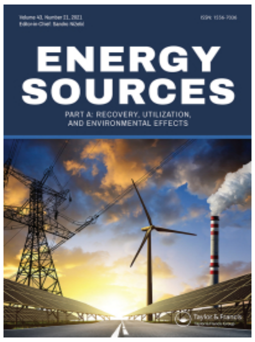

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Investigations and development of novel fuel blends using biodiesel and butylated hydroxytoluene: optimization using D-optimal design and desirability

Van Nhanh Nguyen [a], R. Ganapathi [b], B. Omprakash [c], Prabhakar Sharma [d], Nguyen Dang Khoa Pham [e], Phuoc Quy Phong Nguyen [e], Viet Dung Tran [e], and Duc Trong Nguyen Le [f]

[a]Institute of Engineering, HUTECH University, Ho Chi Minh City, Viet Nam; [b]Department of Mechanical Engineering, ANURAG Engineering College, Kodada, Telangana, India; [c]Department of Mechanical Engineering, JNTUA College of Engineering, Anantapur, A.P, India; [d]Department of Mechanical Engineering, Delhi Skill and Entrepreneurship University, Delhi, India; [e]PATET Research Group, Ho Chi Minh City University of Transport, Ho Chi Minh City, Viet Nam; [f]Faculty of Automotive Engineering, Dong A University, Danang, Vietnam

ABSTRACT

The transportation industry is most concerned about the rising cost of fossil fuels and the deterioration of the environment. Although many alternative fuels currently have enhanced performance characteristics, continuous research attempts to further enhance their quality even more. This research focuses on improving fuel quality by incorporating Waste vegetable oil biodiesel derived from Liza oil and Butylated Hydroxytoluene (BHT). The combination of these factors results in a novel approach that uses experimental and parametric optimization to outperform current constraints in alternative fuels. The objective of this study is to compare the performance and emission characteristics of several blends of diesel, including B10 (20% biodiesel + 500 ppm BHT + diesel), B20 (20% biodiesel + 1000 ppm BHT + diesel), B30 (20% biodiesel + 1500 ppm BHT + diesel), B40 (20% biodiesel + 2000 ppm BHT + diesel), and B50 (20% biodiesel + 2500 ppm BHT + diesel). The tests were carried out at a variety of engine loads and speeds. The performance of Liza oil blends, as assessed by engine performance and emissions characteristics, was found to be comparable to that of diesel. Mechanical and brake thermal efficiency was determined to be highest for the B30 and B40 mixtures. The Liza oil Biodiesel operation exhibited fewer hydrocarbon emissions than the diesel fuel mode at B20. The D-optimal design was utilized for the experiment design. The data collected was used for the analysis of variance (ANOVA) for the development of mathematical expression for each response variable. The response surface methodology (RSM) was employed for the development of response surfaces to explore the effects of control factors on each response variable. The most favorable results were obtained using desirability-based optimization at 8.22 kg engine load and 500 ppm BTH concentration. It resulted in 20.04% brake thermal efficiency, 0.4 kg/kWh brake specific fuel consumption, 39% mechanical efficiency, 0.028 Vol.% carbon mono-oxide, 7.39% carbon-di-oxide, 39.16 ppm hydrocarbon, and 1230 ppm nitrogen oxide as response variables.

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CONTACT Viet Dung Tran dungtv@ut.edu.vn PATET Research Group, Ho Chi Minh City University of Transport, Ho Chi Minh City, Viet Nam; B. Omprakash omprakash1715@gmail.com Department of Mechanical Engineering, JNTUA College of Engineering, Anantapur, A.P, India; Prabhakar Sharma psharmahal@gmail.com Department of Mechanical Engineering, Delhi Skill and Entrepreneurship University, Delhi, India; Duc Trong Nguyen Le nguyenldt@donga.edu.vn Faculty of Automotive Engineering, Dong A University, Danang, Vietnam

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Introduction

Engines are essential in the heavy transportation sector because of their better thermal efficiency and endurance (Korczewski 2022). However, the widespread use of diesel engines has resulted in much higher pollutant emissions, particularly of suspended particulate matter and nitrogen oxides. As a result of the global oil crisis in 2009 and the need to lessen environmental impact, stricter regulations governing exhaust emissions, such as the Euro and Bharath emission standards, were enacted (Aktar, Alam, and Al-Amin 2021). The employment of plant oils as the primary source for biodiesel production offered the transportation sector a sustainable and ecologically favorable choice. Exploration of biodiesel derived from various plant oils has garnered considerable attention as countries seek to establish sustainable energy alternatives and combat the harmful effects of pollution (Ramalingam et al. 2023). Ongoing research efforts are aimed at improving manufacturing methods and improving biodiesel performance while remaining compatible with existing engine technologies. By embracing renewable energy sources and establishing stringent emission rules, we may help to reduce the negative environmental impacts of conventional diesel engines while enhancing energy security and decreasing dependency on nonrenewable resources (Marangon et al. 2023a). The combination of engine design advancements and the usage of biodiesel derived from various plant oil sources provides promise for attaining a more sustainable and environmentally friendly transportation future (Giwa et al. 2023).

The employing of vegetable oil-derived biodiesel as an alternative fuel source has sparked a lot of attention due to its renewable nature and low environmental impact (Riayatsyah et al. 2021). However, the storage stability of biodiesel is a worry since it is prone to oxidation, which causes the formation of toxic byproducts and the degradation of fuel quality (Rajamohan et al. 2022). The addition of antioxidants to biodiesel has emerged as a potential solution to this problem. Butylated Hydroxytoluene (BHT) is one such antioxidant that has shown promise in increasing the durability of biodiesel made from vegetable oils. BHT is a common antioxidant known for its ability to prevent oxidation reactions and extend the shelf life of a variety of products. In biodiesel, BHT serves as a free radical scavenger, successfully inhibiting chain reactions that contribute to fuel quality degradation (İleri and Koçar 2014).

There are various advantages of using BHT in biodiesel made from vegetable oil. For starters, it improves biodiesel's oxidative stability during storage, reducing the development of peroxides and other breakdown products. This ensures that the biodiesel's quality and performance qualities are preserved over time, obviating the need for frequent fuel refills (İleri and Koçar 2014). Furthermore, incorporating BHT into biodiesel can improve its cold flow qualities, making it more appropriate for usage in colder climes. At low temperatures, biodiesel hardens, clogging fuel filters and making engine startup difficult. BHT reduces the formation of solid deposits and improves biodiesel flow properties, improving cold weather performance by minimizing oxidation. In addition to its stabilizing properties, BHT has been demonstrated to have negligible detrimental effects on engine performance and emissions (Ashok et al. 2017). Using BHT-supplemented biodiesel does not influence engine power output, fuel consumption, or exhaust pollutants, according to studies. This makes it a viable option for boosting biodiesel stability while maintaining engine performance. BHT, as an antioxidant in vegetable oil-derived biodiesel, is a viable technique to address the storage stability difficulties connected with biodiesel production and use (Gaur et al. 2022). By extending the shelf life of biodiesel and enhancing its cold flow properties, BHT addition can improve its practicality and reliability as a sustainable fuel choice. More research and development in this field can provide important insights into optimizing the antioxidant dose, compatibility with different feedstocks, and long-term stability of BHT-supplemented biodiesel, paving the way for its wider adoption in the transportation industry (Subramani, Natarajan, and Lakshmi Narayana Rao 2021).

Several investigators have published research on biodiesel-powered engines, especially to show the effects of additives. Kalyani et al (Kalyani, Prasad, and Kolakoti 2023) investigated how triacetin, an oxygenated ingredient, performed in diesel engine powered with biodiesel-diesel blends. Different triacetin concentrations were put into the blend, and tests were run at various engine loads. In comparison to diesel and other biodiesel mixes, the results presented that a 4% triacetin mix achieved higher combustion pressure and better thermal efficiency. While the biodiesel mixes consumed more gasoline, the emissions of carbon monoxide (CO) and oxides of nitrogen (NOx), unburned hydrocarbons (HC), and smoke were much lower with the 4% triacetin blend. Overall, the study indicated that 4% triacetin in a biodiesel-diesel blend lowered emissions and improved efficiency. Londhe et al (Londhe et al. 2019) investigated the effects of two additives, namely methyl acetate, and anisole, on the efficiency and emissions of diesel engines. Diesel-anisole blends were shown to function similarly to diesel but with somewhat higher fuel consumption. Despite a small drop in CO and carbon dioxide (CO_2) emissions, soot and NOx concentrations rose. The test blend outperformed diesel, with just a little increase in fuel consumption rates. Methyl acetates were employed to minimize HC and CO emissions. NOx and soot concentrations rose. Both methyl acetate and anisole were tested at 10% by volume in biodiesel and were found to perform somewhat better than pure biodiesel. Elkelawy et al (Elkelawy et al. 2021). explored the effect of cyclohexane (C_6H_{12}), a flammable liquid additive, on diesel engine performance, combustion, and emissions in blended fuel was studied. The results revealed that raising the Cyclohexane dosage resulted in significant gains in emission levels and efficiency. Because of increased combustion and premixed combustion, higher dosages lowered HC, CO, and smoke density while simultaneously lowering NOx emissions. Injection pressure was increased from 150 to 250 bars, which lowered fuel consumption and emissions while improving thermal efficiency, CO_2 emissions, and overall exhaust gas temperature. Overall, cyclohexane additives appear to hold promise for improving diesel engine performance and lowering emissions (Venu et al. 2021). Several other studies reported that fuel additives helped in improving the combustion in biodiesel-diesel-powered engines (Sedghi et al. 2022; Elkelawy et al. 2021).

Finding the correct balance between efficiency, fuel economy, and emissions control is a complicated task in the search for sustainable and efficient transportation solutions (Veza et al. 2022; Rudzki, Gomulka, and Hoang 2022). Modern approaches like artificial intelligence (Nguyen et al. 2023) and optimization provided solutions for these challenges (Liang and Chen 2022). Exploration of a broad parameter space that includes multiple fuel mix compositions and engine operational parameters is required (Rudzki, Gomulka, and Hoang 2022). RSM is an appealing option in this condition. RSM enables complete investigation of the complex parameter space while minimizing resource-intensive testing and quantitatively modeling connections between factors and responses (Sebayang et al. 2022, 2023). It allows for trade-off analysis, optimum compromises, and resilience testing to assure stability under changing situations (Nguyen et al. 2023). In the face of rising costs and environmental concerns, RSM emerges as a critical instrument for developing sustainable, cost-effective means of transportation that achieve a compromise between performance and environmental responsibility (Nazarpour et al. 2022). In RSM, the Design of Experiments (DOE) involves choosing from many experimental design types to efficiently examine complex interactions between numerous variables and improve processes. Full Factorial Design examines all potential factor level combinations, yielding detailed information on main effects and interactions (Mäkelä 2017). When the complete factorial design is impossible, the fractional factorial design reduces experimentation by statistically approximating the impact of untested elements. Box-Behnken Design is concerned with quadratic effects, Central Composite Design is focused on both linear and quadratic effects, and D-Optimal Design is concerned with efficiency and precision in parameter estimation (Sharma et al. 2023). Design selection is influenced by research objectives, limitations on resources, and required precision, resulting in effective optimization and resource conservation (Bakır et al. 2022).

As compared to Box-Behnken and Central Composite Design, the D-Optimal Design distinguishes out as a highly efficient and exact experimental design technique. Its efficiency is also important, given that it requires fewer experimental runs to achieve comparable levels of precision, resulting in a cost-effective solution, especially when resources are limited (El-Gendy et al. 2016). Furthermore, because of their personalized approach to minimizing parameter uncertainty, D-Optimal designs excel at parameter estimation, producing more accurate predictive models. These designs also provide more factor-setting flexibility, allowing researchers to define factor levels of interest and optimize processes within specific parameter ranges (Uzoh et al. 2021). Furthermore, they solve collinearity difficulties by carefully positioning experimental sites, a fact that Box-Behnken and Central Composite designs do not explicitly address. Finally, D-Optimal designs for optimization tasks are extremely adjustable, allowing investigators to focus on specific portions of the response surface (Parida et al. 2019). The choice of design, however, is ultimately determined by the unique study objectives, available resources, and the characteristics of the response surface, needing careful analysis when picking the most appropriate design methodology.

There is no comprehensive research on the usage of Liza Oil and Butylated Hydroxytoluene as fuel mixtures and their impact on engine combustion, performance, and emissions at this time. Furthermore, there has been limited research into optimizing engine performance and emissions using D-optimal design and Desirability techniques, particularly for fuel blends. The use of Liza Oil and Butylated Hydroxytoluene as fuel mixtures is unusual in this study because it is a new technology that has not been thoroughly investigated in previous works. Furthermore, the application of D-optimal design and Desirability optimization methodologies to optimize engine performance and emissions in the context of fuel blends contributes significantly. The goals of this research are to investigate and develop new fuel blends based on Liza Oil and Butylated Hydroxytoluene. To increase engine performance and emissions, the study employs D-optimal design and Desirability techniques. This study will investigate the effects of these fuel blends on combustion, performance, and emissions, thereby filling gaps in the literature and providing valuable insights into the potential benefits and optimization strategies associated with the use of Liza Oil and Butylated Hydroxytoluene as engine fuel additives.

Material and methods

Fuel

Liza Oil is a promising alternative fuel that has significant advantages in a variety of applications. Because it is generated from nature, it is a renewable and sustainable alternative. Liza Oil has good combustion features, such as a high energy content and good ignition properties, which contribute to efficient and dependable combustion processes. Liza Oil has a low Sulfur concentration, which helps reduce undesirable emissions, such as Sulfur oxides (SOx) when used as a fuel in combustion engines. As a result, it is an environmentally beneficial option that contributes to the goal of lowering air pollution and improving air quality. Liza Oil also has excellent lubricating characteristics, which can help machinery and equipment by minimizing friction and wear. Its lubricity can assist engine components to last longer, resulting in lower maintenance costs and better overall performance. Liza Oil, in addition to its practical benefits, can boost energy security.

Vegetable oil is a biologically active combination obtained from plants that are made up of triglycerides with ester mixes of glycerol and fatty acids (Marangon et al. 2023b; Sebayang et al. 2023). It may also contain trace amounts of monoacylglycerols or diacylglycerols and other substances in varying concentrations, such as phosphides (Tuan Hoang and Viet Pham 2021). The food and non-food industries both benefit from the use of vegetable oils. Vegetable oils are used in food preparation for direct consumption, canning, baking, grilling, etc. Extraction yield, Extraction Efficiency, and extraction loss are among the metrics used to gauge an oil extraction system's effectiveness (Hoang et al. 2022). Extraction Yield is indeed the percentage of oil produced from a specific amount of oleaginous material after a specific extraction procedure (Rains et al. 2017). The quantity of oil extracted as a percentage of the oil contained inside the oleaginous material is defined as extraction efficiency (Gasparatos et al. 2022). As a proportion of the total weight of the material before extraction, extraction loss is indeed the weight of the material that is not accounted for after the extraction process, whether it be oil recovered or even the residual cake. Transesterification occurs when an ester lipid reacts with only oil with methanol of a catalyst resulting in the production of an ester (biodiesel) and glycerin as just a byproduct.

Butylated hydroxytoluene (BHT), often referred to as dibutyl hydroxytoluene, is an organic molecule that is lipophilic and chemically a derivative of phenol that is beneficial for its antioxidant characteristics. BHT is frequently used to stop fluid oxidation caused by free radicals. The properties of test fuel are listed in Table 1.

Experimental setup

The test engine setup had the provision for measuring engine emission, power, efficiency, and fuel consumption. A current addy dynamometer was employed for engine loading. It had provisions for

Table 1. Properties of test fuel.

Properties	Diesel	Properties	BHT
Viscosity (kinematic)	2.39 mm^2/s	Chemical formula	$C_{15}H_{24}O$
Density	0.836 kg/m^3	Molar Mass	220.356 g/mol
Fire point	56°C	Odor	Slight, phenolic
Flash point	45°C	Density	1.048 g/cm^3
Lower heating value	42300 kJ/kg		
Cetane index	56		
Specific gravity	0.821		

storing and supplying the test fuel blends. An air filter and air box were installed to supply clean and pulse-free air for combustion.

Figure 1 depicts the experimental setup schematically. The engine employed in this study is a vertical, water-cooled, direct-injection, naturally aspirated Kirloskar engine with a rated power of 3.7 kW at 1500 rpm. The compression ratio of the engine is modified from 6:1 to 20:1.

The engine is loaded and unloaded using a strain gauge load cell and an eddy current dynamometer. This configuration comes with a 360° pulse crank angle encoder and a Citizen piezoelectric air-cooled durable pressure sensor with an integrated charge amplifier that measures both combustion pressure and the related crank angle. During the experiment, the signals from the pressure sensor are interfaced with a computer by a data acquisition system (DAS) that is used to acquire, store, and evaluate the data. For measuring combustion and engine performance, rotameters are available for measuring the flow of cooling water to an engine and calorimeter. The Engine Test Express v14 installation on the PC is used for online evaluation. Fuel consumption is detected using a burette that seems to have optical sensors just on top and bottom. The top sensor sends a signal to the DAS to start measuring counter time as soon as the fuel passes past it. A signal is sent to the DAS to halt the counter time and replenish the burette from the fuel tank when the fuel reaches the bottom sensor once more. This process is repeated three times. This information is used to compute the engine's mass fuel consumption at various loads. The mass of air consumed can be measured using a differential pressure sensor that has been installed in the air surge tank. The temperature of the exhaust gases was measured using a K-type thermocouple inserted in the exhaust manifold. To detect engine speed, PNP (positive negative positive) type non-contact proximity speed sensors installed near the flywheel are employed. The main specification of the test diesel engine setup is listed in Table 2.

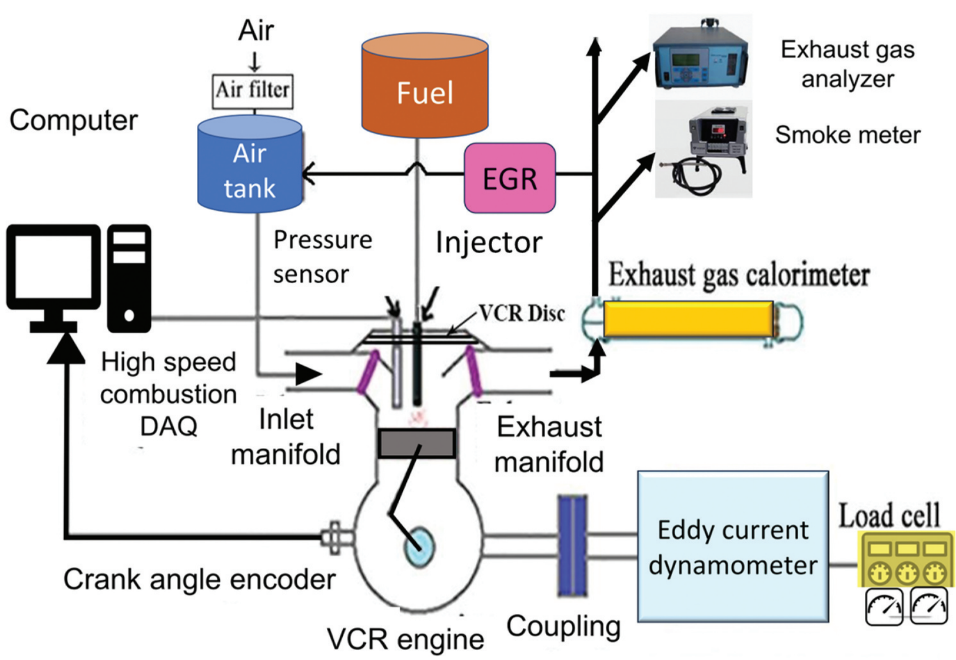

Figure 1. Schematic diagram of the experimental setup.

Table 2. Specifications of engine.

Name	Specification
Base Engine	4 S 1C WC Diesel Engine
Make/Model	Kirloskar Engine
CR Range	6:1 to 10:1 for petrol and 14:1 to 20:1 for Diesel
BHP	5HP @ 1500 rpm
RPM	1500
Bore	80mm
Stroke	110mm
Cubic capacity	661cc
Loading	Eddy current Dynamometer (water-cooled)

Exhaust gas analyzer

An AVL DiGas 444 gas analyzer, approved by the Automotive Research Association of India, was employed to examine the sample of exhaust gas. The electrochemical principle is used to examine the exhaust sample's nitrogen oxide and unused oxygen, while the NDIR (Non-Dispersive Infra-Red) principle is used to analyze emissions like carbon dioxide, carbon monoxide, and unburned hydrocarbons. Volume % is used to quantify CO and CO_2 emissions, whereas ppm is used to assess HC and NOx emissions.

Response surface methodology

RSM is a quantitative and mathematical technique for modeling and optimizing complicated systems by fitting mathematical equations to experimental data. It is especially beneficial when the relationship between the input variables and the response (output) is not linear and may have curvature or interactions (Das and Goud 2021; Keshtegar, Mert, and Kisi 2018). The mathematical models known as response surface models (RSMs) are at the heart of RSM. These models are usually second-order polynomials that approximate the response variable's behavior as a function of the input variables. A general form of second-order RSM takes the following general form (Singh et al. 2021; Nam and Capareda 2015):

$$Y = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \beta_{11} {X_1}^2 + \beta_{22} {X_2}^2 + \beta_{12} X_1 X_2 \quad (1)$$

Herein, Y represents the response variable being studied. X_1 and X_2 are the predictor variables. β_0 is the intercept term, β_1, and β_2 are linear coefficient, and β_{11} and β_{22} are quadratic coefficient for X_1 and X_2, respectively.

RSM seeks the optimum values for the input variables that maximize or reduce the response variable. This is typically achieved by employing optimization techniques such as gradient descent, sharpest ascent, or numerical optimization methodologies (Qader et al. 2019). An RSM is created by performing several carefully prepared experimental runs, and the data from these runs is used to estimate the model equation's coefficients. Various statistical procedures, such as analysis of variance (ANOVA) and regression analysis, are employed to validate the model and identify significant terms (Karimmaslak et al. 2021; Singh et al. 2021). It is a powerful tool for understanding complex systems, improving processes, and making data-driven decisions. RSM helps researchers and engineers acquire helpful insights and improve system performance by using mathematical equations to approximate variable correlations (Gupta, Patel, and Mondal 2022; Srinidhi et al. 2021).

Uncertainty assessment

In most cases, the accuracy of an experiment may be determined through analyzing its potential for error as well as its degree of uncertainty. Errors in the experiments are caused by several factors, including readings, sensor selection, and calibration (Kline and Mcclintock 1953). Because of this, an uncertainty assessment and error selection are both necessary steps in the process of calibrating and measuring equipment, as well as the ambient pressure and temperature. Table 3 displays the ranges and accuracies of the various measuring instruments that were used in this study.

Table 3. Measurement range, precision, and uncertainty.

Measured/estimated parameter	Precision	Range	Uncertainty
Engine speed	±.2%	0–20000 rpm	±0.24%
Cylinder pressure	±.5 bar	Up to 250 bar	±1%
Crank angle encoder	±.125	0–720°Crank angle	±0.3%
Brake power	-	-	1.023%
CO emission	±.1 Vol.%	0–10%	±0.2%
CO2 emission	±1 Vol.%	0–20%	±0.73
HC emission	±1 ppm	0–20000 ppm	±0.3
NOx emission	±1 ppm	0–5000 ppm	+0.2

Results and discussion

The tests were conducted Liza oil with an additive, using with pure diesel fuel, for the aforementioned biodiesel ratios. The performance experiments are done with varied loads that correspond to the maximum loads at 1500 rpm. The characteristics of engine efficiency and emissions are compared to that of diesel operation. The engine performance metrics, like BSFC, BTE, and tailpipe emission, are analyzed and presented versus load for all trials.

Experimental analysis

Load Vs. Brake thermal efficiency is depicted in Figure 2. The Butylated hydroxytoluene (BHT) additive is added to the Liza biodiesel blend. The rate at which chemical energy in the fuel is converted into useful work (thermal efficiency). Calculations were made for the various weights and percentages of the Liza oil + BHT composition biodiesel blend, including 10%, 20%, 30%, 40%, and 50%. As the load increases, the BTE is raised to lessen heat loss (Roy, Wang, and Alawi 2014). An increase in load causes the suction pressure to rise, which improves combustion efficiency. At full load, B10 is almost as powerful as Diesel; however, B30 to B40 is weaker. The graph indicates that B30 is suitable for all factors. The combination of higher viscosity, higher density, & lower calorific value of (Liza oil + BHT) biodiesel blends results in a low brake thermal efficiency valve at low loads. At full load, the BTE of a biodiesel blend is higher than diesel by 4.95%, 5.85%, 7.85%, 8.95%, and 9.95%, respectively.

Load vs. BSFC of Diesel and biodiesel mixes of The Butylated hydroxytoluene (BHT) additive added to Liza biodiesel blends is depicted in Figure 3. The combination of BSFC and calorific value yields BSEC. The amount of energy required to generate one unit of brake power is another way to define BSEC. The use of a mixed fuel with a range of densities and calorific values while employing BSEC enables a more precise evaluation of a diesel engine's capabilities. BSFC is shown to be higher in the B20 blend as compared to pure diesel. As load increases, BSEC decreases as a result of BSFC reductions. Biodiesel mixtures have been documented. The BTE lowers as the BSFC rises (because it is inversely proportional) (Korczewski 2023). The specific fuel consumption of the Diesel, B10, and B20 at full load is the same. Diesel's unit of measure is 0.116,0.129 kg/kW-s. B40 and B50 had lower BSFCs than diesel, at 11.37% and 12.37%, respectively. Because diesel has a higher calorific value than (Liza oil + BHT) biodiesel blends, more energy is needed to generate the same amount of power (Kulanthaivel et al. 2021; Bora and Saha 2016).

Load vs. Mechanical efficiency of diesel and biodiesel blends using (Liza oil + BHT) is depicted in Figure 4. Mechanical efficiency is defined as the ratio of brake power at the crankshaft with indicated work inside the combustion process of an engine. The results show a gain of 2.03% over the diesel engine. Mechanical efficiency is found to increase as the biodiesel proportion in the blended fuel rises when compared to diesel. This might be a result of biodiesel's greater lubricity properties compared to diesel. All combinations' mechanical efficiency falls short of diesel's, with B40 and B50 being more effective than diesel. At lower blends, the B10 to B30 loads are equivalent to Diesel, while at higher loads, the B40 and B50 will be more than Diesel. All combinations, including 10%, 20%, 30%, 40%, and 50%, are tested with Liza oil and BHT. 53.23, 54.34, 55.46, 62.76, and 64.24 are the percentages. Diesel blends' mechanical efficiency rises by about 0.06%, 0.08%, 0.07%, 0.09%, 0.056%, and so on under different load circumstances.

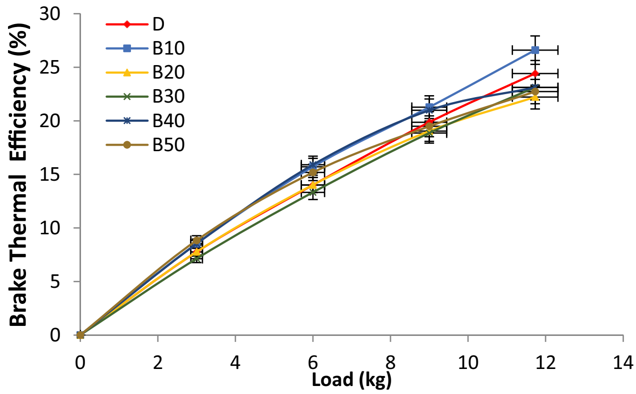

Figure 2. Load vs. Brake thermal efficiency of diesel and its biodiesel blends.

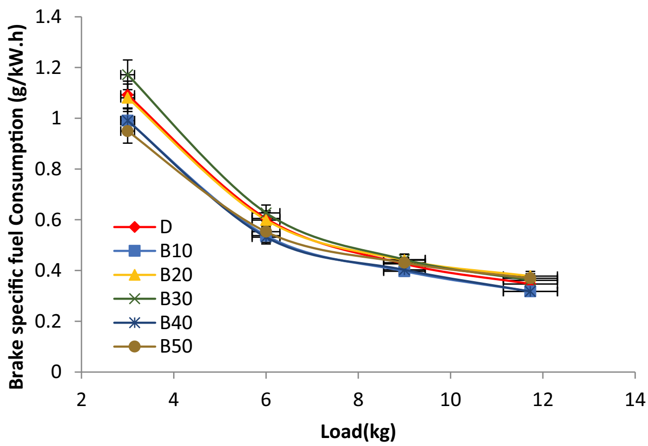

Figure 3. Load vs. Brake specific fuel consumption of diesel and its biodiesel blends.

Figure 5 depicts the Load versus Carbon monoxide of (Liza oil) biodiesel blends with the addition of BHT as an additive. When there is not enough oxygen present to oxidize the fuel, CO is frequently created. A diesel engine is, therefore, less expensive than a gasoline engine. The B50 blend emitted more CO than the Diesel at full loads. Low-volatility polymers affected the atomization process and how air and fuel were mixed, resulting in a rich mixture that made it challenging to atomize and vaporize the (Liza oil) biodiesel blend due to the inappropriate spray pattern formed (Carlucci et al. 2017; Vijayakumar et al. 2016). The B20–30 blend and the Diesel produce lower CO emissions of around 2.84% and 5.1%, respectively, under varied load circumstances, as illustrated in Figure 5.

Figure 6 depicts the load vs. Hydrocarbon of (Liza oil) biodiesel blends with the addition of BHT as an additive. Across all load levels, biodiesel blends showed lower hydrocarbon emissions than diesel fuel. Additionally, it was shown that turbulence causes altered piston geometry for biodiesel mixes, which enhances combustion and reduces emissions. B20 and B10 blends have lower hydrocarbon emissions than B50, B40, & B30 combinations (Silitonga et al. 2018; Ali et al. 2016).

Figure 7 depicts the Load versus NOx emissions of (Liza oil) biodiesel blends with the addition of BHT as an additive. The production of NOx is caused by the oxidation of nitrogen at high temperatures. At all loads, it was observed to be highest in Diesel and lowest in the Liza biodiesel blend. Diesel has increased NOx emissions because it has a high oxygen content, which raises the combustion temperature. The NOx

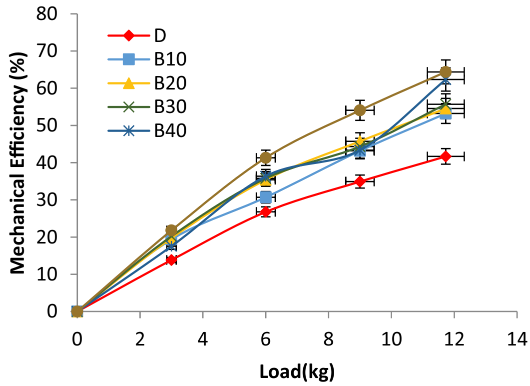

Figure 4. Load vs. Mechanical efficiency of diesel and its biodiesel blends.

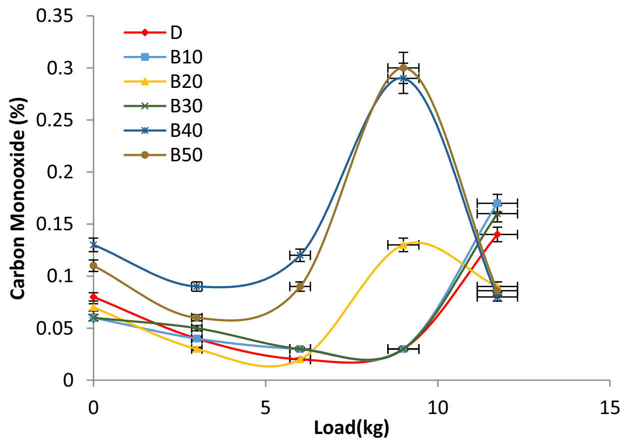

Figure 5. Load vs. Carbon monoxide of diesel and its biodiesel blends.

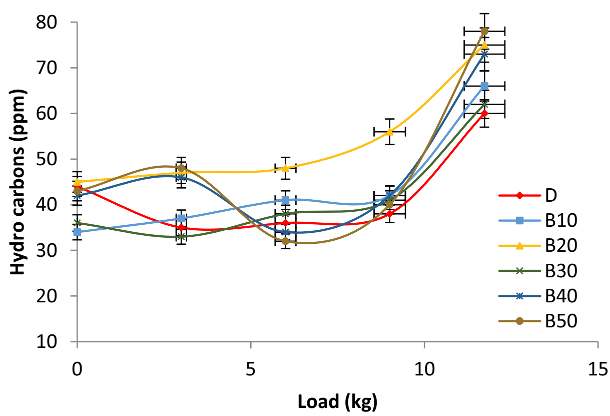

Figure 6. Load vs. Hydrocarbons of diesel and its biodiesel blends.

concentrations for all mixes, including Diesel, are shown above. In comparison to diesel, NOx dropped at greater loads by 2.23%, 3.23%, 3.945%, 4.24%, and 5.21%. On the other hand, biodiesel's greater density and viscosity resulted in a delayed combustion phase and slower combustion characteristics (Soto et al. 2019; Sateesh et al. 2022).

Figure 8 depicts the Braking power versus CO_2 emissions of (Liza oil) biodiesel blends with the addition of BHT as an additive. Even after complete combustion, carbon dioxide is one of the main combustion by-products. The presence of internal air in biodiesel facilitates the formation of water and carbon dioxide vapor, as seen in this analysis. As a result, BHT is added to biodiesel when it is used. The main cause of this is a lean air mixture brought on by a shortage of oil in exhaust gas recirculation. As a result, there are fewer CO_2 emissions brought on by insufficient combustion inside the engine cylinder (Elkelawy et al. 2021; Agrawal et al. 2020). The low proportion at the B20 and B30 blends cause an increase in the CO_2 percentage.

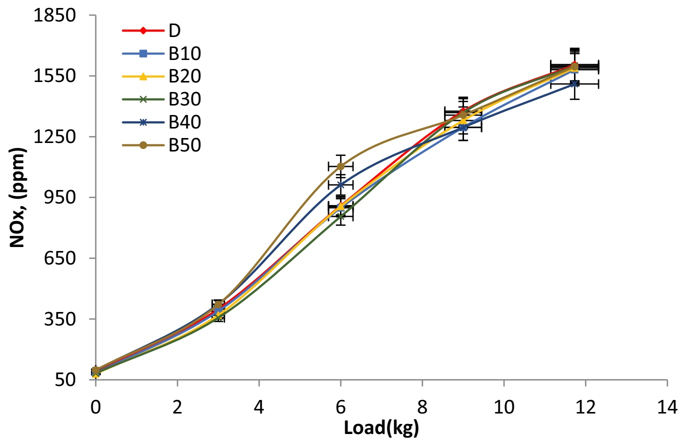

Figure 7. Load vs. NOx of diesel and its biodiesel blends.

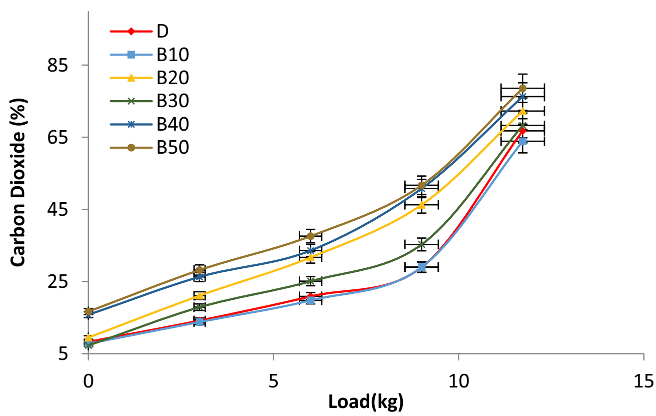

Figure 8. Load vs. Carbon dioxide of diesel and its biodiesel blends.

RSM-based modeling- optimization

Modeling using ANOVA

The experimental results show a complex engineering problem where control factors (load and blends) have different kinds of influence over response variables. In this situation, it becomes imperative to employ scientific optimization methods like RSM. Hence in the present study, the D-optimal design was used for conducting the experiments for the second phase. The design matrix developed using D-optimal design is shown in Table 4.

The correlation among data columns is depicted in Figure 9. The data presented in Table 4 was employed for ANOVA analysis. A strong correlation (0.97) between load and BTE, 0.96 between load and mechanical efficiency, 0.97 between load and CO_2 emission, and 0.98 between load and NOx emission. The blend proportion also influences engine performance and emission; however, the effect is not as strong as that of engine load. The highest effect of BHT was observed in the case of mechanical efficiency (0.29) and HC (0.34). The R^2 values are listed in Table 5. The ANOVA outcomes for engine performance and emission data are listed in Tables 6 and 7, respectively. The ANOVA helped in establishing the mathematical models for each parameter, as shown in equation 2 to equation 8.

$$\mathrm{BTE} = 16.12 + 7.69 \times \mathrm{A} - 0.51 \times \mathrm{B} - 0.80 \times \mathrm{A} \times \mathrm{B} - 1.75 \times \mathrm{A}^2 + 2.09 \times \mathrm{B}^2 \tag{2}$$

$$\mathrm{BSFC} = 0.54 - 0.33\mathrm{A} - 0.0009 \times \mathrm{B} + 0.021 \times \mathrm{A} \times \mathrm{B} + 0.20 \times \mathrm{A}^2 - 0.079 \times \mathrm{B}^2 \tag{3}$$

$$\mathrm{MechEff.} = 38.88 + 19.52 \times \mathrm{A} + 4.81 \times \mathrm{B} + 0.92 \times \mathrm{A} \times \mathrm{B} - 2.5 \times \mathrm{A}^2 + 1.98 \times \mathrm{B}^2 \tag{4}$$

$$\mathrm{CO} = 0.059 + 0.02 \times \mathrm{A} + 0.0053 \times \mathrm{B} - 0.0058 \times \mathrm{A} \times \mathrm{B} + 0.037 \times \mathrm{A}^2 - 0.031 \times \mathrm{B}^2 \tag{5}$$

$$\mathrm{CO2} = 7.09 + 3.5 \times \mathrm{A} + 0.56 \times \mathrm{B} + 0.2 \times \mathrm{A} \times \mathrm{B} + 0.39 \times \mathrm{A}^2 + 0.32 \times \mathrm{B}^2 \tag{6}$$

$$HC = 36.36 + 14.93 \times A + 3.17 \times B - 0.042 \times A \times B + 17.32 \times A^2 + 3.11 \times B^2 \tag{7}$$

$$\mathrm{NOx} = 173.8 + 596.08 \times \mathrm{A} + 30.3 \times \mathrm{B} + 1.71 \times \mathrm{A} \times \mathrm{B} - 182.21 \times \mathrm{A}^2 - 3.79 \times \mathrm{B}^2 \tag{8}$$

The surface diagrams were developed for each parameter to show the combined effects of control factors (load and BHT) on engine response variables, as depicted in Figure 10.

The surface diagrams helped in deciphering the influence of different input factors on response variables. Figure 10(a) illustrates the combined influence of load and BTH concentration on BTE. It was revealed that engine load largely affects the BTE, and peak BTE was observed at 11 kg engine load and low concentration of BTH (500 ppm). The combined influence of load and BTH concentration on BSFC is depicted in Figure 10(b). It was observed that engine load has a significant impact on BSFC, with the lowest BSFC recorded at 11 kg engine load and a medium concentration of BTH (1500 to 2000 ppm). Figure 10(c) illustrates the joint effect of load and BTH concentration on mechanical efficiency. The mechanical efficiency was shown to be significantly affected by engine load, with a peak mechanical efficiency reported at 11.5 kg engine load and the highest concentration of BTH (2500 ppm). The combined effect of engine loading and BTH concentration on CO emission is shown in Figure 10(d). Engine load was shown to have a substantial influence on CO emission, resulting in low CO emission observed at lower engine load, 3 kg engine load, with a low level of BTH (500 ppm). Similarly, Figure 10(e) depicts the

Table 4. Design array used in the study.

	Input factors		Response variables (Output)						
Run	Engine load, kg	BHT, ppm	BTE, %	BSFC, kg/kWh	Mech. Eff. %	CO, %	CO_2, %	HC, ppm	NOx, ppm
6	3	2500	8.84	0.948	21.8	0.06	4.5	48	420
7	3	1500	7.13	1.17	20.21	0.055	4.2	33	356
8	3	2500	8.83	0.949	21.8	0.06	4.5	48	421
9	3	500	8.52	0.99	13.85	0.04	4	37	389
11	3	500	8.51	0.99	13.85	0.04	4	37	390
3	6.37	800	14.81	0.561	33.21	0.025	5.75	45	921
16	7	1700	15.34	0.545	36.1	0.082	6.1	37	1110
12	7	2500	18.42	0.452	48.23	0.028	8.8	34	1248
2	8.7	1200	17.92	0.441	45.01	0.08	8.2	48	1342
14	9.6	500	22.42	0.384	44.01	0.038	8.4	44	1365
15	9.6	500	22.43	0.383	44.02	0.038	8.4	44	1365
10	10	1750	19.81	0.44	44.12	0.06	9.5	43	1482
1	12	1200	22.76	0.368	55.1	0.12	10.95	68	1593
4	12	2500	22.72	0.369	64.35	0.086	11.9	78	1595
5	12	2500	22.71	0.37	64.37	0.086	11.9	78	1595
13	12	1200	22.72	0.368	55.08	0.12	10.95	68	1593

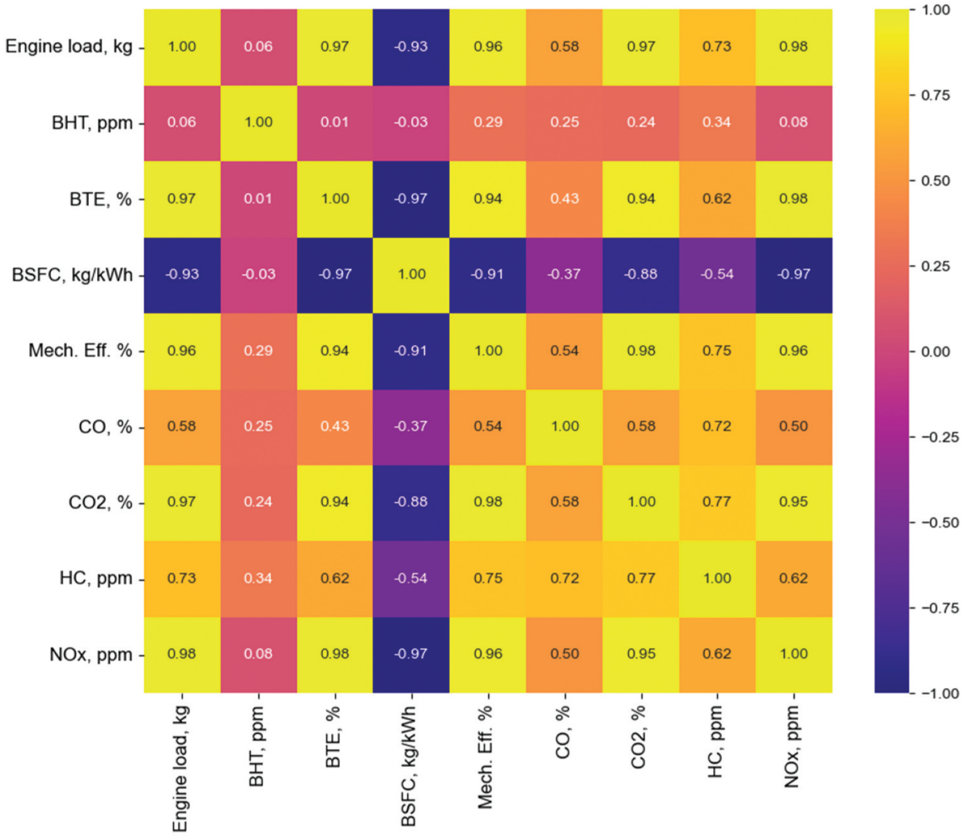

Figure 9. Correlation heat map.

Table 5. R^2 values for all parameters.

	BTE, %	BSFC, kg/kWh	Mech. Eff., %	CO, %	CO2, %	HC, ppm	NOx, ppm
R^2	0.9978	0.9831	0.9807	0.8305	0.9877	.8665	.9967
Adj R^2	0.9967	0.9746	0.971	0.7457	0.9815	.7998	.995
Pred R^2	0.9946	0.9545	0.9612	0.6308	0.9687	.7137	.9924

combined effect of load and BTH concentration on CO_2 emission. CO_2 emission was shown to be significantly affected by engine load, with the low CO_2 emission reported at 3 kg engine load and lower concentration of BTH (500 ppm).

The combined effects of engine load and additives are depicted with the help of a surface diagram (Figure 10(f) on HC emission. A parabolic nature of plots shows that initially increasing the engine load helps in emission reduction, but it is found to increase again at a higher load due to the presence of a richer mixture, resulting in incomplete combustion. The lowest HC emission was observed at 6 kg engine load and the lowest level of BTH concentration. The combined effects of additive and engine load on NOx emission are represented using a surface diagram (Figure 10(g)). The linear shape of the plot reveals that raising the engine load leads to a higher NOx emission. At lower engine loading, the NOx emission was considerably low. The NOx formation behavior is often described with the Zeldovich mechanism (Rao, Liu, and Ma 2022). The higher combustion temperature at a higher engine load results in nitrogen taking part in oxidation, even being almost an inert gas. The lowest HC emission was found at a 3 kg engine load additive concentration of 500 ppm.

Table 6. Outcomes of ANOVA for engine performance.

Parameter	BTE				BSFC				Mech. Efficiency			
Source	Sum of squares	Mean Square	Value 'F'	p-value, Prob > F	Sum of squares	Mean Square	Value 'F'	p-value, Prob > F	Sum of squares	Mean Square	Value 'F'	p-value, Prob > F
Model	577.78	115.55	927.95	<0.0001	1.234	0.247	116.46	<0.0001	4171.37	834.27	101.57	<0.0001
A	518.24	518.24	4161.68	<0.0001	0.937	0.9377	441.98	<0.0001	3343.43	3343.44	407.06	<0.0001
B	2.29	2.29	18.4	0.0016	0.0000072	0.0000072	0.0034	0.9546	205.82	205.82	25.06	0.0005
AB	3.73	3.723	29.94	0.0003	0.0027	0.0027	1.28	0.284	4.98	4.98	0.6	0.4542
A^2	8.23	8.23	66.09	<0.0001	0.1119	0.112	52.8	<0.0001	16.77	16.77	2.042	0.1835
B^2	12.43	12.43	99.8	<0.0001	0.01784	0.0178	8.41	0.0158	11.19	11.189	1.36	0.2702
Residual	1.245	0.125			0.0212	0.002			82.14	8.21		
Lack of fit	1.24	0.249	1244.27	<0.0001	0.0212	0.0042	14135.83	<0.0001	82.135	16.43	182521.81	<0.0001
Corrected total sum of squares	579.02				1.256				4253.5			

Table 7. Outcomes of ANOVA for engine emission.

Parameter	CO				CO_2				HC				NO_x			
Source	Sum of squares	Mean Square	Value 'F'	p-value, Prob > F	Sum of squares	Mean Square	Value 'F'	p-value, Prob > F	Sum of squares	Mean Square	Value 'F'	p-value, Prob > F	Sum of squares	Mean Square	Value 'F'	p-value, Prob > F
Model	0.011	0.0022	9.799	0.0013	126.89	25.38	160.63	<0.0001	2963.31	592.66	12.98	0.0004	3838175.4	767635.08	600.2	<0.0001
A	0.0036	0.00366	16.27	0.0024	108.72	108.71	688.09	<0.0001	1956.59	1956.59	42.86	<0.0001	3117332	3117332	2437.41	<0.0001
B	0.00025	0.00025	1.12	0.3146	2.79	2.79	17.68	0.0018	89.29	89.29	1.96	0.1921	8162.15	8162.15	6.38	0.0301
AB	0.0002	0.0002	0.89	0.3665	0.24	0.24	1.53	0.2443	0.01	0.01	0.000229	0.9882	17.15	17.15	0.013	0.9101
A^2	0.0037	0.0037	16.66	0.0022	0.41	0.41	2.57	0.1397	805.96	805.96	17.66	0.0018	89248.66	89248.66	69.78	<0.0001
B^2	0.0027	0.0027	12.29	0.0057	0.29	0.29	1.85	0.2034	27.5	27.5	0.6	0.4555	40.897	40.897	0.032	0.8616
Residual	0.00225	0.000225			1.58	0.158			456.44	45.64			12789.5	1278.95		
Lack of fit	0.00225	0.00045			1.58	0.316			456.44	91.29			12788.52	2557.7	12788.5	<0.0001
Corrected Total Sum of Squares	579.02				1.256				4253.5				3850964.9			

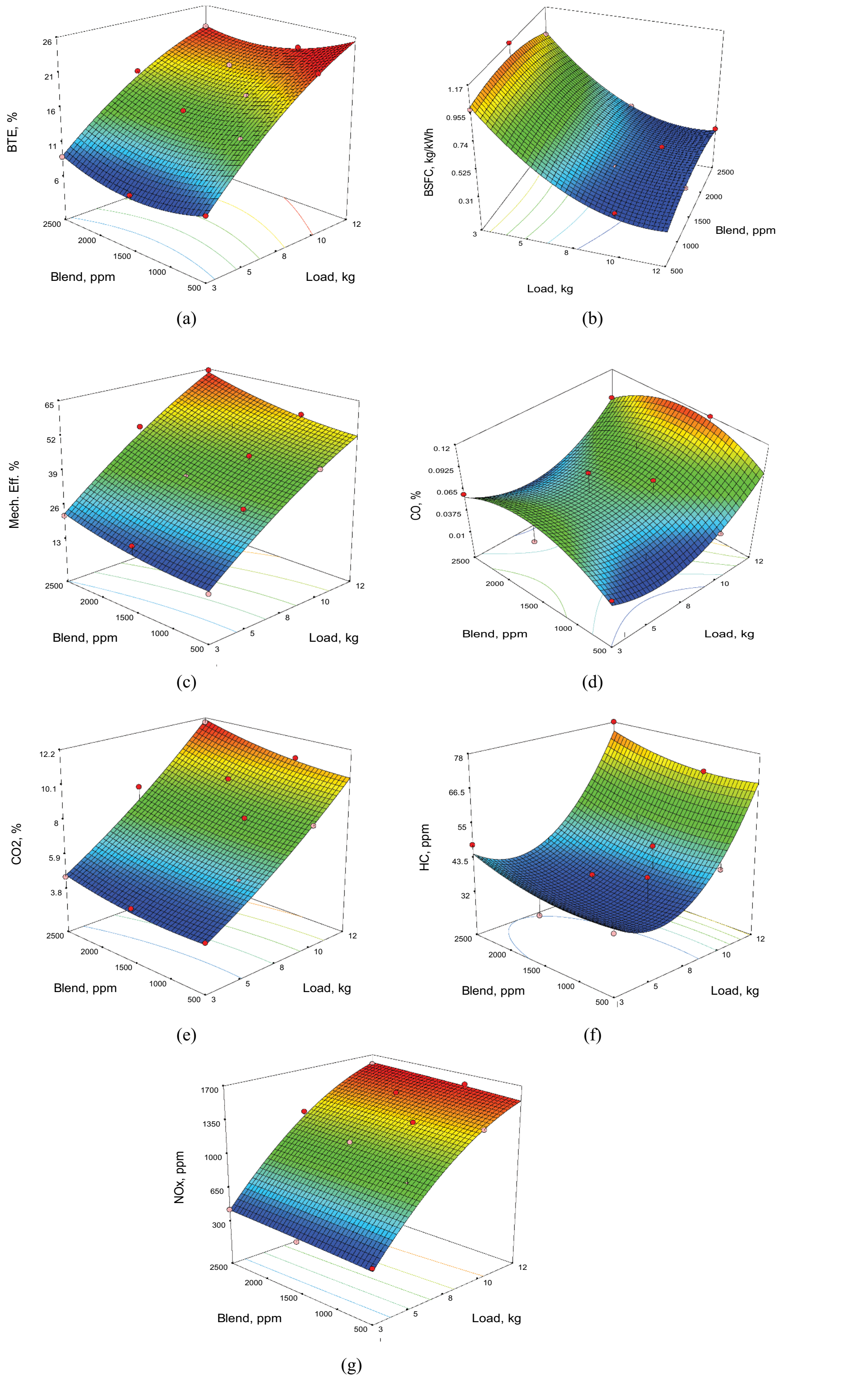

Figure 10. Surface diagrams for (a) BTE; (b) BSFC; (c) Mech Eff.; (d) CO; (e) CO2 (f) HC; (g) NOx.

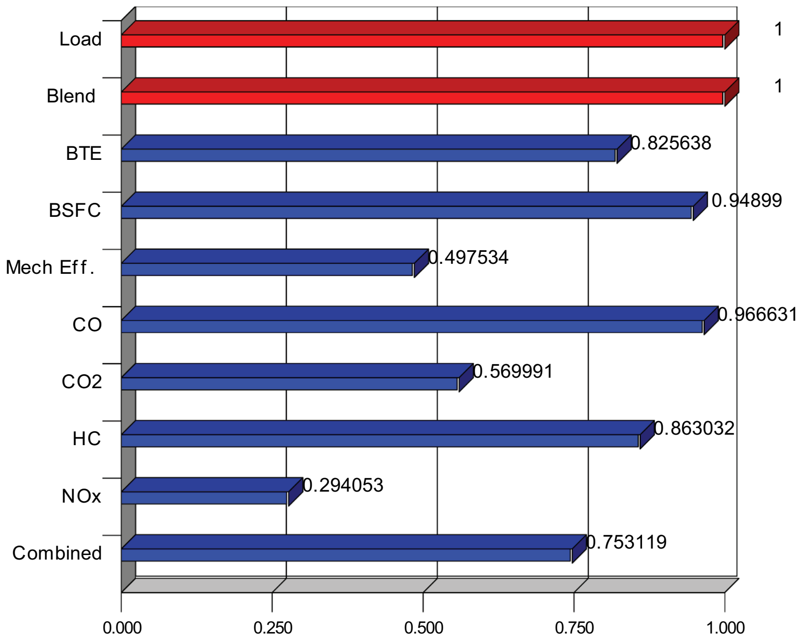

Figure 11. Desirability bar graph.

Optimization

Desirability-based optimization is a technique for simultaneously optimizing numerous response variables by giving desirability values to each response and then determining the combination of parameters that maximizes overall desire (Harington 1965; Kumar et al. 2022). Engine load and additive concentration are the control elements in this scenario, whereas the response variables are BTE, BSFC, CO, CO_2, HC, and NOx. The objective was to maximize the BTE and Mech efficiency while minimizing the fuel consumption and emission characteristics, as shown in Figure 11.

In this setting, it was observed that the best results after the trade-off analysis were 8.22 kg engine load and 500 ppm BTH concentration. It led to the response variable as 20.04% BTE, 0.4 kg/kWh BSFC, 39% mechanical efficiency, 0.028 Vol.% CO emission, 7.39% CO_2, 39.16 ppm HC, 1230 ppm NOx.

Conclusion

The performance and emission characteristics of a small engine powered with biodiesel-additive blends employing (Liza oil + BHT) under various operating circumstances were determined by experimental testing. Based on the findings, it was concluded that the biodiesel blends at all loads had an impact on the BTE, BSFC, and Mechanical efficiency of the Kirloskar engine. Engine performance decreased as the percentage of biodiesel in the blend was increased for similar operating conditions. The D-optimal design was used for experiment design and ANOVA was used for model development. The following are the main outcomes of the study:

(1) At higher loads, B10 blends have a slightly higher brake thermal efficiency than regular diesel. Compared to diesel, 24.57%, the maximum brake thermal efficiency of (Liza oil + BHT) biodiesel is 32.6%.
(2) When compared to conventional diesel, the mechanical efficiency of B10 and B20 is higher; as the load increases, it is seen that mechanical efficiency steadily rises for all mixes.
(3) Due to a longer ignition delay, Liza oil and BHT mixes produce more combustion pressure at higher compression ratios. When compared to diesel, the peak rate of pressure rises, and the rate at which heat is released decreases.

(4) B10 has the highest efficiency when measured against the efficacy of all mixes, including B20 and B30. Higher efficiencies, such as B30 and B40 B50 blends, deliver performance increases while decreasing ignition latency and increasing pollution. We must modify engines for greater effectiveness and reduced pollution.
(5) The desirability-based optimization was employed to attain the best engine operating load of 8.22 kg and 500 ppm of additive.
(6) At this setting, it was observed that the best results after trade-off analysis are 20.04% BTE, 0.4 kg/kWh BSFC, 39% mechanical efficiency, 0.028 Vol.% CO emission, 7.39% CO_2, 39.16 ppm HC, 1230 ppm NOx.

Future research ought to investigate the long-term impact of biodiesel mixes on engine reliability and lifetime. In addition, researching the compatibility of these blends with various engine types and sizes could yield helpful information for larger applications. It is also critical to evaluate the economic feasibility of such mixes on a larger scale, as well as their effect on the overall sustainability of the transportation industry.

Furthermore, research into the combustion properties of biodiesel blends in advanced combustion systems, such as homogeneous charge compression ignition (HCCI) engines, may bring additional efficiency and emissions advantages.

Disclosure statement

No potential conflict of interest was reported by the author(s).

Notes on contributors

Dr. Van Nhanh Nguyen is a lecturer at HUTECH University. Dr. Van Giao Nguyen is a member of the AME Research Group at his university since 2022. His research interests include automobile engineering, biofuels, emission management, and general energy.

Dr. R. Ganapati is an accomplished academic professional currently serving as an Associate Professor in the Department of Mechanical Engineering at ANURAG Engineering College (AUTONOMOUS) in KODAD, Telangana, India. Dr. Ganapati holds a Ph.D. from JNTUA. With a wealth of 15 years of experience in teaching and research, he has made substantial contributions to his field. His academic journey is marked by a remarkable publication record, encompassing 35 research papers published in prestigious national and international journals.

Dr. B. Omprakash is an accomplished academic professional currently serving as an Assistant Professor in the Mechanical Engineering Department at JNTUA College of Engineering, Ananthapuramu, Andhra Pradesh. He holds a Ph.D. in Thermal Science from JNT University Anantapur. His research interests primarily focus on experimental investigations in the field of internal combustion engines, particularly in areas such as ignition systems and alternative fuels. Dr. Omprakash has a substantial publication record, including papers in renowned journals and conferences, and he has also contributed to a patented technology related to effective solar-thermal plants.

Prabhakar Sharma is associated with Delhi Skill and Entrepreneurship University, Delhi, India as an Asst. Professor. He has 13 Years of Academic Experience. He did his PhD in Artificial intelligence-based renewable energy system modeling. He has authored several journal papers in International Collaborations and attended international conferences. He has research interest in renewable energy, emission reduction and artificial intelligence. Presently working on AI based research on Intelligent systems, fuel additives, hybrid nanofluids, and biomass gasification.

Dr. Nguyen Dang Khoa Pham is a lecturer at Ho Chi Minh city University of Transport. He received the Ph.D degree from Ho Chi Minh city University of Transport, Ho Chi Minh, Vietnam in 2021. His research interests lie in the fields of Renewable energy, Alternative fuels, Maritime Safety, and Engineering Transport. Dr. Nguyen Dang Khoa Pham is a member of Progress of Applied Technology and Engineering in Transport Research Group (PATET) at the University since 2022.

Dr. Phuoc Quy Phong Nguyen is a lecturer at Ho Chi Minh city University of Transport, Ho Chi Minh, Vietnam. He received the Ph.D in 2014. His research interests lie in the fields of Renewable energy, Alternative fuels, Maritime Safety, and Engineering Transport. Dr. Phuoc Quy Phong Nguyen is a member of Progress of Applied Technology and Engineering in Transport Research Group (PATET) at the University since 2022.

Dr. Viet Dung Tran is a lecturer at Ho Chi Minh city University of Transport. He received the Ph.D. degree of Mechanical Engineering from Ho Chi Minh city University of Transport, Ho Chi Minh, Vietnam in 2021. His research interests lie in the fields of Renewable energy, Alternative fuels, Maritime Safety, and Engineering Transport. Dr. Viet Dung Tran is a member of Progress of Applied Technology and Engineering in Transport Research Group (PATET) at the University since 2022.

Duc Trong Nguyen Le is a lecturer at the Faculty of Automotive Engineering, Dong A University, Danang, Vietnam. His research interests include automobile engineering, biofuels, emission management, and general energy.

ORCID

Van Nhanh Nguyen http://orcid.org/0000-0003-4241-3359
Prabhakar Sharma http://orcid.org/0000-0002-7585-6693
Nguyen Dang Khoa Pham http://orcid.org/0000-0003-1750-2077

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