in the blends and a consistent decrease in smoke-opacity. This phenomenon is feasible given the presence of oxygen inside the butanol compound. Furthermore, the ternary mixes of diesel, biodiesel, and butanol exhibit reduced viscosity and density values in comparison to B20 fuel, resulting in improved smoke opacity values as against the B20 fuel blend.

4. Conclusions

It is well-known that higher alcohols have smitten with both the environment and the economy, making them ideal additives for use in CI engines and thereby promoting the use of sustainable and renewable resources. Butanol, a higher alcohol with a molecular structure consisting of four carbons, has gotten global relevancy in recent years owing to its increased energy content and oxygen compared to lesser alcohols. Given this study, the current investigation was conducted. Present work studied the engine performance and exhaust emissions of a diesel engine operating different fuel blends. The fuels tested included typical diesel fuel, a mix of diesel fuel and HOB, and three different mixtures of diesel-butanol-biodiesel fuel. The findings and their implications were thoroughly discussed. Specifically, higher alcohol mixes with levels of up to 15% (by vol.) were favored. The findings may be summarized as follows:

The inclusion of butanol improved the cold flow parameters of ternary blends, but it had a negative impact on cetane number, heating value, kinematic viscosity, and density. Furthermore, butanol additive increased the oxygen content of the test fuels.

Based on the tests and observations, all test fuels were successfully used without unmodified to the CI engine. The additional of butanol blends caused rose mass fuel consumption and BSFC compared to D100. Nevertheless, there was no substantial alteration in their BTE ratings, since increased oxygen-content in the blends might enhance combustion efficiency.

The favorable impact on the decrease of EGT was seen not only with B20 but also with higher concentrations of butanol in the blends. For example, according to the EGT results recorded at 25% load, B20, B20Bt5, B20Bt10, and B20Bt15 fuels recorded approximately 3.93%, 6.35%, 8.26% and 11.51% lower EGT than the D100 reference fuel, respectively.

The combustion resulting was improved in the cylinder through the higher oxygen-content, which led to a drop in CO and HC emissions for all tested fuels. The most significant mean decreases were 32% and 23%, respectively, for the 15% butanol percentage.

However, the CO_2 emissions from these alternative fuels showed comparable trends in comparison to diesel fuel, due to their oxygen concentration. The B20Bt15 fuel blend exhibited the highest CO_2 emission value of 489.227 g/kWh at 100% engine load. The CO_2 emissions of diesel and biodiesel were 15.56% and 10.95% higher, respectively, than the specified fuel.

A significant outcome of current study is that the NOx emissions were reduced for all triple mixes in comparison to the B20 fuel mix. While there was an average decrease of 5.22% in the NO_X emissions of B20 fuel in comparison to D100, a similar decrease was detected at an average of 11.87%, 16.73%, and 21.28% for B20Bt5, B20Bt10, and B20Bt15 fuel mixtures, respectively. This is likely because butanol has a higher latent heat of vaporization, which causes a cooling effect. Examining the EGT measurements may help to confirm the cooling effect.

The smoke-opacities of the butanol-blend fuels exhibited a decrease ranging from 13.08% to 68.57% compared to the diesel fuel.

According to the overall results of present work, it is possible to use both HOB and diesel fuel mixes and the combination of HOB, butanol, and diesel fuel with no changes to the engine. Furthermore, experimental findings unequivocally demonstrated that butanol has many notable benefits, making it a promising oxygenated additive. Specifically, ternary mixes may be assessed to decrease the release of emissions. However, it is necessary to conduct more experiments on these fuels under different engine operating circumstances and long-term tests to establish their impact on engine performance and emissions release. Additionally, economic, environmental, and thermodynamic factors can all be considered when evaluating a CI engine running on the developed test fuels.

Acknowledgement

It was funded by the Scientific and Technological Research Council of Türkiye (TUBITAK) through the University Students Domestic Research Projects Support Program (project name: 2209-A, project period: 2022/2, and project number: 1919B012218309).

References

Abrar, I., Arora, T., & Khandelwal, R. (2023). Bioalcohols as an alternative fuel for transportation: Cradle to grave analysis. *Fuel Processing Technology*, *242*, 107646. https://doi.org/10.1016/j.fuproc.2022.107646

Ağbulut, Ü., Sarıdemir, S., & Karagöz, M. (2020). Experimental investigation of fusel oil (isoamyl alcohol) and diesel blends in a CI engine. *Fuel*, *267*. https://doi.org/10.1016/j.fuel.2020.117042

Ahmad, S., Jafry, A. T., Haq, M. ul, Asif, M., Ahmad, K., & Zafar, F. U. (2023). Experimental study of castor biodiesel ternary blends with ethanol, butanol, diethyl ether and dibutyl ether in a diesel engine. *Journal of Thermal Analysis and Calorimetry*, *148*(3), 927–941. https://doi.org/10.1007/s10973-022-11786-7

Alagumalai, A., Jodat, A., Mahian, O., & Ashok, B. (2022). NOx formation chemical kinetics in IC engines. *NOx Emission Control Technologies in Stationary and Automotive Internal Combustion Engines: Approaches Toward NOx Free Automobiles*, 39–68. https://doi.org/10.1016/B978-0-12-823955-1.00002-4

Altarazi, Y. S. M., Abu Talib, A. R., Yu, J., Gires, E., Abdul Ghafir, M. F., Lucas, J., & Yusaf, T. (2022). Effects of biofuel on engines performance and emission characteristics: A review. *Energy*, *238*, 121910. https://doi.org/10.1016/J.ENERGY.2021.121910

Arias, S., Molina, F., Palacio, R., López, D., & Agudelo, J. R. (2022). Assessment of carbonyl and PAH emissions in an automotive diesel engine fueled with butanol and renewable diesel fuel blends. *Fuel*, *316*. https://doi.org/10.1016/j.fuel.2022.123290

Asokan, M. A., & Prabu, S. S. (2023). Effect of n-butanol on cotton seed oil biodiesel: an approach for improving the emission behavior of DI diesel engine. *Petroleum Science and Technology*, *41*(11), 1162–1180. https://doi.org/10.1080/10916466.2022.2092131

Baek, S., Lee, H., & Lee, K. (2021). Fuel efficiency and exhaust characteristics of turbocharged diesel engine equipped with an electric supercharger. *Energy*, *214*. https://doi.org/10.1016/j.energy.2020.119049

Bhanu Teja, N., Devarajan, Y., Mishra, R., Sivasaravanan, S., & Thanikaivel Murugan, D. (2023). Detailed analysis on sterculia foetida kernel oil as renewable fuel in compression ignition engine. *Biomass Conversion and Biorefinery*, *13*(4), 2959–2970. https://doi.org/10.1007/S13399-021-01328-W/FIGURES/12

Bonenkamp, T. B., Middelburg, L. M., Hosli, M. O., & Wolffenbuttel, R. F. (2020). From bioethanol containing fuels towards a fuel economy that includes methanol derived from renewable sources and the impact on European Union decision-making on transition pathways. *Renewable and Sustainable Energy Reviews*, *120*, 109667. https://doi.org/10.1016/j.rser.2019.109667

Celenk, V. U., Argon, Z. U., & Gumus, Z. P. (2020). Cold pressed hazelnut (Corylus avellana) oil. In *Cold Pressed Oils: Green Technology, Bioactive Compounds, Functionality, and Applications* (pp. 241–254). Elsevier. https://doi.org/10.1016/B978-0-12-818188-1.00020-7

Deepanraj, B., Senthilkumar, & N., Mala, & D., & Sathiamourthy, & A. (2022). Cashew nut shell liquid as alternate fuel for CI engine-optimization approach for performance improvement. *Biomass Conversion and Biorefinery*, *12*, 1715–1728. https://doi.org/10.1007/s13399-021-01312-4/Published

Devarajan, Y., Munuswamy, D. B., Teja Nalla, B., Choubey, G., Mishra, R., & Vellaiyan, S. (2022). Experimental analysis of Sterculia foetida biodiesel and butanol blends as a renewable and eco-friendly fuel. *Industrial Crops and Products*, *178*. https://doi.org/10.1016/j.indcrop.2022.114612

Elgharbawy, A. S., Sadik, W. A., Sadek, O. M., & Kasaby, M. A. (2021). Glycerolysis treatment to enhance biodiesel production from low-quality feedstocks. *Fuel*, *284*. https://doi.org/10.1016/j.fuel.2020.118970

Fernández-Rodríguez, D., Lapuerta, M., & German, L. (2021). Progress in the use of biobutanol blends in diesel engines. In *Energies* (Vol. 14, Issue 11). MDPI AG. https://doi.org/10.3390/en14113215

Gao, J., Chen, H., Dave, K., Chen, J., & Jia, D. (2020). Fuel economy and exhaust emissions of a diesel vehicle under real traffic conditions. *Energy Science and Engineering*, *8*(5), 1781–1792. https://doi.org/10.1002/ese3.632

Garg, R., Sabouni, R., & Ahmadipour, M. (2023). From waste to fuel: Challenging aspects in sustainable biodiesel production from lignocellulosic biomass feedstocks and role of metal organic framework as innovative heterogeneous catalysts. In *Industrial Crops and Products* (Vol. 206). Elsevier B.V. https://doi.org/10.1016/j.indcrop.2023.117554

Gowthama Krishnan, M., Rajkumar, S., Thangaraja, J., & Devarajan, Y. (2023). Exploring the synergistic potential of higher alcohols and biodiesel in blended and dual fuel combustion modes in diesel engines: A comprehensive review. *Sustainable Chemistry and Pharmacy*, *35*, 2352–5541. https://doi.org/10.1016/j.scp.2023.101180

Hamid, M. F., Idroas, M. Y., Sa'ad, S., Saiful Bahri, A. J., Sharzali, C. M., Abdullah, M. K., & Zainal, Z. A. (2018). Numerical investigation of in-cylinder air flow characteristic improvement for Emulsified biofuel (EB) application. *Renewable Energy*, *127*, 84–93. https://doi.org/10.1016/j.renene.2018.04.006

Hassan, T., Rahman, M. M., Rahman, M. A., & Nabi, M. N. (2022). Opportunities and challenges for the application of biodiesel as automotive fuel in the 21st century. *Biofuels, Bioproducts and Biorefining*, *16*(5), 1353–1387. https://doi.org/10.1002/BBB.2375

Hicks, D. (2022). Biological Flora of Britain and Ireland: Corylus avellana: No. 302. *Journal of Ecology*, *110*(12), 3053–3089. https://doi.org/10.1111/1365-2745.14008

Holman, J. P. (2021). *Experimental Methods for Engineers Eighth Edition* (Eighth). McGraw-Hill series. www.mhhe.com/holman

İslam, A., Ayan, S., Turan, A., Yılmaz, M., Karagol, S., & Çolak, S. (2023). Morphometric Diversity for Rootstock Characteristics of Turkish Hazel (Corylus colurna L.) Populations in The Western Black Sea Region of Türkiye. *The Black Sea Journal of Sciences*, *13*(4), 1416–1426. https://doi.org/10.31466/kfbd.1285059

Jariah, N. F., Hassan, M. A., Hin Taufiq-Yap, Y., Roslan, A. M., García, T., Francisco, J., Martín, G., & Álvarez-Mateos, P. (2021). Technological Advancement for Efficiency Enhancement of Biodiesel and Residual Glycerol Refining: A Mini Review. *Processes 2021, Vol. 9, Page 1198*, *9*(7), 1198. https://doi.org/10.3390/PR9071198

Kadir Yesilyurt, M., Eryilmaz, T., & Arslan, M. (2018). A comparative analysis of the engine performance, exhaust emissions and combustion behaviors of a compression ignition engine fuelled with biodiesel/diesel/1-butanol (C4 alcohol) and biodiesel/diesel/n-pentanol (C5 alcohol) fuel blends. *Energy*, *165*, 1332–1351. https://doi.org/10.1016/j.energy.2018.10.100

Karpanai Selvan, B., Das, S., Chandrasekar, M., Girija, R., John Vennison, S., Jaya, N., Saravanan, P., Rajasimman, M., Vasseghian, Y., & Rajamohan, N. (2022). Utilization of biodiesel blended fuel in a diesel engine – Combustion engine performance and emission characteristics study. *Fuel*, *311*. https://doi.org/10.1016/j.fuel.2021.122621

Kattimani, S. S., Topannavar, S. N., Shivashimpi, M. M., & Dodamani, B. M. (2020). Experimental investigation to optimize fuel injection strategies and compression ratio on single cylinder DI diesel engine operated with FOME biodiesel. *Energy*. https://doi.org/10.1016/j.energy.2020.117336

Kumar Mahla, S., Goga, G., Cho, H. M., Dhir, A., Bhupendra, &, & Chauhan, S. (2020). Separate effect of biodiesel, n-butanol, and biogas on performance and emission characteristics of diesel engine: a review. *Biomass Conversion and Biorefinery*, *13*, 447–469. https://doi.org/10.1007/s13399-020-01056-7/Published

Kumar, S., Dinesha, P., & Rosen, M. A. (2019). Effect of injection pressure on the combustion, performance and emission characteristics of a biodiesel engine with cerium oxide nanoparticle additive. *Energy*, *185*, 1163–1173. https://doi.org/10.1016/J.ENERGY.2019.07.124

Liu, H., Wang, X., Zheng, Z., Gu, J., Wang, H., & Yao, M. (2014). Experimental and simulation investigation of the combustion characteristics and emissions using n-butanol/biodiesel dual-fuel injection on a diesel engine. *Energy*, *74*, 741–752. https://doi.org/10.1016/j.energy.2014.07.041

Mahmood, L., Zangana, K., Hameed Yaseen, A., Hassan, H., Mohammed, M. M., Mohammed, M. F., & Alalwan, H. A. (2023). Investigated kerosene-diesel fuel performance in internal combustion engine. *Cleaner Engineering and Technology*, *12*, 100591. https://doi.org/10.1016/j.clet.2022.100591

Mathew, G. M., Raina, D., Narisetty, V., Kumar, V., Saran, S., Pugazhendi, A., Sindhu, R., Pandey, A., & Binod, P. (2021). Recent advances in biodiesel production: Challenges and solutions. *Science of the Total Environment*, *794*, 148751. https://doi.org/10.1016/j.scitotenv.2021.148751

Mohammad, A. S., Balla, H. H., & Al-Zuhairy, M. S. (2023). Emission and Performance in a Diesel Engine Operating on Diesel-Biodiesel-Butanol Blends Derived from Waste Cooking Oil. *International Journal of Energy Production and Management*, *8*(4), 241–249. https://doi.org/10.18280/ijepm.080406

Mourad, M., Mahmoud, K. R. M., & Noureldeen, E.-S. H. (2021). Improving diesel engine performance and emissions characteristics fuelled with biodiesel. *Fuel*, *302*, 121097. https://doi.org/10.1016/j.fuel.2021.121097

Nayab, R., Imran, M., Ramzan, M., Tariq, M., Taj, M. B., Akhtar, M. N., & Iqbal, H. M. N. (2022). Sustainable biodiesel production via catalytic and non-catalytic transesterification of feedstock materials – A review. *Fuel*, *328*, 125254. https://doi.org/10.1016/J.FUEL.2022.125254

Örs, İ., Sarıkoç, S., Atabani, A. E., & Ünalan, S. (2020). Experimental investigation of effects on performance, emissions and combustion parameters of biodiesel–diesel–butanol blends in a direct-injection CI engine. *Biofuels*, *11*(2), 121–134. https://doi.org/10.1080/17597269.2019.1608682

Paradinas, A., Ramade, L., Mulot-Greffeuille, C., Hamidi, R., Thomas, M., & Toillon, J. (2022). Phenological growth stages of 'Barcelona' hazelnut (Corylus avellana L.) described using an extended BBCH scale. *Scientia Horticulturae*, *296*, 110902. https://doi.org/10.1016/J.SCIENTA.2022.110902

Raza Abbasi, K., Shahbaz, M., Zhang, J., Irfan, M., & Alvarado, R. (2022). Analyze the environmental sustainability factors of China: The role of fossil fuel energy and renewable energy. *Renewable Energy*, *187*, 390–402. https://doi.org/10.1016/j.renene.2022.01.066

Sahu, T. K., & Shukla, P. C. (2022). Combustion and Emission Characteristics of Butanol-Diesel Blend (B15) Doped with Diethyl Ether, Diglyme and Ethyl Diglyme in a CRDI Diesel Engine. *SAE Technical Papers*. https://doi.org/10.4271/2022-01-1073

Satsangi, D. P., & Tiwari, N. (2018). Experimental investigation on combustion, noise, vibrations, performance and emissions characteristics of diesel/n-butanol blends driven genset engine. *Fuel*, *221*, 44–60. https://doi.org/10.1016/j.fuel.2018.02.060

Scopus. (2024). *Scopus - Document search results | Signed in*. https://www.scopus.com/results/results.uri?sort=plf-f&src=s&st1=hazelnut+oil+and+biodiesel&sid=094aec4e4df867b224088187e863e3ec&sot=b&sdt=b&sl=41&s=TITLE-ABS-KEY%28hazelnut+oil+and+biodiesel%29&origin=searchbasic&editSaveSearch=&yearFrom=Before+1960&yearTo=Present&sessionSearchId=094aec4e4df867b224088187e863e3ec&limit=10

Şimşek, S. (2020). Increasing Cetane Number of the Diesel Fuel by Fuel Additives. *International Journal of Automotive Science And Technology*, *4*(4), 300–306. https://doi.org/10.30939/IJASTECH..795984

Singh, D., Sharma, D., Soni, S. L., Sharma, S., Kumar Sharma, P., & Jhalani, A. (2020). A review on feedstocks, production processes, and yield for different generations of biodiesel. In *Fuel* (Vol. 262). Elsevier Ltd. https://doi.org/10.1016/j.fuel.2019.116553

Swamy, D. L. S. V. N., Kowsik, Y., Dhana Raju, V., Appa Rao, K., Venu, H., Subramani, L., & Bala Prasad, K. (2023). Effect of 1-butanol on the characteristics of diesel engine powered with novel tamarind biodiesel for the future sustainable energy source. *Energy Sources, Part A: Recovery, Utilization and Environmental Effects*, *45*(3), 6547–6565. https://doi.org/10.1080/15567036.2019.1675810

Temizyurek-Arslan, M. (2023). Evaluation of hazelnut production in Türkiye in environment, energy and economy using life cycle assessment approach. *Science of the Total Environment*, *892*. https://doi.org/10.1016/j.scitotenv.2023.164468

Thakkar, K., Kachhwaha, S. S., Kodgire, P., & Srinivasan, S. (2021). Combustion investigation of ternary blend mixture of biodiesel/n-butanol/diesel: CI engine performance and emission control. *Renewable and Sustainable Energy Reviews*, *137*. https://doi.org/10.1016/j.rser.2020.110468

Thiruselvam, K., Ganesan, S., & Senthil, S. (2023). Efficacy of performance and mitigate pollution of CI engine: Delonix regia biodiesel with n-butanol and exhaust gas recirculation. *Environmental Progress & Sustainable Energy*, e14315. https://doi.org/10.1002/EP.14315

Thiyagarajan, S., Sonthalia, A., Geo, V. E., Viswanathan, K., & Balasubramaniyam, D. (2021). Effect of low carbon biofuel on carbon emissions in biodiesel fueled CI engine. *Bioenergy Resources and Technologies*, 291–326. https://doi.org/10.1016/B978-0-12-822525-7.00006-8

Tipanluisa, L., Thakkar, K., Fonseca, N., & López, J. M. (2022). Investigation of diesel/n-butanol blends as drop-in fuel for heavy-duty diesel engines: Combustion, performance, and emissions. *Energy Conversion and Management*, *255*. https://doi.org/10.1016/j.enconman.2022.115334

Truong, T. T., Nguyen, X. P., Pham, V. V., Le, V. V., Le, A. T., & Bui, V. T. (2021). Effect of alcohol additives on diesel engine performance: a review. In *Energy Sources, Part A: Recovery, Utilization and Environmental Effects*. Taylor and Francis Ltd. https://doi.org/10.1080/15567036.2021.2011490

Tucki, K., Orynycz, O., Wasiak, A., Świć, A., Mruk, R., & Botwińska, K. (2020). Estimation of Carbon Dioxide Emissions from a Diesel Engine Powered by Lignocellulose Derived Fuel for Better Management of Fuel Production. *Energies 2020, Vol. 13, Page 561*, *13*(3), 561. https://doi.org/10.3390/EN13030561

Tunji Oloyede, C., Elijah Itabiyi, O., Adewemimo Popoola, O., Olatayo Jekayinfa, S., Adeolu Olaniyan, M., Oyejide Adebayo, A., Ogunkunle, O., Faiz Muaz Ahmad Zamri, M., Md Rizwanul Fattah, I., & Md Rizwanul, I. (2023). Navigating prospects and challenges for green fuels for achieving economical, environmental and ecological resilience: a scientific review. *Biofuels*, 1–13. https://doi.org/10.1080/17597269.2023.2299090

Usmani, R. A., Mohammad, A. S., & Ansari, S. S. (2023). Comprehensive biofuel policy analysis framework: A novel approach evaluating the policy influences. *Renewable and Sustainable Energy Reviews*, *183*, 113403. https://doi.org/10.1016/J.RSER.2023.113403

Venu, H., Raju, V. D., & Subramani, L. (2019). Combined effect of influence of nano additives, combustion chamber geometry and injection timing in a DI diesel engine fuelled with ternary (diesel-biodiesel-ethanol) blends. *Energy*, *174*, 386–406. https://doi.org/10.1016/J.ENERGY.2019.02.163

Veza, I., Irianto, Tuan Hoang, A., Yusuf, A. A., Herawan, S. G., Soudagar, M. E. M., Samuel, O. D., Said, M. F. M., & Silitonga, A. S. (2023). Effects of Acetone-Butanol-Ethanol (ABE) addition on HCCI-DI engine performance, combustion and emission. *Fuel*, *333*, 126377. https://doi.org/10.1016/J.FUEL.2022.126377

Viswanathan, K., & Paulraj, A. (2023). A comprehensive study on the performance and emission characteristics of a diesel engine with the blends of diesel, jojoba oil biodiesel, and butylated hydroxyl anisole as an alternative fuel. *Energy Sources, Part A: Recovery, Utilization and Environmental Effects*, *45*(2), 3216–3230. https://doi.org/10.1080/15567036.2020.1849451

Wei, L., Cheung, C. S., & Ning, Z. (2018). Effects of biodiesel-ethanol and biodiesel-butanol blends on the combustion, performance and emissions of a diesel engine. *Energy*, *155*, 957–970. https://doi.org/10.1016/j.energy.2018.05.049

Xiao, H., Guo, F., Wang, R., Yang, X., Li, S., & Ruan, J. (2020). Combustion performance and emission characteristics of diesel engine fueled with iso-butanol/biodiesel blends. *Fuel*, *268*, 117387. https://doi.org/10.1016/J.FUEL.2020.117387

Yesilyurt, M. K. (2020). A detailed investigation on the performance, combustion, and exhaust emission characteristics of a diesel engine running on the blend of diesel fuel, biodiesel and 1-heptanol (C7 alcohol) as a next-generation higher alcohol. *Fuel*, *275*, 117893. https://doi.org/10.1016/J.FUEL.2020.117893

Yesilyurt, M. K., Aydin, M., Yilbasi, Z., & Arslan, M. (2020). Investigation on the structural effects of the addition of alcohols having various chain lengths into the vegetable oil-biodiesel-diesel fuel blends: An attempt for improving the performance, combustion, and exhaust emission characteristics of a compression ignition engine. *Fuel*, *269*, 117455. https://doi.org/10.1016/J.FUEL.2020.117455

Yesilyurt, M. K., Yilbasi, Z., & Aydin, M. (2020). The performance, emissions, and combustion characteristics of an unmodified diesel engine running on the ternary blends of pentanol/safflower oil biodiesel/diesel fuel. *Journal of Thermal Analysis and Calorimetry*, *140*(6), 2903–2942. https://doi.org/10.1007/s10973-020-09376-6

Yilbaşi, Z., Yesilyurt, M. K., Yaman, H., & Arslan, M. (2022). The industrial-grade hemp (Cannabis sativa L.) seed oil biodiesel application in a diesel engine: combustion, harmful pollutants, and performance characteristics. *Science and Technology for Energy Transition (STET)*, *77*. https://doi.org/10.2516/stet/2022011

Yilmaz, N., Atmanli, A., & Trujillo, M. (2017). Influence of 1-pentanol additive on the performance of a diesel engine fueled with waste oil methyl ester and diesel fuel. *Fuel*, *207*, 461–469. https://doi.org/10.1016/j.fuel.2017.06.093

Yilmaz, N., & Davis, S. M. (2016). Polycyclic aromatic hydrocarbon (PAH) formation in a diesel engine fueled with diesel, biodiesel and biodiesel/n-butanol blends. *Fuel*, *181*, 729–740. https://doi.org/10.1016/j.fuel.2016.05.059

Yilmaz, N., Vigil, F. M., Atmanli, A., & Donaldson, B. (2023). Influence of Fuel Oxygenation on Regulated Pollutants and Unregulated Aromatic Compounds with Biodiesel and n-Pentanol Blends. *International Journal of Energy Research*, *2023*. https://doi.org/10.1155/2023/3040073

Yoro, K. O., & Daramola, M. O. (2020). CO2 emission sources, greenhouse gases, and the global warming effect. *Advances in Carbon Capture: Methods, Technologies and Applications*, 3–28. https://doi.org/10.1016/B978-0-12-819657-1.00001-3

Zhang, Q., Xia, J., Wang, J., He, Z., Zhao, W., Qian, Y., Zheng, L., Liu, R., & Lu, X. (2022). Experimental study on ignition and combustion characteristics of biodiesel-butanol blends at different injection pressures. *Renewable and Sustainable Energy Reviews*, *160*, 112289. https://doi.org/10.1016/J.RSER.2022.112289

Zhang, Y., Gao, S., Zhang, Z., Li, W., Yuan, T., Tan, D., Duan, L., & Yang, G. (2023). A comprehensive review on combustion, performance and emission aspects of higher alcohols and its additive effect on the diesel engine. *Fuel*, *335*, 127011. https://doi.org/10.1016/J.FUEL.2022.127011

Zhao, H. C., Wang, S. B., Yu, T. Z., & Sun, P. (2023). Study on combustion and emissions characteristics of acetone-butanol-Ethanol(ABE)/gasoline premixed fuel in CISI engines. *Case Studies in Thermal Engineering*, *51*. https://doi.org/10.1016/j.csite.2023.103591

Zhao, P., Wang, H., Atmanli, A., Han, J., He, W., & Somers, L. M. T. (2020). Experimental Investigation of Performance and Emissions of Ethanol and n-Butanol Fuel Blends in a Heavy-Duty Diesel Engine. *Frontiers in Mechanical Engineering*, *6*. https://doi.org/10.3389/fmech.2020.00026