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Optimization of Performance and Emission Parameters of a CI Engine Fueled with Waste Cooking Oil Biodiesel Using Response Surface Methodology (RSM)

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Abstract

Interest in biofuels and other alternative fuels has grown due to environmental concerns and the rising demands and costs of traditional liquid fuels. This study evaluated the biodiesel's engine emissions and performance indicators prepared from waste cooking oil. A regression model, Box Behnken Design (BBD), was used for the multi-response optimization of various input parameters, i.e., load, blend, and preheating temperature, to enhance engine performance and the optimization of emissions. The performance metrics examined included brake specific fuel consumption (BSFC), brake thermal efficiency (BTE), while emissions included carbon dioxide (CO2), carbon monoxide (CO), nitrogen oxides (NO_x), and unburned hydrocarbons (UBHC). The highest desirability score of 0.724 was achieved with the combination of B23, a load of 57%, and a preheating temperature of 62°C, which was also validated with an error margin of less than 5%. Optimized results showed a 5.88% decrease in BSFC and a 0.84% increase in BTHE. Furthermore, CO2 and NOx emissions were increased by 9.73% and 2.88% respectively; however, emissions of CO and UBHC were reduced by 25% and 54% respectively.

1. Introduction

The global demand for energy is increasing due to several factors, including industrialization, growing populations, and urbanization [1]. According to a report published by the International Energy Agency [2], global energy demand increased by 2.2% in 2024, that is relatively faster than the average growth rate of the past decade. Furthermore, fossil fuels contributed for 54% of total global energy consumption in 2024, despite significant advancements in renewable energy sources. The International Energy Agency [2] has predicted that the demand for oil, gas, and coal will peak before 2030. In 2024, the contributions of various energy sources to global energy supply are projected to be as follows: renewable energy at 38%, natural gas at 28%, coal at 15%, oil at 11%, and nuclear power at 8%. This data highlights the growing interest in renewable energy sources over the past decade [2]. The shift towards alternative fuels such as biodiesel, hydrogen, and synthetic fuels etc is crucial for long-term sustainability, climate goals, to reduce greenhouse gas emissions, and decrease dependence on fossil fuels. Biofuels have the potential to significantly reduce greenhouse gas emissions and other indicators of pollution compared to fossil fuels. Additionally, biofuels offer several advantages, including biodegradability, low operational costs, and renewability [3]. The production of biodiesel from waste cooking oil (WCO) not only provides substantial environmental benefits by decreasing reliance on virgin vegetable oils and fossil fuels but also promotes effective waste management through the recycling of oils [4]. WCO is an excellent raw material for biodiesel production due to its availability at minimal or no cost, as it can be easily sourced from restaurants and food processing units [5]. In recent years, numerous theoretical and experimental studies have been conducted on biodiesel production. Blending biodiesel with conventional diesel fuel can lead to a notable reduction in various exhaust emissions, such as carbon dioxide. However, some studies have observed that the use of biodiesel can significantly increase other exhaust emissions, such as carbon monoxide (CO) and hydrocarbons (HC). This highlights the need for further research and technological development to address these issues [6]. The utilization of Waste Cooking Oil (WCO) as a biodiesel feedstock has gained considerable attention due to its environmental advantages and cost-effectiveness, but optimizing its application in diesel engines requires a detailed understanding of various operational parameters. A study on mixed biodiesel from canola, safflower, and waste vegetable oils employed RSM to optimize engine parameters, identifying optimal conditions at a load of 1484.85 W, injection pressure of 215.56 bar, and 25.79% biodiesel blend. This configuration achieved a BTE of 20.54%, with NOx emissions recorded at 558.44 ppm and an exhaust gas temperature of 199.88 °C, demonstrating the robustness of the models with high R^2 values exceeding 98% [7]. Another investigation into sunflower-soybean biodiesel, produced through transesterification, determined an optimal blend of 70% biodiesel at a 2.05 kW load, yielding a BTE of 13.656%, NOx at 234.89 ppm, and UHC at 120.77 ppm, with error rates below 5% validating the improved environmental profile associated with higher biodiesel concentrations [8]. Additionally, a study evaluating biodiesel made from canola, safflower, and WCO with varying levels of an EHN additive optimized to 100% biodiesel, 1.1% EHN, and 1515 W load, achieved a BTE of 19.782%, BSFC of 385.79 g/kWh, and NOx emissions of 436.95 ppm, confirming the beneficial role of EHN in reducing emissions [9]. The potential of cassia tora biodiesel in a direct injection diesel engine was evaluated using central composite rotating design, resulting in an optimal configuration of a 40% blend, 221 bar pressure, 15° BTDC, and 47% load, maximizing BTE while minimizing NOx and UHC [10]. Bio-oil blends derived from waste biomass were similarly optimized, revealing that a 20% bio-oil blend, with an 18:1 compression ratio at full load, minimized emissions and maximized BTE, with validation error rates under 5%, pointing to bio-oil's promise for sustainable engine operation [11]. Karanja biodiesel blends of 20%, 25%, and 30% tested across multiple compression ratios found a 25% blend at 18:1 CR to be optimal for reducing emissions and fuel consumption, confirmed by experimental analyses that highlighted significant performance improvements over standard diesel [12]. Moreover, waste soybean oil biodiesel blends of 20–35% with up to 15% EGR demonstrated optimal results at B35EGR15, which reduced smoke by 19.09% and NOx by 59.04%, albeit with a 5.3% drop in BTE, while achieving a 23.34% cost reduction in operation, indicating the economic viability of WSCO blends in conventional diesel engines [6]. Further, Garcinia Indica-derived biodiesel optimized using RSM and teaching-learning-based methods produced a promising result of 27% BTE with minimal emissions, showcasing the potential of underutilized feedstocks for greener fuel [13]. Several studies have used statistical techniques to optimize biodiesel production and engine performance. S. V. Kodate et. al. [14] optimize engine load and biodiesel blend percentages, resulting in enhanced BTE and reduced CO and HC emissions. Preheating biodiesel can improve its physicochemical properties, leading to better combustion. T. Yuksel [15] demonstrated that preheating WCO biodiesel enhances engine performance and reduces emissions. Kodate et. al. [16] observed that preheated biodiesel blends improved BTE, it also led to higher NO_x emissions. This trade-off underscores the need for multi-response optimization strategies to balance performance and environmental concerns. Optimizing engine performance often impacts emission characteristics. While individual parameters have been studied extensively, integrated optimization considering blend ratio, engine load, and preheating temperature is limited. Such comprehensive studies are crucial for developing practical guidelines for biodiesel usage in diesel engines. Therefore, the combined effects of preheating with varying blend ratios and engine loads require further exploration. Table-1 provides a summary of various research studies for multi-response optimization for engine performance and emissions. (Table 1)

Table 1 Summary of Various Research Studies for multi-Response Optimization for Engine Performance and Emissions

Study	Fuel Type	Blend (v.%)	Load (%)	Preheating Temp (°C)	Key Findings
[14]	Vateria indica methyl ester blends	B30	100	95	↑ BTE by 9.7%, ↓ BSFC by 8.9%, ↓ CO by 16.2%, ↓ HC by 34.4%, ↑ NO_x by 12.9%, ↑ CO_2 by 17.7%,
[16]	KOME	B30	100	95	↑ BTE by 2.9%, ↓ BSFC by 5.1%, ↓ CO by 1.11%, ↓ HC by 2.5%, ↑ NO_x by 1.2%, ↑ CO2 by 2.3%,
[15]	Arlic methyl ester fuels	B20	------	70	↑ BSFC by 3.0%, ↓ CO by 9.9%, ↓ HC by 10.7%, ↑ NO_x by 8.6%, ↑ CO2 by 4.4%,
[17]	waste animal fat-oil	------	25-100	60-120	↑ BTE by 4.13%, ↓ BSFC by 3.71 %, ↓ CO by 14.08%, ↑ HC, ↑ NO_x by 14.39%, ↑ CO2 by 12.92%,
[18]	Waste cooking oil methyl ester	B20	66 and 100	100-250	↑ BTE by 6.15%, ↓ BSFC by 5.4 %, ↓ CO by 38%, ↑ HC by 25.5%, ↑ NO_x by 4-6%
[19]	virgin sunflower oil	B100	100	70	↑ in BTE by 5%, ↓ in BSFC ↑ in performance, ↓in CO by8.16%, ↓ in HC by 6.13%
[20]	Jatropha biodiesel	B100	75	40	↑ in BTE by 2%, ↓ in BSFC by 2%, ↓in CO by51%, ↓ in NOx by 7%

The following are the major research gaps identified from the systematic literature review:

- There is a significant lack of comprehensive optimization studies involving blend ratio, load, and preheating temperature for Waste Cooking Oil (WSO) biodiesel using statistical techniques.
- The relationship between improving engine performance and reducing harmful emissions under optimal conditions requires further exploration.
- The impact of fuel preheating on enhancing combustion efficiency and reducing emissions in WCO blends has not been adequately addressed.
- A more detailed analysis is needed on the interactions between increased CO_2/NO_x emissions and improvements in Brake Thermal Efficiency (BTE) and Brake Specific Fuel Consumption (BSFC) under optimized conditions is needed.

1.1. Motivation and Novelty

The Biodiesel WCO is a promising solution for waste management and provides an alternate low-cost energy source. However, optimizing the engine performance and emissions in internal combustion engines fuelled with WCO biodiesel is crucial and motivates us. This study evaluates and optimizes engine parameters to enhance efficiency and minimize emissions by employing RSM statistical modelling. The optimization technique BBD is used to identify optimal conditions for using biodiesel to contribute to sustainable energy sources and environmental preservation. The rest of the manuscript is structured as follows: Section 2 discusses the methodology, Section 3 presents the findings from the experiments conducted, and Section 4 summarizes the research work along with suggestions for future research.

2. Materials and Methodology

This section outlines the materials used and the methodology adopted for the present study. All experiments were conducted using standardized procedures to ensure reliability. A detailed description of the preparation of test fuels, the experimental setup and specifications, the designer of the heat exchanger, the statistical techniques used to optimize, and the analysis conducted.

2.1. Preparation of Test Fuels

In the preparation process for test fuels, the waste cooking oil (WCO) is transformed into biodiesel through transesterification. Triglycerides in waste cooking oil (WCO) react with methanol, ethanol, and catalyst, usually sodium or potassium hydroxide. The chemical reaction process produces two main products: Esters, which is the biodiesel, and glycerol which is the by-product. Transesterification lowers the viscosity of the waste cooking oil, which is essential to improve fuel properties, which are vital for better engine performance. The resulting biodiesel was tested to meet the fuel quality standards set such as ASTM D6751 and EN 14214 [21]. The biodiesel was blended with conventional diesel in various ratios labeled B10, B20, B30, B40, and B50, which, indicate the blends contain 10% to 50% biodiesel by volume. Further, the blended fuel was stored properly before it was tested in the engine, ensuring that biodiesel remained effective. Figure 1 shows the complete process of preparing the test fuels.

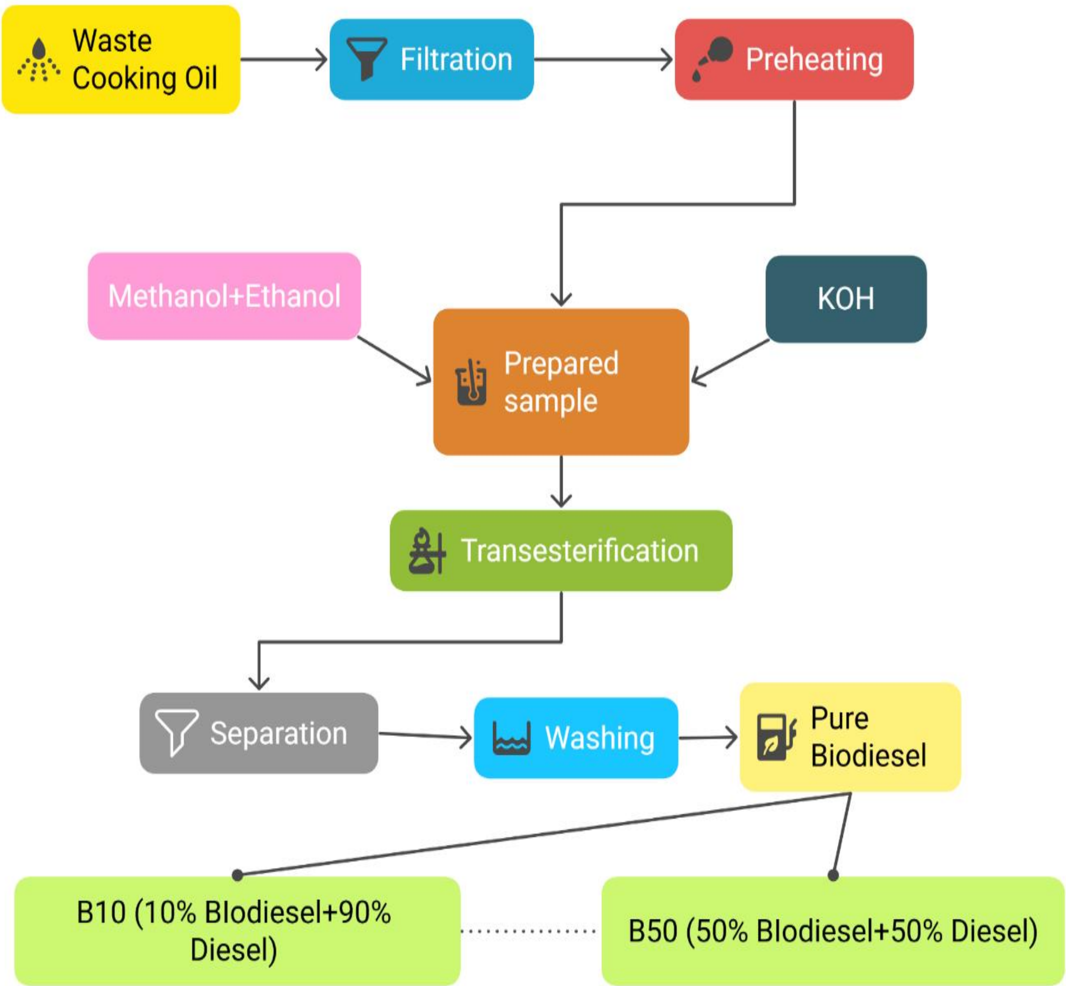

Figure 1 Biodiesel Transesterification Process

2.2. Experimental Setup and Specifications

In this study, a micro-cogeneration system was utilized, featuring a 7 HP single-cylinder four-stroke compression ignition (C.I.) engine. To manage the engine load, an eddy current dynamometer was employed. Fuel consumption was monitored using a gasoline burette and a stopwatch, ensuring that all measurements were taken under stable conditions. During testing, the engine operated at a compression ratio of 17.5:1 and at a speed of 1500 rpm. Data was collected through a data acquisition system in conjunction with IC engine software, version 9.0. To assess the environmental impact, exhaust emissions were analysed using an AVL 444 N multi-gas analyser. to assess the environmental impact. (Figure 2)

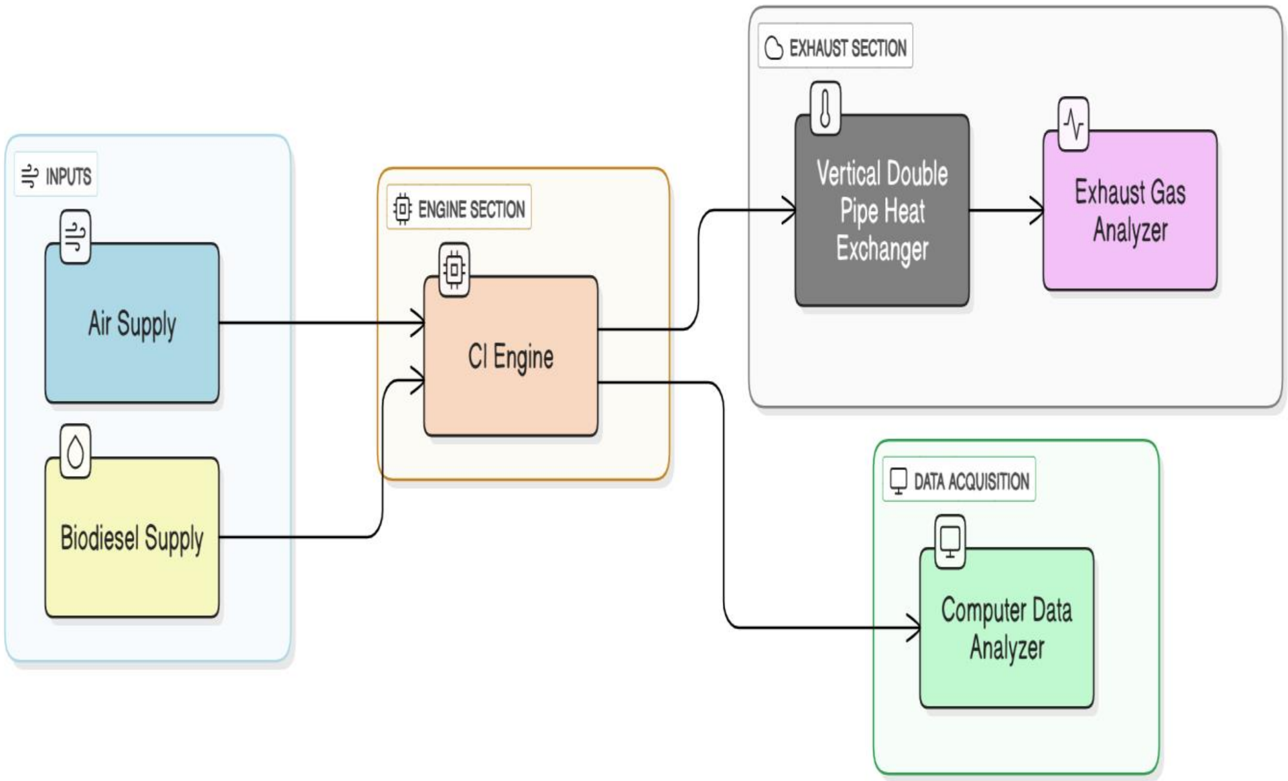

Figure 2 Experimental Setup Block Diagram

2.3. Double Pipe Heat Exchanger

A double-pipe heat exchanger was utilized to extract heat from hot gases in a combined heat and power (CHP) system specifically designed to heat biodiesel blends. This heat exchanger consists of two concentric circular pipes, along with fins that enhance heat transfer efficiency. The diameter of the inner pipe is 38 mm, while the outer pipe measures 101 mm. To monitor the process effectively, thermocouples are strategically placed at different locations to measure the temperatures of both the biodiesel and the exhaust gases during operation. The setup allows for precise control and optimization of the heating process, ensuring efficient energy use. An illustration of the double-pipe heat exchanger used in this study is shown in Figure 3. Overall, this design not only improves energy recovery but also contributes to the enhance engine performance and optimum emissions in a sustainably. (Figure 3)

2.4. Optimization of Experimental Design

Internal combustion engines operate with various input parameters, making their interaction analysis both complex and time-intensive. By combining numerical modelling with experimental data, the usefulness of Response Surface Methodology (RSM) in experimental research can be increased. RSM serves as a statistical method for optimizing scenarios influenced by multiple factors, including blend ratio, preheating temperature, and engine load. This research examined five different biodiesel blends (B10, B20, B30, B40, and B50) using a micro-cogeneration compression ignition (CI) engine, where air and heated biodiesel were introduced to enhance combustion efficiency. The experimental methodology involved optimization using Response Surface Methodology (RSM). Initially, a design of experiments (DoE) was developed to determine the number of experimental runs and the levels of input parameters, particularly focusing on various biodiesel blends (B10, B20, B30, B40, B50), as shown in (Table 2)

Figure 3 Fabricated Heat Exchanger

Table 2 Factors Considered for Design of Experiment by RSM

Factors	Symbol	Coded Factor level		
		-1	0	+1
Load (%)	(A)	20	60	100
Blend (%)	(B)	10	30	50
Preheating Temperature (^{0}c)	(C)	40	60	80

These blends were preheated using a dedicated module and supplied, along with air, to a micro-cogeneration compression ignition (CI) engine. During engine operation, performance parameters (such as efficiency and power output) and emission parameters (such as CO, NOx, and HC levels) were recorded. The collected experimental data was then used to generate a statistical model. (Figure 4) The adequacy of the model was assessed through a fit summary. If the model was found to be inadequate, the experiments were repeated. Once a satisfactory model was achieved, ANOVA analysis was performed to evaluate its significance. Following this, optimization was conducted to determine the most desirable input conditions, which were then validated through experimental testing. Finally, the optimized results were compared to those obtained from conventional diesel in order to evaluate improvements in both performance and emissions. The optimization process aimed to identify the best combination of input parameters that delivered optimal performance with minimal emissions. The optimized results were then compared to conventional diesel results.

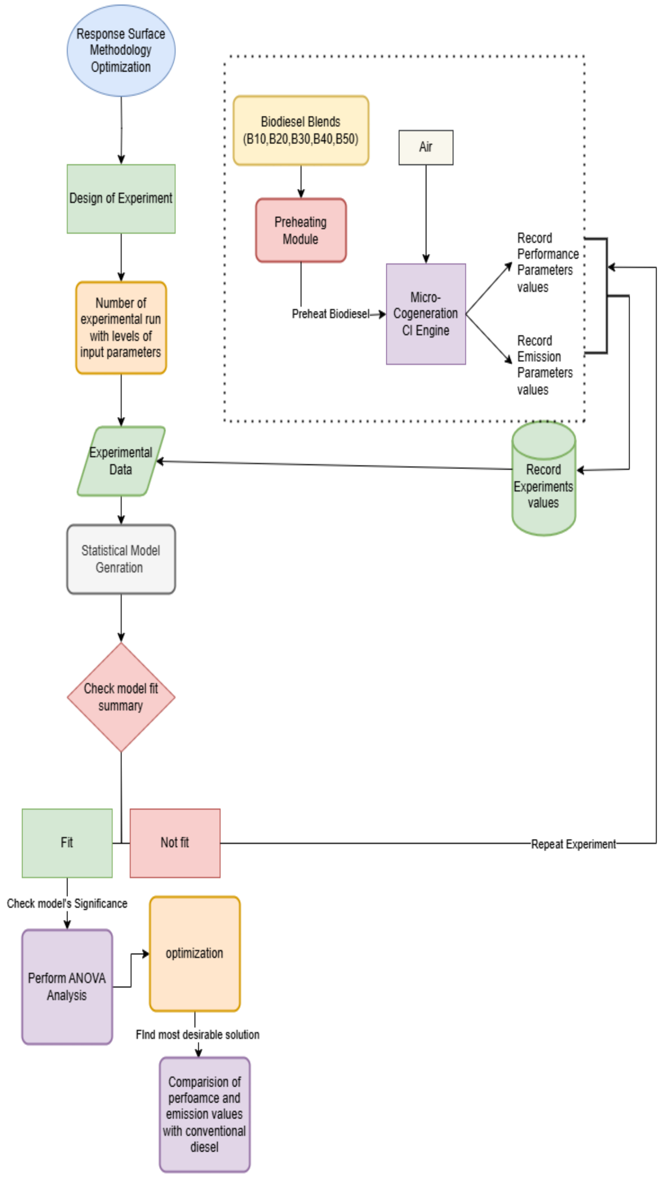

Figure 4 Flowchart Illustrating the Experimental Methodology for Optimization of Biodiesel Blend Performance and Emissions Using Response Surface Methodology (RSM)

3. Results

3.1. Response Surface Methodology

RSM is used to optimize response parameters. The biodiesel blend, biodiesel preheating temperature, and engine load were chosen as input parameters in this study because these have an impact on the performance and emission parameters of the ci engine. In this section, the Design Expert 9.0 software by Stat-Ease was utilized to analyze engine input parameters and reaction parameters. A regression model developed using the Box-Behnken Design (BBD) approach was employed to investigate the properties of diesel engines. To achieve the desired response parameters, the optimization of input parameters was performed, and ultimately, a comparison was made between the same responses and traditional diesel.

3.2. Design of Experiment

The design of the experiment is crucial and the first step towards the analysis of input parameters and responses using RSM. A total of 18 experiments was designed to analyze the effect of input parameters on the performance and emission parameters of the engines. According to given set of equation

Number of Run= 2n (n-1) + CP

where n represents the number of parameters studied, and CP stands for replicas of central points. As per requirement, there are three factors that are described in Tables 1 and 6 central points, so according to BBD, 18 trials were generated to generate a statistical model to analyse further.

3.3. Statistical model

In this section, a statistical model was developed using a set of data obtained through experimentation. A regression model was generated for each response. The significance of the model was validated using statistical parameters such as R^2, adjusted R^2, and predicted R^2. The accompanying Table 3 provides a summary of the fit for all responses, confirming the significance of the models.

Table 3 Statistical Parameters of Model Generated by RSM

Response parameter	R^2	Adjusted R^2	Predicted R^2	Model suggestion
Brake thermal efficiency (BTHE)	0.9997	0.9994	0.9964	Quadratic
Brake specific fuel consumption (BSFC)	0.9967	0.9931	0.9686	Quadratic
Unburnt hydrocarbon (UBHC)	0.9909	0.9806	0.9038	Quadratic
Carbon Mono-dioxide (CO)	0.9980	0.9958	0.9758	Quadratic
Carbon di oxide (CO_2)	0.9995	0.9989	0.9942	Quadratic
Oxides of nitrogen (NOx)	0.9999	0.9998	0.9993	Quadratic

3.4. ANOVA Analysis

ANOVA analysis was done to check the model's significance and this also suggest the order in which input parameters affects the responses (Table 4)

Table 4 ANOVA Analysis of Response Parameters

Parameters	SS	DOF	MS	F-value	P-value	SS	DOF	MS	F-value	P-value	
	BTHE					BSFC					
Model	405.93	9	45.01	2975.69	<0.0001	0.2448	9	0.0272	271.98	<0.0001	Significant
A-load	245.31	1	245.31	16184.37	<0.0001	0.1513	1	0.1513	1512.50	<0.0001	
B-blend	1.06	1	1.06	69.84	<0.0001	0.0018	1	0.0018	18.00	0.0028	
C-Temp	0.3655	1	0.3655	24.11	0.0012	0.0005	1	0.0005	4.50	0.0667	

	NOx					CO					
Model	1211000	9	134555	11389.40	<0.0001	0.9100	9	0.1011	499.23	<0.0001	Significant
A-load	1113000	1	1113000	94224.93	<0.0001	0.5724	1	0.5724	2826.46	<0.0001	
B-blend	2450	1	2450	207.41	<0.0001	0.0007	1	0.0007	3.48	0.0990	
C-Temp	4140.50	1	4140.50	350.52	<0.0001	0.0031	1	0.0031	15.24	0.0045	
	UBHC					CO_2					
Model	2907.75	9	323.08	96.62	<0.0001	108.27	9	12.03	1765.55	<0.0001	Significant
A-load	2346.13	1	2346.13	701.64	<0.0001	104.33	1	104.33	15312.01	<0.0001	
B-blend	55.13	1	55.13	16.49	0.0036	0.0036	1	0.0036	0.5302	0.4873	
C-Temp	84.50	1	84.50	25.27	0.0010	0.1105	1	0.1105	16.21	0.0038	

ANOVA is capable of identifying the significance of input parameters, and it can also show the significance of the interaction of input parameters, which helps to make data-driven decisions. The statistical significance of input parameters was shown using the P-value and the order in which input parameters have an impact on the response decided by the F-value. [[23] [24]]. Table 4 shows the ANOVA analysis of all response parameters. For BTHE & BSFC, load is the most influential input parameter, followed by blend and preheating temperature. for emission parameters, load is the most influential input parameter, followed by preheating temperature and blend percentage.

3.5. Optimization

Multi-response optimization is based on the desirability approach. The primary objective for all responses was to find an optimized solution that maximizes Brake Thermal Efficiency (BTHE) while minimizing Brake Specific Fuel Consumption (BSFC), carbon monoxide (CO), hydrocarbons (HC), carbon dioxide (CO2), and nitrogen oxides (NOx). The chosen optimized results produced the highest desirability score of 0.707. The optimized results of all responses for the value of input parameters are shown in Table 5. This also shows a comparison of the optimized result of response parameters with conventional diesel in the same condition.

Table 5 Optimized Results

	Load (%)	**Blend (%)**	**Preheating Temperature (^{0}c)**	**BTHE (%)**	**BSFC (kg/kW.h)**	**CO (%)**	**UBHC (ppm)**	**CO_2(%)**	**NOx(ppm)**
Optimized RSM input	57.03	23.15	62.27	25.23	0.32	0.03	22	7.22	926
Diesel	60	-	-	25.02	0.34	0.04	48	6.58	900

For the input data, the optimum experimental results compared to the diesel results show the following improvements: Brake Thermal Efficiency (BTE) increased by 1.92%, Brake Specific Fuel Consumption (BSFC) decreased by 5.89%, Carbon Monoxide (CO) emissions dropped by 25%, and Hydrocarbon (HC) emissions were reduced by 54%. However, Nitric Oxide (NOx) emissions increased by 3.89%. Therefore, with the optimum input data, there is a notable reduction in HC and CO emissions alongside a slight rise in NOx and CO2 emissions. Additionally, BSFC decreased while BTHE showed a marginal increase. The table presents a comparison of this study with similar work conducted in the past. Table 5 shows Optimized Results

Table 6 Research Work

Load	Blend	Preheating Temperature	BTHE	BSFC	CO	HC	CO_2	NOx	Desirability	References
57.031	23.15	62.27	25.23	0.32	0.03	22	7.22	926	0.724	This work
70	9	-	20	0.307	-	12	9	209	0.73	[25]
100	16	-	19.60	0.330	0.06	0.8	0.80	140.85	0.587	[26]
48	100	-	21.35	--	0.04	49.47	--	525.43	0.77	[27]

Conclusion

This study successfully demonstrated that biodiesel produced from waste cooking oil (WCO) can serve as a viable alternative fuel for compression ignition (CI) engines. By utilizing response surface methodology (RSM) for optimization, the research analyzed diesel-WCO blends, focusing on variable loads, blend ratios, and preheating temperatures. To strengthen the findings, future research could include optimizing diesel-WCO blends using Box-Behnken Design and comparing the optimized results with conventional diesel under equivalent conditions without preheating. The investigation revealed that the statistical model created through RSM-BBD was validated with high accuracy as indicated by R^2 values for various response parameters, including Brake Thermal Efficiency (BTHE), Brake Specific Fuel Consumption (BSFC), unburned hydrocarbons (UBHC), carbon monoxide (CO), carbon dioxide (CO_2), and nitrogen oxides (NOx). The RSM desirability method achieved a desirability value of 0.707, leading to optimized conditions that highlighted significant performance improvements – specifically, a 5.89% decrease in BSFC and a 1.92% increase in BTE, alongside considerable reductions in CO and HC emissions. These findings indicate that the eco-friendly preheated WCO blend could effectively replace conventional diesel fuel, enhancing performance while reducing emissions and addressing energy crises. Moreover, the recycling of waste cooking oil contributes to lower greenhouse gas emissions, prevents pollution, and supports renewable energy initiatives, offering substantial environmental and societal benefits. To further commercialize these findings, additional tests with antioxidant additives, real-world driving conditions, and the integration of hybrid systems or after-treatment technologies could enhance emission reductions and energy efficiency in compression ignition (CI) engines, creating a pathway for a more sustainable future.

Declaration of Competing Interests

The authors declare that they have no known financial conflicts of interest or personal relationships that could have influenced the work reported in this paper.

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