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Experimental Investigation for Determining an Ideal Algal Biodiesel–Diesel Blend to Improve the Performance and Mitigate Emissions Using a Response Surface Methodology

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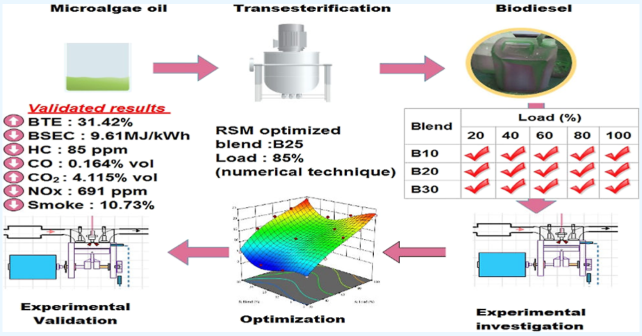

ABSTRACT: The ongoing depletion of the world's fossil fuel sources and environmental damage has compelled the quest for alternative energy. Excellent characteristics of biodiesel include its renewable nature, safety, absence of sulfur, environmental advantages, and biodegradability, which can eradicate the above problems. In this study, algal oil was characterized to obtain the fatty acid profile, and the free fatty acid value of algal oil suggested a two-step process of esterification and transesterification for efficient biodiesel production. The performance and emission results of biodiesel and its blends (B10, B20, and B30) were investigated in a constant speed, single-cylinder, 4-stroke, 3.5 kW compression ignition engine at different loads for arriving at an appropriate fuel blend ratio. The response surface methodology technique is used to predict the ideal composition of microalgae–diesel using the experimental data with due weightage for the optimization criterion. The predicted blend ratio of B25 was tested on the engine and authenticated. The findings recorded an improvement in brake thermal efficiency to 31.42% and reduction in brake specific energy consumption to 9.82 MJ/kW h, unburned hydrocarbon to 85 ppm, carbon monoxide to 0.164% v/v, carbon dioxide to 4.115% v/v, nitrogen oxides to 691 ppm, and smoke opacity to 16.93%.

1. INTRODUCTION

Compression ignition (CI) engines are crucial power systems for both on- and off-road vehicles. Diesel engines are used to drive the majority of heavy-duty vehicles due to their well-known dependability and efficiency.[1] The world is increasingly aware of the possibility of "energy crises" as the result of depleting fossil fuel reserves, which are made worse by the fact that fossil fuels are non-renewable sources of energy.[2] Burning fossil fuels is also a major problem because it releases greenhouse gases that cause global warming which over time has a negative impact on ecosystems, and it releases pollutants into the atmosphere such as nitrogen oxides (NO_x), carbon monoxide (CO), and hydrocarbon (HC) that cause air pollution resulting in acid rain.[3] Therefore, the development of alternative fuels from renewable and sustainable sources, such as biofuel, is desperately required to replace fossil fuels. Since they are non-toxic, ecological, and environmentally benign, biodiesels have a variety of benefits over fossil fuels. Biodiesels also have similar characteristics like diesel.[4] On the other hand, the manufacture of biodiesel from edible oils will directly impact the cost of food, which also needs a significant quantity of freshwater and arable land. The amount of biodiesel that can be produced from waste products like animal fats and cooking oils will be capped, so it cannot meet the rising demand for energy. Animal and vegetable waste served as the biodiesel first generation source, while agricultural and forestry waste products were employed as the fuel second generation source. However, edible oils are in high demand and might become limited because they are used as food sources, which worsens economic inequality. The absence of a second-generation source in many countries limits the feasibility of replacing petroleum on a large scale. Numerous studies are focusing on third-generation source for biodiesel as a means of overcoming the difficulties associated with developing biodiesel from first- and second-generation sources because of the enormous environmental and financial benefits of non-agricultural and non-edible sources.[5] According to reports, microalgae are the most viable alternative because of their rapid

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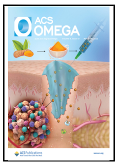

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development rate, which can fulfill the rising worldwide need for energy.[6]

Production of microalgae is considerably simpler. Since algae have a shorter lifespan, a huge volume of cultivation is conceivable. Because it needs less sunlight, H_2O, CO_2, and nutrients for the embolic process, microalgae are rich in lipids and easy to grow.[7] Microalgae are environmentally friendly, sustainable, and renewable, which is why research on microalgal biofuel usage is on the rise. Although microalgal biofuel seems to have a high scope to replace conventional petroleum diesel, its suitability as the engine fuel needs to be studied on the conventional CI engine for improving the combustion, performance, and emission characteristics.[8] In a research, Can et al.[9] examined a soybean biodiesel B20 fueled ,naturally aspirated direct injection engine with variable loading at 2200 rpm for 5, 10, and 15% exhaust gas recirculation. In comparison to diesel fuel, the results indicated 6% reduced thermal efficiency for 5% EGR and 3% less for 15% EGR. In an earlier study using second-generation jatropha biodiesel on a CI engine, it was found that the B25 blend ratio had an impressive brake thermal efficiency (BTE) and fuel economy that were on a par with neat diesel. The HC and CO emissions were reduced, but the NO_x emissions were higher compared to neat diesel.[10] In another study with 100% Pongamia biodiesel in a CI engine, the test results revealed that it was less efficient than diesel. The B20 blend improved the BTE with a slightly lower brake thermal energy consumption (BSEC) compared to diesel.[11] Therefore, addition of biodiesel to diesel as a blend was found to be a laudable strategy to improve the performance. Asokan et al.[12] employed Juliflora biodiesel with B20, B30, B40, and B100 in a direct injection diesel engine. B20 was discovered to have similar engine efficiency and combustion to diesel fuel. At full load, the BSEC of B20 (0.27 kg/kW h) was almost equal to that of diesel (0.26 kg/kW h). Similarly, the BTE for neat biodiesel was 31.11%, compared to neat diesel (32.05%). The third-generation biofuel that is particularly appealing and promising among the alternative fuels is biodiesel made from microalgae. In addition to being widely available, it is environmentally beneficial and produces cleaner gas during burning. Microalgal biodiesel is a fuel that significantly lowers NO_x emissions by between 47 and 70% while still producing some particulate matter and smoke in CI engines.[13] Reddy et al.[14] experimentally studied microalgal biodiesel as a potential partial diesel fuel replacement in CI engines, and it was discovered that the BTE remained quite similar to that of diesel and HC and CO emissions were mitigated than diesel, with higher NO_x emissions leaving scope for further improvement.

The traditional technique of engine testing is currently found to be time-consuming and expensive, prompting the development of innovative strategies.[15] Some of the research published so far has used chemical and statistical methods to explore the use of alternative computational analysis for faster, more reliable, and less expensive operations.[16] Chemometric analysis is a potent data analysis approach. It is feasible to solve issues and provide solutions based on the characteristics of examined items and their connections.[17] Chemometrics is a subfield of chemistry that conducts research experiments using probability and statistics to collect relevant data as possible for analysis. It is feasible to discover a mutual relationship between fuel qualities and a number of examined results.[18] Similarly, response surface methodology (RSM) has proven to be a trustworthy technique that delivers outcomes that are statistically acceptable.[19] The RSM approach was used in a diesel engine with different compression ratios, different injection pressures, and injection time settings. The RSM approach using experimental data discovered that the ideal engine input parameters were a compression ratio of 18, an injection pressure of 250 bar, and an injection timing of 21° crank angle (CA) before top dead center (bTDC). Different RSM models have been created to predict engine reactions. The coefficients of determination (R^2) values for the performance emission parameters are found to range from 0.9256 to 0.9991 to assess the model's accuracy.[20] The best diesel biodiesel blend for a variable compression ratio engine is investigated with the use of multi-response optimization utilizing the RSM model in conjunction with a central composite design (CCD). Less than 5% inaccuracy was discovered in the engine reaction forecast.[21]

The evidence reviewed above leads to the conclusion that CI engines operate better and emit less pollution when using biofuel. Additionally, RSM statistical studies on the performance and emissions of diesel engines have reduced the number of experiments required to tune the engine and fuel parameters. As a result, an effort has been undertaken in this work to improve the algal biodiesel energy substitution rate for improved engine performance and reduced emissions with diesel for varying loads. To predict the engine responses, the RSM model was developed. Based on the optimization criteria for optimum performance and lowest pollution, the best biodiesel ratio was determined. Finally, validation was carried out for the statistical results by experimentation.

2. MATERIALS AND METHODS

2.1. Preparation of Microalgal Biodiesel. The microalgae oil was outsourced from the vendors. The fat-free acid (FFA) content of raw algal oil was assessed in this work using the neutralization titration method, and it was observed as 6%, which is very high for the conventional alkaline-catalyzed transesterification method because of undesirable soap formation that lowers the biodiesel yield.[22] Normally, oils with more than 3% FFA concentration are required to go through the two-step esterification and transesterification processes. Numerous researchers have successfully used this technology to maximize the synthesis of biodiesel from a variety of sources.[23]

2.1.1. Esterification. The most straightforward procedure is the esterification of FFA with methanol in the presence of acidic catalysts. The acid catalysts convert the FFA into oil to improve biodiesel yield. The esterification of oil is carried out with six times of methanol by molar ratio, 1% sulfuric acid by volume ratio added, and the reaction conditions are 60 °C temperature with a stirring speed of 8000 rpm for 90 min. After esterification, the FFA reduced to 0.6%.

2.1.2. Transesterification. The most widely used crop oil derivatives for fuel are methyl esters. This was produced from the transesterification method of 8:1 CH_3OH to bio-oil molar ratio in the presence of potassium hydroxide (1% wt) catalyst for reaction conditions of 60 °C at 60 min with stirring speed of 8000 rpm.[22] Additionally, some of the crucial characteristics of the generated biodiesel are assessed and displayed in Table 1 and a photographic view of the transesterification setup is shown in Figure 1.

2.2. Experimental Setup. The artistic layout of the engine test setup is illustrated in Figure 2 and Table 2. The engine can be operated at various engine loads by using an eddy current dynamometer. An anemometer was used to determine the intake air velocity in the air box. The burette configurations were used to compute the fuel rate of flow. An AVL make (model: 444

Table 1. Physicochemical Properties of the Test Fuel

property	diesel	microalgae
viscosity (cSt)-40 °C	2.95	5.06
density (g/mL)-20 °C	0.836	0.876
cetane number	46	44
heating value (MJ/kg)	40.9	41.08
latent heat of vaporization (LHoV) (kJ/kg)	253	315

Figure 1. Transesterification.

di-gas) gas analyzer was used to measure the five gas emissions, and an AVL make (model: 437C) smoke meter was used to determine the amount of smoke opacity. The optimal injection time for neat microalgal biodiesel was adjusted to 27° CA bTDC in this investigation. Kistler make piezoelectric pressure transducer flush-mounted on the cylinder head received the in-cylinder pressure, and a Kistler make charge amplifier was used to transform the transducer output into an analogue signal, which was then collected and analyzed using a Kistler make (model: KiBox) combustion analyzer. Pressure data of 100 stable consecutive cycles was captured for each operating point at a resolution of 0.2 CAD using an AVL make crank angle encoder.

Table 2. Engine Specifications

parameters	details
make	Kirloskar
cylinder	single
stroke	4 stroke
cooling method	water
stroke length	110 mm
bore	87.5 mm
start of injection	27° CA bTDC
capacity	661 cc
connecting rod length	234 mm
rated power	3.5 kW @ 1500 rpm
CR	17.5
piezosensor range	350 bar
dynamometer	eddy current

2.3. Experimental Procedure.

The test was run with varied loads of 20, 40, 60, 80, and 100% at the constant speed of 1500 rpm. The experimental matrix is depicted in Table 3. Preparatory stage diesel fuel was used to ignite the test engine. After steady-state operation, the engine air, fuel consumption, brake force, and exhaust pollutants were all measured and recorded for comparison with test fuel. The tests are repeated three times, and the average values are taken for analysis. The engine was turned off for cooling testing after every new set of experiments with different blend ratios. Based on experimental data, the RSM model was created to predict engine responses under varied loads. The optimum blend was identified with due consideration and weightage to each input and output criteria to maximize the performance and minimize emission. Finally, the determined blend ratio underwent experimental confirmation. The investigations were limited to blend B30 because the performance parameters showed a diminishing trend with

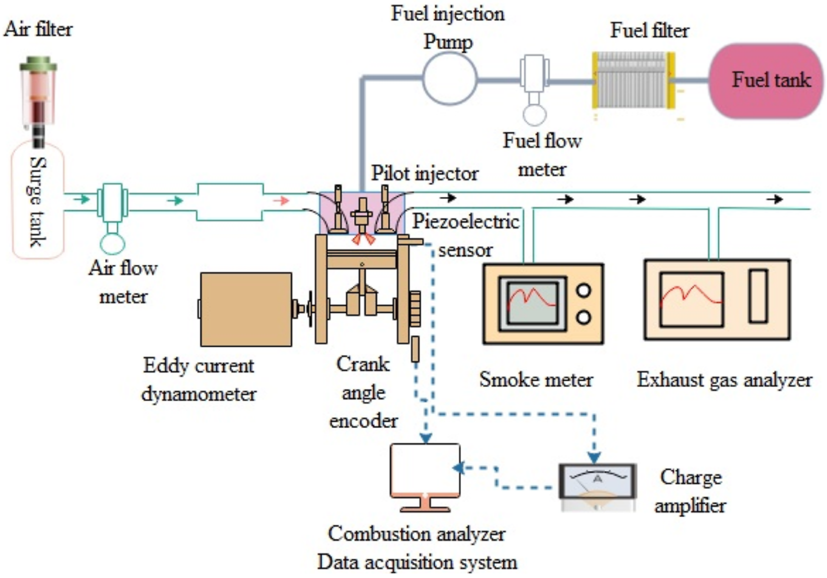

Figure 2. Experimental layout.

Table 3. Experimental Matrix

	microalgal blend													
	biodiesel (%)				diesel (%)				load (%)					
fuel no	0	10	20	30	100	90	80	70	20	40	60	80	100	blend acronym
1	√				√				√	√	√	√	√	diesel
2		√				√			√	√	√	√	√	B10
3			√				√		√	√	√	√	√	B20
4				√				√	√	√	√	√	√	B30

increasing pollution. This is attributed to increasing blend viscosity and poor atomization with the increase in biodiesel content in diesel increased.

2.4. RSM Statistical Analysis. RSM is a popular method for planning experiments and determining the best values of dependent variables by the statistical approach between independent variables. RSM greatly reduces the test experiments and analyze the impact of parameter interaction effects. The CCD is an experimental design system in Design-Expert 12 software. It was used for RSM statistical analysis as it provides precise predictions. The factorial component of the CCD is a complete factorial design with all factor combinations at three levels (high +1, 0, and low 1).In this study, CCD is used to evaluate the impact of performance and exhaust emission metrics. The fuel blend and engine load at five different levels were independent variables. Tables 4 and 5 list the experimental matrix and the software-proposed experimental design, respectively. Model evaluation details are presented in the Table 6.

Table 4. RSM Matrix

		levels		
engine inputs	code	−1	0	1
load (%)	A	20	20	100
blend (%)	B	0	10	30

3. RESULTS AND DISCUSSION

Studies were undertaken to improve engine performance and reduce the emission with diesel and various microalgae blends in CI mode at varying loads while running at a speed of 1500 rpm.

3.1. Performance Characteristics. *3.1.1. Brake Thermal Efficiency.* Brake thermal efficiency is an important engine performance parameter which represents how well the engine transforms the fuel's chemical energy into valuable work output. The observed BTE values for diesel, B10, B20, and B30 were 31.34, 30.7, 31.82, and 30.18%, respectively. Figure 3 illustrates how BTE varies with load for biodiesel and its blends. The BTE for B20 was found to be 1.53% higher than diesel due to the oxygen availability of biodiesel fuel. Increased BTE of B20 may be explained by all of the oxygen that is present in the biodiesel was enhanced the rate of combustion.[24] The greater viscosity of the biodiesel makes it more difficult to inject and atomize the fuel when the blend is increased, which leads to improper combustion and impedes the enhanced use of biofuel.[25] The efficiency is decreased at 100% load because greater energy usage causes a higher rate of combustion and deficient time for absolute combustion.[26] Lower in-cylinder temperature at low load leads to incomplete combustion and consequently lower BTE.[27]

3.1.2. Brake Specific Energy Consumption. The key indicator of performance is the amount of energy used for production of unit power. Figure 4 illustrates how BSEC varies with load for diesel and its blends. It gradually decreases when the load gradually increases. Diesel, B10, B20, and B30 each

Table 5. RSM Proposed Design

std	run	A: load (%)	B: blend (%)	BTE (%)	BSEC (MJ/kW h)	HC (ppm)	CO (% vol)	CO_2 (% vol)	NO_x (ppm)	smoke (opacity %)
1	1	20	0	14.79	16.76	123	0.284	2.61	72	3.4
18	2	20	10	14.25	17.23	125	0.292	2.64	88	4.1
11	3	20	20	15.25	16.47	121	0.274	2.73	113	5.4
17	4	20	30	13.75	17.56	127	0.295	2.5	41	2.4
19	5	40	0	21.7	13.39	106	0.243	3.17	224	7.6
5	6	40	10	21.1	13.8	108	0.251	3.27	245	9.2
7	7	40	20	22.48	13.04	105	0.236	3.39	286	10.3
4	8	40	30	20.25	14.13	111	0.259	3.06	166	6.1
20	9	60	0	27.96	11.14	94	0.201	3.72	386	12.3
2	10	60	10	26.98	11.43	97	0.208	3.83	430	14.5
3	11	60	20	28.89	10.87	92	0.192	3.95	483	16.2
15	12	60	30	26.39	11.65	99	0.218	3.68	332	10.8
16	13	80	0	31.34	10.04	88	0.168	4.06	568	17.5
9	14	80	10	30.7	10.28	90	0.176	4.15	639	18.5
8	15	80	20	31.82	9.7	87	0.163	4.25	698	20.7
12	16	80	30	30.18	10.47	92	0.184	3.99	504	15.4
10	17	100	0	31.16	10.27	91	0.171	3.96	702	20.1
6	18	100	10	30.49	10.55	93	0.179	4.06	751	22.2
14	19	100	20	31.64	9.79	88	0.166	4.12	799	23.7
13	20	100	30	29.82	10.89	95	0.187	3.87	597	17.1

Table 6. Model Evaluation

parameters	BTE	BSEC	HC	CO	CO_2	NO_x	smoke
std. dev.	0.2237	0.0793	0.495	0.0014	0.0233	13.57	0.3891
mean	25.05	12.47	101.66	0.2173	3.55	406.2	12.88
C.V. %	0.8932	0.6357	0.4869	0.6412	0.655	3.34	3.02
R^2	0.9994	0.9995	0.9993	0.9995	0.9992	0.9984	0.9982
adjusted R^2	0.9988	0.9991	0.9986	0.9991	0.9984	0.997	0.9966
predicted R^2	0.9972	0.9978	0.9961	0.9983	0.9939	0.9899	0.9914
AP	116.719	141.41	115.173	134.738	108.359	80.0669	77.9027

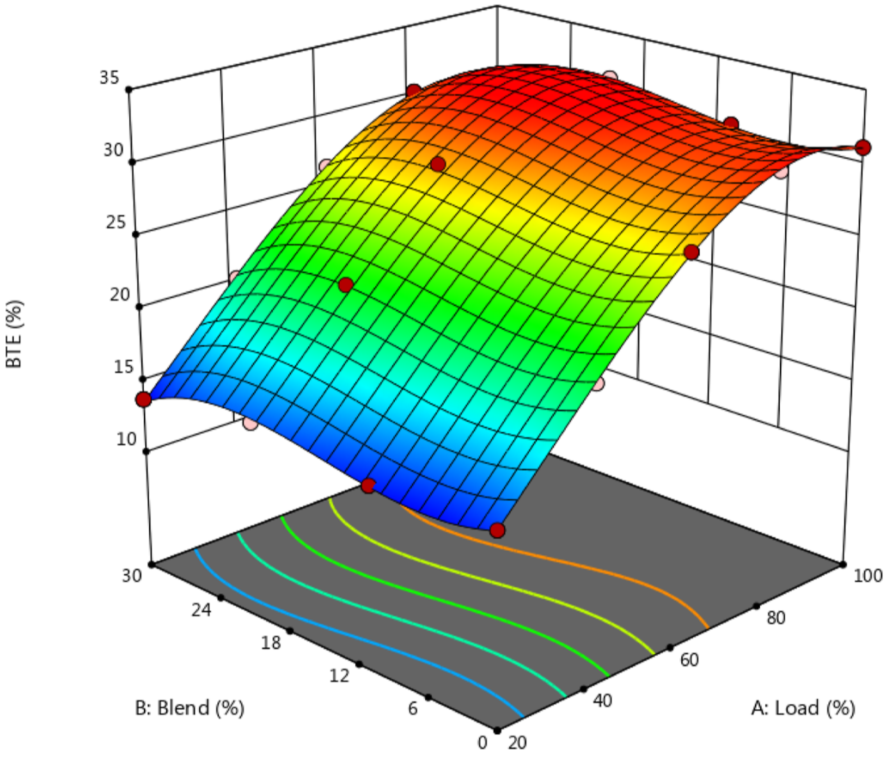

Figure 3. Interactive effect of load and blend with BTE.

showed an average BSEC of 10.04, 10.28, 9.7, and 10.47 MJ/kW h under peak load. In comparison to diesel, the BSEC for B20 was lowered by 3.38%. It was discovered that the higher heating value of biodiesel accounts for its superior combustion contrast to diesel.[28]

3.2. Emission Characteristics. *3.2.1. Hydrocarbon Emission.* Figure 5 displays the HC emission for the diesel and biodiesel blends at different loads. For diesel, B10, B20, and B30, the observed HC emission values were 88, 90, 87, and 92 ppm, respectively, at peak load. In comparison to diesel, the HC for B20 was lowered by 1.08%. The engine load conditions and the A/F ratio have an effect on HC.[29] More fuel was introduced into the combustion at full load, which expanded the quench zone and caused fuel to accumulate in crevices, increasing the formation of HC. At low load conditions, the lean A/F ratio and lower in-cylinder temperature lead to incomplete combustion. The ignition delay, which is the duration of start of biodiesel injection to start of combustion, gets reduced by adding more biodiesel to combustion because biodiesel contains more oxygen, which causes a larger premixed combustion and less HC formation.[30,31] The increasing blend viscosity and poor atomization may be the reason why there was no discernible decrease in HC emissions when the biodiesel concentration was raised above.[32]

3.2.2. Carbon Monoxide. The CO emission exemplifies ineffective combustion. The proper fuel combustion is demonstrated by CO_2 emissions. The release of CO also serves as a further indicator of the fuel's worst chemical reaction. Increasing CO will reduce the CO_2 formation because of a lack of oxygen molecule availability and conversion.[33] Figure 6 depicts how CO and CO_2 contrast with one another with respect to BP. The main causes of CO emissions are fuel heterogeneity, lack of oxygen, succinct burning residence time, and ineffective CO_2 formation.[34] Among other things, the A/F ratio has a significant role in the formation of carbon monoxide.[8] The CO emission was high in the low load states. This might be attributed to lower combustion temperatures and a slower oxidation rate due to the lean air fuel mixture, which results in higher CO emissions. The CO levels for diesel, B10, B20, and B30 were 0.168, 0.176, 0.163, and 0.184% vol, respectively. The CO for B20 was reduced by 2.97% than diesel. The homogeneous fuel condition, enough oxygen, and suffice burning time are the main causes of CO_2 emissions. Among other things, the generation of carbon dioxide is greatly influenced by the air fuel ratio. Diesel, B10, B20, and B30 had CO_2 emissions that were 4.06, 4.15, 4.25, and 3.99% vol, respectively. In comparison to diesel, the CO_2 for B20 was increased by 4.68%. It was identified that B20 exhibits the least

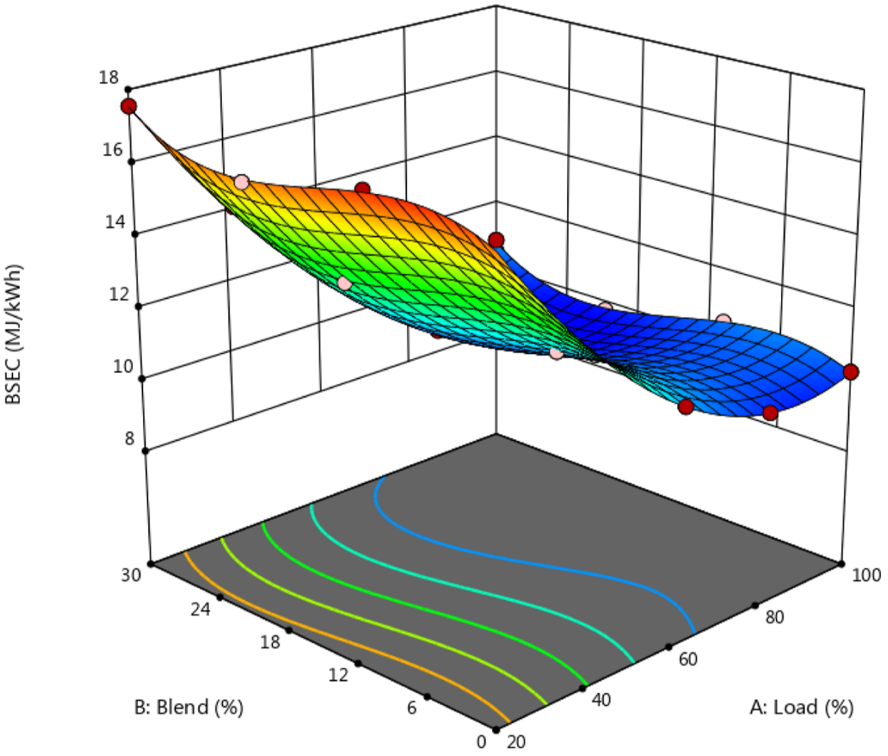

Figure 4. Interactive effect of load and blend with BSEC.

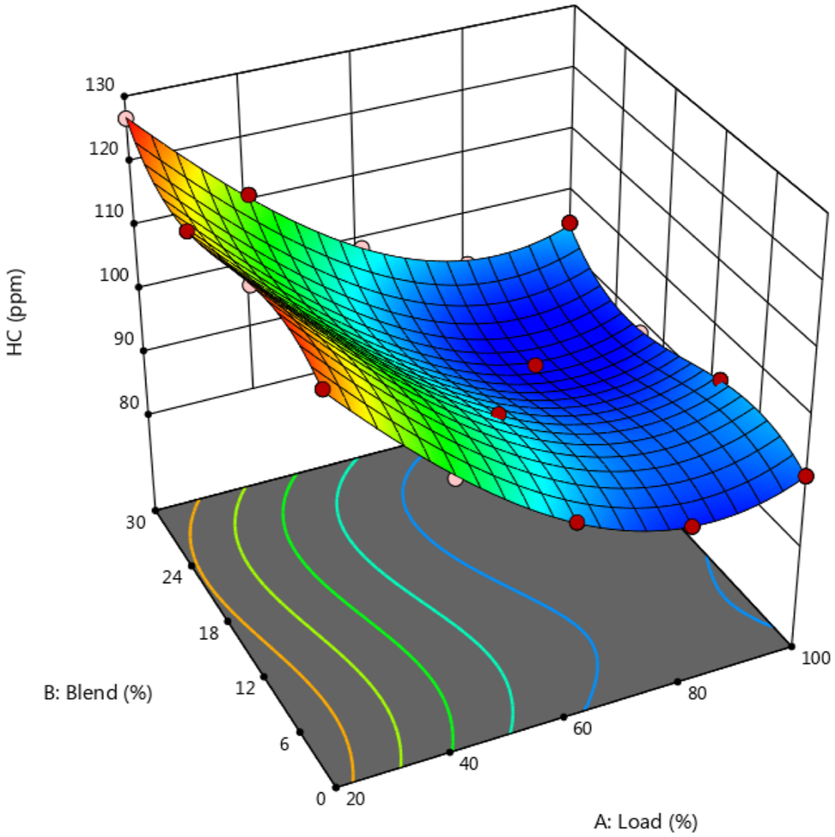

Figure 5. Interactive effect of load and blend with HC emission.

amount of CO emissions. This may be as a result of complete combustion. The addition of biodiesel, which increases the fuel O_2 content, resulted in a higher rate of CO_2 generation.[35]

3.2.3. Nitrogen Oxide. When fossil fuels are burned, three types of NO_x are produced: thermal NO_x, which results from the dissociation and reaction of atmospheric and fuel-bound nitrogen at when combustion temperatures exceed 1300 °C.

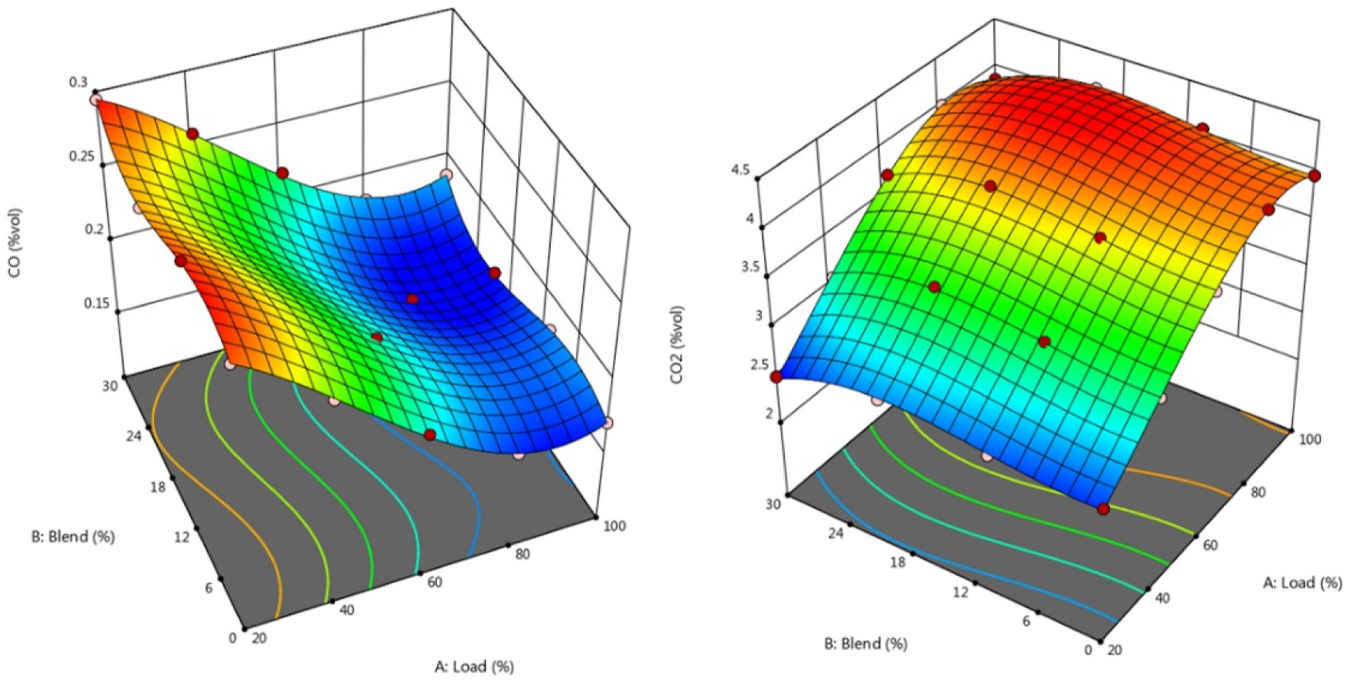

Figure 6. Interactive effect of load and blend with carbon emission.

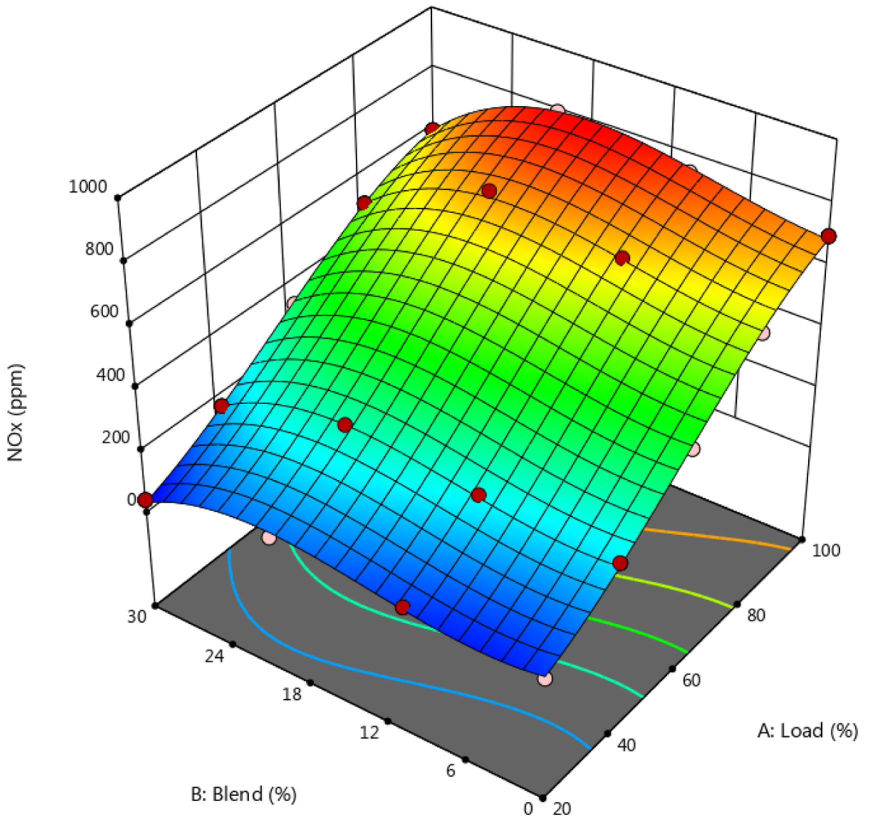

Figure 7. Interactive effect of load and blend with NO_x emission.

Prompt NO_x is produced instantly when CH radicals are present at temperatures well below 1300 °C; fuel NO_x is produced when fuels with chemically bound nitrogen are burned.[36] As the diesel engine combustion zone temperature exceeds 1300 °C, thermal NO_x is significant in CI engine combustion.[37] The prompt NO_x and fuel NO_x formation are irrelevant as the combustion zone temperature is high enough and the nitrogen content in biodiesel fuel is very low. Another significant contributing element to the production of NO_x is the stoichiometric combustion of air-fuel. Higher loads result in more air and fuel mixing, forms stoichiometric mixture, which causes the fuel molecules to burn fully. This raises the temperature within the cylinder, which raises NO_x levels.[38] When the load is decreased, the surplus air mixes with the less fuel and creates a lean mixture,

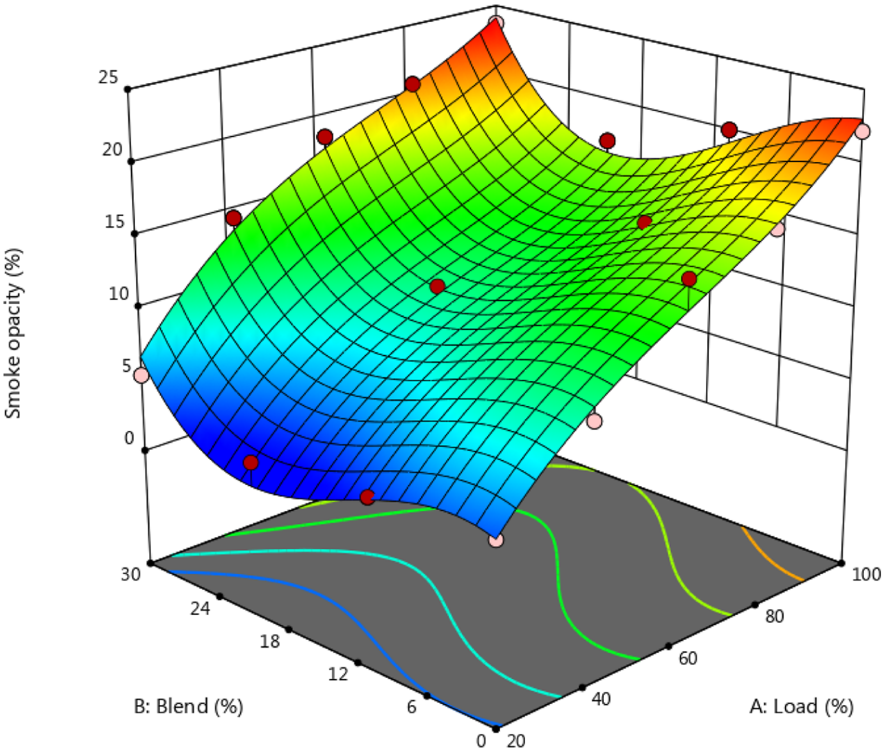

Figure 8. Interactive effect of load and blend with smoke opacity.

Table 7. Optimization Criteria

name	goal	lower limit	upper limit	lower weight	upper weight	importance
A: load	is in range	20	100	1	1	3
B: blend	is in range	0	30	0.1	1	3
BTE	maximize	13.75	31.82	0.1	1	5
BSEC	minimize	9.7	17.56	1	0.1	5
HC	minimize	87.36	126.72	1	0.1	4
CO	minimize	0.163	0.295	1	0.1	4
CO_2	is in range	2.5	4.25	1	1	3
NO_x	is in range	41	799	1	1	3
smoke	minimize	2.4	23.7	1	0.1	3

which results in incomplete combustion without further flame propagation, a lower cylinder temperature, and a reduction in NO_x. NO_x emissions were substantially higher around the peak load area. The variation in NO_x emission for the various test fuels is shown in Figure 7. Diesel, B10, B20, and B30 were found to emit 568, 639, 698, and 504 ppm of NO_x, respectively. In comparison to diesel, the NO_x for B20 was increased by 22.88%. The most significant occurrence of NO_x emissions was found for B20. This may be the outcome of complete combustion, which promotes the production of more NO_x. This can be explained by the use of additional oxygen in biodiesel to improve combustion.[39]

3.2.4. Smoke Opacity. Smoke opacity is a sign of dry soot emissions, which are the major particulate matter constituent. The opacity is the measure of extinction of light between a light source and a receiver for an effective length. The reduced smoke opacity may be explained because fuel oxygen decreases the likelihood of rich zone formation and promotes the oxidation of soot nuclei during fuel combustion.[40] The primary cause of smoke opacity production is typically poor combustion based on an excessively rich or lean mixture. This may be addressed by increasing the amount of O_2 molecules in the chamber, which leads to improved combustion.[24,41−43] Variability in smoke opacity for the tested fuels is shown in Figure 8. The study concluded that smoke emissions increased as engine load increased from idle to maximum condition. Smoke opacity measurements for diesel, B10, B20, and B30 were 17.5, 15.4, 10.8, and 20.7%, respectively. In comparison to diesel, B20 smoke opacity was lowered by 38.28%.

3.3. RSM Analysis. *3.3.1. Optimization Criteria.* It is crucial to optimize the biodiesel blend parameters based on their influence on effects of the outcomes and their significance. The optimization criteria, together with their lower and upper limits, importance, and weight applied based on enhancement of engine performance, are displayed in Table 7. The weight varies from 0.1 to 1. One denotes an objective that is more significant, whereas a weight of less than one denotes an objective that is less essential. From one trait to the next, others are more or less important than others.

3.3.2. Experimental Validation. These solutions led to the discovery that an operation that produced 25.664% biodiesel had 97% desirability. RSM optimization ideal blend validation was done for the blend B25 at 85% load. The reliability of optimized solutions is verified by experimental analysis, and error % is calculated. Table 8 and Figure 9 demonstrate that the percent errors of the selected solution are within the acceptable range and demonstrating the accuracy of the anticipated model.

Table 8. Experimental Validation

engine parameters	RSM prediction	experimental result	deviation	error (%)
load (%)	85.874	85	0.87	1.02
blend (%)	25.664	25	0.66	2.59
BTE (%)	32.043	31.42	0.62	1.94
BSEC (MJ/kW h)	9.729	9.61	0.12	1.22
HC (ppm)	87.435	85	2.44	2.78
CO (ppm)	0.162	0.158	0.004	2.47
CO_2 (ppm)	4.195	4.115	0.08	1.91
NO_x (ppm)	659.255	691	31.75	4.82
smoke (N)	11.23	10.73	0.50	4.45

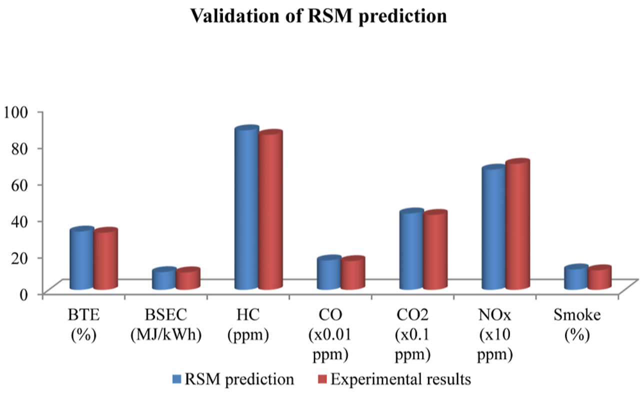

Figure 9. Variation of RSM prediction with experimental values.

4. CONCLUSIONS

The 25.66% microalgal−biodiesel blend is identified as the optimal mixture by the RSM statistical approach using the experimental findings for CI engine operation at 85.9% load condition with consideration of the weightages of each performance and emission parameters.

The following conclusions from the study are drawn:

- For the B20 microalgae blend had performance of 1.53% higher BTE, 3.38% lower BSEC, and emission parameters HC, CO, CO_2, and smoke were reduced 1.08, 2.97, 4.67, and 38.28%, respectively, while 22.88% increased NO_x than diesel.
- Using the RSM approach, the optimal microalgal energy ratio was identified based on optimization criteria. Statistical results show that 25.664% biodiesel at 85.874% load had 97% desirability.
- For the B25 microalgae blend had better performance of 31.42% BTE, 9.61 MJ/kW h BSEC, and emission parameters HC, CO, CO_2, NO_x, and smoke opacity were 85 ppm, 0.164% vol, 4.115% vol, 691 ppm, and 10.73% at 85% load. Obtained result was better than the neat diesel and B20 at 80% load.
- The predicted values were validated by experimental studies, and the percentage error was within the acceptable range. The model predicted is accurate and can be used for further studies.

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Notes

The authors declare no competing financial interest.

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