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RESEARCH ARTICLE

Optimization of Noise Emission Level in Diesel Engine with Biodiesel Application Using Response Surface Methodology

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ABSTRACT – This study used biodiesel to run a single-cylinder direct-injection diesel engine. The palm oil methyl ester is blended in different ratios of up to 20% and tested with different engine speeds and loads for noise level measurement. Mathematical modeling was then developed to correlate responses obtained by the noise levels of the engine components to the factors, including engine speed, engine load, and biodiesel blending percentage. Finally, using the developed models, all the numeric factors were optimized. Modeling results indicated that the significance of factors could vary for the engine components, whereas in this study, the intake phase-related factors showed the significance of all factors. Meanwhile, the optimization results highlighted that the best solution with the highest desirability number to satisfy all the responses was the B20 fuel blend (20% biodiesel fuel and 80% diesel fuel blend by volume) with 1200 rpm of engine speed. In conclusion, the study's outcomes revealed that optimization should be considered in developing a new policy for using biofuel in internal combustion engines.

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1. INTRODUCTION

According to current predictions, energy needs are expected to rise by 50%. As developing countries increasingly use diesel for internal combustion engines (ICE), it has grown to be the second-largest energy source in the transportation sector. Diesel now accounts for nearly one-third of global energy production [1]. To address the scarcity of fossil fuels and the substantial exhaust emissions of ICE, ecologically friendly alternative fuels are being developed to satisfy the increasing global energy demands while simultaneously reducing dependence on fossil fuels and mitigating environmental pollution in comparison to conventional fuel sources [2], [3]. For these reasons, studies into the practice of using renewable energy sources, in particular, oxygenated biofuel/biodiesel as a substitute for diesel, have been intensified to a great extent [4]. Primary biofuels refer to those fuels that are incorporated directly into conventional diesel without the need for additional processing. These biofuels offer a substantial cost advantage in various aspects, including production, initial capital investment, and transportation logistics [5].

Despite the excellent power density, high thermal efficiency, high dependability, durability, low fuel consumption, and specific cost [6], diesel engines generate higher noise levels due to the piston slap [7]. Due to the fixed position of the engine on the vehicle frame and its higher compression ratio—owing to the rougher combustion process and higher structural dynamics of the engine—the vibration of the vehicle body is noted to be greater than with a petrol engine [8]. This has contributed a lot to the noise generation in the engine. Interestingly, it is said that biodiesel-diesel blends can reduce those vibrations because of the smooth combustion process. However, the change may progress with greater compression ratios due to increased cylinder pressure [9]. With the substantial advantages of employing these fuels, which are renewable, easily accessible, and can be obtained from many feedstocks of edible and non-edible oil categories [10], the researchers' efforts to lessen the noise and vibration produced by the engine were therefore strengthened.

A few years back, Ağbulut et al. [11] conducted an experimental investigation to assess the noise properties of a compression ignition engine operating on waste cooking oil methyl ester supplemented with metal-oxide-based nanoparticles. They noticed that the maximum noise value was measured for B10 fuel at all engine loads. In general, it was observed that as the engine load increased, the corresponding noise levels also exhibited a rise. This correlation can be attributed to the increasing maximum heat release rate (HRRmax) and maximum combustion pressure (CPmax). However, it is noteworthy that a decrease in noise levels was recorded specifically at the engine load of 10 Nm. In a different study, Sarıdemir and Ağbulut [12] tested the cottonseed methyl ester as an alternative fuel at a constant engine speed of 1500 rpm and under other engine loads. It can be reported that the noise emissions produced by internal combustion engines are closely associated with the mechanical forces exerted within the cylinder. These forces vary based on maximum cylinder pressure (CPmax) and maximum heat release rate (HRRmax). The results demonstrated that the increased noise values of 5 Nm and 7.5 Nm for all fuel blends were attained due to the HRR_{max} being higher at 5 Nm and 7.5 Nm loads than at 2.5 Nm and 10 Nm loads. Nonetheless, with the same load, there was no significant difference in noise levels between test types. Recently, Jaikumar et al. [13] assessed the noise characteristics of variable compression ratio (VCR) diesel engines run with mesua ferrea oil methyl ester in different injection pressures. They found that lower

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noise was produced with B20 among all the test fuels. Additionally, the noise intensity diminished with higher injection pressures, regardless of the test fuel blends employed. At elevated injection pressures, the combustion performance improved due to enhanced fuel vaporization; however, the biodiesel blends exhibit commendable combustion characteristics.

Various techniques can be employed to optimize the engine's performance. Numerous elements, referred to as "calibration parameters," can be easily modified on an actual engine within a lab setting to assess its performance; nevertheless, this approach does not yield the exact insights needed to comprehend the reasons behind changes in performance. Furthermore, component design characteristics, such as piston bowl shape, port geometry, spark plug placement, and injector location/number of holes, can be challenging and costly to test through experiments [14]. Therefore, developing a reliable model for calibrating the parameters involved is crucial [15]. In the work by Deb et al. [16], the performance and emission characteristics of the hydrogen-diesel dual fuel strategy have been predicted using a multi-linear response methodology. The response function equations are further used to carry out the optimization using the Genetic Algorithm. Meanwhile, Lan et al. [17] used the response surface methodology (RSM) combined with the non-dominated sorting genetic algorithm II (NSGA-II) to improve the pressure performance of a fuel system. The authors emphasized that while the empirical analysis of the effects of structural parameters on significant performance indicators of the system represents a more reliable methodological approach, it is also cost-prohibitive and considerably time-intensive. They posited that developing a fully validated numerical model could effectively address these challenges. In a different study, Motlagh et al. [18] utilized the outcomes of numerical experiments to construct response surfaces to elucidate the relationships between injection parameters and objective variables. The genetic aggregation algorithm generated response surfaces to provide the most appropriate response surfaces for the response variables. They noted that because the verification points are near y = x, the values for gross indicated efficiency, F_{merit}—which assesses all emissions at once—and the maximum pressure rise rate predicted by the response surfaces closely match those obtained from numerical experiments. Similarly, the identical combination of methodology can be found in the work by Moradi et al. [19].

Several studies illustrate that the RSM has the potential to be one of the best optimization methods for carrying out the optimization. This includes the work of Sahu and Sharma [20] that optimizes thermal efficiency (BTE) and nitrogen oxides (NOx) based on different load conditions, compression ratios, and mixtures. Using the RSM, they gave equal weight to both responses, and an acceptable solution was reported based on the desirability value. To optimize the biodiesel-methanol blend-fueled VCR engine for maximum BTE, minimum brake-specific fuel consumption (BSFC), CO, HC, NOx, and smoke emissions, Bharadwaz et al. [21] proposed the use of RSM. Using the analysis of variance (ANOVA) to determine the stability of the model and desirability approach in addition to weightage, the importance of each response can be assigned from 1 to a value of 5. In this manner, the author has set all the emission responses at 5, whereas the brake thermal efficiency and brake-specific fuel consumption are set at 3 and 4, respectively. They reported that the engine parameters with the highest desirability of 0.978 were 18 compression ratios, 5% fuel blend, 9.03 kg load, or 45% full load. Taking into account the influential effects of engine input parameters on desirability function using RSM, Ashok et al. [22] reported that the desirability values obtained for orange peel oil (OPO) blend, OPO10 and OPO20 in the engines are 0.68 and 0.681, respectively. The analysis of the perturbation plots for diesel indicated that the pilot mass (PM) significantly influences the desirability function. In contrast, the PM of OPO blends exhibits less influence on the desirability function, as an increased quantity of fuel is necessary to compensate for the diesel. When engine speed is considered, it is more influenced by the OPO10 blend, followed by OPO20; as the quantity of diesel decreases, speed will be reduced.

The aforementioned literature review reveals that biodiesel usage does not ensure the consistency of lower noise levels generated by the engine. It is the fuel properties that significantly affect the response. Optimization is needed to find the optimum blending ratio. Therefore, by using the RSM to calibrate the design parameters, this study minimizes the noise level of a single-cylinder DI diesel engine run with palm oil methyl ester (POME) biodiesel. This was purposely done to obtain the best possible blending ratio of biodiesel as a substitution for fossil fuel based on the investigation of different engine speeds and load conditions.

2. METHODS AND MATERIAL

The steps of the research are:

a) Preparing the biodiesel mixture.

b) Assess the noise level produced by the engine running on POME biodiesel.

c) Developing mathematical models to establish a correlation between engine noise and the operational conditions of the engine.

d) Calibrating the engine's operating condition to minimize the engine noise level.

2.1 Properties of the Fuel

The biodiesel fuel used in this study is palm oil methyl ester, produced through the transesterification method and supplied by Felda Global Ventures (FGV) Holdings Berhad. Meanwhile, the diesel fuel used is pure diesel. Table 1 shows the properties of the pure diesel and biodiesel blends. As can be seen from the table, the viscosity, density, and cetane number of the biodiesel fuel are somewhat higher than those of pure diesel fuel.

Table 1. Properties of the fuel tested

Property	D100	B5	B10	B20
Acid Value (mg KOH/g)	0.16	0.17	0.18	0.22
Viscosity at 40 °C (mm2/s)	3.8	3.83	3.86	3.91
Density (kg/m3)	847	848.5	850	853
Cloud Point (°C)	-8	-6.5	-5	-2
Pour Point (°C)	-14	-12.5	-11	-8
Heating Value (MJ/kg)	45.21	44.72	44.23	44.12
Cetane Number	50.5	50.83	51.15	51.8
Calorific Value (MJ kg^{-1})	45.89	45.67	45.45	45.01

2.2 Test Engine Specifications

A horizontal single-cylinder, direct-injection diesel engine (YANMAR TF 120M) was employed in this work, and it was coupled with an eddy current dynamometer to provide load for the engine. The experiment used three engine speeds: low, medium, and high, with a 480-rpm increase from 1200 to 2160 rpm. For the actual application, combustion experts have advised applying the load to the engine from 0 Nm to 28 Nm with a 14 Nm increase. The test bed engine is shown from the side view in Figure 1 with the specifications in Table 2.

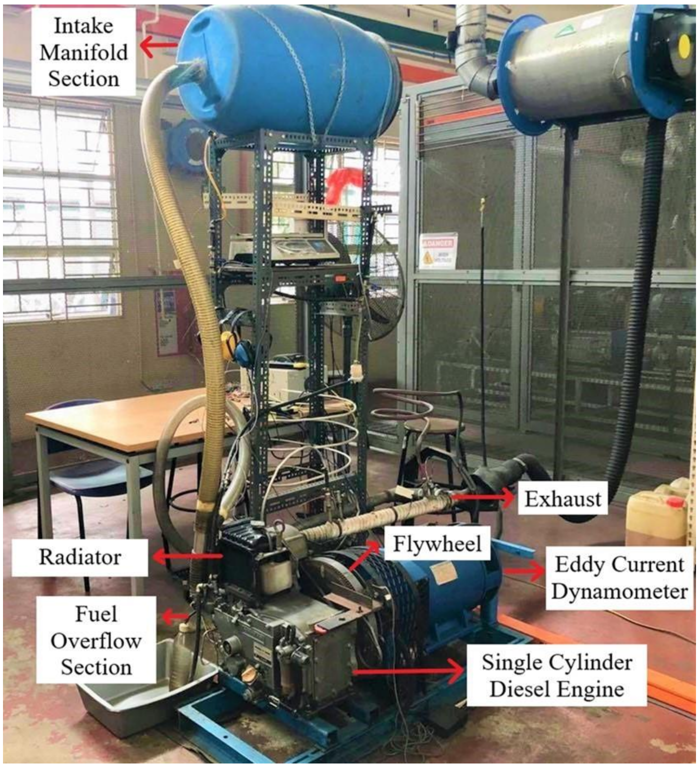

Figure 1. Side view of test bed engine

Table 2. Specifications of the evaluated engine

Model	YANMAR TF 120M
No of Cylinder	1
Cylinder Bore x Stroke, mm	92 x 96
Displacement, cc	0.638
Cooling System	Hopper/Radiator
Dimensions: Length x Width x Height, mm	695 x 348.5 x 530
Compression Ratio	17.7

2.3 Design of Experiments

Table 3 displays the factors and levels considered for this study. The multilevel factorial design is favored over the central composite design (CCD) and the Box-Behnken design for processes involving multiple independent variables, necessitating a comprehensive examination across a broad range. Unlike CCD and Box-Behnken, which primarily focus on exploring linear and quadratic relationships, multilevel factorial designs can accommodate complex interactions with a more extensive array of factor levels. This approach is particularly advantageous when each factor has more than two or three levels, enabling a deeper investigation into how responses vary under a broader range of conditions. While CCD and Box-Behnken are effective for analyzing quadratic surfaces with factors typically limited to two or three levels, the multilevel factorial design provides the flexibility to examine nonlinear and higher-order interactions across diverse levels. This capability makes it especially valuable for experiments where simple quadratic models may not adequately capture the behavior of responses and where understanding interactions among factors at different levels is crucial to the research [23].

The engine was evaluated at three distinct speeds and loads using POME biodiesel blends, varying from 0% (pure diesel) to 20% (B20). For data collection, the Brüel and Kjær handheld analyzer alongside the Type 2270 sound intensity probe were used, as depicted in Figure 2. Measurements were conducted once the engine achieved a steady-state condition, adhering to ISO 9614-1 standards, which stipulate that point measurements be taken at a distance of 1 meter from the noise source. As shown in Figure 3, 36-point measurements (6x6) based on the dimensions of the noise source were conducted. These measurements can subsequently be simplified to 18 points, corresponding to the location of the components, referred to as "responses," as detailed in Table 4. This approach facilitates the identification of the relationship between the mechanisms of the components and their noise generation

Table 3. Matrix of experiments (factors)

Factor	Level 1	Level 2	Level 3	Level 4
Biodiesel percent (%)	0	5	10	20
Engine speed (rpm)	1200	1680	2160	-
Engine load (Nm)	0	14	28	-

Figure 2. B&K handheld analyzer with sound intensity probe

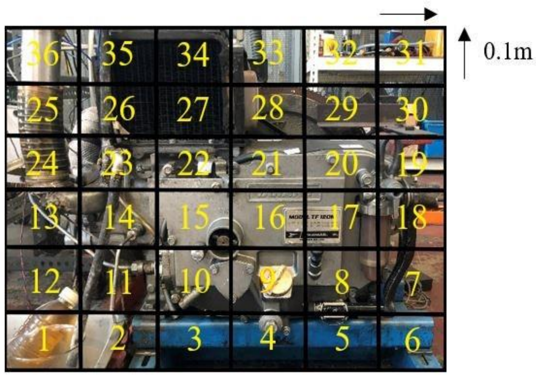

Figure 3. Gridding for measurement guidance

Table 4. Responses of the experiment in dB(A)

Response	Engine components	Response	Engine components
1	Fuel overflow hose	10	Crankcase and belting
2	Engine mounting	11	Radiator base
3	Engine base	12	Lower intake and exhaust pipe
4	Fuel overflow	13	Middle intake pipe
5	Intake manifold	14	Radiator
6	Cylinder head	15	Belting and flywheel
7	Piston	16	Flywheel and dynamometer
8	Connecting rod	17	Top radiator
9	Crankshaft	18	Upper intake pipe

2.4 Response Surface Methodology Approach

Response surface methodology (RSM), which combines statistical and mathematical methods, can enhance and optimize the operation in various engineering applications [24]. Using RSM, it was possible to comprehend more clearly how significant design parameters affected the sub-objectives. Prior to creating RSM functions, the most crucial design parameters were found using the SS-ANOVA algorithm [25]. Additionally, using RSM with the DoE enables detailed results with fewer tests, saves time, and uses fewer resources to estimate the optimal outcomes [26]. Apart from that, a mathematical equation may also be developed utilizing the variables and the responses. This equation can be used to predict the responses for the following observations.

Empirical statistical models will be developed to explore the range of contributing factors. These models approximate the correlation between the factors and the variables. In other words, statistical models similar to Eq. (1) will be established to predict response y in accordance with variables x_1, x_2, …, x_k.

$$y = f(x_1, x_{2,} \dots, x_k) + \varepsilon \tag{1}$$

The exact form of function *f* is unspecified and may be highly complex, with ε representing the variables that the *f* function might not have taken into account. In general, ε is the outcome of response measurement error, background noise, and the impact of unaccounted-for variables [27]. Here the factors or independent variables are biodiesel blend (%), engine speed (rpm), and engine load (Nm). The responses are noise emission levels based on the engine components evaluated using dB(A). The models generally take the following form:

$$\begin{bmatrix} R_1 \\ R_2 \\ R_3 \\ . \\ . \\ . \\ R_{18} \end{bmatrix} = f(biodiesel\ blend\ (\%), engine\ speed\ (rpm), engine\ load\ (Nm)) + \varepsilon \tag{2}$$

The following stages and optimizations involve finding the best input parameter values through the set of targeted response parameter values, also known as maximization or minimization [28]. Optimization by the RSM approach typically consists of three main steps: statistically designing experiments, determining the coefficients in a mathematical model, estimating the response, and evaluating the model's adequacy [29]. The desirability function is a proper function that can be used to evaluate the quality of the solution. One or more responses can be enhanced by maximizing or minimizing the item being assessed and transforming the response values into desirability function values ranging from 0 to 1. When values may not have the desired effect, they are given a value of 0, and when they do, they are given a value of 1, meaning the study factor is working at its best [30].

In the present study, biodiesel percent, engine speed, and engine load are the process parameters that should be calibrated to minimize the noise emission levels of the components simultaneously. Therefore, this research has opted for a multi-objective-based RSM optimization technique. Tables 5 and 6 indicate the calibration range for the parameters and the optimization goal.

Table 5. Variables to be calibrated

Parameter	Unit	Range
Biodiesel percent	%	[0-20]
Engine speed	rpm	[1200-2160]
Engine load	Nm	[0-28]

Table 6. Optimization goal for the responses

Response	Goal	Response	Goal
Fuel overflow hose	Minimize	Crankcase and belting	Minimize
Engine mounting	Minimize	Radiator base	Minimize
Engine base	Minimize	Lower intake and exhaust pipe	Minimize
Fuel overflow	Minimize	Middle intake pipe	Minimize
Intake manifold	Minimize	Radiator	Minimize
Cylinder head	Minimize	Belting and flywheel	Minimize
Piston	Minimize	Flywheel and dynamometer	Minimize
Connecting rod	Minimize	Top radiator	Minimize
Crankshaft	Minimize	Upper intake pipe	Minimize

3. RESULTS AND DISCUSSION

3.1 Model and Data Analysis

According to the analysis of variance (ANOVA) of the quadratic model for responses, Table 7 displays the relevance of the model terms. A glance at the table reveals that the amount of biodiesel, engine speed, and engine load are all significantly correlated with the noise emissions from the fuel overflow, intake manifold, and cylinder head. These parts are related to the intake phase of the engine combustion cycle, as can be seen. It is also noteworthy that although the noise generation of the fuel overflow system is not directly responsible for the biodiesel percentage, the table clearly shows the significance of the factor. Due to the clogging of fuel lines, filters, and injectors, this scenario may allow us to understand how the fuel system may indirectly impact noise generation [31].

On the other hand, it is astounding how the engine load and speed substantially impact responses across all components, not just the three that have been discussed. Thus, this corroborates the idea that faster combustion occurs as engine speed increases, leading to higher cylinder pressure and temperature [32]. This sudden pressure rise may result in a louder combustion [33]. In addition, since various mechanical components, including pistons, connecting rods, crankshafts, and valvetrains, move and interact with one another, these components may generate more mechanical noise as the engine speed rises because of their fast motion and contact [22]. Furthermore, diesel engines' intake and exhaust systems may also produce noise. Increased airflow noise occurs due to the intake of air being sucked in and compressed more quickly at higher engine speeds—similarly, quicker exhaust gas discharge results in louder exhaust noise [34].

In the meantime, a diesel engine load—the amount of work or power required—can contribute to the noise it produces. This was produced by the combustion process, which was affected by the engine load in a diesel engine. Higher engine loads often necessitate injecting more fuel into the cylinders to accommodate the increased power needs. This increased fuel injection causes more fuel to be burned, which raises the peak pressures and temperatures inside the combustion chamber. Consequently, at increasing engine loads, the combustion noise tends to be louder and more pronounced [35]. Additionally, the operation of several mechanical components inside the engine might be impacted by engine load. Parts, including pistons, connecting rods, crankshafts, and valvetrains, endure greater forces and stresses while the engine operates at a high load. As the components move and interact, the increased forces may cause the mechanical noise to become louder [36]. For the same reason, more air is drawn into the engine at higher loads as the fuel injection rate rises [37], increasing the noise of the intake airflow. Similarly, under high load conditions, the amount of exhaust gases released from the cylinders is tremendous, producing louder exhaust noise.

Table 7. Significance of model terms based on ANOVA

Response	A	B	C	AB	AC	BC	A^2	B^2	C^2
Fuel overflow hose	x	✓	✓	✓	x	x	✓	x	✓
Engine mounting	x	✓	✓	x	x	x	x	x	x
Engine base	x	✓	✓	x	x	x	x	x	x
Fuel overflow	✓	✓	✓	x	x	x	✓	x	x
Intake manifold	✓	✓	✓	x	x	x	✓	x	x
Cylinder head	✓	✓	✓	x	x	x	✓	x	x
Piston	x	✓	✓	✓	x	x	✓	x	✓
Connecting rod	x	✓	✓	✓	x	x	✓	x	x
Crankshaft	x	✓	✓	✓	x	x	✓	x	x
Crankcase and belting	x	✓	✓	x	x	x	✓	x	x
Radiator base	x	✓	✓	✓	x	x	✓	x	x
Lower intake and exhaust pipe	x	✓	✓	✓	x	x	✓	x	x
Middle intake pipe	x	✓	✓	x	x	x	✓	x	x
Radiator	x	✓	✓	✓	x	x	✓	x	✓
Belting and flywheel	x	✓	✓	✓	x	✓	✓	x	x
Flywheel and dynamometer	x	✓	✓	✓	x	x	✓	x	x
Top radiator	x	✓	✓	✓	x	✓	✓	x	x
Upper intake pipe	x	✓	✓	✓	x	x	✓	x	x

✓ – significant at 95% confidence interval, x – not significant at 95% confidence interval
A – Biodiesel percent
B – Engine speed
C – Engine load

Furthermore, it is clear from the table that the interaction between the engine speed and biodiesel percentage substantially impacted nearly two-thirds of the responses, demonstrating that the interaction between the two parameters is essential for optimizing the responses. However, the interaction of engine speed and engine load very slightly affects the responses, except for the belting, flywheel, and top radiator. In contrast, the interaction of engine load and biodiesel percentage does not affect any responses. This has supported the hypothesis that as engine load and speed rise, the flywheel experiences a greater force, increasing the load on the belting section. Therefore, to prevent running noise, which includes meshing noise, noise from belt transversal vibrations, friction noise, air-pumping noise, and noise from pulley vibrations, the quality of the belting must be taken into account [38].

Table 8 presents the statistical characteristics of the developed models. As seen in the table, all the F-values suggested that the models are all statistically significant. On the other hand, the correlation coefficient (R^2) and adjusted correlation coefficient are higher than 0.50 and within the acceptable range for all models. These parameters demonstrate how well and accurately the model could predict the parameter's actual value [39]. The models are sufficient if the differences between the R square and the adjusted R square are minimal. The table shows that the belting and flywheel have the highest adjusted correlation coefficient (R^2 = 0.8887). Various models were assessed to estimate the engine parameters. The software automatically chose a quadratic for predicting various engine parameters based on the correlation coefficient values except for engine mounting and base, which have been selected as linear.

Table 8. ANOVA for the response model

Response	Sum of Squares	df	Mean Square	F-value	R^2	Adjusted R^2
Fuel overflow hose	532.18	5	106.44	20.24*	0.7713	0.7332
Engine mounting	436.82	2	231.41	61.11*	0.7874	0.7745
Engine base	432.75	2	216.37	61.94*	0.7896	0.7769
Fuel overflow	547.74	4	136.94	20.39*	0.7246	0.6890
Intake manifold	557.26	4	139.31	23.60*	0.7528	0.7209
Cylinder head	649.82	4	162.45	25.28*	0.7653	0.7351
Piston	479.87	5	95.97	19.79*	0.7674	0.7286
Connecting rod	526.24	4	131.56	49.37*	0.8643	0.8468
Crankshaft	514.26	4	128.57	49.77*	0.8653	0.8479
Crankcase and belting	433.94	3	144.65	51.06*	0.8272	0.8110
Radiator base	509.67	4	127.42	33.40*	0.8117	0.7874
Lower intake and exhaust pipe	486.23	4	121.56	24.39*	0.7589	0.7277
Middle intake pipe	460.53	3	153.51	14.53*	0.5766	0.5369
Radiator	500.62	5	100.12	33.34*	0.8475	0.8221
Belting and flywheel	543.28	5	108.66	47.89*	0.8887	0.8701
Flywheel and dynamometer	482.01	4	120.50	34.18*	0.8152	0.7913
Top radiator	556.36	5	111.27	32.60*	0.8446	0.8186
Upper intake pipe	429.06	4	107.27	19.18*	0.7122	0.6751

* - model is significant

The mathematical models obtained after eliminating model terms are presented in equations (3)-(20). The formulation of the equation, when articulated in terms of its actual factors, serves as a valuable tool for forecasting responses across various levels of each factor. It is imperative to specify these levels using the original units corresponding to each factor to ensure the precision of the predictions. As can be noticed, the elimination process is essential in excluding insignificant model terms from the mathematical models to reduce their complexity. Thus, different lengths of mathematical models can be expected as different data are used for each component, leading to different values in the ANOVA.

$$\text{Fuel overflow hose} = 79.3139 + 0.003569 * B + (-0.0885208 * C) + 0.000359138 * AB + (-0.0269732 * A^2) + 0.00988967 * C^2 \tag{3}$$

$$\text{Engine mounting} = 76.5874 + 0.0065276 * B + 0.219774 * C \tag{4}$$

$$\text{Engine base} = 77.2173 + 0.00607248 * B + 0.220565 * C \tag{5}$$

$$\text{Fuel overflow} = 72.5608 + 0.79346 * A + 0.00655851 * B + 0.210571 * C + (-0.0328786 * A^2) \tag{6}$$

$$\text{Intake manifold} = 72.2401 + 1.04955 * A + 0.00653516 * B + 0.180027 * C + (-0.0456463 * A^2) \tag{7}$$

$$\text{Cylinder head} = 71.865 + 0.874201 * A + 0.00660035 * B + 0.248551 * C + (-0.0374264 * A^2) \tag{8}$$

$$\text{Piston} = 79.647 + 0.00379922 * B + (-0.033122 * C) + 0.000291419 * AB + (-0.0206191 * A^2) + 0.00825531 * C^2 \quad (9)$$

$$\text{Connecting rod} = 80.2902 + 0.00329339 * B + 0.221467 * C + 0.000338107 * AB + (-0.0255072 * A^2) \quad (10)$$

$$\text{Crankshaft} = 78.8293 + 0.00458252 * B + 0.211699 * C + 0.000256938 * AB + (-0.0195787 * A^2) \quad (11)$$

$$\text{Crankcase and belting} = 77.9601 + 0.00593411 * B + 0.208539 * C + (-0.000559604 * A^2) \quad (12)$$

$$\text{Radiator base} = 79.5348 + 0.00349435 * B + 0.19642 * C + 0.000356985 * AB + (-0.0270143 * A^2) \quad (13)$$

$$\text{Lower intake and exhaust pipe} = 81.0817 + 0.00208554 * B + 0.196491 * C + 0.000422932 * AB + (-0.0314287 * A^2) \quad (14)$$

$$\text{Middle intake pipe} = 76.1208 + 0.00606762 * B + 0.212649 * C + 0.000754873 * A^2 \quad (15)$$

$$\text{Radiator} = 82.0466 + 0.00275461 * B + (-0.0756756 * C) + 0.000382013 * AB + (-0.0304571 * A^2) + 0.00929358 * C^2 \quad (16)$$

$$\text{Belting and flywheel} = 76.407 + 0.00563999 * B + 0.446028 * C + 0.000284437 * AB + (-0.000126842 * BC) + (-0.0211974 * A^2) \quad (17)$$

$$\text{Flywheel and dynamometer} = 81.0752 + 0.00333697 * B + 0.223423 * C + 0.000287313 * AB + (-0.0221797 * A^2) \quad (18)$$

$$\text{Top radiator} = 74.6346 + 0.00661291 * B + 0.524746 * C + 0.000311571 * AB + (-0.000186737 * BC) + (-0.0245289 * A^2) \quad (19)$$

$$\text{Upper intake pipe} = 80.0721 + 0.00312416 * B + 0.159488 * C + 0.000367884 * AB + (-0.0270455 * A^2) \quad (20)$$

Figure 4 displays the correlation between the predicted and actual values of the parameters. Most data are located near the 45-degree line, indicating a strong correlation between the actual and predicted values. Thus, the developed model could estimate the engine noise emission level responses based on the correlation coefficient values for various parameters.

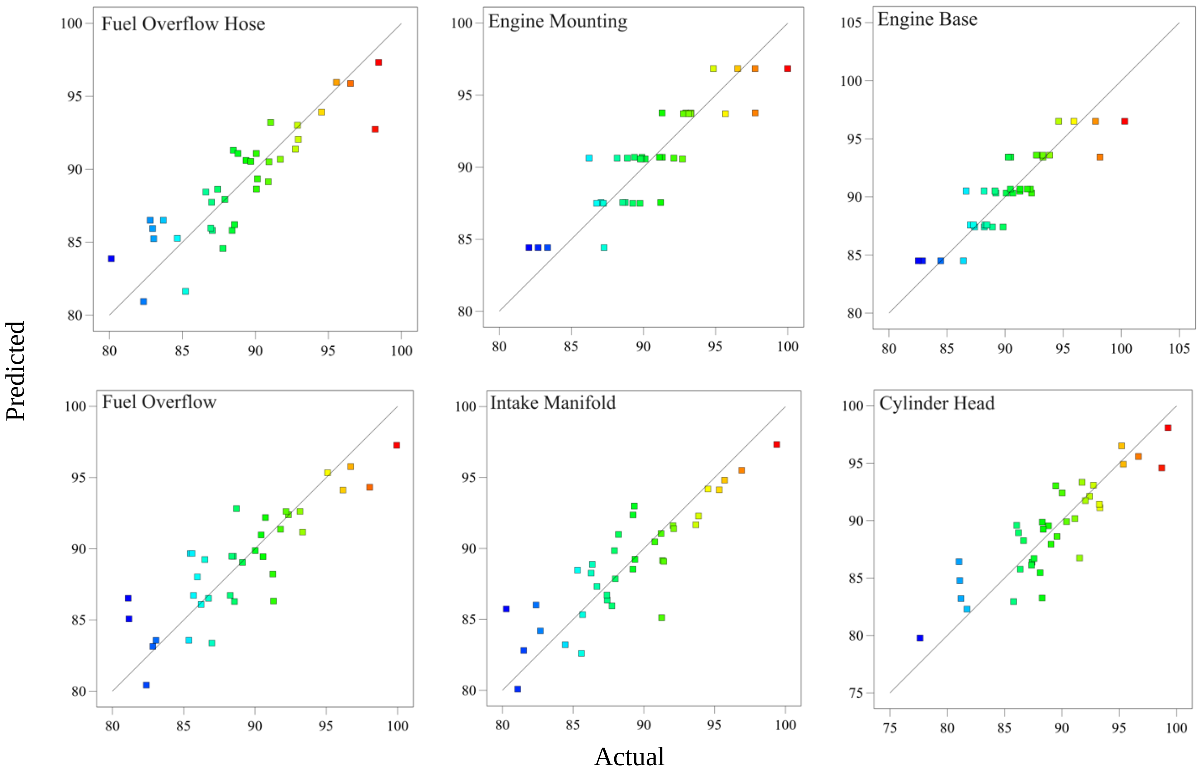

Figure 4. Experimental vs. predicted values of different responses

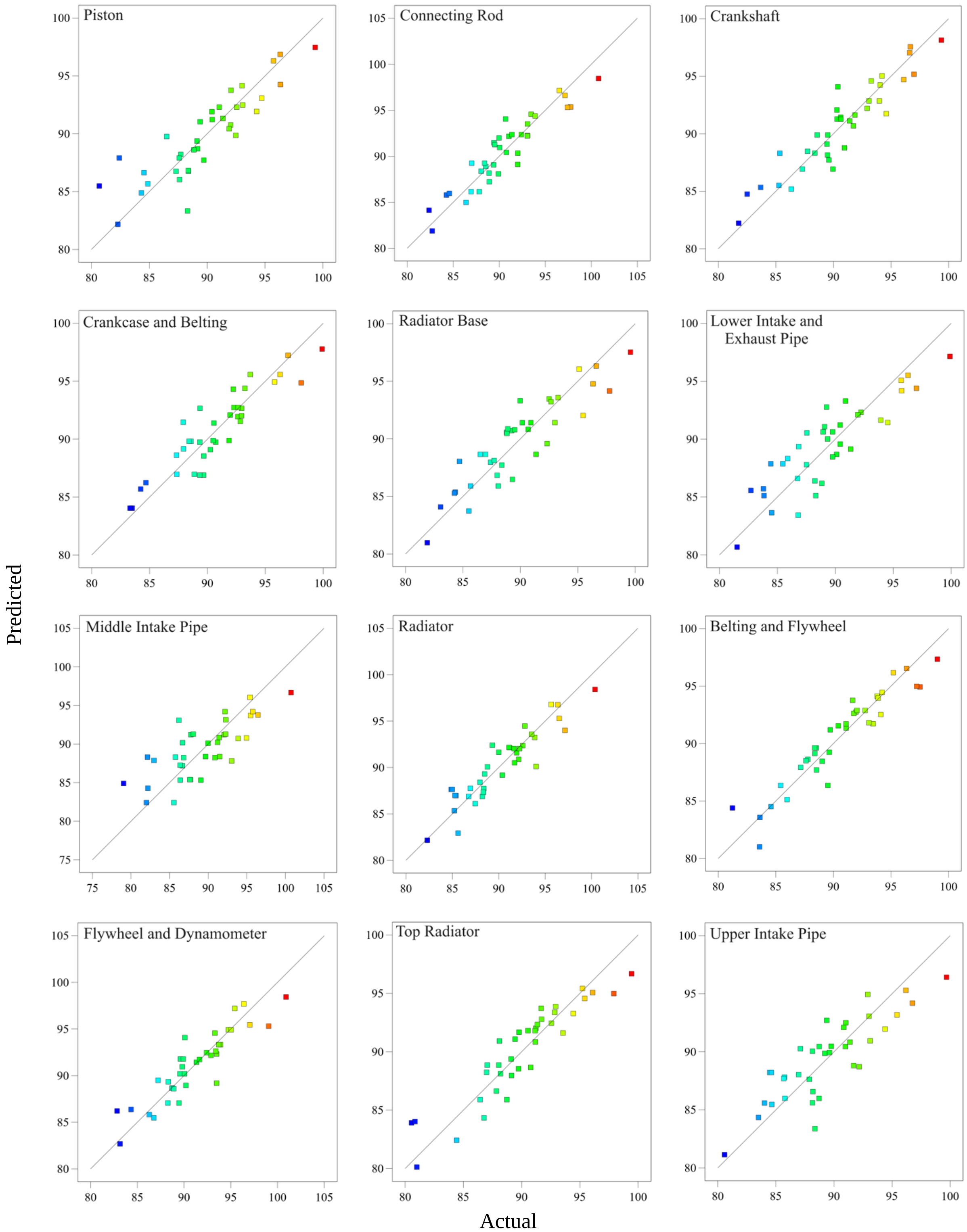

Figure 4. (cont.)

The aforementioned proposed models were used for optimization. It is necessary to discuss how the factors under consideration vary and affect the responses. The 3D surface graphs can be used to understand how the variables may impact the noise generation in particular components. As indicated in Table 7, these components are further addressed since the fuel overflow, intake manifold, and cylinder head are all significant model terms.

As shown in Figure 5, when the percentage of biodiesel is considered, a clear trend is noticed where the higher the biodiesel percentage, the greater the noise level obtained. Regardless of the engine speed or load level, the upward trend usually stops in the middle of the biodiesel percentage increment before it displays a descending tendency. Ironically, it is believed that the use of biodiesel itself has no direct impact on the fuel overflow noise level. Usually, fuel overflow noise happens when the fuel tank or fuel system is overfilled and too much fuel leaks or overflows. The mechanical components of the fuel system, as opposed to the properties of the fuel being used, such as biodiesel, are primarily responsible for this noise [13].

Nevertheless, it is essential to remember that biodiesel, like any other diesel fuel, might have different physical properties from petroleum diesel, such as increased viscosity or additional lubricity. These characteristics might impact fuel flow, fuel pressure, and other aspects of fuel handling while influencing how the fuel behaves inside the fuel system [40]. Any changes in the fuel system performance or fuel flow characteristics due to using biodiesel could indirectly affect the likelihood of fuel overflow. Therefore, the significant effects of biodiesel percent, engine speed, and load on the fuel overflow area suggested that the fuel system in the engine has malfunctioned, or else the fuel overflow noise level should not be directly related to the factors.

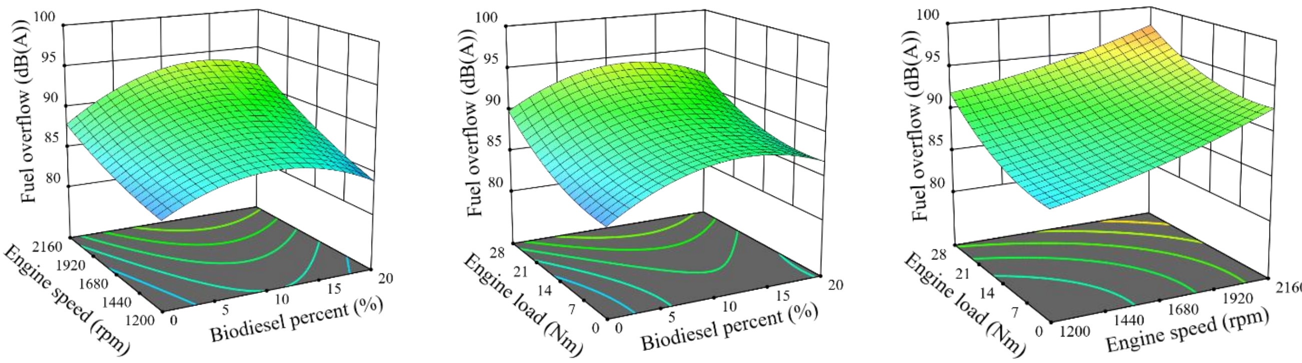

Figure 5. Variation of the noise emission at fuel overflow vs. influential factor (statistically significant effect)

Figure 6 shows that the graphs do follow the same pattern as the previous component and that, since the use of biodiesel as a fuel in diesel engines typically does not have a direct impact on the noise level produced by the intake manifold, it can be concluded that the noise level in the intake manifold is primarily influenced by factors like engine design, intake system design, and the operating conditions of the engine [41]. However, there are a few indirect ways that using biodiesel may impact the noise of the intake manifold. Compared to petroleum diesel, biodiesel has slightly different combustion properties. Possessing a higher cetane value means that it has superior ignition characteristics. This may lead to smoother combustion and lower noise levels brought on by knocking or uneven combustion [42]. As a result, the noise transferred through the intake manifold may be slightly reduced. In addition, biodiesel can differ from petroleum diesel in terms of its lubrication ability. Changes in the fuel lubricity can impact the fuel injection system, which comprises parts like injectors and fuel pumps. The fuel injection system might run more smoothly with biodiesel and produce less noise in the intake manifold [43]. Finally, using biodiesel may have an impact on engine resonance and vibration, which may have an indirect effect on intake manifold noise. The amount of vibrations transmitted through the engine may vary due to changes in the qualities of the fuel, combustion, or engine response when using biodiesel [44]. This has potentially changed the noise levels of the intake manifold.

Meanwhile, the impacts of engine speed and engine load are found to be directly related to the noise level produced by the intake manifold as the amount of air flowing through the intake manifold increases with the engine speed [45]. Higher airflow rates via the intake manifold due to the increased air demand can result in more turbulence as the air travels through the intake manifold and related parts, increasing noise levels [46]. Induction noise may also be created, a distinctive sound associated with airflow via the intake manifold. Because of the increased volume and speed of air entering the cylinders at greater engine speeds and engine loads, the induction noise may become more noticeable. However, the design of the intake manifold, the presence of resonators or mufflers in the intake system, and the overall engine arrangement can all affect the noise level [47]. On the other hand, the engine speed and load might also impact the timing of valve events and the opening and closing of intake valves. These dynamics of the intake system and related valve movements might affect how loud the intake manifold sounds [48]. As the engine speed increases, the valve operation becomes more rapid, which can contribute to higher noise levels in the intake manifold [49]. At the same time, the intake valves stay open longer at higher engine loads to let more air into the cylinders. This is demonstrated by increased combustion time and engine load because more charge mixture is burnt throughout the combustion process [50]. As a result, the dynamics of the valve and intake systems are increased, which might cause more vibration and noise inside the intake manifold [51]. Furthermore, it is generally agreed that larger engine loads put the engine components, including the intake manifold, under greater mechanical stress. The intake system may experience higher vibrations and resonance due to these elevated stresses, resulting in louder noises [52].

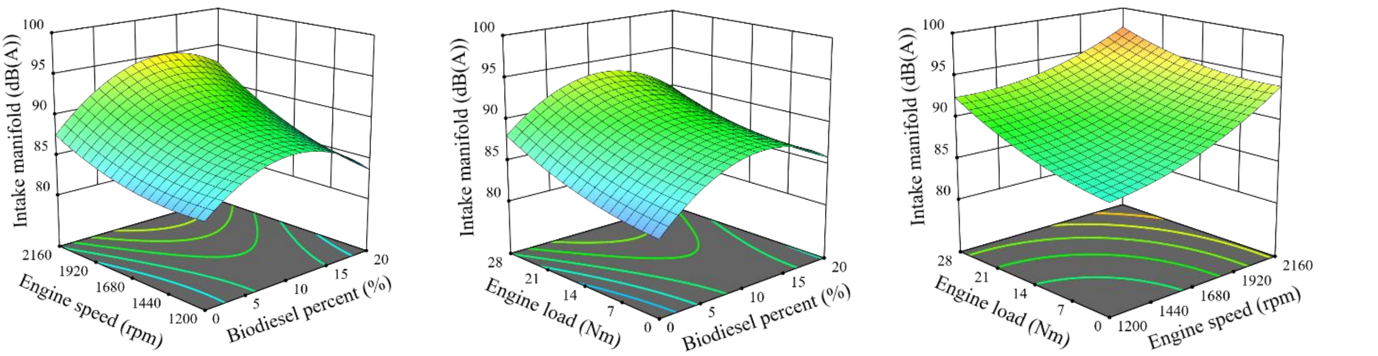

Figure 6. Variation of the noise emission at intake manifold vs. effective factor (statistically significant effect)

One of the most apparent findings when exploring the impact of factors on the cylinder head is that in all the graph variations depicted in Figure 7, the noise emission produced is larger than the other two components. It should be noted that the noise level produced by the cylinder head is often not directly impacted by using biodiesel as a fuel in diesel engines. The fuel injection system and engine design are the main determinants of the noise generation by the cylinder head [53]. The engine's design, including features like the geometry of the combustion chamber, piston design, valve arrangement, and overall engine architecture, also significantly impacts the noise the cylinder head produces [54]. These design considerations control how fuel and air are moved during combustion, which can affect noise levels. Furthermore, biodiesel and petroleum diesel have differing lubricating characteristics, which can impact the fuel injection system. Therefore, it is safe to say that the fuel injection mechanism significantly influences the engine's noise level. In addition, injector wear or inappropriate spray patterns may result from improper fuel injection system maintenance or adjustment for biodiesel use, which could increase noise levels. This agrees with the statement of Kanth et al. [55], which highlights that the combustion chamber design, fuel quantity injected, injection pressure, and timing all enhance engine performance.

In the meantime, as the noise level produced by the cylinder head is closely correlated with both engine speed and load, a more significant level of noise may be anticipated during the increase in engine speed and load. Various mechanical parts of the engine, such as the pistons, valves, camshafts, and rocker arms, move much faster as engine speed rises. Increased friction and movement between these parts may cause higher mechanical noise levels, such as piston slap and valve train noise, which may add to the cylinder head's overall noise [56]. The noise level produced by the cylinder head is also influenced by the combustion process occurring inside the cylinders. The frequency and intensity of combustion events increase as engine speed increases. When engines are working under excessive loads or with insufficient fuel-air mixture conditions, this can result in increased combustion noise, also known as "combustion knock" or "detonation," which is highly audible [57]. Higher engine speeds might also increase vibrations throughout the entire engine, including the cylinder head. These vibrations could propagate as noise, which would produce more sound. Unbalances in rotating components, uneven combustion, or resonance inside the engine construction are some phenomena that might generate vibrations [58], [59].

Engine load frequently affects how much air and fuel are mixed in the cylinders. A richer fuel mixture is usually needed to fulfill the increased need for power at greater loads. Richer mixtures may alter combustion and result in greater combustion noise, contributing to the overall noise produced by the cylinder head [60]. Aside from that, higher engine loads could cause the engine to experience more mechanical stresses and friction. Vibrations and noise levels may become more pronounced as a result. As a crucial part of the engine, the cylinder head is subjected to these increased forces and vibrations, which raise noise levels [61]. On top of that, engine load can affect the noise made by the exhaust system, which can affect how loud an engine is perceived to be overall. A more audible exhaust noise may result from the increased exhaust gas flow that higher engine loads normally necessitate. Hence, the noise produced by the exhaust system may be reflected in the area around the cylinder heads and contribute to the total noise level [7].

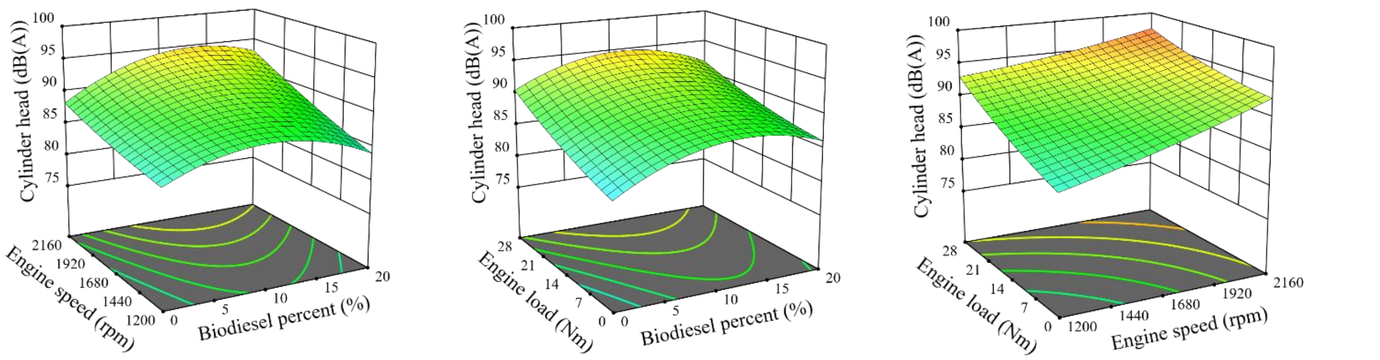

Figure 7. Variation of the noise emission at cylinder head vs. effective factor (statistically significant effect)

3.2 Optimization Result

The mathematical models that have been listed previously are used to optimize the noise emission level in different components using multi-objective optimization. The optimization was run numerically, and 55 solutions were suggested. There are various optimal solutions with multiple values for different variables. This is because the other variable values will change as the software tries to optimize one variable. Therefore, the desirability function can be used as an indicator to evaluate the quality of the solution. The optimal solution is suggested since its desirability value is near 1. As such, 0.938 represents the highest desirability value for the optimum solution. It was indicated that the lowest noise emission levels of the engine were predicted when running using B20 biodiesel percentage at 1200 rpm under no load conditions. The variation of the solution desirability vs. factors is highlighted in Figure 8, and the noise emission levels in each component for the optimal solution are tabulated in Table 9.

As mentioned, it is evident that the engine speed has a considerable impact on the noise emissions produced. It has been previously discussed that the various mechanical components of the engine, such as the pistons, valves, camshafts, and rocker arms, move at rates depending on the engine speed [62]. Lower mechanical noise levels, such as valve train noise and piston slap, which can add to the overall noise generated, might be caused by the slower movement and contact between these parts. Additionally, combustion events became less frequent and intense; there was more complete combustion. This may result in reduced combustion noise, often known as "combustion knock" or "detonation," which is more audible in engines running under high loads or inadequate fuel-air mixture conditions [63]. Apart from that, it is advised that the load should not be applied to achieve lower noise emission levels. The lower power demand may be the cause of this. Lower combustion noise can be anticipated because the rich fuel mixture is not required to produce the necessary power [64]. Undeniably, the application of engine load may contribute to noise reduction noise when higher engine speeds are used due to the balanced rotation that takes place with the presence of load. However, this only applies at certain engine load levels, as the higher load level could make the imbalanced forces more prominent due to the greater inertia forces [65]. Nevertheless, in this study, the remarkable reduction in noise emissions achieved by operating the engine at lower speeds without any load has contributed to most of the proposed solutions with higher desirability values.

Meanwhile, it is interesting that the largest concentration is recommended for biodiesel application to reduce noise generation. One thing that should be noted is that biodiesel burns more efficiently than regular diesel fuel. A higher cetane value means that it has superior igniting properties. The enhanced ignition quality of biodiesel produces a more complete and efficient combustion process—less unburned fuel results from more effective fuel ignition, which lowers noise levels [66]. Moreover, biodiesel provides superior lubricating qualities than regular diesel fuel. The improved lubricity of biodiesel reduces wear and friction between moving engine components. Biodiesel can help smooth engine operation and minimize noise levels by reducing mechanical friction [67].

In conclusion, the optimization analysis reveals that operating the B20 at low engine speeds without any load does not necessarily mean that both the engine speed and load must be kept at this level. The analysis showed that the most significant reduction in noise emission levels occurs under these conditions; however, comparable reductions can also be achieved at different engine speeds and loads. Ultimately, it is crucial to highlight the proportion of biodiesel that can be utilized as a substitute. Factors such as engine speed and load were constantly included in optimizing noise emissions in diesel engines powered by biodiesel, as they significantly influence both the combustion process and mechanical vibrations, contributing to noise levels. Engine noise primarily stems from combustion events, mainly due to the variations in pressure and temperature within the combustion chamber, which are affected by engine speed and load [68]. Increased engine speeds often lead to a rise in the frequency and intensity of combustion noise, while higher loads can raise the overall combustion pressure, resulting in elevated noise emissions [69]. Furthermore, engine load affects the mechanical stress on components such as pistons, bearings, and the crankshaft, leading to greater vibrations and noise under high-load conditions [70]. By optimizing engine speed and load, researchers strive to minimize noise emissions while maintaining optimal engine performance and fuel efficiency, particularly since biodiesel use may introduce variations in noise levels compared to traditional diesel fuels.

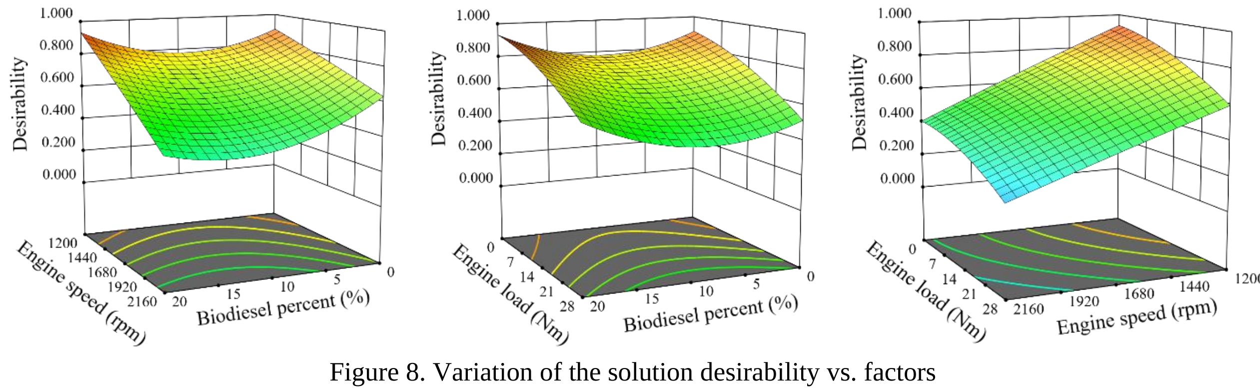

Figure 8. Variation of the solution desirability vs. factors

Using the recommended parameters, experiments were conducted to record the optimum engine operating condition point. Then, a comparison is made between the experimental and numerical data in Table 9. The RSM does not provide a specific error percentage range; hence, the agreement between predicted and experimental data should be described. The table shows the most prominent and smallest discrepancies between predicted and experimental values, which are 3.42 % and 0.51 %, respectively. The largest deviation occurs in the belting and flywheel, while the smallest is at the cylinder head. Despite the influence of random sources on noise emission levels, this methodology accurately predicts engine noise with a low error percentage. Moreover, the effectiveness of the RSM has been demonstrated by the consistency in the low rate of errors, regardless of some responses indicating overfitting. As a result, the findings suggest that this approach is suitable for predicting engine-generated output.

Table 9. Noise emission levels obtained by the optimization

Response	Experimental value, dB(A)	Predicted value, dB(A)	Error percentage (%)
Fuel overflow hose	82.140	80.932	1.47
Engine mounting	82.392	84.421	2.46
Engine base	82.368	84.504	2.59
Fuel overflow	81.438	83.149	2.10
Intake manifold	81.608	82.815	1.45
Cylinder head	81.883	82.299	0.51
Piston	82.749	82.179	0.69
Connecting rod	82.786	81.886	1.09
Crankshaft	83.686	82.226	1.74
Crankcase and belting	85.120	84.046	1.26
Radiator base	81.774	80.980	0.97
Lower intake and exhaust pipe	81.463	80.678	0.96
Middle intake pipe	82.230	82.414	0.22
Radiator	82.413	82.161	0.31
Belting and flywheel	83.882	81.015	3.42
Flywheel and dynamometer	83.582	82.689	1.07
Top radiator	81.020	80.127	1.10
Upper intake pipe	80.567	81.140	0.71

4. CONCLUSION

In this study, biodiesel has been used as an alternative fuel in a small single-cylinder engine. The engine was run under different test conditions. The factors considered were engine biodiesel percentage in fuel blend, engine speed, and engine load. As the engine's noise emission responses were measured, a mathematical approach was established to correlate them to the considered factor. Finally, a multi-objective optimization using RSM has been applied to calibrate the engine factor according to all components' minimum noise emission levels. Based on the study's findings, the following conclusions can be formed:

i) The proportion of biodiesel in the engine has an insignificant effect on the noise emission generated except for the fuel overflow, intake manifold, and cylinder head.

ii) Both engine speed and engine load significantly contributed to the noise generated in all components.

iii) The adjusted R-square for all models is within the acceptable range, with the highest of 0.8887 at the belting and flywheel sections. Hence, the mathematical model can predict the engine noise emission level.

iv) The optimization suggested that the minimum noise emission level can be obtained using B20 run at RPM 1200 without load conditions.

v) The optimization shows an excellent capability to optimize the responses. Therefore, this method can be used to optimize the other engine responses.

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