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Application of response surface methodology to optimize the dual-fuel engine running on producer gas

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Abstract. This work develops a computational framework that optimizes the performance and emissions of a dual-fuel diesel engine running on biomass-derived producer gas as the main fuel and diesel as the pilot fuel. The study connects essential responses, brake thermal efficiency, peak combustion pressure, and emissions of nitrogen oxides (NOx), carbon monoxide (CO), and unburnt hydrocarbon (HC) with controllable factors like engine load and pilot fuel injection duration. The approach consists of simulating the impacts of these controllable inputs on engine performance, then optimization to find the optimal fuel injection pressure to balance performance and emissions. The results show that engine load considerably affects NOx emissions and brake thermal efficiency; greater loads lower CO emissions but raise HC emissions at low compression ratios. Although it had little effect on NOx emissions, fuel injection pressure was vital in balancing general engine performance. Using optimization, an optimal fuel injection pressure value of 218.5 bar was identified, thereby producing a brake thermal efficiency of 27.35% and lowering emissions to 80 ppm HC, 202 ppm NOx, and 92 ppm CO. This computational method offers a strategic means for improving the efficiency of dual-fuel engines while reducing their environmental impact, hence guiding more sustainable and effective engine operation.

Keywords: Biomass gasification; Optimization; Alternative fuel; Sustainability; Emission characteristic; Response surface methodology

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1. Introduction

There are significant synergies that might drive global evolution when emissions are reduced, the Sustainable Development Goals (SDGs) are met, and net zero is being approached (Yu *et al.*, 2022). Emissions reduction is a key element in the battle against climate change and is one of the main objectives of SDG13 (Razzaq *et al.*, 2023). In keeping with SDG8, clean energy solutions provide jobs and support economic growth. This cooperation covers the social as well as the economic aspects. Lowering the incidence of respiratory and cardiovascular diseases, emissions reduction also improves air quality, which directly affects SDG3 (Grimshaw & Kühn, 2019). By reducing pollution levels and safeguarding ecosystems, the shift to net zero also serves to increase environmental protection, which in turn helps to advance SDG14 and SDG15. By basically coordinating with and quickening the accomplishment of many SDGs, the effort to reduce emissions and attain net zero helps to build a coherent strategy for sustainable development (Hoang *et al.*, 2023; Skaug Saetra *et al.*, 2021).

While diesel engines have been vital to transportation and manufacturing, their pollutants have seriously jeopardized the environment and human health (Cao & Johnson, 2024; S. K. Nayak *et al.*, 2022). Particulate matter (PM) and nitrogen oxides (NOx) are byproducts of diesel engines, and they aggravate respiratory conditions and air pollution (Cao *et al.*, 2020; Dhahad *et al.*, 2019; Paramasivama *et al.*, 2024). The main causes of smog and acid rain, which damage biodiversity and ecosystems, are NOx emissions (Shammas *et al.*, 2020). Particularly microscopic particles may go deep into the lungs, putting public health at risk and triggering respiratory and cardiovascular problems (Barid & Hadiyanto, 2024; Riediker *et al.*, 2019). These problems have a workable solution in dual-fuel technology, which combines biofuels with diesel. Less dangerous emissions are produced by biofuels made from renewable biological sources than by traditional diesel (Hebbar, 2014; Shaafi *et al.*, 2015). The overall carbon footprint of diesel engines may be significantly reduced when biofuels are used in a dual-fuel system. The reduction of PM and NOx emissions brought about by this integration instantly enhances public health and air quality. Moreover, dual-fuel technology increases fuel efficiency and may be easily adapted with few modifications into existing diesel engines (Kan *et al.*, 2020; Liu *et al.*, 2024). It is therefore an affordable and practical way to cut emissions in the

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transportation sector (Wagemakers *et al.*, 2012). In efforts to reduce dependency on fossil fuels and promote renewable energy sources, the use of biofuels in dual-fuel systems improves energy variety and sustainability. In addition to improving communities' health and air quality, this shift supports the more general goals of climate action and sustainable development. Synergistic benefits of dual-fuel technology make it a significant player in the quest for a more robust and sustainable future (Singh *et al.*, 2021; Sorathia & Yadav, 2012).

Several authors attempted this approach to use dual-fuel technology for diesel engines and other thermal engines (Goyal *et al.*, 2023; Serbin *et al.*, 2021, 2023; Sharma *et al.*, 2023). The biomass gasification-derived producer gas (PG) used in combination with diesel/biodiesel for powering engines is considered as an useful solution (Akkoli *et al.*, 2021; S.S. Halewadimath *et al.*, 2022; B. Nayak *et al.*, 2021). Alruqi *et al.* (Alruqi *et al.*, 2023) used third-generation biodiesel derived from algae as pilot fuel and waste biomass-derived PG for powering the diesel engine, resulting in a reduction of NOx emissions while saving the fossil-based diesel fuel. Le et al. (Le *et al.*, 2024) used mango wood-derived PG for powering the diesel engine successfully. It was reported that Standard modelling techniques face a special difficulty because of the complex and nonlinear nature of combustion in dual-fuel engines. Though they are black-box techniques, neural networks and fuzzy-based techniques, which are extensively used in machine learning, are quite helpful in this regard. For accurate engine performance and emissions predictions, the study combined SHAP analysis with Tweedie and Huber-based regression approaches in a unique glass-box modelling approach. Percy et al. (Percy & Edwin, 2023) in the course of their research on the emissions and performance of a dual-fuel engine, tried different load and compression ratios. The PG was employed as secondary fuel. Among the feedstocks tested, the rubber shell-driven PG-powered dual fuel engine has the best diesel replacement and brake thermal efficiency (BTE). Both the experimental and the optimization data lead to this conclusion. The best operating conditions, after much trade-off analysis between power and emission, were determined to be a compression ratio of 17 and an engine load of 1.87 kW. Raj et al. (Raj *et al.*, 2023) used peach biomass for the generation of PG for employment as fuel blended with propane in spark ignition engines. By using numerical modelling in conjunction with multi-objective optimizations, this study was able to determine the optimal response of an SI engine in terms of its performance and emission qualities. The engine was fuelled by a mixture of peach-based PG and propane. FORTRAN programming language was used to build a quasi-dimensional computer simulation model. A comparison of the model's results with the experimental cylinder pressure trace from the earlier work supported its conclusions. This model was then used to assess the effects of the blending percentage, start of injection timing, and equivalency ratio on the emissions as well as engine performance of a PG-propane dual fuel sark-ignition engine.

Biomass gasification produces a mixture of carbon monoxide, hydrogen, and other gases that burn differently than diesel fuel. Complicating combustion dynamics, combining these two fuels changes the patterns of heat release, flame propagation, and ignition latency (Dabi & Saha, 2016; Sushrut S. Halewadimath *et al.*, 2023). This complexity could work against better engine performance, emissions, and fuel economy. Response Surface Methodology (RSM) is a useful statistical technique that may help with the parametric optimization of this dual-fuel system (Kashyap *et al.*, 2021). RSM experiments are made to carefully investigate how various factors and their interactions impact a response variable, such as engine performance or pollution levels (El-Sheekh *et al.*, 2022). Researchers can find the best values for every parameter by developing a mathematical model of the process, which will boost overall performance and lower emissions. Air-fuel ratio, injection time, and fuel composition are only a few of the complex interactions between which RSM utilized to dual-fuel engines may assist to elucidate. By giving a systematic way of analysing the many connections in the combustion process, this methodology enables exact adjustments and improvements. As such, RSM might be used to produce more effective and cleaner dual-fuel engines, therefore encouraging greener energy sources and lessening the negative effects of diesel engines.

The majority of current research on dual-fuel engines especially those running PG derived from biomass has explored several ways to improve engine performance and lower the emissions. Still, there is a notable research vacuum in methodically improving controllable variables utilizing advanced statistical techniques, including engine load and pilot fuel injection time. Although many studies have concentrated on experimental evaluations, few have used a computational framework including RSM to maximize both performance and emissions in dual-fuel engines. The uniqueness of this work is in using configurable parameters to build a strong link between important engine responses, such as braking thermal efficiency, peak combustion pressure, and emission characteristics, with respect to RSM. This study aims to maximize the fuel injection pressure so that engine performance and emissions are reasonably balanced. Particularly in the context of employing renewable PG as the main fuel, the study helps to build more sustainable and efficient dual-fuel engine technologies by bridging this gap.

2. Materials and methods

2.1. Biomass gasification

Mangifera indica wood was employed in this study to create ecologically friendly gaseous fuel in a downdraft gasifier. Under controlled conditions, the process known as gasification thermochemically converts organic material into a flammable gas mixture (Hoang *et al.*, 2022). By use of gasification, Mangifera indica wood, and other biomass resources may be converted into producing gas (Nguyen *et al.*, 2024). In a downdraft gasifier, biomass passes through many stages, among these phases are drying, oxidation, reduction, and pyrolysis. Pyrolysis is the process of heating biomass in the absence of oxygen to break it down into volatile gasses, tar, and char (Akubo *et al.*, 2019; Alawa & Chakma, 2023; Fahmy *et al.*, 2020). After this, in the oxidation zone, the volatile gases mix with the air to create a high-temperature environment that promotes more chemical reactions. In the reduction zone, at last, the gases become PG, the main components of PG are methane, hydrogen, and carbon monoxide (Omar *et al.*, 2018; Sharma & Bora, 2023).

The use of Mangifera indica wood during this process has many advantages. It also provides conveniently available and renewable fuel, which helps to effectively manage agricultural waste. Furthermore, several uses for the generated PG include the creation of electricity, the supply of heat for industrial processes, and the operation of internal combustion engines. Furthermore, benefits for the environment are provided by using Mangifera indica wood in combination with downdraft gasification. Apart from decreasing dependence on fossil fuels and greenhouse gas emissions, it also helps to establish sustainable energy practices. Further uses for the gasification

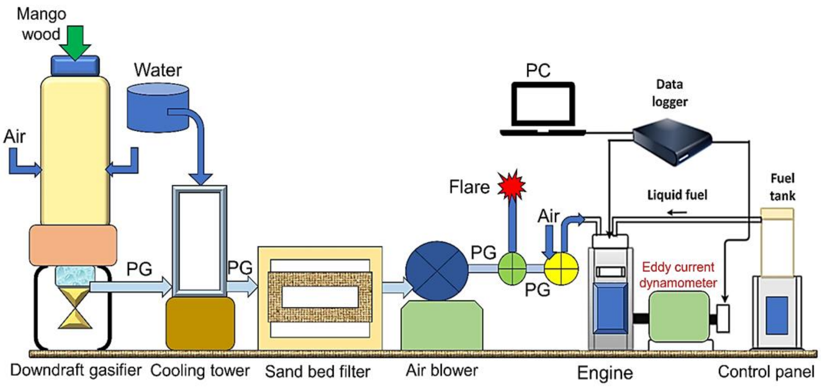

Fig. 1 Downdraft gasifier engine system

byproducts, including biochar, in agriculture include increasing soil fertility and carbon sequestration.

2.2. Test setup

In this study, a diesel engine was converted to work in dual-fuel mode. A 3.5 kW diesel engine was used in the study for this purpose. It was connected with the biomass gasifier with the help of a mixer which facilitates the mixing of PG and air for supply to the engine as fuel. Diesel was used as pilot fuel for igniting the air-PF mixture as it is a low-energy fuel. The biomass gasifier-engine setup is depicted in Figure 1. The specifications of the test setup are listed in Table 1, while the fuel properties of PG and diesel are given in Table 2.

2.3. Response surface technology

It is a highly developed statistical and mathematical technique that is widely used to understand and optimize challenging processes, especially in studies of engine combustion and emission. This method is critical in studies when many factors affect a certain response, including the quantity of pollution an engine produces or the fuel economy (El-Sheekh *et al.*, 2023). To investigate the relationships between these components and their effects on response, RSM constructs trials. Since it makes response measurement possible, this makes it possible to identify the ideal engine performance circumstances (Das & Goud, 2021). The foundation of RSM is the hypothesis that a polynomial equation fitted to the experimental data may provide an approximation model of the actual system. This is the main idea of RSM. Researchers get the chance to evaluate the effect of each variable and their interactions on response when they examine this model (Keshtegar *et al.*, 2018). Usually, a second-order polynomial model is used as it can precisely capture the curvature effects seen in real-world combustion processes. RSM can optimize the air-fuel ratio, ignition timing, and injection pressure while doing research on engine combustion to improve engine efficiency and reduce emissions. By methodically changing these elements, for instance, researchers would be able to produce a response surface. This surface would show how various arrangements of these components impact particulate matter and NOx emissions. As such, it becomes feasible to ascertain the parameters that provide the best performance-to-emissions ratio.

Table 1
Engine specification

Parameter	Specification
Power	3.5 kW
Fuel injection timing	23°bTDC
Fuel injection pressure	210 bar
Cooling	Water cooled
Make	Kirloskar, India
Loading	Eddy Current Dynamometer
Speed	1500 rpm $\pm$ 50 rpm
Fuel injector	Three holes
Temperature sensor	K-type thermocouple
Load sensor	Strain gauge type
Water pump	Monoblock

Table 2
Test fuel specification

Parameter	Diesel	Producer gas (PG)
Cetane	60	-
Density, kg/m^3	833	1.283
Lower heating value, kJ/kg	43350	4850
Fire point, °C	70	-
Viscosity, cst	2.98	-

Scheduling the experiment, running the tests, fitting the model, and verifying its correctness are only a few of the procedures involved. In RSM, two models often used for experimental purposes are the Box-Behnken Design (BBD) and the Central Composite Design. These techniques effectively traverse the experimental space and minimize the number of trials while nevertheless providing enough data to build a workable model. Because RSM not only finds ideal circumstances but also offers details on the combustion process, it is a vital instrument in the area of engine study. When engineers are more aware of the factors that affect emissions, like the kind of fuel, the shape of the combustion chamber, and the recirculation of exhaust gas, they may create cleaner and more efficient engines. Furthermore, interactions between components may be shown by RSM that are often not easily seen by traditional experimental techniques.

2.4. Uncertainty analysis

In the present study, each test was conducted thrice to reduce uncertainty in measurement. The uncertainty analysis primarily estimates possible differences between reference and calibrated data. As such, experiments have been conducted precisely. Still, occasionally error could occur during measurement (Elkelawy, El Shenawy, *et al.*, 2021). The errors usually creep in from human errors or vibrations, and the calibration methods. Summing the squares of each and every parameter obtained during the uncertainty analysis helped one to get a result. Appendix A lists all the specifics related to measuring tools.

Table 3
Design matrix

Control factors (input)			Response variables (output)			
FIP, bar	***CR***	***Load, %***	***BTE, %***	***HC, ppm***	***NOx, ppm***	***CO, ppm***
240	17.5	100	24.33	106	197	100
220	17.5	60	16.84	51	174	110
220	17.5	60	16.84	51	174	110
240	17.5	20	9.68	80	147	118
220	17.5	60	16.84	51	174	110
240	16.5	60	14.34	140	172	137
220	16.5	20	9.46	125	143	138
200	18.5	60	17.54	45	191	103
200	17.5	20	10.11	75	147	118
200	17.5	100	24.7	105	197	101
220	16.5	100	21.84	220	196	141
220	17.5	60	16.84	51	174	110
220	17.5	60	16.84	51	174	110
240	18.5	60	17.14	50	191	101
200	16.5	60	14.54	136	172	139
220	18.5	100	27.35	77	214	85
220	18.5	20	11.64	50	164	115

3. Results and discussion

3.1. Data pre-analysis

The design matrix, as given in Table 3, developed using BBD used in the present study was employed for conducting analysis of variance (ANOVA), modelling, and development of surface diagram followed by optimization. The data was also used for the development of a correlation matrix to comprehend the relationship between the data columns of the design matrix. The correlation heatmap is depicted in Figure 2. Light is cast on the connections between different engine performance and emission parameters, including Fuel Injection Pressure (FIP, bar), Compression Ratio (CR), Load (%), Brake Thermal Efficiency (BTE, %), Hydrocarbon emissions (HC, ppm), Nitrogen Oxides emissions (NOx, ppm), and Carbon Monoxide emissions (CO, ppm), by the supplied correlation matrix.

There is little impact on BTE as shown by the extremely significant negative (-0.02) correlation with it. With an increase in FIP, HC marginally rises, as shown by the very faintly positive (0.03) relationship with it. The correlation with CO is very little negative (-0.03), indicating that CO marginally reduces with rising FIP, but the correlation with NOx is insignificant. The compression ratio, or CR, and load zero are unrelated. But CR and BTE have a little positive correlation (0.23), suggesting that higher CR slightly improves BTE. A strongly negative correlation (-0.74) with HC indicates that raising CR significantly reduces HC emissions. With a slight positive correlation of 0.35, CR increases NOx levels. It is clear from the very negative (-0.84) correlation with CO that raising CR significantly reduces CO emissions (Elkelawy *et al.*, 2018; Elkelawy, Etaiw, *et al.*, 2021).

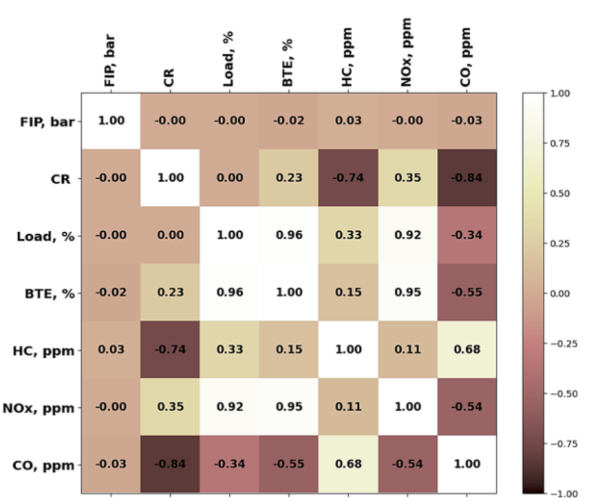

Fig. 2 Correlational heatmap

It is clear from the strong positive correlation between load (%) and BTE (0.96) that raising load greatly improves BTE. Because load and HC have a moderately positive correlation (0.33), higher loads translate into higher HC emissions. As shown by the strong positive correlation (0.92) with NOx, increasing load significantly increases NOx emissions. Because the connection with CO is so negative (-0.34), it seems that a higher load reduces CO emissions. BTE and HC are somewhat positively correlated (0.15), meaning that higher BTE causes HC to rise somewhat. It is clear from the highly positive correlation (0.95) with NOx emissions that higher BTE levels significantly increase NOx emissions. It seems from the relatively negative (-0.55) correlation with CO that higher BTE reduces CO emissions. Increased hydrocarbons (HC) cause a little increase in NOx, as shown by the little positive correlation (0.11) between the two. As the correlation with CO is somewhat positive (0.68), higher HC emissions are associated with higher CO emissions. As the relationship between CO and NOx (Nitrogen Oxides) is somewhat negative (-0.54), it seems that higher NOx emissions result in lower CO emissions (Singh *et al.*, 2021; Sridhar *et al.*, 2005).

This matrix is a helpful tool for analyzing and maximizing the trade-offs between emissions and engine performance, which drives modifications in engine design and operating conditions to achieve the intended outcomes. As is consistent with established combustion dynamics, CR has a significant impact on emission characteristics, specifically reducing HC and CO emissions while boosting NOx emissions. Since load is strongly correlated with both BTE and NOx emissions, higher engine loads both increase efficiency and raise NOx emissions. Efficiency and NOx production are traded off as shown by the positive correlation of BTE with NOx emissions and the negative correlation with CO emissions. FIP's low effect on the measured parameters suggests that other factors are more important in determining engine performance and emissions.

3.2. Analysis of variance

The ANOVA was conducted for the design matrix data. The results are listed in Table 4. The effects of many factors on engine performance and emissions were ascertained using an ANOVA on the design matrix data; the results are shown in Table 4. Indeed, BTE, HC, NOx, and CO are among the sources

Table 4
Results of ANOVA for design matrix data

	BTE, %		HC, ppm		NOx, ppm		CO, ppm	
Source	Value (F)	p-value	Value (F)	p-value	Value (F)	p-value	Value (F)	p-value
Model	558.4508	< 0.0001	178.5483	< 0.0001	3818.569	< 0.0001	206.5056	< 0.0001
F	2.780367	0.1394	1.617043	0.2441	0	1	1.434426	0.27
C	258.1487	< 0.0001	952.23	< 0.0001	4150.3	< 0.0001	1308.254	< 0.0001
L	4662.405	< 0.0001	146.9641	< 0.0001	28846.3	< 0.0001	220.5574	< 0.0001
FC	0.113484	0.7461	0.014374	0.9079	0	1	0	1
FL	0.010214	0.9223	0.229979	0.6462	0	1	0.114754	0.7447
CL	31.46042	0.0008	15.65298	0.0055	12.6	0.0093	124.9672	< 0.0001
F^2	20.73546	0.0026	34.86005	0.0006	0.368421	0.563	0.120794	0.7384
C^2	4.053259	0.084	214.2592	< 0.0001	1282.474	< 0.0001	203.0544	< 0.0001
L^2	50.07954	0.0002	196.6324	< 0.0001	106.4737	< 0.0001	0.483175	0.5094

F denotes Fuel injection pressure, C denotes compression ratio, and L denotes engine load

of variation for which this table provides the F-values and p-values. The extremely high F-values of the entire model for BTE (558.4508), HC (178.5483), NOx (3818.569), and CO (206.5056) indicate that the models are very significant and that the variables examined have a substantial impact on the responses. The FIP values for BTE are 2.780367, HC is 1.617043, NOx is 0 and CO is 1.434426, with matching p-values of 0.1394, 0.2441, 1, and 0.27, respectively. These results show that these response variables are unaffected statistically by fuel injection pressure.

With F-values of 258.1487 for BTE, 952.23 for HC, 4150.3 for NOx, and 1308.254 for CO, all with p-values < 0.0001, compression ratio, or C, has a highly substantial impact on all response variables. Accordingly, engine performance and emissions are significantly influenced by the compression ratio. With F-values of 4662.405 for BTE, 146.9641 for HC, 28846.3 for NOx, and 220.5574 for CO - all with p-values less than 0.0001, engine load (L) also had a substantial impact. Relevant interaction terms include Compression Ratio and Load (CL), FIP and CR, and both. CL interacts particularly significantly for BTE (F-value 31.46042, p-value 0.0008), HC (F-value 15.65298, p-value 0.0055), NOx (F-value 12.6, p-value 0.0093), and CO (F-value 124.9672, p-value < 0.0001). This implies that these two factors acting together have a substantial impact on the response variables.

Non-linear relationships are shown by the significant consequences quadratic factors like F^2 (Fuel Injection Pressure squared) and C^2 (Compression Ratio squared) have in many situations, particularly for HC and NOx emissions. Significant effects of C^2 are shown, for instance, on HC (F-value 214.2592, p-value < 0.0001), NOx (F-value 1282.474, p-value < 0.0001), and CO (F-value 203.0544, p-value < 0.0001). The ANOVA results demonstrate overall that engine load and compression ratio are significant variables that affect engine performance and emissions, even if fuel injection pressure may not be a significant one. Complementary optimization strategies are required because of the complexity and nonlinearity of the combustion process, which is highlighted by the interactions and quadratic components.

3.3. Model development and analysis

The ANOVA was employed for the development of mathematical models for each parameter as given in the following Eq. (1) to Eq. (4). These models were used for making predictions and estimating residuals for each run as shown in Figure 3(a&b), respectively for BTE. The comparison of measured and model predicted HC values are depicted in Figure 3c while the model residuals are shown in Figure 3d, for HC emission. Similarly, the measured and model forecasted values of NOx emission are shown in Figure 3f and model residuals are shown in Figure 3f. The CO emission actual values and model predicted values are compared in Figure 3g for CO emission, while the model residuals are shown in Figure 3h. It can be observed that all models were robust enough for efficient use in this process.

$$BTE = -175.62 + 0.76\times FIP + 11.18\times CR - 0.27\times Load - 0.0025\times FIP\times CR + 0.0000187\times FIP\times Load + 0.021\times CR\times Load - 0.0016\times FIP^2 - 0.29\times CR^2 + 0.00064\times Load^2 \quad (1)$$

$$HC = 11241.94 - 13.25\times FIP - 1077.12\times CR + 2.19\times Load + 0.0125\times FIP\times CR - 0.00125\times FIP\times Load - 0.21\times CR\times Load + 0.03\times FIP^2 + 29.75\times CR^2 + 0.0178\times Load^2 \quad (2)$$

$$NOx = 2216.75 - 0.138\times FIP - 247.38\times CR + 1.122\times Load - 0.019\times CR\times Load + 0.0003\times FIP^2 + 7.38\times CR^2 - 0.0013\times Load^2 \quad (3)$$

$$CO = 3345.81 + 0.26\times FIP - 365.25\times CR + 3.52\times Load - 0.0003\times FIP\times Load - 0.21\times CR\times Load - 0.000625\times FIP^2 + 10.25\times CR^2 - 0.0003\times Load^2 \quad (4)$$

3.4. Response surfaces and parametric influence

The 3-D response surface diagrams as depicted in Figure 4, are useful tools to comprehend the influence of control factors on response variables. It is a fact that single factor time plots do not depict the influence of multiple control factors in a multi-factor environment as in the case of dual-fuel engines. The surface diagrams for BTE are depicted in Figure 4 (a&b).

It is seen that engine load has the largest influence over BTE, followed by CR, while the FIP has the least impact on BTE. The highest BTE is observed in that zone of full load, 18.5 CR, and 220 bar FIP. In the case of the HC emission model, the surface diagrams are depicted in Figure 4 (c&d). In this case, it was observed that CO emission was higher at low load and decreased at mid-range and then again at higher engine load, and a higher supply of PG led to a spike in CO emission. Similarly, at low CR the HC emission was higher which reduced at higher CR (Yaliwal *et al.*, 2014).

On the other hand, the NOx emission response surfaces, shown in Figure 4 (e&f), depict that engine load is the main factor influencing the NOx emission. The influence of CR was

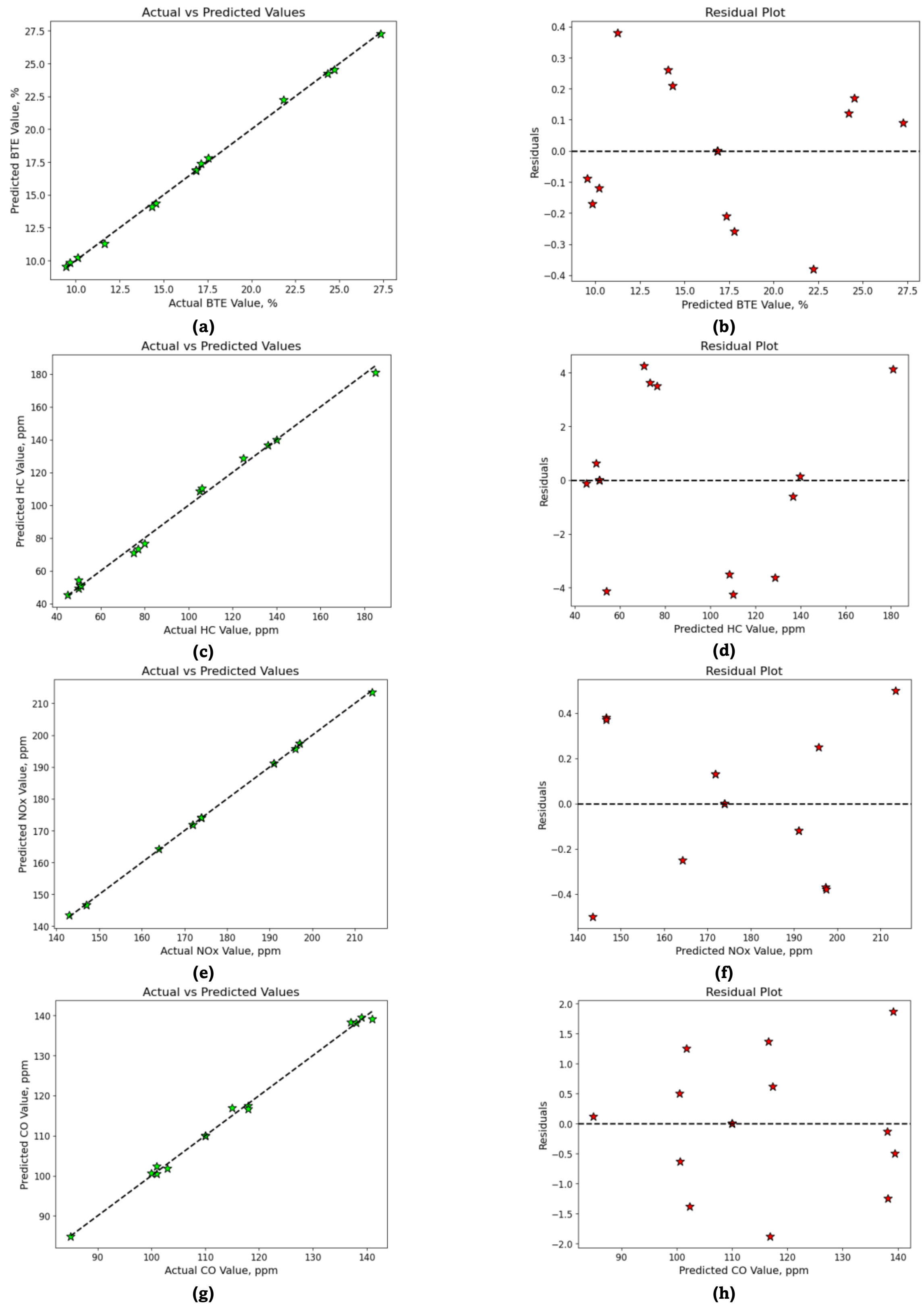

Fig. 3 (a) BTE actual vs predicted model; (b) BTE model residuals; (c) HC actual vs predicted model; (d) HC model residuals; (e) NOx actual vs predicted model; (f) NOx model residuals; (g) CO actual vs predicted model; (h) CO model residuals

also noteworthy, however the FIP could not influence the NOx emission much. The lowest NOx emission was observed in the zone of 20% engine load, 16.5 CR, and 200 bar FIP. In the case of CO emission model, as depicted in Figure 4 (g&h), the lowest CO emission was observed at full engine load and CR of 18.

3.5. Desirability-based parametric optimization

The previous section demonstrated that engine load has the most influence on emissions and engine performance. This effect is evident in many different parameters; however, it has both positive and bad effects, so an optimization plan is

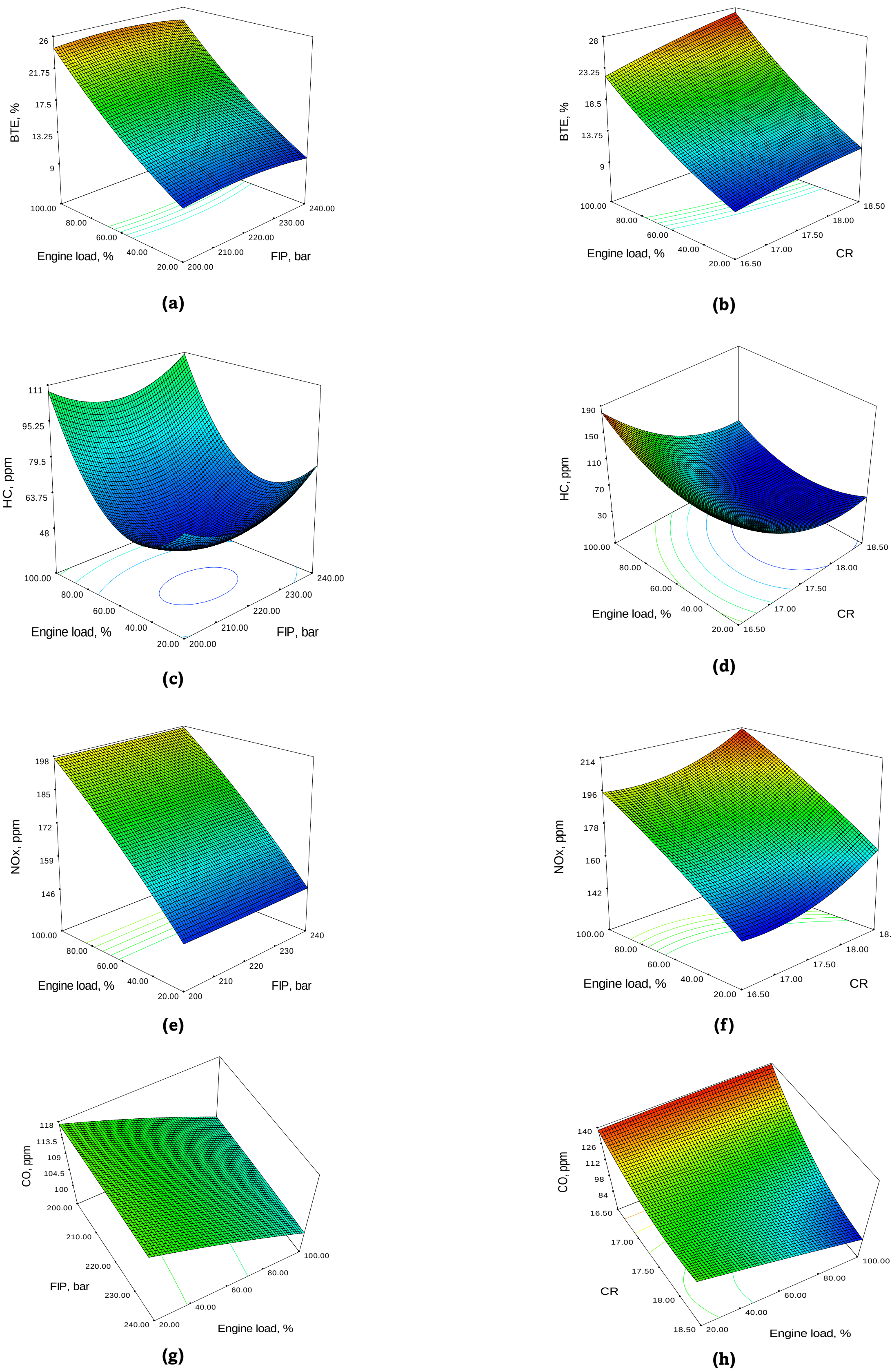

Fig. 4 (a) BTE model's response diagrams engine load vs FIP; (b) BTE model's response diagrams engine load vs CR; (c) HC model's response diagrams engine load vs FIP; (d) HC model's response diagrams engine load vs CR; (e) NOx model's response diagrams engine load vs FIP; (f) NOx model's response diagrams engine load vs CR; (g) CO model's response diagrams engine load vs FIP; (h) CO model's response diagrams engine load vs CR;

necessary to balance the outcomes. For this goal, the desirability approach seems to be a good fit. One may simplify the optimization process by combining many responses into a single composite score using the desirability function (Padilla-

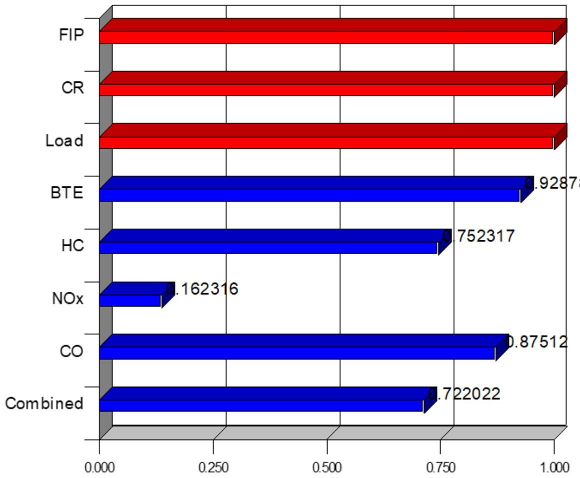

Fig. 5 Desirability bar plot

Atondo *et al.*, 2021; Vera Candioti *et al.*, 2014). This approach assesses the trade-offs between several performance and emission metrics, therefore enabling the choice of optimal operating conditions that satisfy the required criteria. The desirability approach may be used to optimize the engine load to get a balanced rise in engine performance and emission control, therefore raising overall efficiency and environmental compliance. The Design-Expert commercial software was employed for optimization. The developed desirability plots are shown in Figure 5.

It was noted in the previous part that the engine load has the most impact on emissions and engine performance. This impact is noticeable for several factors, but it is also positive and negative, hence an optimization strategy is required to balance these results. For this reason, the desirability strategy seems to be a desirable choice. Simplifying the optimization process, one may combine many answers into a single composite score by using the desirability function. This method enables the finding of ideal operating conditions that meet the required requirements by considering the trade-offs between various performance and emission indicators. The optimal parameter values for improving engine performance and reducing emissions are shown by the desirability-based optimization results in Table 5.

In the measured range of 200 to 240 bar, the ideal FIP value is 218.5 bar, suggesting that a rather high injection pressure is advantageous for reaching the required balance between performance and emissions. The higher compression ratio adds favourably to the optimization requirements, perhaps increasing combustion efficiency and lowering certain emissions. The optimal CR is 17.9, near the top limit of the measured range (16.5 to 18.5). Although it must be carefully controlled because of its major influence on emissions and performance, running the engine at full load is advantageous for achieving the overall optimization objectives since the engine load is optimized at the greatest level tested, 100%. The success of the optimization in raising engine performance is shown by the 26.08% optimized BTE, which is near the highest measured efficiency (27.35%). Significantly below the top limit of 185 ppm, the optimized HC emission level of 80 ppm indicates a successful optimization in reducing unburned hydrocarbons, which helps to improve emission control. In the upper end of the measured range (143 to 214 ppm), the NOx emissions are optimal at 202 ppm. Even if this suggests a trade-off, it also shows how important it is to balance NOx emissions with other performance criteria. Lowering the top limit of 141 ppm, the optimized CO emission level of 92 ppm shows how well the optimization reduced CO emissions, which are essential for achieving environmental criteria.

Table 5
Optimized control factors and response

Parameter	Lower level	Higher level	Optimized value
FIP	200 bar	240 bar	218.5 bar
CR	16.5	18.5	17.9
Load	20%	100%	100%
BTE	9.46%	27.35%	26.08%
HC	45 ppm	185 ppm	80 ppm
NOx	143 ppm	214 ppm	202 ppm
CO	85 ppm	141 ppm	92 ppm

4. Conclusion

In the present study, PG was used as fuel in diesel engines through dual-fuel technology. Diesel fuel was utilized as pilot fuel and a waste biomass-derived PG was used as primary fuel. A computational framework to establish a link between adjustable engine parameters and the dependent response variables was employed. Controllable factors were engine load, pilot fuel injection pressure, and compression ratio. Response variables were chosen to be BTE and exhaust emission. It was observed that engine load was the main influencing factor and had positive effects on BTE and a negative influence on NOx emission. The highest BTE was observed in the full load zone, 18.5 CR, and 220 bar FIP. Higher CO emission was observed at lower load, it decreased at mid-range, and again at higher engine load. Higher PG supply spikes CO emissions. The lowest CO emission at full engine load and 18.5 CR. At low CR, HC emission is higher at low load, and it tends to reduce at higher CR. Engine load is the main factor influencing NOx emission. FIP has minimal influence on NOx emission. Desirability-led optimization revealed the ideal FIP value as 218.5 bar for balance between performance and emissions. The optimized value of CR was 17.9, near the top limit of the range, and full engine load. At the optimized settings, the engine BTE was 27.35%, the optimized HC emission level was 80 ppm, the optimized NOx emissions were 202 ppm, and the optimized CO emission was 92 ppm. The future scope of the study includes investigation of co-gasification with low grade coal.

Nomenclature

ANOVA	Analysis of variance
BBD	Box-Behnken Design
BTE	Brake thermal efficiency
CO	Carbon monoxide
CR	Compression Ratio
FIT	Fuel injection pressure
HC	Hydrocarbon
NOx	Nitrogen oxide
RSM	Response Surface Methodology
PG	Producer gas
PM	Particulate matter
SDG	Sustainable Development Goal

References

Akkoli, K. M., Banapurmath, N. R., Shivashimpi, M. M., Soudagar, M. E. M., Badruddin, I. A., Alazwari, M. A., Yaliwal, V. S., Mujtaba, M. A., Akram, N., Goodarzi, M., Safaei, M. R., & Venu, H. (2021). Effect of injection parameters and producer gas derived from redgram stalk on the performance and emission characteristics of a diesel engine. *Alexandria Engineering Journal*, *60*(3), 3133–3142. https://doi.org/10.1016/j.aej.2021.01.047

Akubo, K., Nahil, M. A., & Williams, P. T. (2019). Pyrolysis-catalytic steam reforming of agricultural biomass wastes and biomass components for production of hydrogen/syngas. *Journal of the Energy Institute*, *92*(6), 1987–1996. https://doi.org/10.1016/j.joei.2018.10.013

Alawa, B., & Chakma, S. (2023). Experimental Investigation in Compression Ratio on Performance, Combustion and Emission of VCR Engine using Pyrolysis-oil Produced from Waste Plastic Materials. *Materials Today: Proceedings*, *72*, 2593–2609. https://doi.org/10.1016/j.matpr.2022.07.228

Alruqi, M., Sharma, P., & Ağbulut, Ü. (2023). Investigations on biomass gasification derived producer gas and algal biodiesel to power a dual-fuel engines: Application of neural networks optimized with Bayesian approach and K-cross fold. *Energy*, *282*, 128336. https://doi.org/10.1016/j.energy.2023.128336

Barid, A. J., & Hadiyanto, H. (2024). Hyperparameter optimization for hourly PM2.5 pollutant prediction. *Journal of Emerging Science and Engineering*, *2*(1), e15. https://doi.org/10.61435/jese.2024.e15

Cao, D. N., Hoang, A. T., Luu, H. Q., Bui, V. G., & Tran, T. T. H. (2020). Effects of injection pressure on the NOx and PM emission control of diesel engine: A review under the aspect of PCCI combustion condition. *Energy Sources, Part A: Recovery, Utilization, and Environmental Effects*, 1–18. https://doi.org/10.1080/15567036.2020.1754531

Cao, D. N., & Johnson, A. J. T. (2024). A Simulation Study on a Premixed-charge Compression Ignition Mode-based Engine Using a Blend of Biodiesel/Diesel Fuel under a Split Injection Strategy. *International Journal on Advanced Science, Engineering and Information Technology*, *14*(2), 451–471. https://doi.org/10.18517/ijaseit.14.2.20007

Dabi, M., & Saha, U. K. (2016). Experimental Analysis of a Dual-Fuel Engine Fueled by Producer Gas Derived From Pine Leaves and Cattle Dung Briquettes. *ASME 2015 Gas Turbine India Conference, GTINDIA 2015*. https://doi.org/10.1115/GTINDIA2015-1263

Das, S., & Goud, V. V. (2021). RSM-optimised slow pyrolysis of rice husk for bio-oil production and its upgradation. *Energy*, *225*, 120161. https://doi.org/10.1016/j.energy.2021.120161

Dhahad, H. A., Chaichan, M. T., & Megaritis, T. (2019). Performance, regulated and unregulated exhaust emission of a stationary compression ignition engine fueled by water-ULSD emulsion. *Energy*, *181*, 1036–1050. https://doi.org/10.1016/J.ENERGY.2019.05.200

El-Sheekh, M. M., Bedaiwy, M. Y., El-Nagar, A. A., ElKelawy, M., & Alm-Eldin Bastawissi, H. (2022). Ethanol biofuel production and characteristics optimization from wheat straw hydrolysate: Performance and emission study of DI-diesel engine fueled with diesel/biodiesel/ethanol blends. *Renewable Energy*, *191*, 591–607. https://doi.org/10.1016/J.RENENE.2022.04.076

El-Sheekh, M. M., El-Nagar, A. A., ElKelawy, M., & Bastawissi, H. A. E. (2023). Maximization of bioethanol productivity from wheat straw, performance and emission analysis of diesel engine running with a triple fuel blend through response surface methodology. *Renewable Energy*, *211*, 706–722. https://doi.org/10.1016/J.RENENE.2023.04.145

Elkelawy, M., Bastawissi, H., Sathyamurthy, R., Chandra Sekar, S., Karuppasamy, K., Vedaraman, N., & Sathiyamoorthy, K. (2018). Numerical and Experimental Investigation of Ethyl Alcohol as Oxygenator on the Combustion, Performance, and Emission Characteristics of Diesel/Cotton Seed Oil Blends in Homogenous Charge Compression Ignition Engine. *SAE Technical Papers*, *2018-Septe*(September). https://doi.org/10.4271/2018-01-1680

Elkelawy, M., El Shenawy, E. A., Almonem, S. khalaf A., Nasef, M. H., Panchal, H., Bastawissi, H. A.-E., Sadasivuni, K. K., Choudhary, A. K., Sharma, D., & Khalid, M. (2021). Experimental study on combustion, performance, and emission behaviours of diesel /WCO biodiesel/Cyclohexane blends in DI-CI engine. *Process Safety and Environmental Protection*, *149*, 684–697. https://doi.org/10.1016/j.psep.2021.03.028

Elkelawy, M., Etaiw, S. E. din H., Alm-Eldin Bastawissi, H., Ayad, M. I., Radwan, A. M., & Dawood, M. M. (2021). Diesel/ biodiesel /silver thiocyanate nanoparticles/hydrogen peroxide blends as new fuel for enhancement of performance, combustion, and Emission characteristics of a diesel engine. *Energy*, *216*, 119284. https://doi.org/10.1016/J.ENERGY.2020.119284

Fahmy, T. Y. A., Fahmy, Y., Mobarak, F., El-Sakhawy, M., & Abou-Zeid, R. E. (2020). Biomass pyrolysis: past, present, and future. *Environment, Development and Sustainability*, *22*(1), 17–32. https://doi.org/10.1007/s10668-018-0200-5

Goyal, D., Goyal, T., Mahla, S. K., Goga, G., Dhir, A., Balasubramanian, D., Hoang, A. T., Wae-Hayee, M., Josephin, J. S. F., Sonthalia, A., Varuvel, E. G., & Brindhadevi, K. (2023). Application of Taguchi design in optimization of performance and emissions characteristics of n-butanol/diesel/biogas under dual fuel mode. *Fuel*, *338*, 127246. https://doi.org/10.1016/j.fuel.2022.127246

Grimshaw, D., & Kühn, S. (2019). 3 Sustainable Development Goal 8. *World Employment and Social Outlook*, *2019*(1), 57–72. https://doi.org/10.1002/wow3.152

Halewadimath, S.S., Banapurmath, N. R., Yaliwal, V. S., Prasad, M. G., Jalihal, S. S., Soudagar, M. E. M., Yaqoob, H., Mujtaba, M. A., Shahapurkar, K., & Safaei, M. R. (2022). Effect of manifold injection of hydrogen gas in producer gas and neem biodiesel fueled CRDI dual fuel engine. *International Journal of Hydrogen Energy*, *47*(62), 25913–25928. https://doi.org/10.1016/j.ijhydene.2022.02.135

Halewadimath, Sushrut S., Banapurmath, N. R., Yaliwal, V. S., Gaitonde, V. N., Khan, T. M. Y., Vadlamudi, C., Krishnappa, S., & Sajjan, A. M. (2023). Experimental Investigations on Dual-Fuel Engine Fueled with Tertiary Renewable Fuel Combinations of Biodiesel and Producer—Hydrogen Gas Using Response Surface Methodology. *Sustainability*, *15*(5), 4483. https://doi.org/10.3390/su15054483

Hebbar, G. S. (2014). NOx from diesel engine emission and control strategis-A review. *Int. J. Mech. Eng. & Rob. Res.*, 3(4), 473-482 https://www.ijmerr.com/uploadfile/2015/0409/20150409042911754.pdf

Hoang, A. T., Huang, Z., Nižetić, S., Pandey, A., Nguyen, X. P., Luque, R., Ong, H. C., Said, Z., Le, T. H., & Pham, V. V. (2022). Characteristics of hydrogen production from steam gasification of plant-originated lignocellulosic biomass and its prospects in Vietnam. *International Journal of Hydrogen Energy*, *47*(7), 4394–4425. https://doi.org/10.1016/j.ijhydene.2021.11.091

Hoang, A. T., Pandey, A., Martinez De Osés, F. J., Chen, W.-H., Said, Z., Ng, K. H., Ağbulut, Ü., Tarełko, W., Ölçer, A. I., & Nguyen, X. P. (2023). Technological solutions for boosting hydrogen role in decarbonization strategies and net-zero goals of world shipping: Challenges and perspectives. *Renewable and Sustainable Energy Reviews*, *188*, 113790. https://doi.org/10.1016/j.rser.2023.113790

Kan, X., Wei, L., Li, X., Li, H., Zhou, D., Yang, W., & Wang, C.-H. (2020). Effects of the three dual-fuel strategies on performance and emissions of a biodiesel engine. *Applied Energy*, *262*, 114542. https://doi.org/10.1016/j.apenergy.2020.114542

Kashyap, D., Das, S., & Kalita, P. (2021). Exploring the efficiency and pollutant emission of a dual fuel CI engine using biodiesel and producer gas: An optimization approach using response surface methodology. *Science of the Total Environment*, *773*(February), 145633. https://doi.org/10.1016/j.scitotenv.2021.145633

Keshtegar, B., Mert, C., & Kisi, O. (2018). Comparison of four heuristic regression techniques in solar radiation modeling: Kriging method vs RSM, MARS and M5 model tree. *Renewable and Sustainable Energy Reviews*, *81*, 330–341. https://doi.org/10.1016/j.rser.2017.07.054

Le, T. T., Sharma, P., Le, H. C., Le, H. S., Osman, S. M., Truong, T. H., Le, D. T. N., Rowinski, L., & Tran, V. D. (2024). A glass-box approach for predictive modeling based on experimental data for a waste biomass derived producer gas-powered dual-fuel engine. *International Journal of Hydrogen Energy*, *58*, 1122–1137. https://doi.org/10.1016/j.ijhydene.2024.01.284

Liu, J., Zhao, W., Zhang, X., Ji, Q., Ma, H., Sun, P., & Wang, P. (2024). Optimizing combustion and emissions in natural gas/diesel dual-fuel engine with pilot injection strategy. *Thermal Science and Engineering Progress*, *48*, 102418. https://doi.org/10.1016/j.tsep.2024.102418

Nayak, B., Singh, T. J., & Hoang, A. T. (2021). Experimental analysis of performance and emission of a turbocharged diesel engine operated in dual-fuel mode fueled with bamboo leaf-generated gaseous and waste palm oil biodiesel/diesel fuel blends. *Energy Sources, Part A: Recovery, Utilization, and Environmental Effects*, 1–19. https://doi.org/10.1080/15567036.2021.2009595

Nayak, S. K., Nižetić, S., Pham, V. V., Huang, Z., Ölçer, A. I., Bui, V. G., Wattanavichien, K., & Hoang, A. T. (2022). Influence of injection timing on performance and combustion characteristics of compression ignition engine working on quaternary blends of diesel fuel, mixed biodiesel, and t-butyl peroxide. *Journal of Cleaner Production*, *333*, 130160. https://doi.org/10.1016/j.jclepro.2021.130160

Nguyen, V. G., Tran, M. H., Paramasivam, P., Le, H. C., & Nguyen, D. T. (2024). Biomass: A Versatile Resource for Biofuel, Industrial, and Environmental Solution. *International Journal on Advanced Science, Engineering and Information Technology*, *14*(1 SE-Articles), 268–286. https://doi.org/10.18517/ijaseit.14.1.17489

Omar, M. M., Munir, A., Ahmad, M., & Tanveer, A. (2018). Downdraft gasifier structure and process improvement for high quality and quantity producer gas production. *Journal of the Energy Institute*, *91*(6), 1034–1044. https://doi.org/10.1016/j.joei.2017.07.005

Padilla-Atondo, J. M., Limon-Romero, J., Perez-Sanchez, A., Tlapa, D., Baez-Lopez, Y., Puente, C., & Ontiveros, S. (2021). The Impact of Hydrogen on a Stationary Gasoline-Based Engine through Multi-Response Optimization: A Desirability Function Approach. *Sustainability*, *13*(3), 1385. https://doi.org/10.3390/su13031385

Paramasivama, P., Naima, K., & Dzida, M. (2024). Soft computing-based modelling and optimization of NOx emission from a variable compression ratio diesel engine. *Journal of Emerging Science and Engineering*, *2*(2), e21. https://doi.org/10.61435/jese.2024.e21

Percy, A. J., & Edwin, M. (2023). Studies on the performance and emission characteristics of a dual fuel VCR engine using producer gas as secondary fuel: An optimization approach using response surface methodology. *Energy*, *263*, 125685. https://doi.org/10.1016/j.energy.2022.125685

Raj, R., Kumar Singh, D., & Vachan Tirkey, J. (2023). Performance simulation and optimization of SI engine fueled with peach biomass-based producer gas and propane blend. *Thermal Science and Engineering Progress*, *41*, 101816. https://doi.org/10.1016/j.tsep.2023.101816

Razzaq, I., Amjad, M., Qamar, A., Asim, M., Ishfaq, K., Razzaq, A., & Mawra, K. (2023). Reduction in energy consumption and CO2 emissions by retrofitting an existing building to a net zero energy building for the implementation of SDGs 7 and 13. *Frontiers in Environmental Science*, *10*. https://doi.org/10.3389/fenvs.2022.1028793

Riediker, M., Zink, D., Kreyling, W., Oberdörster, G., Elder, A., Graham, U., Lynch, I., Duschl, A., Ichihara, G., Ichihara, S., Kobayashi, T., Hisanaga, N., Umezawa, M., Cheng, T.-J., Handy, R., Gulumian, M., Tinkle, S., & Cassee, F. (2019). Particle toxicology and health - where are we? *Particle and Fibre Toxicology*, *16*(1), 19. https://doi.org/10.1186/s12989-019-0302-8

Serbin, S., Diasamidze, B., Dzida, M., & Chen, D. (2023). Investigation of the Efficiency of a Dual-Fuel Gas Turbine Combustion Chamber with a Plasma–Chemical Element. *Polish Maritime Research*, *30*(2), 68–75. https://doi.org/10.2478/pomr-2023-0022

Serbin, S., Diasamidze, B., Gorbov, V., & Kowalski, J. (2021). Investigations of the Emission Characteristics of a Dual-Fuel Gas Turbine Combustion Chamber Operating Simultaneously on Liquid and Gaseous Fuels. *Polish Maritime Research*, *28*(2), 85–95. https://doi.org/10.2478/pomr-2021-0025

Shaafi, T., Sairam, K., Gopinath, A., Kumaresan, G., & Velraj, R. (2015). Effect of dispersion of various nanoadditives on the performance and emission characteristics of a CI engine fuelled with diesel, biodiesel and blends—a review. *Renewable and Sustainable Energy Reviews*, *49*, 563–573. https://doi.org/10.1016/j.rser.2015.04.086

Shammas, N. K., Wang, L. K., & Wang, M.-H. S. (2020). *Sources, Chemistry and Control of Acid Rain in the Environment* (pp. 1–26). https://doi.org/10.1142/9789811207136_0001

Sharma, P., & Bora, B. J. (2023). Modeling and optimization of a CI engine running on producer gas fortified with oxyhydrogen. *Energy*, *270*, 126909. https://doi.org/10.1016/j.energy.2023.126909

Sharma, P., Sahoo, B. B., Said, Z., Hadiyanto, H., Nguyen, X. P., Nižetić, S., Huang, Z., Hoang, A. T., & Li, C. (2023). Application of machine learning and Box-Behnken design in optimizing engine characteristics operated with a dual-fuel mode of algal biodiesel and waste-derived biogas. *International Journal of Hydrogen Energy*, *48*(18), 6738–6760. https://doi.org/10.1016/j.ijhydene.2022.04.152

Singh, P., Kumar, R., Sharma, S., & Kumar, S. (2021). Effect of engine parameters on the performance of dual-fuel CI engines with producer gas—a review. *Energy & Fuels*, *35*(20), 16377–16402. https://doi.org/10.1021/acs.energyfuels.1c02279

Skaug Saetra, H., Wynsberghe, van, Bolte, L., & Nachid, J. (2021). A Framework for Evaluating and Disclosing the ESG Related Impacts of AI with the SDGs. *Sustainability 2021, Vol. 13, Page 8503*, *13*(15), 8503. https://doi.org/10.3390/SU13158503

Sorathia, H. S., & Yadav, H. J. (2012). Energy analyses to a ci-engine using diesel and bio-gas dual fuel—a review study. *World*, *1*(5).

Sridhar, G., Dasappa, S., Sridhar, H. V., Paul, P. J., & Rajan, N. K. S. (2005, April). *Gaseous Emissions Using Producer Gas as Fuel in Reciprocating Engines*. https://doi.org/10.4271/2005-01-1732

Vera Candioti, L., De Zan, M. M., Cámara, M. S., & Goicoechea, H. C. (2014). Experimental design and multiple response optimization. Using the desirability function in analytical methods development. *Talanta*, *124*, 123–138. https://doi.org/10.1016/j.talanta.2014.01.034

Wagemakers, A. M. L. M., Leermakers, C. A. J., Wagemakers, A. M. L. M., & Leermakers, C. A. J. (2012). Review on the Effects of Dual-Fuel Operation, Using Diesel and Gaseous Fuels, on Emissions and Performance. *SAE Technical Papers*. https://doi.org/10.4271/2012-01-0869

Yaliwal, V. S., Nataraja, K. M., Banapurmath, N. R., & Tewari, P. G. (2014). Honge oil methyl ester and producer gas-fuelled dual-fuel engine operated with varying compression ratios. *International Journal of Sustainable Engineering*, *7*(4), 330–340. https://doi.org/10.1080/19397038.2013.837108

Yu, M., Kubiczek, J., Ding, K., Jahanzeb, A., & Iqbal, N. (2022). Revisiting SDG-7 under energy efficiency vision 2050: the role of new economic models and mass digitalization in OECD. *Energy Efficiency*, *15*(1), 2. https://doi.org/10.1007/s12053-021-10010-z

Appendix A

Accuracy of measuring apparatus and instruments

Parameter	Measuring instrument	Accuracy
Gas flow meter	Thermal type	+ 0.2 lpm
Engine load	Load cell (Staring gauge)	+ 0.1
Flow rate of diesel	Burette	0.2 mL
Temperature	Thermocouple	0.1 °C
Crank angle	Encoder optical type	0.5 °CA
Flow rate of air	Orifice meter	0.000006 m^3/s
In-cylinder pressure	Pressure sensor piezo electric type	33 pC/Bar
Emission NOx, CO, HC	Exhaust gas analyser	2%
BTE	Calculated	0.5%