DIESEL ENGINE PERFORMANCE AND EMISSION PARAMETERS OPTIMIZATION USING TAGUCHI AND RESPONSE SURFACE METHODOLOGY

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SUMMARY

In present study, the ideal engine functioning condition for pollutants as well as functionality was determined using RSM. The L16 Orthogonal Array experiment table was designed using Minitab 16 software with Taguchi's design of experiments methodology with Three variables—fuel type, engine speed, and engine load, each of which was varied across four distinct levels. After a comprehensive model examination, the R^2 and modified R^2 values are close, indicating a low risk of including unimportant components. The model found that an engine load of 6.85 kgf, an engine speed of 2000 rpm, and the 20% OPB blended fuel (OPB20) would optimise BTE, EE, BSFC, and NO, HC, and CO emissions. The model's maximum desirability was 86.79%, indicating that the predicted optimum answers and experimental responses were similar. The utilisation of RSM optimisation in conjunction with OPB fuel has the potential to enhance engine performance and mitigate emissions.

KEYWORDS

OPB, RSM, Taguchi method, Orthogonal array, Transesterification technique, ppm

NOMENCLATURE

Al_2O_3	aluminium oxide
BP	brake power
BTE	brake thermal efficiency
BSFC	brake specific fuel consumption
CeO_2	cerium oxide
CO	carbon monoxide
CR	compression ratio
CRDI	common rail direct injection
DICI	direct injection compression ignition
EE	exergy efficiency
EGR	exhaust gas recirculation
HC	hydrocarbon
IP	injection pressure
LHV	lower heating value
$\mathring{m}_f$	fuel flow rate
MWCNT	multiwall carbon nanotube
N	engine speed(rpm)
NO	oxides of nitrogen
OPB	orange peel biodiesel
OPB10	10% blends of orange peel biodiesel
OPB20	20% blends of orange peel biodiesel
OPB30	30% blends of orange peel biodiesel
PM	particulate matter
T	engine torque (N-m)
TiO_2	titanium oxide
RSM	response surface methodology
VCR	variable compression ratio
v/v	volume to volume ratio
Ø	combustion efficiency

1. INTRODUCTION

Diesel engines emerged as the dominant prime movers in modern society owing to their notable reliability and efficiency. The exponential increase in the world's population and the accompanying surge in automobile use, driven by the escalating consumption of fossil fuels and the accelerated depletion of such resources, has resulted in this phenomenon. The accelerated depletion of fossil fuels has resulted in increased fuel costs and emissions of carbon dioxides (CO_2), NOx, and particulate matter (PM), which contribute significantly to the phenomenon of climate change and the phenomenon of global warming (Agrwal, 2007).

Kumar et al., 2017 conducted an experimental analysis on the energy and emission parameters of a diesel engine, utilising a 20% blend of Pongamia biodiesel and a ferrofluid nanocatalyst. According to a study, the incorporation of a nanocatalyst fuel containing 20% biodiesel and the incorporation of a 1% concentration of ferrofluid led to enhanced BTE and a reduction in emissions. Ganesan et al., 2020 conducted an inquiry and refinement of engine operational characteristics for diverse blends of biodiesel and diesel, with compression ratio (CR) that varied. The engine's maximum performance and minimum emissions levels were observed when utilising a 30% lemongrass biodiesel blend, 45 ppm CeO_2 nano additive, 14 CR, and 4.4 kW brake power.

Natrajan et al., 2018 utilised the Taguchi-grey technique to optimise emission levels and operational remarks of the PPCCI engine powered with mixes of diesel and ethanol. The study found that the utilisation of a 20% blend of ethanol yielded the most favourable results in terms of emission levels and outcomes remarks for the PPCCI engine. Singh et al., 2022 investigated the potential improvement of CI engine emitted and functional responses by employing the Taguchi and Response Surface Methodology (RSM). The study involved the control of fuel IP, CR, fuel blend, and engine load. The study determined that the most effective engine settings for achieving optimal responses were a compression ratio of 17.98, an IP of 269.96 bar, and an engine load of 12 kgf.

Kumar et al., 2020 examined impact of operating conditions on pollution and operational characteristics of direct injection engines powered with jatropha biodiesel. The RSM optimisation technique was employed for this purpose. The study found that the highest degree of smoke reduction occurred at 12 degrees crank angle, 70% engine brake power, and an engine speed of 2300 rpm. Additionally, the most significant increase in NOx emissions was observed at 15 degrees crank angle, 70% engine load, and an engine speed of 2300 rpm when using jatropha biodiesel fuel. Reddy et al., 2022 conducted an analysis of the combustion, pollution, and operational attributes of CI engines that were powered with a blend of biodiesel derived from schizochytrium microalgae. The study revealed that the parameters related to combustion, pollution, and operational of the CI engine exhibited enhancement in comparison to those observed with diesel fuel. Yessian et al., 2020 conducted an analysis of the response parameters of diesel powered engine, which were subsequently optimised. The engine was fuelled with cottonseed biodiesel and utilised a catalytically coated piston. The optimisation was performed using Taguchi-grey relational analysis. The implementation of a copper zirconium catalytic coated piston engine resulted in enhanced performance parameters and decreased emission levels.

Ağbulut et al., 2021 studied the environmental and operating attributes of diesel-powered engines that were supplemented with different nano additives. This study utilised different machine learning algorithms. Incorporating a nano additive was observed to rise the rate of transfer of heat from the combustion chamber, while simultaneously reducing CO and NOx emissions as well as engine BSFC. The algorithms employed exhibited R^2 values ranging from 0.901 to 0.994, with the deep learning algorithm yielding the most optimal outcome compared to the other algorithms. Singh et al., 2021 utilised the RSM optimisation technique to optimise the performances of diesel engines and emission parameters when powered with blends of microalgae spirulina biodiesel and diesel. At an engine load of 64.634%, CR of 16.50, and utilisation of 20% biodiesel blended fuel, the anticipated model yielded 274.97 g/kWh BSFC, 31.57% BTE, and reduced levels of PM, CO_2, and NOx emissions. Rai et al., 2021 utilised the Taguchi-grey optimisation method to optimise the VCR engine's performance, heat losses, and emission parameters. The optimal combination of engine performance and emission reduction was achieved through the utilisation of a 17:1 CR, a 10 kgf engine load, and a biodiesel blend consisting of 30% shorearobusta.

Saraswat et al., 2022 carried out an experimental investigation on a VCR engine using different compression ratios and mixtures of algae biodiesel and diesel. The experimental findings showed that while NO emissions increased, HC and CO emissions decreased when biodiesel was blended in. Kothare et al., 2023 carried out the experimental examination of SI engine using a combination of binary and ternary n-pentanol, ethanol and gasoline to enhance the performance and reduce emissions. The engine with 10% ethanol, 1.5% n-pentanol, and gasoline blend provides minimul CO and HC emissions with highest BTE and lowest BSFC. The operational stability of a dual fuel engine using a combination of diesel and methanol under varied injection strategies was investigated by Kakati et al., 2024. It is demonstrated that the partially premixed mode under the split injection strategy shows considerable promise in lowering the operating harshness, backed up by a lower peak pressure grow, and raising the combustion cycle recurrence as indicated by significantly lower ratings of the parameters taken into consideration for visualizing stability.

Prior studies have extensively examined the operational and pollution attributes of diesel-powered engines when employing various mixtures of biodiesel as well as diesel fuel, including the use of nanocatalysts and optimization methods such as Taguchi, RSM, and Grey techniques. However, there is a scarcity of literature on the specific topic of orange peel biodiesel (OPB) and OPB blended with nanocatalysts, and no optimization techniques have been applied to optimize engine performance and emission parameters in this context. Therefore, the main objectives of this current research work are to examine the impact of blending 10%, 20%, and 30% OPB in diesel fuel on engine performance and emission parameters, as well as to optimize these parameters using the RSM multi-responses optimization technique. To design the experiments, the Taguchi method will be employed with the aid of Minitab 16 software. The selection of factors and their corresponding levels will be based on an L16 orthogonal array.

2. COMPREHENSIVE APPROACH TO FUEL RESEARCH: PREPARATION, PROPERTY ASSESSMENT, EXPERIMENTAL DESIGN, AND ANALYSIS

This segment comprises four distinct sections. The first segment of the text delineates the methodology for the production of biofuels and measuring the properties of the aforementioned fuels. The subsequent segment is centred on elucidating the methodology employed in devising the experiments and the choice of an orthogonal array. The third section pertains to the description of the experimental techniques utilised. The fourth subsection presents mathematical equations aimed at data reduction.

2.1 FUEL PREPARATION AND PROPERTIES MEASUREMENTS

Orange peel oils were obtained from a trader in Varanasi, India. A local chemical supplier in Varanasi, India, provided methanol, sodium hydroxide (NaOH), and potassium hydroxide (KOH). The OPB is generated in a single step transesterification process by reacting methanol with triglycerides in the presence of a KOH catalyst.

At 65°C, a 0.5% (w/w) KOH catalyst was poured to the mixed fuel during the transesterification process. The procedure continued for 90 minutes while maintaining an agitating speed of 450 rpm. The procedures for the preparation of orange peel biodiesel are shown in Fig.1.

Methanol + Triglycerides ⟶ glycerol + Mixture of fatty ester

During the transesterification process, a mixed fuel was subjected to the addition of a 0.5% (w/w) KOH catalyst at a temperature of 65°C. The process was sustained for duration of 90 minutes, with a consistent agitation rate of 450 revolutions per minute. Figure 1 illustrates the methodologies employed in the production of biodiesel from orange peel.

2.1.1 FUEL PROPERTIES

Table 1 presents the measured fuel properties for various fuel blends used in the experimental analysis. The fuel blends tested were diesel, OPB10, OPB20, and OPB30. These blends were prepared specifically for the purpose

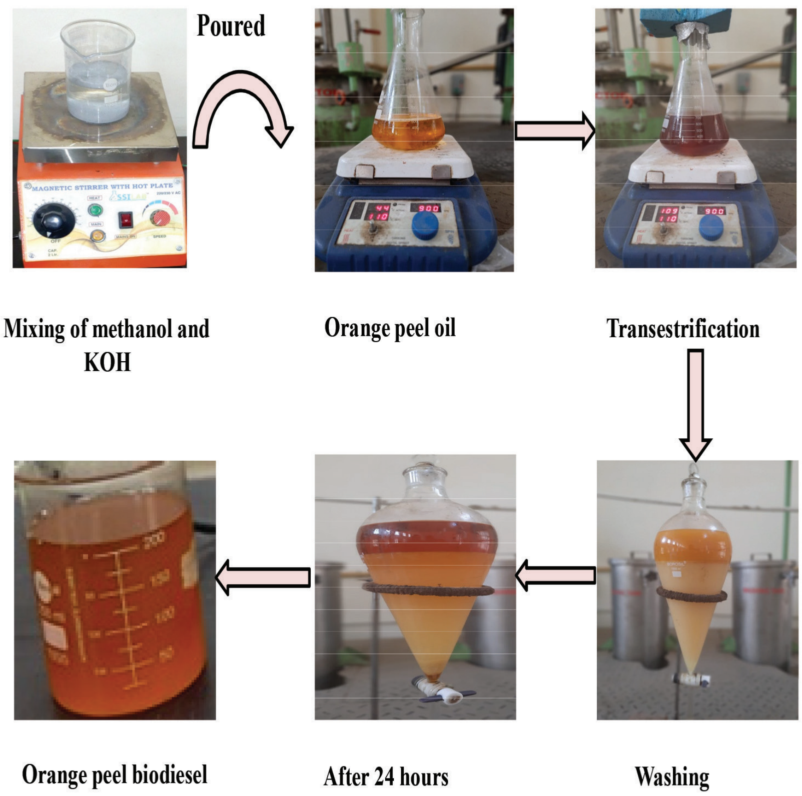

Figure 1. Preparation of for orange peel biodiesel

Table 1. Fuel properties measurement

Characteristics	ASTM	Diesel	OPB10	OPB20	OPB30
Density (kg/m^3)	ASTMD1298	863	868.8	869.4	871.3
Viscosity (cP)	ASTMD445	3.28	3.57	3.73	3.81
CV (MJ/kg)	ASTMD240	42.76	39.98	39.64	39.32
Flash Point (^{o}C)	ASTMD93	68.4	74.6	78.7	81.2
Fire Point (^{o}C)	ASTMD93	78.3	84.3	88.6	91.2

Table 2. The control factors and their levels

Factors	Level 1	Level 2	Level 3	Level 4
Engine load (kgf)	4 (**A1**)	6 (**A2**)	8 (**A3**)	10 (**A4**)
Engine speed (rpm)	1400 (**B1**)	1600 (**B2**)	1800 (**B3**)	2000 (**B4**)
Fuel type	Diesel (**C1**)	OPB10 (**C2**)	OPB20 (**C3**)	OPB30 (**C4**)

Table 3. L16 Orthogonal array

S.No.	Engine Load	Engine Speed	Fuel Type
1	4	1400	Diesel
2	4	1600	OPB10
3	4	1800	OPB20
4	4	2000	OPB30
5	6	1400	OPB10
6	6	1600	Diesel
7	6	1800	OPB30
8	6	2000	OPB20
9	8	1400	OPB20
10	8	1600	OPB30
11	8	1800	Diesel
12	8	2000	OPB10
13	10	1400	OPB30
14	10	1600	OPB20
15	10	1800	OPB10
16	10	2000	Diesel

of this experiment, and the ASTM standard was adopted to establish the fuel characteristics.

2.2 EXPERIMENTS DESIGN METHOD

The study employs the Taguchi-grey optimisation technique to optimise the response characteristics of the engine. The Taguchi method is employed to conduct the experimental design, while the optimisation of the engine response is executed by taking into account three control factors, namely fuel type, engine speed, and engine load. The aforementioned factors have been allocated four levels each, as delineated in Table 2, accompanied by their corresponding degrees of freedom. The study was conducted utilising the Taguchi methodology with the assistance of Minitab16 software. The specifics of the experimental configuration can be found in Table 3.

2.3 EXPERIMENTAL ANALYSIS

Experimental The experiment was performed on a four-cylinder, water-cooled, variable-speed, four-stroke diesel engine. To load the engine, a hydraulic dynamometer was utilized. Figure 2 shows schematic drawing of the experimental setup. The experiments were designed to investigate the engine's performance and emission characteristics under different conditions. The engine load was varied from 0 to 10 kg, and the speed ranged from 1000 to 2000 rpm. Additionally, four different fuel samples were used: diesel, OPB10, OPB20, and OPB30. To collect data; an L16 orthogonal array was employed, enabling a systematic and efficient experimental design. The engine's performance parameters, including BTE, BSFC, and exergy efficiency, were measured. Furthermore, emission parameters such as HC, CO, and NO were also monitored.

2.4. DATA EXTRACTION FOR PERFORMANCE EVALUATION

Considering steady-state engine functioning, perfect gas facets for exhaust gas, and homogenous combustible product as a homogeneous mixture, the energy and emission parameters of the diesel engine have been established [Sayin et al., 2011, Pali et al., 2016].

The engine's power is denoted as,

$$BP = \frac{2\pi NT}{60} \tag{1}$$

The engine BTE is estimated as,

$$BTE = \frac{BP}{\dot{m}_f .CV} \tag{2}$$

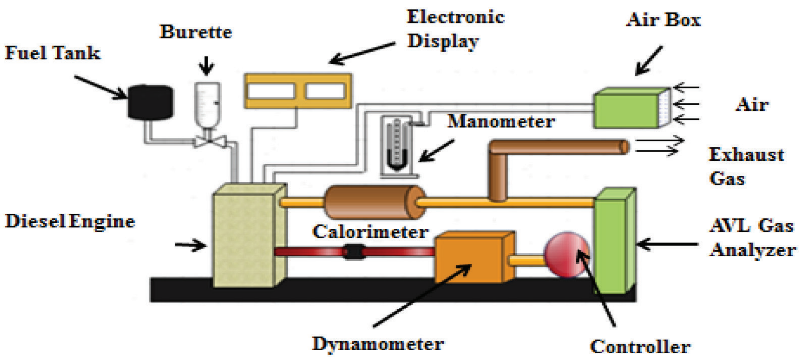

Figure 2. Schematic drawing of testing setup

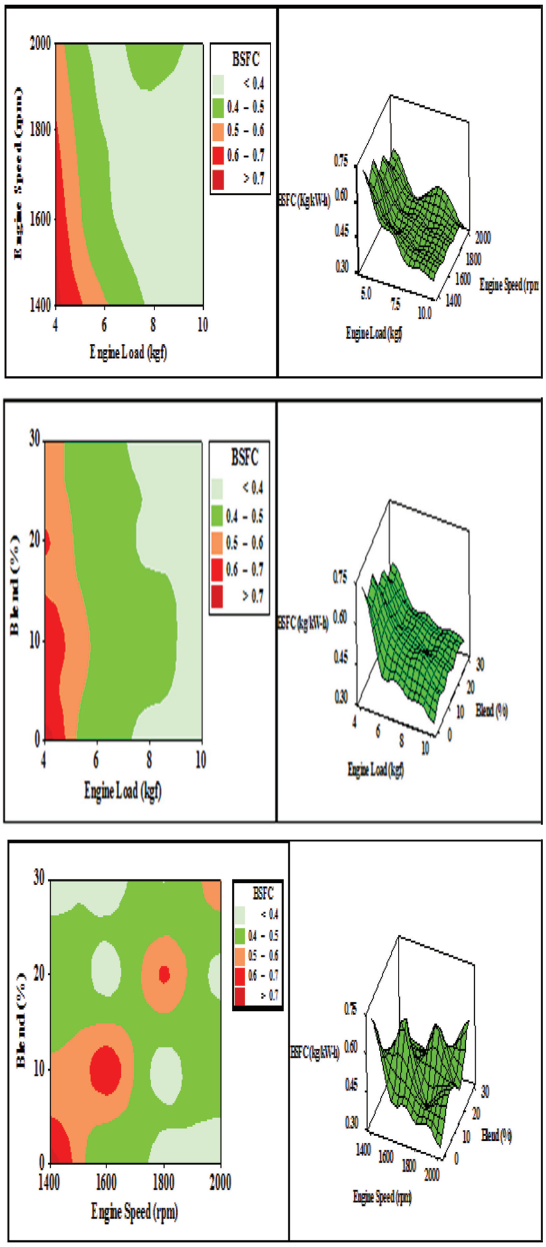

Figure 3. Contour and surface plot of BSFC vs. engine load, engine speed and fuel blends

The engine's BSEC and BSFC are stated as,

$$BSFC = \frac{\dot{m}_f}{BP} \tag{3}$$

3. RESULT AND DISCUSSION

The findings from the experiment have been recorded in accordance with the performance and emissions parameters of OPB10, OPB20, and OPB30 fuel, as well as variable engine loads and diesel speed in Table 3 of Taguchi's experimental design.

3.1 INFLUENCE OF ENGINE LOAD AND ENGINE SPEED, ENGINE LOAD AND FUEL BLEND, ENGINE SPEED AND FUEL BLEND VARIATION ON ITS BSFC

Figure 3 depict the contour and surface plots showcasing the engine BSFC in relation to the engine load, speed, and blend.

These plots specifically represent at the mean value of engine load at 7 kg, engine speed at 1700 rpm, and an OPB blend of 15%. In the contour and surface plots presented in Figure 3, it was observed that the engine BSFC reached its lowest value within the light green range, which corresponds to higher engine load and speed. The reason for this can be attributed to the fact that as engine power increases at a constant speed, mechanical efficiency improves. Consequently, there is an initial rise in indicated fuel conversion efficiency, followed by a subsequent decline. The overall impact is a decrease in BSFC. Figure 3 also illustrates that when the engine load is maintained at 7 kg, the BSFC of the engine increases as the percentage of fuel blend increases. This can be attributed to the higher kinematic viscosity and lower calorific value of the fuel blend compared to pure diesel fuel. Consequently, a greater quantity of fuel needs to be injected during the combustion process in order to achieve an equivalent power output to

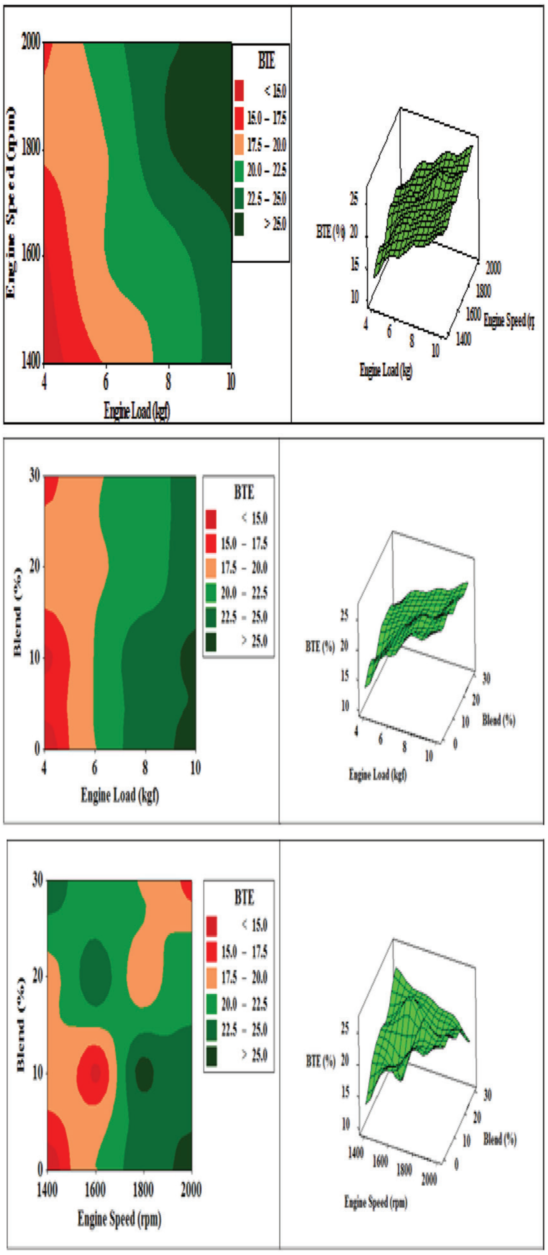

Figure 4. Contour and surface plot of BTE vs. engine load, engine speed, and fuel blends

that of diesel fuel. Figure 3 also illustrates that at a constant engine load of 7 kg, the minimum BSFC was observed for a fuel blend of 20% and an engine speed of 1600 rpm.

3.2 INFLUENCE OF ENGINE LOAD AND ENGINE SPEED, ENGINE LOAD AND FUEL BLEND, ENGINE SPEED AND FUEL BLEND VARIATION ON ITS BTE

In Figure 4, the contour and surface plot illustrate the relationship between engine BTE and engine load and engine speed. It was observed that when fuel blend 15% was withheld, the engine BTE was highest within the dark green range, which corresponds to higher load conditions and higher speeds. The increase in engine load was found to enhance the engine BTE due to the corresponding increase in engine power at a fixed speed. This increase in power leads to a rise in the fuel-air ratio, thereby improving the combustion process within the cylinder and ultimately benefiting the engine BTE.

Figure 4 also demonstrate a decrease in engine BTE as the percentage of fuel blend increases. This can be attributed to the elevated viscosity of biodiesel blended fuels, as well as the larger size of fuel droplets and reduced rate of fuel atomization compared to diesel fuel. The data presented in the figure indicates that when the engine load is held constant at 7 kg, the BTE of the engine is observed to increase with higher fuel blending at lower engine speeds, and decrease with lower fuel blending at higher engine speeds. Figure 4 also illustrates that at a constant engine load of 7 kg, the maximum BTE was observed for a fuel blend of 20% and an engine speed of 1600 rpm.

3.3 INFLUENCE OF ENGINE LOAD AND ENGINE SPEED, ENGINE LOAD AND FUEL BLEND, ENGINE SPEED AND FUEL BLEND VARIATION ON ITS HC EMISSIONS

The contour and surface plots depicted in Figure 5 illustrate the relationship between engine HC emissions and various operating conditions. Specifically, when fuel blend 15% was withheld, it was observed that HC emissions were most pronounced in the dark brown range, which corresponds to higher load and higher speed conditions.

Additionally, when the engine power increased while maintaining a constant speed, the fuel supply rate increased while the air supply rate remained unchanged. Consequently, the aforementioned phenomenon yields a heterogeneous blend within the cylinder and inadequate combustion of fuel, thereby leading to escalated emissions of HC. Figure 5 also demonstrate that when the engine speed is held constant at 1700 rpm and the engine load at 7 kgf, the emissions of HC from the engine decrease as the percentage of fuel blend increases. This reduction can be attributed to the higher oxygen content present in biofuels. Biofuel blends with higher cetane numbers have been found to enhance fuel combustion by reducing the ignition delay, resulting in a more efficient combustion process. This improvement in combustion efficiency also leads to a further reduction in HC emissions.

According to the data presented in Figure 5, it can be observed that when the engine load was maintained at a value of 7 kgf, the engine's HC emissions were recorded to be the lowest, measuring less than 20 ppm. This result was obtained specifically when the engine was operating at an engine speed of 2000 rpm and utilising a fuel blend consisting of 20%.

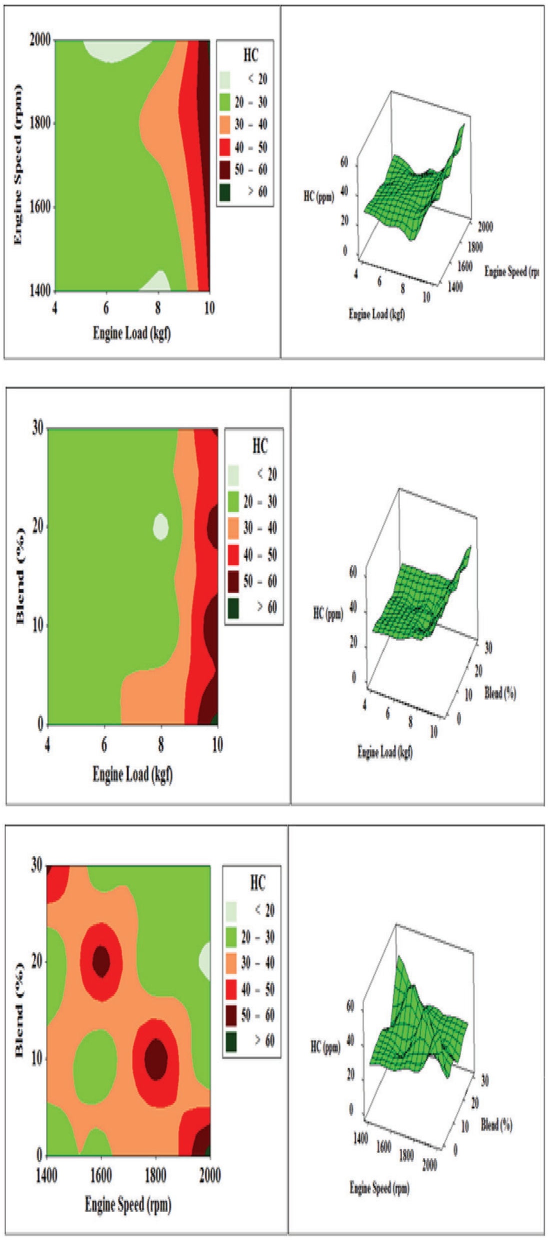

Figure 5. Contour and surface plot of HC emissions vs. engine load, engine speed and fuel blends

3.4 INFLUENCE OF ENGINE LOAD AND ENGINE SPEED, ENGINE LOAD AND FUEL BLEND, ENGINE SPEED AND FUEL BLEND VARIATION ON ITS NO EMISSIONS

In the contour and surface plots depicted in Figure 6, it was observed that the engine's NO emissions were at their lowest when fuel blend 15% was withheld. Specifically, these emissions were found to be situated within the light green range, which corresponds to lower load and lower speed conditions. As the engine's rotational speed and power output escalate, the emissions of NO experience a corresponding increase across all fuel types. Figures 6 illustrates that, when maintaining the engine speed at 1700 rpm and the engine load at 7 kgf, the emissions of NO from the engine were observed to increase as the percentage of fuel blend increased. According to Figure 6, it can be observed that when the engine load is maintained at 7 kgf, the engine's NO emissions were recorded to be the lowest, measuring less than 450 ppm. This occurred when the fuel blend consisted of 0% biofuel and the engine speed was set at 1400 rpm.

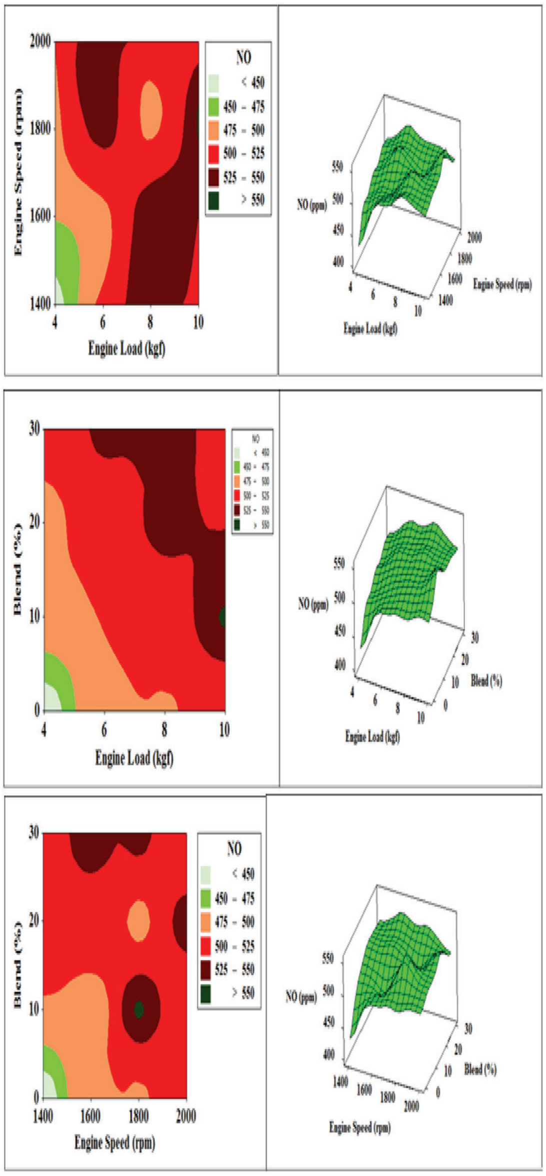

Figure 6. Contour and surface plot of NO emissions vs. engine load, engine speed, and fuel blends

3.5 INFLUENCE OF ENGINE LOAD AND ENGINE SPEED, ENGINE LOAD AND FUEL BLEND, ENGINE SPEED AND FUEL BLEND VARIATION ON ITS CO EMISSIONS

Figure 7 contour and surface plot of CO emissions vs. engine load, engine speed, and fuel blends load, 1700

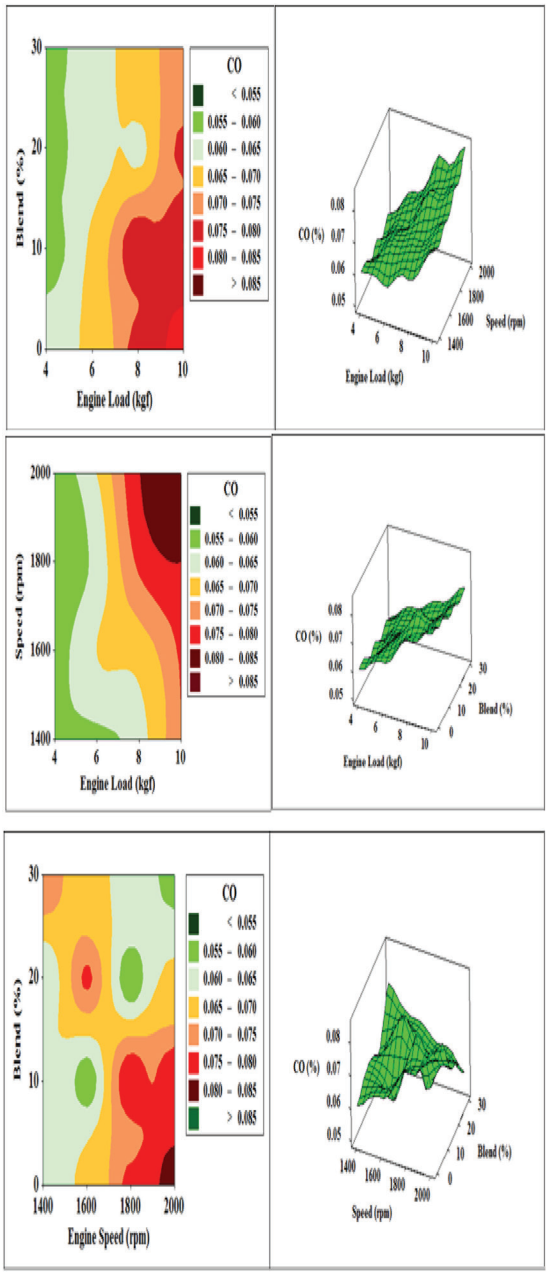

Figure 7. Contour and surface plot of CO emissions vs. engine load, engine speed, and fuel blends

revolutions per minute for engine speed, and 15% for OPB blend, respectively. With 15% of the fuel mix withheld, the contour and surface plots in Figure 7 also demonstrates that the engine CO emissions were found to be at their lowest in the green range, which corresponded to a lower load and a slower speed. The greater the speed and load of the engine, the higher the fuel consumption will be. This will result in a lower oxygen supply within the cylinder as well as a higher fuel-air equivalency ratio. Consequently, CO emissions grow. Notably, as the engine load exceeds 5 kgf, there is a discernible increase in CO emissions. This is shown in figure 7, which show that the CO emissions from the engine decreased as the fuel blend percentage

Table 4. Model validation table

Term	BSFC (kg/kWh)	BTE (%)	NO (ppm)	HC (ppm)	CO (%)
SD	0.0516	0.7075	12.45	5.44	0.0017
R^2	93.30	98.81	92.77	94.64	98.79
R^2(Adj)	91.26	97.03	91.92	92.60	96.98
R^2(Pred)	81.23	84.80	80.50	83.15	86.49
Mod. degree	Quadratic	Quadratic	Quadratic	Quadratic	Quadratic

increased. Figure 7 demonstrates that the engine CO emissions were determined to be at their lowest (0.060%) for 0% fuel mix at 1400 rpm engine speed when the load on the engine was held constant at 7 kgf.

3.6 MODEL VALIDATION

The findings of an in-depth analysis of the developed model's applicability are presented in Table 4, which may be found here. It is recommended to have a high anticipated R^2 value from the model in order to ensure that the higher predictive performance is maintained. According to Table 4, the R^2 and corrected R^2 values suggest that the data generated by the intended model closely coincide with the experimental data. This conclusion is drawn from the fact that the R^2 value has been changed. In particular, when it comes to approximating experimental data, a value of R^2 that is higher than 80% is often deemed to be adequate. The fact that the R^2 value in this experiment was greater than 90% demonstrates that the regression model successfully represented the underlying methodology.

4. CONCLUSION

The RSM technique for optimization facilitates the continuous monitoring and control of engine parameters, thereby enabling the achievement of optimized combustion and the subsequent reduction of emissions. The experimental investigation and optimization revealed the following important conclusions:

1. In the current study, the R^2 and adjusted R^2 values suggest that the data acquired through the constructed model closely approximate the experimental data.
2. The R^2 value exceeded 90%, indicating that the regression model effectively characterised the technique.
3. The model demonstrated that by utilising an engine load of 6.85 kgf, an engine speed of 2000 rpm, and B20 fuel, it would be possible to achieve optimal values for BTE as well as lower values for BSFC and NO, HC, and CO.

4. An attainment of 86.79% represents the highest level of desirability, suggesting that the predicted optimised responses closely align with the experimental responses.
5. The highest recorded values for BTE was 22.43%. Additionally, the lowest observed value for BSFC was determined to be 0.4038 kg/kW-h. The observed minimum values for NO, CO, and HC emissions were recorded as ppm, 0.0709%, and 15.82 ppm, respectively.

In conclusion, the model can maximize BTE, reduce BSFC, and NO, CO, and HC emissions by identifying the optimal combination of these variables. RSM optimization with OPB fuel might improve engine performance and reduce emissions. This study advances sustainable automobile technologies.

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