Date of publication March 05, 2025, date of current version March 05, 2025.
Digital Object Identifier 10.21608/pesj.2025.354280.1015

Influence of Diesel Engine Load, Waste Cooking Oil Biodiesel Blend Percentage, and Nanoparticles Concentrations on Brake Thermal Efficiency and NOx Emissions Using Response Surface Methodology

Medhat Elkelawy[1, 2], Hagar Alm-Eldin Bastawissi [2], and Mahmoud Shams [2]
[1] Mechanical engineering department, Faculty of Engineering, Pharos University in Alexandria, Alexandria, Egypt
[2] Department of Mechanical Power Engineering, Faculty of Engineering, Tanta University, Tanta, Egypt
Corresponding author: Medhat Elkelawy (medhatelkelawy@f-eng.tanta.edu.eg).

Abstract: The depletion of fossil diesel fuel presents a significant challenge due to the rising global energy demand. The waste cooking oil (WCO) usage as a biodiesel resource offers a promising approach to address both the energy shortage and emissions concerns associated with fossil diesel. In this manuscript, we investigate the influence of diesel engine load, WCO biodiesel blend percentage and concentrations of nanoparticles on the diesel engine brake thermal efficiency (BTE) and NOx emissions of a single cylinder diesel engine rotates at 1400 rpm speed. The nanoparticles used include multi-walled carbon nanotubes (MW-CNTs) and graphene oxide (GO), each tested at various concentrations are 50, 100, and 150 ppm, dispersed in the fuel using 4% toluene as a surfactant. The experimental study is designed to predict and optimize BTE and NOx emissions using Response Surface Methodology (RSM). The study examines three cases: (1) without nanoparticles, (2) with MW-CNTs, and (3) with GO nanoparticles. Optimum percentage of BTE is 18.97% at load 2.47 kW, WCO biodiesel blend of 3.63%, and GO nanoparticles concentration of 50 ppm. The lowest NOx emissions of 506.45 ppm occurred at load of 2.40 kW, a WCO biodiesel blend of 16.96%, and a MW-CNT concentration of 100.50 ppm. These results confirm that the addition of MW-CNTs or GO nanoparticles enhances engine performance and reduces NOx emissions, demonstrating their efficacy in improving the sustainability of biodiesel blends.

Keywords: Waste Cooking Oil Biodiesel, MW-CNTs, Graphene Oxide, Brake Thermal Efficiency, NOx Emissions, Response Surface Methodology (RSM)

I. INTRODUCTION

Diesel engines have large importance due to their incorporation in different industrial applications[1].Most of governments now established stringent rules to organize and reduce the pollution of the environment [2-8]. Because of fossil fuels depletion, now the global demand for the alternative fuels is on the rise [9-15]. Now, all governments enforce the universities and the academic institutions to perform researches and experimental studies replacing the fossil fuels by the alternative fuels [16-20]. The primary goal of the alternative fuels is to mitigate pollution caused by internal combustion engines in addition enhance their performance and facilitate the broader adoption of renewable energy sources[8]. Due to the emissions that can be generated by using fossil diesel fuels in diesel engine operation, biofuels can be used as a fuel partially or totally [21-25]. The main barriers for substituting fossil fuel with biofuels are the production cost also the edible resources that may distress the food suppliers [26-29].

Waste cooked oil (WCO) biodiesel is a monoalkyl ester that has characteristics mostly like the fossil diesel fuel for example Cetane number, calorific value and flash point [30-36]. WCO can be converted to biodiesel by one of the following chemical process micro-emulsion, dilution, pyrolysis and transesterification [37-41]. Transesterification is the most used method to convert WCO to WCO biodiesel and glycerol than used in cosmetics. Sodium hydroxide (NaOH) is used a catalyst to speed the reaction. Transesterification consists of the reaction, separation and washing steps. The reaction step includes mixing the oil with methanol and NaOH then heating for an hour at 65 °C. The separation step is leaving the mix for 24 hours to guarantee the separation of WCO biodiesel from the glycerol. Finally, the washing step for the final product using 100 °C water[30, 42-45]. Partially charge compression ignition (PCCI)/ direct injection engine was charged by two percentage of WCO biodiesel/diesel blends were B20 and B40. The PCCI-DI combustion strategy is attempted by pre-vaporizes a fraction of the injected fuel prior to intake manifold, while the remaining fuel undergoes conventional combustion before TDC. By varying the premixed fuel ratio at 20%, 25%, and 30%, this research highlights substantial engine performance enhancements. These include a decrease in peak in-cylinder pressure, reduced apparent heat release rate, in addition an increase in average BTE from 19.34% (conventional DI) to 29.91% at PR3. Furthermore, CO emissions were reduced from 0.324% to 0.083%, also NOx emissions decreased from 559.3 ppm to 150.5 ppm[14, 46-50]. Previous study examines the effects of water-diesel emulsions on the performance and emissions of PPCCI engine. A conventional diesel engine, modified for PPCCI operation, was utilized to test three water-diesel emulsion concentrations. The findings demonstrate that increasing the water concentration results in reduced brake specific fuel consumption, increased BTE, and lower emissions of CO, UHC, smoke opacity, in addition NOx[23]. An experimental study explores the characteristics of a PPLCCI engine under varying premixed fuel-air ratios. PPLCCI is a combustion strategy that bridges the gap between conventional diesel combustion and HCCI combustion, often referred to as Low-Temperature Combustion (LTC). A four-stroke diesel engine modified with an external fuel injection system was used to introduce a partially premixed lean charge into the intake manifold. The remaining fuel was injected in the cylinder via the original diesel injector. The engine was operated in conventional diesel mode then to lean charge mode, and PPLCCI mode at premixed ratios of 20%, 25%, and 30%. The experimental results demonstrate substantial improvements in the characteristics for PPLCCI compared to conventional diesel combustion [24, 51-54].

Nanoparticles, the fundamental components of nanotechnology, are incredibly tiny particles ranging from 1 to 100 nanometers in size[55]. They have various shapes as flat, cylindrical and spherical and can exist in crystalline or amorphous forms. Depending on their physical and chemical properties, nanoparticles can be categorized as organic, metallic, semiconducting, polymeric, or composite [56-59]. Organic nanoparticles are primarily utilized in the medical field. On the other hand, metal nanoparticles and their oxides are particularly well-suited for use in diesel engines. The oxygen content helps to reduce the emissions, while their high surface-to-volume ratio enhances the evaporation rate for the fuel mixture. Nowadays, nanoparticles can be utilized in enhancing the attributes of the engine with dispersing in biodiesel/diesel blends [60-64]. Nanofuels characterized by high oxygen content, high reaction rate, combustion with less emissions, increase the mixture stability, short ignition delay period and high surface area to volume ratio[65, 66]. Nanoparticles can be stabilized within base fuels by employing solvents and surfactants. These additives enhance the solubility of nanoparticles and ensure the stability of the fuel-nanoparticles blend. To characterize and analyze nanoparticles, researchers utilize various methods such as X-ray diffraction, scanning electron microscopy, and transmission electron microscopy [30, 67-70].

Multi wall-Carbon nanotubes (MW-CNTs) are a remarkable type of nanoparticles known for their exceptional properties, particularly their high thermal conductivity. MW-CNTs are classified as non-metallic; one of the significant applications of MW-CNTs lies in their use as catalysts for the nanofuel. When added to diesel fuel, MW-CNTs can significantly enhance the diesel engine performance due to the high surface area-to-volume ratio, MW-CNTs contribute to a higher Cetane number, leading to improved combustion efficiency and reduced emissions. Furthermore, the high chemical reactivity of MW-CNTs results in increasing the BTE of diesel engine. Also, by combining with diesel-water emulsions, MW-CNTs can further optimize BTE compared to using water alone. The addition of MW-CNTs to the base fuel also impacts combustion characteristics. It leads to increased peak in-cylinder pressure and shorter combustion duration. The enhancement in surface area-to-volume ratio, can enhance the rate of evaporation, and chemical reactivity of MW-CNTs contribute to a higher peak heat release rate, resulting in more efficient energy utilization[71].MW-CNTs have a clear influence on the emissions produced by diesel engines. By promoting complete combustion through improving the atomization of the fuel and a higher surface area-to-volume ratio, MW-CNTs can reduce the CO emissions. Similarly, the completion of combustion helps to lower UHC emissions. The effect of MW-CNTs on NOx emissions is more complex and depends on variables like the fuel type, the combustion duration, and combustion temperatures. However, in many cases, MW-CNTs have been shown to reduce NOx emissions. One of the most notable benefits of using MW-CNTs is the significant reduction in soot because the high surface area-to-volume ratio that lead to the complete combustion facilitated by MW-CNTs contribute to cleaner combustion and lower soot formation[72] [73-77].Single walled and double walled carbon nano-tubes were dispersed in diesel fuel individually at 100 mg/l concentration using ultrasonication. The diesel engine was running at 1500 rpm and operating at varying loads. The combustion characteristics were enhanced like the pressure of the cylinder, the net heat release rate, cumulative heat release, rate of the pressure rise and the exhaust gas temperatures for the two fuel specimens. The emission characteristics like the carbon monoxide and smoke decreased but the NO_x and CO_2 emissions increased [78-84].

Graphene oxide (GO) nanoparticles, their fuels characterized by high oxygen content, substantial surface area-to-volume ratio, and rapid evaporation rate, represent a promising non-metallic nanoparticle for diesel engine applications. Incorporating GO nanoparticles into the fuel at varying concentrations can lead to significant performance enhancements, such as increased BTE[85]. Furthermore, GO nanoparticles can mitigate carbon monoxide (CO) emissions by supplying supplementary oxygen atoms, thereby facilitating the complete oxidation of fuel. Moreover, GO nanoparticles can mitigate nitrogen oxide (NOx) emissions by providing a larger surface area for catalytic reactions that decompose NOx[86]. The performance plus emissions of the engine were examined using blends of diesel/biodiesel dispersed with reduced graphene oxide (rGO) nanoparticles. The fuel specimens were jatropha curcas biodiesel, conventional diesel fuel, and ethanol and rGO nanoparticles. The study proved that adding rGO nanoparticles have cleared effects in reduction the NO_x and UHC emissions [30, 87-90].

Response Surface Methodology (RSM) is a statistical approach used to model, analyze and optimize the relationship between multiple independent variables and a dependent response variable. It employs a series of designed experiments to identify optimal conditions for a desired response. The conventional methods for diesel engine optimization are often inefficient and costly, RSM provides a more effective and affordable approach [91-95]. Design of Experiment (DoE) is a procedure used to design experiments that investigate the impact of independent variables on diesel engine responses[96].A function becomes first-order when the relationship between independent variables and responses is linear as in Eq. (1) and curvature in the relationship leads to a quadratic or second-order function as in Eq. (2) [97-99].

$$y = \beta_\circ + \sum_{i=1}^{k} \beta_i X_i + \varepsilon \qquad (1)$$

$$y = \beta_0 + \sum_{i=1}^{k} \beta_i x_i + \sum_{i=1}^{k} \sum_{j\geq 1}^{k} \beta_{ij} x_i x_j + \sum_{i=1}^{k} \beta_{ij} x_i^{\,2} + \varepsilon \qquad (2)$$

Where :(i) is the first order coefficient, (k) is parameter numbers,(j) is the quadratic coefficient, (β) is the coefficient of regression, and (ε) is the response error.

Figure 1 illustrates generally the typical RSM procedure for optimizing diesel engine attributes using alternative fuels. The procedure includes firstly the defining for the independent variables in addition the responses then, the DOE by using central composite design (CCD), Box-Behnken method or full factorial design (FFD) by selecting specified values for the independent variables to get the responses by using statistical software application like MINITAB17 (MINITAB Inc.). Full Factorial Design (FFD) is an effective for low-order models, providing accurate results, but becomes less practical for high-order models.CCD is an efficient method for creating second-order models, requiring fewer experiments than a full factorial design while providing comparable accuracy[100-103].The Box-Behnken design, developed in 1960 by reducing the number of experiments required for second-order models. After the DOE then executing the experiments on the laboratory, make analysis, representation for the models and finally make validation between the experimental results and the predicted responses [10].

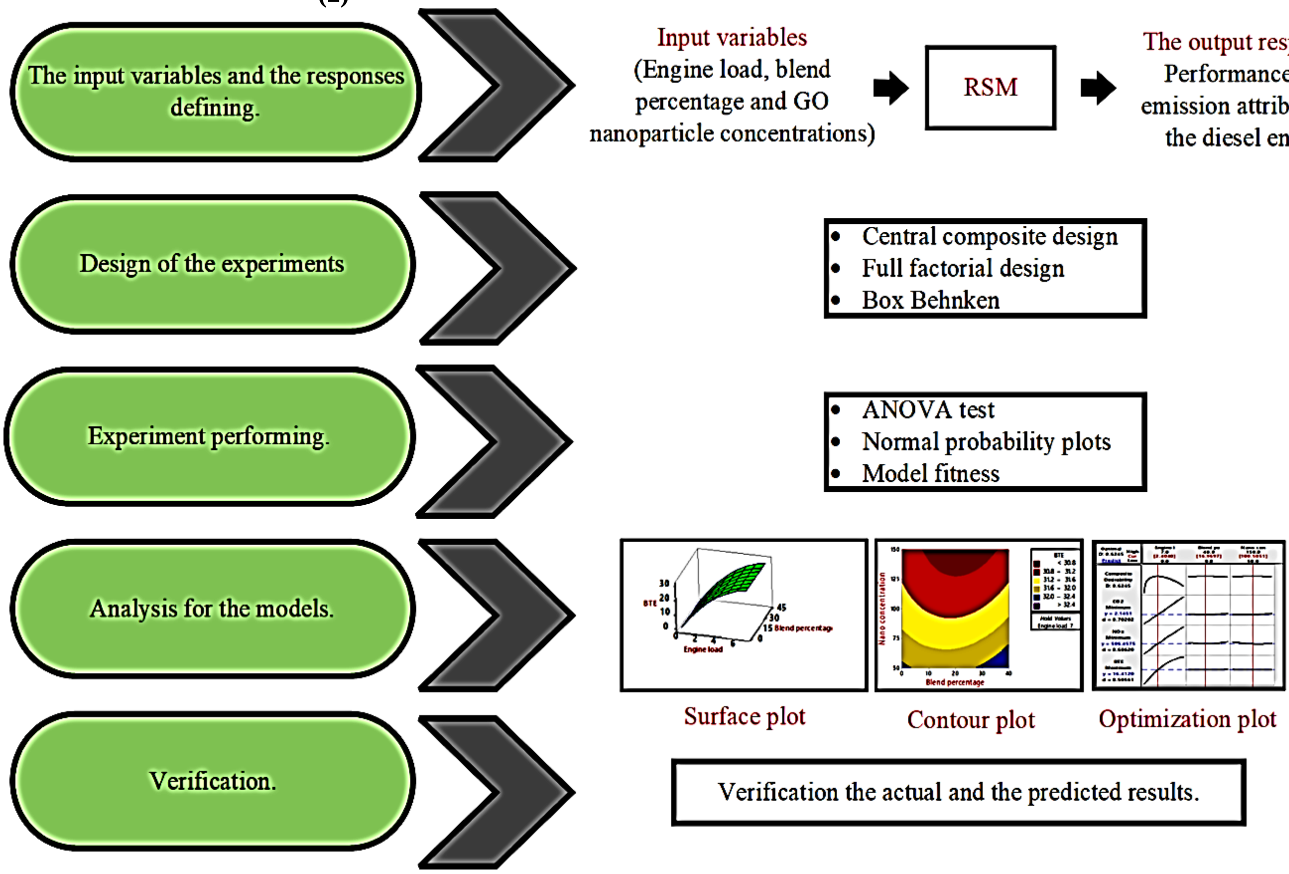


Figure 1 RSM procedure for predicting and optimizing the attributes of diesel engine.

Multi blends of diesel/diethyl ether (D/DEE) were 0, 5 and 10% were injected in diesel engine operated at 1200, 1400 and 1600 rpm. The responses were the brake power (BP), the BTE, the BSFC and the CO_2 emission were predicted and optimized using RSM. The responses were enhanced using D/DEE blends. the optimum responses were 9.57% for the D/DEE blend percentage, 1.267 kW for the brake power, 20.861% for the BTE and 0.335 kg/Kw.hr for the BSFC and 7.837% for the CO_2 emission at 1600 rpm diesel engine speed [104].Diesel with ultra-low sulfur (ULSD) fuel was blended with waste soy bean cooking oil (WSCO) biodiesel at percentages ranges from 20 to 35% and injected in agriculture-based diesel engine using different percentages of exhaust gas recirculation (EGR) by applying RSM. The maximum desirability for the responses was at 35% blend percentage and 15% EGR [16, 105-107].

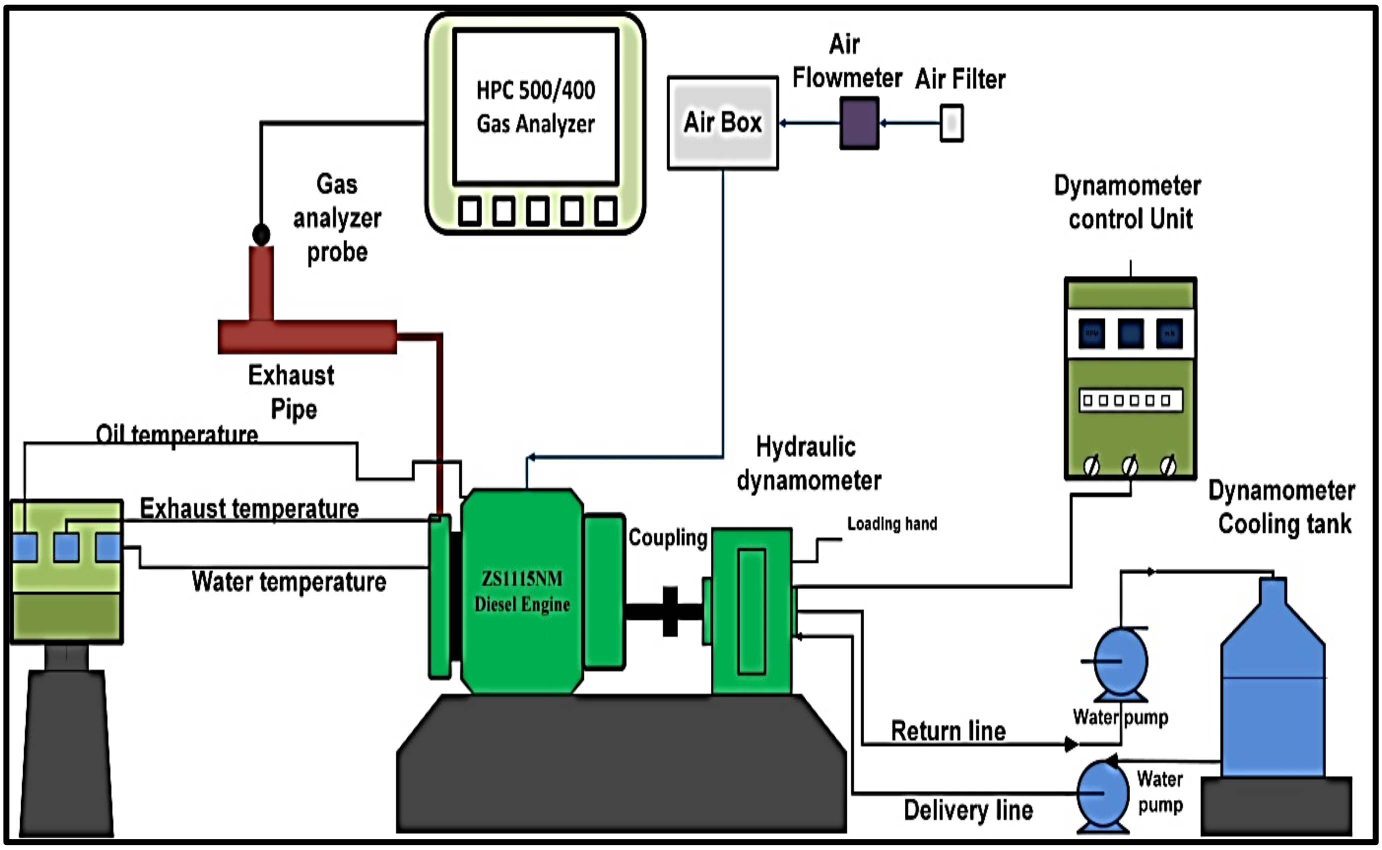
The present manuscript seeks to study the influences of dispersing various concentrations of MW-CNTs or GO nanoparticles in various blends of WCO biodiesel and fossil diesel fuel. The BTE and the NO_x emissions are predicted as well as optimized responses using RSM at different independent variables that are the values of diesel engine load, percentages of WCO biodiesel blend besides the nanoparticles concentrations.

II. Material and methods

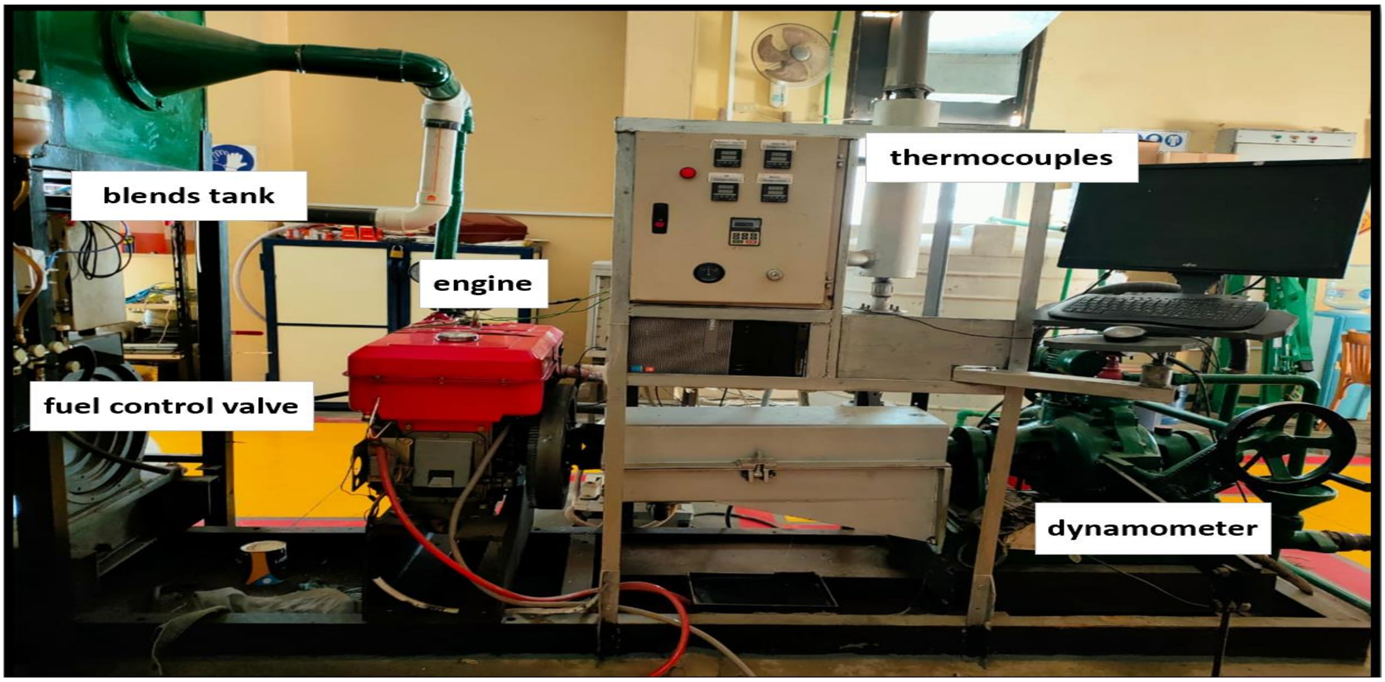
This part discusses the details of the setup of experiments and instrumentations used to examine the BTE and NO_x emissions for a ZS1115 diesel engine operating at 1400 rpm speed. The diesel engine is coupled to a hydraulic dynamometer to control the load. The fuel consumption is measured using a graduated burette connected to the fuel tank. Thermocouples are installed to monitor the temperatures. WCO is transformed into WCO biodiesel through a transesterification process. Graphene oxide (GO) nanoparticles and multi-walled carbon nanotubes (MW-CNTs) are individually dispersed in the fuel samples at different concentrations. The NO_x emissions are examined using a Gas Board 5020 gas analyzer. RSM is anapproach utilized to predict and optimize the responses, reducing the number of experiments, time, and cost[108-113].

A. The experiment setup

Figure 2 presents the outline diagram in addition a photograph for the setup of the experiments that consists of a ZS1115 single-cylinder diesel engine operating at speed of 1400 rpm. The engine is coupled to an ATE-160LC hydraulic dynamometer to control the load and torque. Thermocouples are installed to monitor the temperatures of the lubrication oil, exhaust gases, and cooling water [114-117]. The dynamometer is controlled by a control unit to maintain the engine load. The description of the diesel engine and hydraulic dynamometer are provided in **Tables 1** and **2**, in the same order. A Gas Board 5020 gas analyzer is employed to measure the concentrations of various emissions, including NOx (in ppm) using pulse infrared and single-source two-beam non-dispersion infrared (NDIR) methods. The gas analyzer is described in **Table 3**[4, 118-122].



(a)



(b)

Figure 2 the outline diagram and photograph for the setup and the instrumentations

Table 1 The detailed features of the diesel engine

ZS1115 diesel engine features	
Cylinder numbers	Single cylinder
System of cooling	Condenser
Weight	185 kg
Displacement	1.194 L
Cylinder dimensions	(115*115) mm
Lubrication system	Pressure/splash
Starting system	Electrical start

Table 2 hydraulic dynamometer detailed features

ATE-160 LC hydraulic dynamometer	
Load cell capacity	0 - 350 Kg (0 - 1050N.m)
Calibration arm	0.7645 m
Connection with diesel engine	Using half coupling
Sense of RPM	Sensor and 60-tooth wheel
Absorption	Hydraulic

Table 3The detailed specifications of the gas analyzer

Gas board 5020 gas analyzer	
Measurements	CO_2, CO, UHC, NO_x and Lambda display
Technology	NO_x (ECD)
Resolution	NO_x=1ppm
Relative error	NO_x=±5%
Absolute error	NO_x=±25ppm
Warm-up time	10 min
Display	LCD display
Power	220 V±10% 50HZ ±1HZ
Temperature	0-40°C
Weight	6 kg

B. The production of the WCO biodiesel and nanofuels

Waste cooking oil (WCO), a significant food waste, can have adverse effects on human health besides the environment. One effective recycling method is converting WCO into biodiesel. WCO biodiesel have several advantages in diesel engine combustion including reduced emissions of CO, UHC, and NOx. However, its high free fatty acid content and distinct properties necessitate a chemical treatment process known as transesterification. This process as indicated in **Figure 3**involves mixing WCO with methanol and a catalyst, followed by heating, separation, and washing. The resulting WCO biodiesel, with the specifications detailed in **Table 4**, can be used as a viable fuel option.

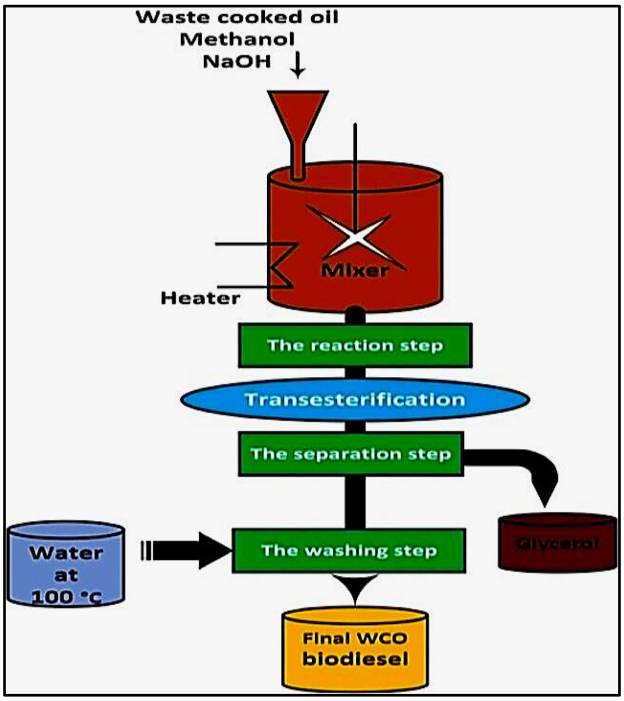


Figure 3WCO biodiesel manufacturing according to transesterification[30]

Table 4Fossil diesel fuel besides WCO biodiesel specifications

Specification (Unit)		Standard (ASTM)	Diesel fuel	WCO biodiesel Biodiesel
Calorific value	(MJ kg-1)	D240	42.10	39.51
Density	(kg m-3)	D1298	830	875
Cetane number	---	D976	55	68
Kinematic viscosity	(mm2 s-1)	D445	2.38	3.54
Flashpoint	(°C)	D93	45	158
Auto-ignition	(°C)	D6751	263	273
Cloud point	(°C)	D2500	0	6
Oxygen content	(wt. %)	D5291	0	9.414

A critical aspect of nanofuels preparation is the effective dispersion of nanoparticles within the base fuel. Electrostatic dispersion, a technique that involves coating nanoparticles with a surfactant, can enhance dispersion by introducing repulsive forces between nanoparticles. The choice of surfactant and its concentration is crucial in achieving optimal dispersion. In this study, toluene was employed as a surfactant to disperse GO nanoparticles or MW-CNT nanoparticles that have specifications indicated in **Table 5** and **6**. Experiments conducted with various toluene volume percentages (2%, 4%, and 6%) demonstrated that a 4% concentration provided the best results in terms of blend stability, homogeneity, and nanoparticles dispersion.

Table 5 MW-CNTs specifications

Attributes	MW-CNTs
Color and appearance Solubility Length and diameter ranges (TEM) Shape (TEM)	Black and powder Soluble in water (L > 660 nm) (D 15 ± 7 nm) Tubular

Table 6 GO nanoparticles specifications

GO Nanoparticles Specifications	
Color	Brownish-black
Formation	Powder
Ability to dissolve	Water soluble
Average Sizes	Length in microns and thickness in nanometers
Shape	Sheets

C. The procedure of prediction and optimization for the BTE and the NOx emissions

This manuscript investigates the impact of fuel blends and nanoparticles additives on the BTE and NO_x emissions of a ZS111S diesel engine. The fuel blends comprise diesel fuel in addition WCO biodiesel; while the nanoparticles include MW-CNTs and GO. To efficiently explore the experimental space, RSM is implemented. RSM utilizes a Central Composite Design (CCD) to systematically select values for the independent variables that are include engine load, WCO biodiesel/diesel blend percentages, and nanoparticles concentrations. The resulting polynomial regression models predict and optimize the engine's BTE and the NOx emission using gas analyzer. The cases of predicting and optimizing of the BTE and the NOx emissions are:

- RSM for the BTE and NOx emissions without dispersing nanoparticles.
- RSM for the BTE and NOx emissions with dispersing MW-CNTs at different concentrations.
- RSM for the BTE and NOx emissions with dispersing GO nanoparticles at different concentrations.

III. Results and discussion

RSM is utilized to predict and optimize the BTE and the NOx emissions of a diesel engine under three experimental conditions. MINITAB17 software is employed to generate polynomial regression models that represent the relationships between the independent variables that include the diesel engine load, biodiesel/ diesel fuel blend percentage, and nanoparticles concentrations and the responses that are the BTE and NOx emissions. The Central Composite Design (CCD) is employed to efficiently design the experiments. The results are presented for each scenario, providing insights into the influence of fuel composition and nanoparticles on the BTE and NO_x emissions.

A. RSM for the BTE and NOx emissions without dispersing nanoparticles

In this case, engine load (kW) and WCO blend percentage (%) are identified as the independent variables. The specific levels of these variables are presented in **Table 7**. CCD is used to design the experiments, resulting in a total of thirteen experimental runs. The responses obtained from these experiments are tabulated in **Table 8**. The interactions between the independent variables and the responses are indicated by two quadratic regression equations are Eq. (3) and (4).

Table 7The independent variables and its levels

The independent variable	Minimum	Medium	Maximum
Load of engine (A)	0	4	8
Biodiesel/diesel blend percentage (B)	0	40	80

Table 8 The experimental and predicted responses according the experiments

Runs	Load value	Blend %	Experimental		Predicted	
			BTE	NO_x	BTE	NO_x
1	4	40	23.34	805	22.7755	773.00
2	4	80	20.70	620	21.4762	621.00
3	4	0	22.50	820	23.0862	842.00
4	4	40	23.30	795	22.7755	773.00
5	4	40	22.70	755	22.7755	773.00
6	0	0	0.00	315	-0.1173	296.42
7	8	0	30.93	1402	30.4611	1398.58
8	0	80	0.00	250	-0.2123	241.92
9	8	80	27.90	1004	27.3361	1011.08
10	0	40	0.00	284	0.3295	310.67
11	4	40	23.10	770	22.7755	773.00
12	4	40	22.80	763	22.7755	773.00
13	8	40	28.36	1250	29.3929	1246.33

$$BTE = -0.117 + 7.779\ A + 0.0235\ B - 0.4946\ A^2 - 0.000309\ B^2 - 0.00473\ AB \quad \text{Eq. (3)}$$

$$NOx = 296.4 + 135.02 A + 1.394 B + 0.344 A2 - 0.02594 B2 - 0.5203 AB \quad \text{Eq. (4)}$$

Analysis of Variance (ANOVA) is employed to evaluate the significance of the quadratic regression models and the interactions between the independent variables influencing the responses. The degrees of freedom (DF), adjusted sum of squares (Adj SS), and adjusted mean squares (Adj MS) are calculated to assess the variability within the models. The F-value and P-value are used to identify the statistical significance of the regression models. The P-value less than 0.05 indicate that the model is statistically significant. The ANOVA results for BTE and NOx presented in **Table 9** and **10**, respectively, reveal significant F-values and P-values, confirming the validity of the models. The high values of R^2, adjusted R^2, and predicted R^2 indicate a strong correlation between the experimental results and predicted values, suggesting an excellent fit of the models to the data.

The difference between the actual experiments values and predicted values is known as the residual. **Figure 4** illustrates the normal probability plots for BTE and NOx where the straight-line distribution of the residuals confirms that they follow a normal distribution.

Table 9 ANOVA for the BTE

BTE (%) Model	D.F	Adjusted MS	Adjusted SS	F-value	P-Value
Model	5	297.20	1485.98	607.66	0.000
A	1	1267.02	1267.02	2590.57	0.000
B	1	3.89	3.89	7.95	0.026
Linear	2	635.45	1270.90	1299.26	0.000
A×A	1	173.00	173.00	353.71	0.000
B×B	1	0.67	0.67	1.38	0.279
Square	2	106.39	212.78	217.53	0.000
A×B	1	2.30	2.30	4.69	0.067
Interaction	1	2.30	2.30	4.69	0.067
Error	7	0.49	3.42		
Lack of fit	3	1.03	3.09	12.33	0.017
Pure error	4	0.08	0.33		
Total	12		1489.41		
R^2= 99.77%Adjusted R^2= 99.61% Predicted R^2= 98.46%					

Table 10 ANOVA for the NOx emissions

NOx (ppm)	D.F	Adjusted MS	Adjusted SS	F-value	P-Value
Model	5	283858	1419292	548.43	0.000
A	1	1313208	1313208	2537.19	0.000
B	1	73262	73262	141.55	0.000
Linear	2	693235	1386470	1339.37	0.000
A×A	1	84	84	0.16	0.700
B×B	1	4757	4757	9.19	0.019
Square	2	2550	5100	4.93	0.046
A×B	1	27722	27722	53.56	0.000
Interaction	1	27722	27722	53.56	0.000
Error	7	518	3623		
Lack of fit	3	596	1788	1.30	0.390
Pure error	4	459	1835		
Total	12		1422915		
R^2= 99.75%Adjusted R^2=99.56%PredictedR^2=98.71%					

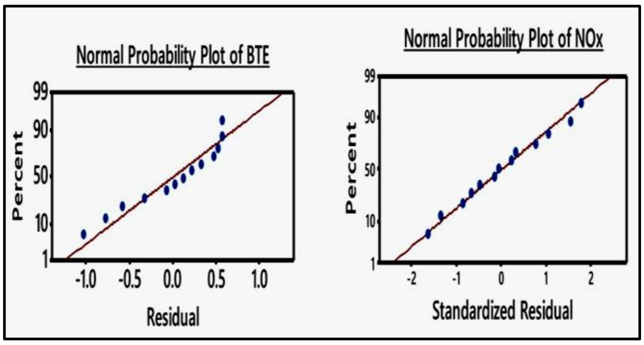


Figure 4 the plots of normal probability for the residuals

Figure 5 depicts the influence of independent variables on the BTE. A significant enhancement in BTE is observed with increasing engine load, as more fuel energy is converted into mechanical work, leading to higher brake power and consequently, higher BTE. Additionally, a gradual increase in BTE is noted with increasing WCO biodiesel blend percentages. This can be occurred due to the higher oxygen content in WCO biodiesel that enhances the combustion. However, the elevated density and viscosity of WCO biodiesel can tend to challenges in atomization and so lengthened durations of combustion compared to using pure diesel fuel.

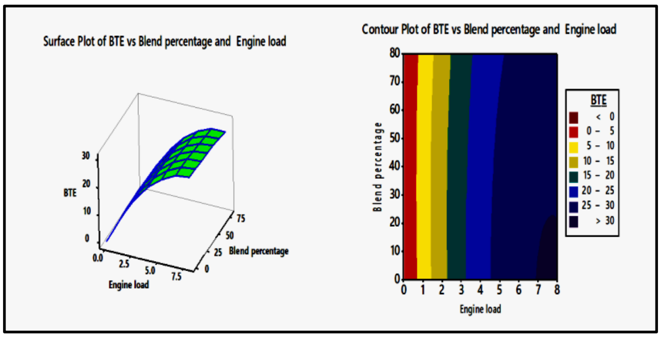


Figure 5 indicates the plots for the influences of the independent variables on the BTE

Figure 6 illustrates the influence of the independent variables on NOx emissions. The increase in engine load leads to higher NO_x emissions, primarily due to the combustion completion and the elevated temperatures of combustion. In contrast, increasing the WCO biodiesel blend percentage leads to a decrease in NOx emissions. The reduction is attributed due to the lower temperatures of the combustion associated with the higher oxygen content and different combustion characteristics of WCO biodiesel in comparison with using pure diesel fuel only.

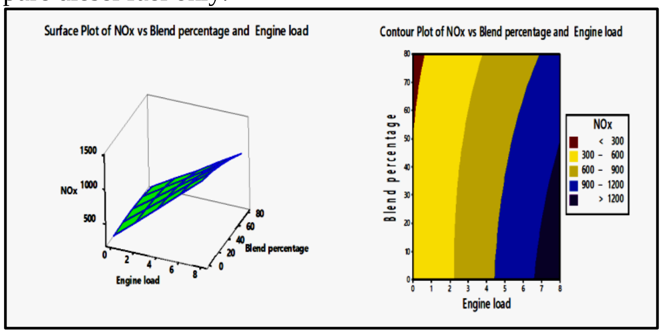


Figure 6 indicates the plots for the independent variables influences on the NOx values

MINITAB 17 optimizer tool is utilized to identify the optimal results of the independent variables that would lead to the desired levels of the response variables as indicated in **Figure 7**. The Individual desirability (d) and the composite desirability (D) are employed to evaluate the desirability of different experimental settings. Individual desirability assesses the desirability of each response individually, while composite desirability considers the overall desirability of all responses. A composite desirability (D) of 0.65 is recorded at an engine load of 2.66 kW and 0% WCO biodiesel blend, resulting in optimal values of 17.11% BTE and 658.9 ppm NOx.

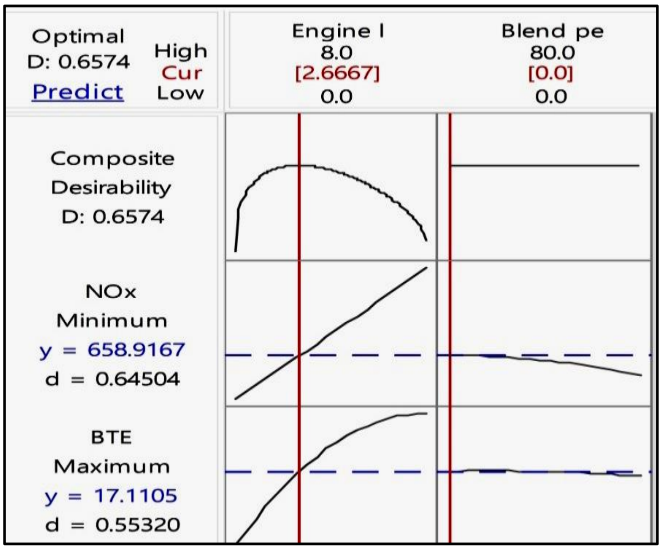


Figure 7The optimization plot for optimizing the BTE and NOx

B. RSM for the BTE and NOx emissions with dispersing MW-CNTs

To optimize the BTE and the NOx emissions RSM is applied. The independent variables such as engine load, WCO biodiesel blend percentage, and MW-CNTs concentrations are varied according to the CCD to observe their impact on response variables like the BTE besides the NOx emissions. Data is collected and analyzed using MINITAB 17 software to fit polynomial regression models and identify optimal operating conditions.**Table 11** indicates the levels of the independent variables and **Table12** indicates the performed experiments according to the central composite design.

Table 11The independent variables levels

Variable	Symbol	Minimum	Medium	Maximum
Engine load (kW)	A	0	3.5	7
Blend percentage (%)	B	0	20	40
Nano concentration (ppm)	C	50	100	150

Table 12The DOE according to the CCD

Runs	The independent variables			The responses			
	Load (kW)	Blend (%)	Nano concentration (ppm)	Exp. BTE (%)	Pre. BTE (%)	Exp. NOx (ppm)	Pre. NOx (ppm)
1	0.0	40	150	0	0	290	328
2	3.5	20	150	22	22	682	650
3	3.5	20	100	21	22	506	644
4	3.5	20	100	23	22	565	645
5	3.5	40	100	23	22	706	720
6	7.0	0	50	32	32	1240	1203
7	0.0	0	150	0	0	276	245
8	7.0	20	100	31	31	1063	1043
9	7.0	0	150	31	31	915	970
10	3.5	20	100	22	22	669	645
11	3.5	20	100	22	22	778	645
12	7.0	40	150	31	31	1185	1155
13	3.5	20	100	22	22	649	645
14	3.5	20	100	22	22	692	645
15	0.0	40	50	0	0	270	216
16	0.0	20	100	0	0	171	186
17	3.5	0	100	22	22	695	677
18	0.0	0	50	0	0	284	315
19	7.0	40	50	32	32	1174	1206
20	3.5	20	50	22	22	684	711

The process of prediction and optimization are investigated using quadratic regression model equations. Second-order regression equations for the BTE and the NOx emissions according to the independent variables are stated in Equ. 5 and 6.

$$BTE = 0.28 + 8.498A - 0.0199B - 0.0110C - 0.5439A^2 + 0.000880B^2 + 0.000067C^2 - 0.00027AB - 0.001836AC - 0.000109BC$$

$$NOx = 459 + 155.4A - 10.11B - 3.59C - 2.42A^2 + 0.134B^2 + 0.0145C^2 + 0.364AB - 0.233AC + 0.0455BC$$

To understand the impact of the single and combined of the independent variables on the responses (BTE and NOx), the ANOVA is conducted in **Table 13**. The F-value for the BTE and NOx are respectively 1238.5and 34.36 that is a statistical measure derived from the ratio of mean square group variance to mean square error is used to assess the regression models significance. The low p-values (less than 0.05) for all models indicate their statistical significance.

Table 13ANOVA for the BTE and NOx

	BTE		NO_x	
	F-value	P-value	F-value	P-value
Model	1238.52	0.000	34.36	0.000
Linear	3434.43	0.000	100.06	0.000
Square	279.85	0.000	1.13	0.382
Interaction	1.28	0.335	1.89	0.194
Lack of fit	0.50	0.765	0.34	0.872
R^2	R^2 = 99.91%		R^2 = 94.8 %	
R^2 adj	R^2adj = 99.83%		R^2 adj = 94.05%	

The discrepancies between the predicted values by the model and the actual values are known as residuals. The normal probability plots depicted in **Figure 8** show that these residuals are normally distributed, suggesting that the model assumptions are met.

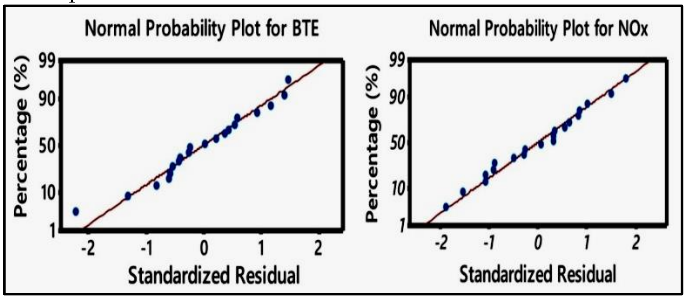


Figure 8 indicates the plots of normal probability for the residuals for the responses

The influence of diesel engine load in addition WCO blend percentage on the BTE at fixed MW-CNTs concentration of 150 ppm is depicted in **Figures 9**.An enhancement in BTE is detected with both increasing engine load and WCO blend percentage. Higher engine loads result in enhanced fuel energy conversion to mechanical work, while higher WCO blends contribute to increased heating value, oxygen content, besides the surface area-to-volume ratio that produced from adding MW-CNTs.

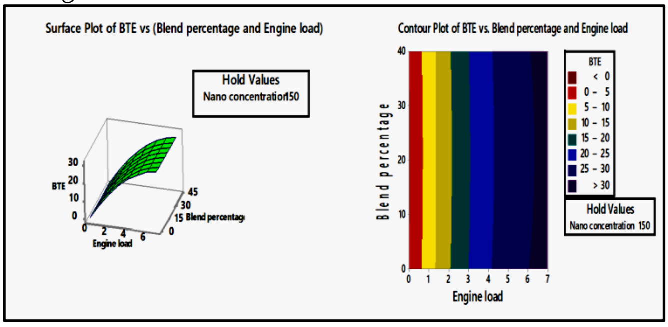


Figure 9The independent variables influence on the BTE at 150 ppm MW-CNTs nano concentration fixed value

The influence of WCO blend ratios and MW-CNTs concentrations on the BTE at a fixed load for the diesel engine of 7 kW is depicted in **Figures 10**.An initial decline in the BTE is observed with rising WCO blend percentages up to 20%, attributed to reduced heating value, prolonged ignition delay, and lower combustion temperatures. Subsequent increases in BTE can be ascribed to the elevated oxygen content in addition the high combustion temperatures of biodiesel blends. The addition of MW-CNTs results in enhanced BTE, owing to increased heating values, catalytic effects, besides the great ratio of surface area-to-volume.

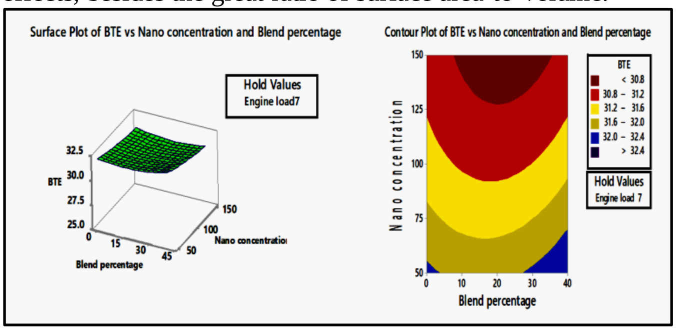


Figure 10 The independent variables influence on BTE at 7 kW engine load constant value

The influence of load of diesel engine in addition WCO blend percentage on NOx emissions at fixed MW-CNTs concentration of 150 ppm is depicted in **Figure 11**.Elevated values for NOx emissions are detected with rising engine load and WCO blend percentage. Higher engine loads cause combustion completion and elevated temperatures, while higher WCO blends contribute to increased oxygen content, promoting more complete combustion.

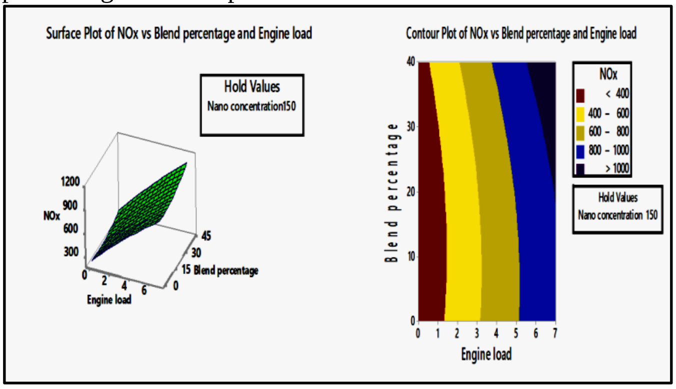


Figure11The independent variables influence on the NOx emissions at 150 ppm MW-CNTs concentration

The influence of WCO blend percentages and MW-CNTs concentrations on NOx emissions at a fixed engine load of 7 kW is depicted in **Figure 12**.A decrease in NOx emissions is observed with increasing WCO blend percentages up to 20%, attributed to reduced heating values and low combustion temperatures. Subsequent increases in NOx emissions can be ascribed to higher oxygen content and increased combustion temperatures. The addition of MW-CNTs results in decreased NOx emissions due to lower combustion temperatures, due to the complete combustion at reduced ignition delay periods and the increased ratio for surface area-to-volume.

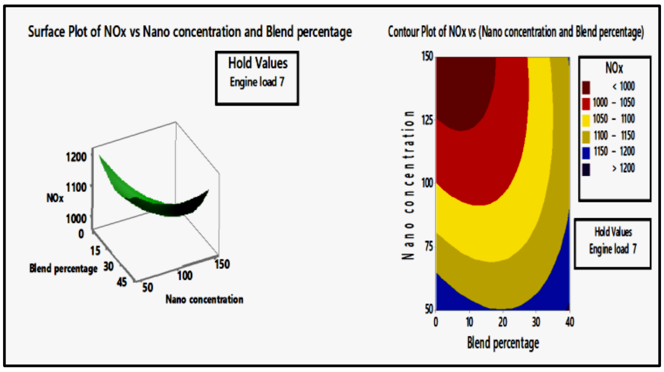


Figure 12 The influences of the independent variables influences on the NOx emission sat 7 kW diesel engine load

MINITAB 17 software is employed to optimize the BTE and the NOx emissions, as illustrated in **Figure 13**. Optimal conditions are identified at a 17% WCO blend, 2.40 kW engine load, and 100 ppm MW-CNTs concentration, yielding a composite desirability (D) of 62.5%. Under these conditions, the optimal values for BTE and NOx emissions are determined to be 16.4%, and 506.5 ppm respectively. The individual desirability (d) for each response, ranging from 0 to 1, indicates the degree to which each response meets the desired criteria.

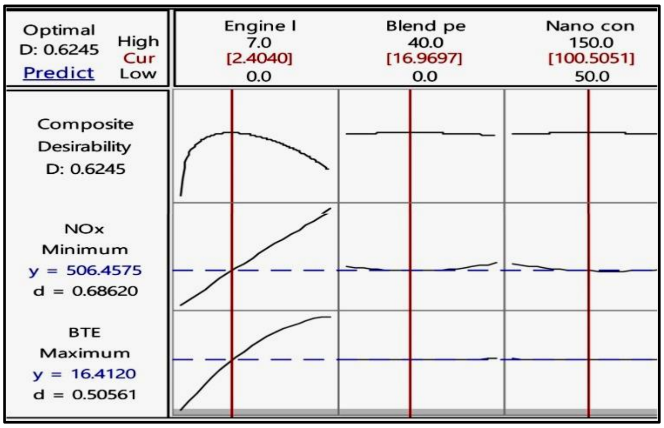


Figure 13The optimization plot for optimizing the BTE and NOx

C. RSM for the BTE and NOx emissions with dispersing GO nanoparticles

CCD is applied to produce20experiments using MINITAB 17 software, enabling efficient exploration of the design space. The independent variables, namely engine load, WCO blend percentage, and GO nanoparticles concentration, as detailed in **Table 14**, are identified as significant variables influencing on the BTE and NOx emissions.

Table 14The levels of the independent variables

	Levels of the independent variables		
	Minimum-level	**Medium-level**	**Maximum-level**
Loading of Diesel engine (A) (kW)	0	3.5	7
WCO biodiesel Blend (B) (%)	0	20	40
GO concentration (C) (ppm)	50	100	150

Quadratic regression models were employed to analyze the relationships between independent variables (engine load, WCO blend percentage, and GO nanoparticles concentration) and response variables (BTE, NOx, and CO2 emissions). The derived second-order regression equations are provided in Equations 7and 8.

$$BTE = 0.662 + 9.354A + 0.0749B - 0.0214C - 0.6923A^2 - 0.001839B^2 + 0.000120C^2 - 0.000359AB - 0.000250AC - 0.000066BC$$

$$NO_x = 268.8 + 128.7A - 5.23B - 0.30C - 2.84A^2 + 0.121B^2 - 0.00051C^2 + 0.491AB - 0.0321AC + 0.0131BC$$

Table 15 outlines the experimental design and corresponding responses, derived from the CCD, incorporating the levels of the independent variables.

Table 15 Design of experiments with the actual plus the predicted responses

Runs	The independent			Actual		Predicted	
	A	B	C	BTE	NO_x	BTE	NO_x
1	7	0	150	31.35	940	31.4416	941.166
2	3.5	20	100	24.31	643	24.2702	643.309
3	3.5	20	100	24.52	655	24.2702	643.309
4	0	40	150	0	290	-0.1974	277.266
5	3.5	20	50	24.12	675	24.5527	654.436
6	3.5	20	100	24.39	656	24.2702	643.309
7	3.5	20	100	24.28	661	24.2702	643.309
8	7	40	150	30.08	1170	30.0946	1142.97
9	0	20	100	0	210	0.348727	204.436
10	3.5	20	100	24.44	626	24.2702	643.309
11	7	0	50	31.26	995	31.3626	1003.47
12	7	40	50	30.52	1158	30.2806	1152.77
13	3.5	20	100	24.44	635	24.2702	643.309
14	3.5	0	100	24.12	672	23.8907	638.636
15	3.5	20	150	24.64	592	24.5867	629.636
16	0	40	50	0	270	-0.1864	264.566
17	0	0	150	0	212	0.144568	212.966
18	0	0	50	0	230	-0.1094	252.766
19	3.5	40	100	22.57	695	23.1787	745.436
20	7	20	100	31.2	990	31.2307	1012.64

Table 16 presents the ANOVA results for BTE and NOx emissions. The high F-values are 2917.14 and 217.63, respectively and low P-values that are less than 0.05 indicate that the significance of the regression models and provide a good fit to the data. The high values of R^2 are 99.96% and 99.49%, correspondingly and the R^2_{adj} values are 99.93% and 99.03%, further confirming the strong predictive power of the models.

Table 16ANOVA for the BTE and NOx

	BTE		NO_x	
	Fisher test value	**probability value**	**Fisher test value**	**probability value**
Model	2917.14	0.000	217.63	0.000
Linear	7537.60	0.000	645.62	0.000
Square	1212.08	0.000	2.97	0.083
Interaction	1.76	0.219	4.30	0.034
Lack of fit	25.29	0.001	9.60	0.013
R^2	R^2 = 99.96%		R^2 = 94.49 %	
R^2 adj	R^2adj = 99.93%		R^2 adj = 94.03%	

The difference between the actual results and predicted responses is known as the residual. **Figure 14** illustrates the normal probability plots for BTE and NOx where the straight-line distribution of the residuals confirms that they follow a normal distribution.

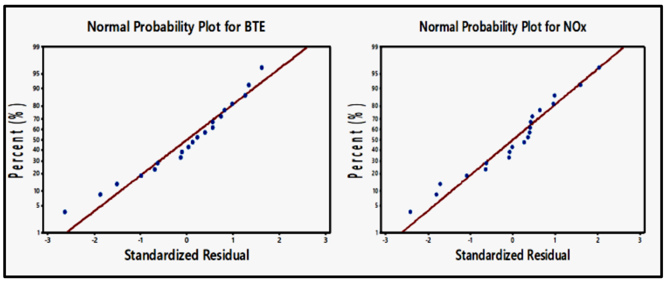


Figure 14 Indicates the plots of normal probability for the BTE and NOx

Figure 15 depicts the influence of load for the diesel engine and WCO blend percentage on BTE at a fixed GO nanoparticles concentration of 150 ppm. BTE percentages increase with both rising the load plus WCO blend percentage, attributed to the elevated calorific value, high oxygen content, and high ratio of surface area-to-volume.

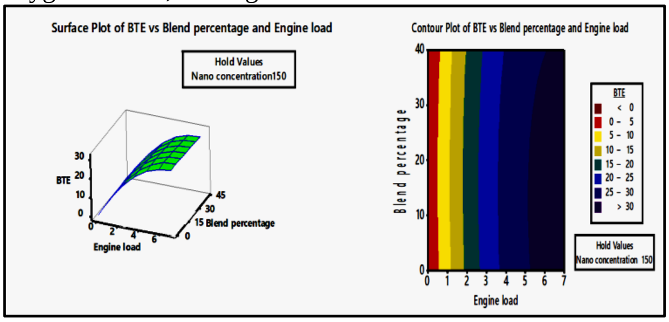


Figure 15 the influence of the engine load values and WCO biodiesel blend percentage on the BTE with fixed concentration of GO nanoparticles at 150 ppm

Figure 16 depicts the influence of WCO blend percentage and GO nanoparticles concentration on BTE at a fixed engine load of 7 kW. BTE initially increases with increasing WCO blend percentage up to 15%, but subsequently decreases due to increased fuel viscosity, which results in impaired atomization and prolonged ignition delay period.

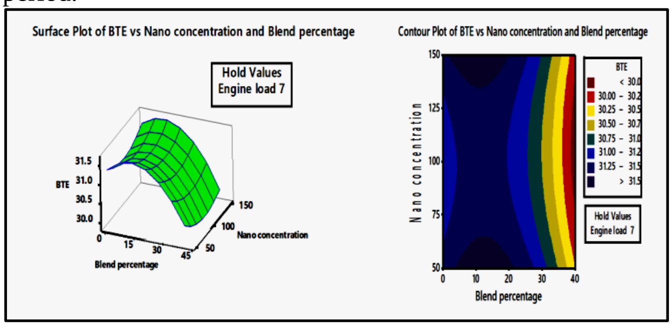


Figure 16 the effect of the WCO blend percentage and GO nanoparticles on the BTE with fixed value of the diesel engine load at 7kW

Figure 17 depicts the influence of loading for the diesel engine besides the WCO blend percentage on NOx emissions at a fixed GO nanoparticles concentration of 150 ppm. NOx emissions values rise with both rising engine load and WCO blend percentage. As higher loads and higher oxygen content from WCO blends result in more complete combustion and higher temperatures, tending to rising in the NOx emissions.

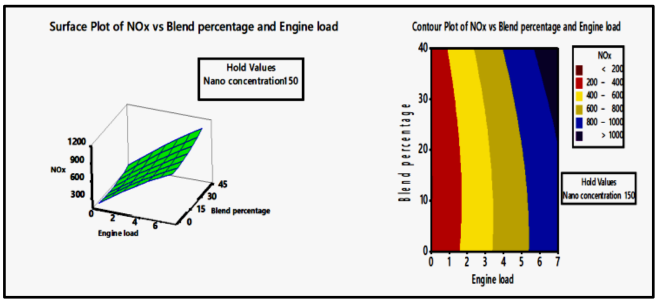


Figure 17 the influence of loading for the engine load in addition WCO blend percentage on the NOx emissions values with fixing GO nanoparticles concentration at 150 ppm

Figure 18 depicts the influence of WCO blend percentage and GO nanoparticles concentration on NOx emissions at a fixed engine load of 7 kW. NOx emissions increase with both increasing WCO blend percentage and GO nanoparticles concentration. As higher oxygen content from WCO blends and the catalytic effect of GO nanoparticles result in more complete combustion in addition higher temperatures that leading to rising NOx emissions.

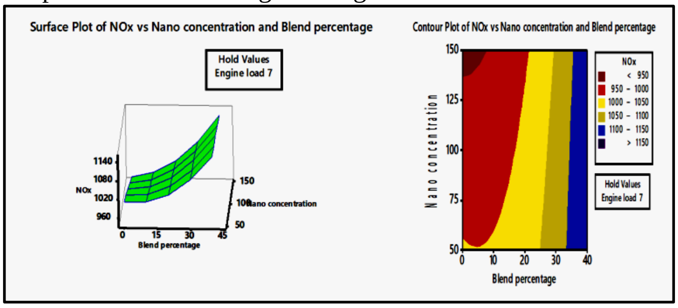


Figure 18 the influence of WCO blend percentage and GO nanoparticles on the NOx emissions with fixing the diesel engine load at 7 kW

Figure 19 depicts the optimal conditions determined using MINITAB's response optimizer tool to optimize engine BTE and NO_x emissions. The optimal conditions, identified as a 2.47 kW engine load value, 3.6364% WCO blend percentage, and 50 ppm GO nanoparticles concentration, yield a composite desirability of 65.22%. Under these conditions, the maximum BTE is 18.973% and the minimum NOx emissions is 539.33 ppm.

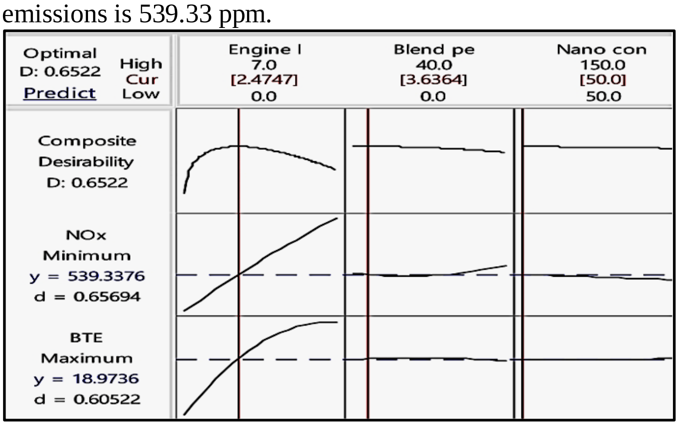


Figure 19The best independent variables values to optimize the BTE and NOx emissions

IV. Conclusions and future recommendations

This manuscript goal is to predict besides optimize the BTE and NOx emissions of a ZS111S diesel engine. To achieve this, the engine is fueled with various WCO biodiesel/ diesel blends. Additionally, different concentrations of MW-CNTs or GO nanoparticles are dispersed in the fuel blends to enhance combustion. The engine is operated under various load conditions. The CCD is holding a job is to analyze the engagements between fuel blend percentages, nanoparticles concentrations, and diesel engine load on the BTE and NOx emissions. MINITAB 17 software is used to predict and optimize the experimental design and analyze the results.

- WCO biodiesel is manufactured through transesterification and meet the ASTM biodiesel standard, making it suitable for diesel engine operation.
- The specifications of MW-CNTs and GO nanoparticles, including shape, size, and solubility, were verified through various examinations provided by the manufacturer.
- Increased WCO biodiesel blend percentages led to improvements in BTE and NOx emissions owing to the higher oxygen content.
- The addition of nanoparticles at various concentrations enhanced the BTE and NOx emissions. Owing to the high ratio of surface area to volume, increased chemical reactivity, evaporation rate, and combustion efficiency compared to fuel without nanoparticles.
- The DOE that employed by CCD effectively determined the optimum combination of independent variables to achieve the levels of the responses with high accuracy.
- The predicted responses from the RSM software are validated through experimental verification and confirming the statistical significance of the models.
- For the base fuel without nanoparticles, the optimal conditions are 2.66 kW diesel engine load with 0% WCO blend, resulting a BTE of 17.11% and NOx emissions of 659 ppm with a composite desirability (D) of 0.65.
- For MW-CNTs dispersed fuel, the optimal conditions are 2.40 kW engine load, 16.9% WCO blend, and 100 ppm MW-CNTs concentration, resulting in a BTE of 16.41% and NOx emissions of 506 ppm and a composite desirability (D) of 0.62.
- For GO nanoparticles dispersed fuel, the optimal conditions are 2.47 kW engine loads, 3.63% WCO blend, and 50 ppm GO nanoparticles concentration, resulting in a BTE of 18.97% and NOx emissions of 539 ppm and a composite desirability (D) of 0.65.
- The high R-squared values, close to unity, indicate the strong accuracy of the models for all cases.

V. Future recommendations include:

- Investigating the combined effects of various alternative fuel blends and different types of nanoparticles at varying concentrations on the attributes of the diesel engine.
- Exploring alternative optimization techniques besides RSM to further refine engine performance and emission reduction strategies.
- Leveraging computational fluid dynamics (CFD) simulations to reduce the number of physical experiments while maintaining accurate results.

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