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Influence of aluminum oxide nanoparticles addition with diesel fuel on emissions and performance of engine generator set using response surface methodology

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ABSTRACT

The present study investigates the effect of small-sized aluminum oxide nanoparticle concentration and engine load on the emissions and performance parameters of a single-cylinder diesel engine connected to an AC generator. Response surface methodology (RSM) based on central composite design (CCD) was employed to simulate the design of the experiment. The ultrasonication-assisted preparation method has been used to mix the diesel (D) with two different concentrations of aluminum oxide, namely 50 ppm and 100 ppm. The tested fuels are called D, (D + 50AL_2O_3), and (D + 100AL_2O_3) accordingly. The tests were carried out at various engine loads of 0.9, 1.8, and 2.7 kW at a rated speed of 3000 rpm without engine modification. The evaluated characteristics were nitrogen oxide (NOx), hydrocarbons (HC), carbon dioxide (CO_2), carbon monoxide (CO), brake-specific fuel consumption (BSFC), brake thermal efficiency (BTE), and exhaust gas temperature (EGT). According to the analysis of variance (ANOVA) results, the experimental outputs were found to be in good agreement with that of the predicted. Furthermore, the results revealed that the tested fuel D + 50Al_2O_3 favorably reduced the harmful emissions at all loads investigated. For instance, NOx, HC, and CO emissions decreased by 32.28%, 21.74%, and 20%, respectively. In addition, the BTE improved by 4.91% at 2.7 kW compared to pure diesel. The aforementioned potential results revealed that aluminum oxide nanoparticles could effectively reduce emissions parameters and enhance engine performance. Furthermore, the small nanoparticle size of 11 nm and low concentration of only 50 ppm (mixed with diesel) revealed positive technical, environmental, and economic perspectives on the applicability of the proposed nanofuel.

1. Introduction

Currently, the demand for thermal energy is unavoidable, and the amount of emissions produced by many engines is also rising. Diesel engines will still be employed in heavy-duty transportation and electrical power generation [1]. Due to environmental and human health concerns, it is crucial to regulate emissions from generator engines that run continuously for long periods [1]. To mitigate environmental pollution, many efforts are being performed in different areas, such as modification of engine piston [2], enhancement of combustion quality [3], recovery of waste heat [4], exhaust gas recirculation (EGR) [5], alternative fuels such as hydrogen [6], biodiesel [7–9], bioethanol and biogas [10], bio oils [11], water in diesel emulsion [12], diesel blend with alcohols [13] and others. Of them, fuel additives stand out for reducing pollutant emissions and enhancing engine performance [2]. Nanoparticles can be used as potential additives to improve the combustion characteristics of conventional liquid fuels because of their superior characteristics. Due to the increased surface area of nanoparticles and depending on the properties of the added nanoparticles, nanofuels could perform better than pure fuels [14,15].

Basha et al. [16] investigated how water in a diesel emulsion fuel and aluminum oxide (Al_2O_3) nanoparticles with a size of 51 nm affected a diesel engine's performance, emissions, and combustion characteristics. According to the test results, using nanoparticles improved combustion characteristics and decreased exhaust pollutants. D'Silva et al. [17] used titanium dioxide (TiO_2) nanoparticles with a size ranging from 10 to 20

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nm as a fuel additive in a compression ignition engine to explore how engine performance characteristics and emissions were affected. The results showed that adding TiO_2 nanoparticles to neat diesel enhanced brake thermal efficiency (BTE) and fuel consumption. Furthermore, compared to pure diesel, harmful emissions such as nitrogen oxide (NOx), hydrocarbons (HC), and carbon monoxide (CO), were reduced. Abdel-Rehim and Akl [18] evaluated the performance and emissions by adding of aluminum oxide (Al_2O_3) nanoparticles with a size of 20 nm to the fuel. They found that nanoscale aluminum oxide can improve the performance of diesel engines while reducing emissions of harmful pollutants like CO_2 and HC in comparison to conventional diesel fuel. Chen et al. [19] utilized three kinds of nanoparticles (silicon oxide with a size ranging from 20 to 30 nm, carbon nanotubes with a size of 50 nm and aluminum oxide with a size ranging from 20 to 30 nm). With plain diesel, the nanoparticles were combined in 25, 50, and 100 ppm dosages. The study's findings demonstrated a notable improvement in exhaust emissions and engine performance.

Gumus et al. [20] utilized two types of nanoparticles (aluminum oxide with a size ranging from 27 to 43 nm and cerium oxide with a size ranging from 30 to 50 nm) in a dose of 50 ppm for each type. The 50 ppm of AL_2O_3 nanoparticles blended biodiesel demonstrates higher thermal efficiency and lower emissions than pure diesel at full load because the blends contain nanoparticles that enhance the fuel atomization characteristics. Khatri and Goyal [21] investigated how a water-diesel emulsion of silicon dioxide (SiO_2) nanoparticles with a size of 50 nm affected diesel engines. SiO_2 nanoparticles were added to water diesel emulsion fuel at various quantities ranging from 25 to 100 ppm with increments of 25 ppm. Compared to neat diesel at full load condition, the tested fuel with 50 ppm dosage reduces 64.28% for CO, 69.69% for HC, 29.32% for smoke opacity and 52.52% for NOx emissions making it the best fuel. Backiyaraj et al. [22] in their study, AL_2O_3 nanoparticles with a size of 10 nm added mahua biodiesel and its diesel blends were used as the fuel for a single cylinder compression ignition engine used to assess the experimental investigation. 20% mahua biodiesel, 80% diesel, and 10, 25, and 50 ppm of nano AL_2O_3 were utilized to make nano mixed biodiesel. Due to nanoparticles in the blends that improve the fuel atomization characteristics, biodiesel with 50 ppm of displays greater thermal efficiency and reduced emissions. Kaushik et al. [23] in their study, Al_2O_3 nanoparticles with a size ranged from 27 to 43 nm incorporated with diesel–biodiesel blends to evaluate the diesel engine performance and emission characteristics. Two quantities of alumina nanoparticles (25 and 50 ppm) were mixed into two different amounts of biodiesel to create the test fuel samples. The investigation results showed that the use of Al_2O_3 nanoparticles results in improved engine performance and reduced harmful exhaust emissions. The above literature review, shows that nanodiesel is a promising fuel used in diesel engines.

Reponse surface methodology (RSM) is an effective design used to optimize the conditions by performing a few selected experiments [1,9]. In addition, such a design could bring out the finer details about the process of investigation [24,25]. Unlike the conventional optimization method that includes changing one parameter at a time and maintaining the other variables fixed, RSM describes the process by plotting three-dimensional graphs to study the interactive effect of two parameters against response [26–28]. The cylinder wears out more quickly when adding nanoparticles, especially when the particle size is large. On the other hand, smaller-sized nanoparticles improve the stability of fuel solutions and shield fuel injectors from clogging and atomization issues. In addition, tiny nanoparticles do not significantly affect engine wear. In this regard, smaller-size aluminum oxide nanoparticles reduce wear and friction in high-pressure fuel systems due to their excellent dispersion [29].

Few research studies addressed the impact of smaller-sized aluminum oxide nanoparticles in lower concentrations on compression ignition engines. The main aim of this study is to demonstrate the impact of adding small average size (11 nm) alumina nanoparticles at lower concentrations of 50, and 100 ppm with diesel fuel on emissions and engine performance. In addition, the interactive effect of nanoparticles amount and engine load was studied on the following responses: NOx, HC, CO_2, CO, brake specific fuel consumption (BSFC), BTE, and exhaust gas temperature (EGT).

2. Materials and methods

2.1. Nanoparticles properties

Al_2O_3 nanoparticles were purchased from Nanotech Egypt Company, their characteristics are shown in Table 1. The Transmission electron microscopy (TEM) of Al_2O_3 nanoparticles is illustrated in Fig. 1.

2.2. Nanodiesel fuel preparation and fuel properties

The effect of aluminum oxide nanoparticles concentration in the base fuel was studied. Two dosing levels of 50 and 100 ppm (mg of Al_2O_3 per liter of diesel) were studied. Nanodiesel fuel was prepared by directly mixing nanoparticles with the neat diesel fuel using a magnetic stirrer (model: 79–1 Magnetic heated stirrer) at a speed of 2400 rpm for 30 min to prevent the gathering of particles. Ultrasonication was then used to disperse the nanoparticles and distribute them equally in the base fuel using a sonicator (model: Hartridge HM1031, power 200 W, frequency 38 kHz) for one hour. The stages of the fuel preparation are shown in Fig. 2. The physical appearance of neat diesel fuel and nanodiesel fuels is illustrated in Fig. 3. The nanodiesel fuels were fed immediately after preparation into the engine [17]. For the testing purpose, the calorific value and density of pure diesel are assumed to be 42000 kJ/kg and 829 kg/m^3, respectively, according to ASTM standards of Egyptian diesel fuel listed in Table 2. Also, it is assumed in our work that the calorific value and density of nanodiesel fuels will be equal to the pure diesel fuel due to the marginal effect with the addition of nanoparticles; similar assumptions were utilized in previous studies [30,31]. Therefore, D + $50AL_2O_3$ and D + $100AL_2O_3$ are the names given to the nanoparticle concentrations in neat diesel fuel, respectively, of 50 ppm and 100 ppm.

2.3. Facilities of the test rig

The test rig comprises of engine generator set, fuel supply, electric load bank, and measuring devices. The experimental facilities used for diesel engine tests are shown in Fig. 4 (a), and a schematic diagram of the test rig is presented in Fig. 4 (b). The technical specifications of the engine generator set are listed in Table 3. The gas analyzer (model: AVG 688, Brain Bee) was utilized to measure the exhaust emissions. Table 4 contains a list of the exhaust gas analyzers' technical specifications. The K-type thermocouple installed in the exhaust manifold and an analog-to-digital signal converter MAX6675 linked to an Arduino UNO R3 microcontroller were used to measure the EGT. The electric load was observed using a digital multimeter (model: EM-06, Tense). A calibrated fuel burette and stopwatch were used to calculate the fuel consumption. For this, the time it took to consume 20 ml of fuel was observed, and the mass was then divided by the time.

Table 1
Nanoparticles properties.

Item	Specification
Supplier	Nanotech, Egypt
Chemical name	Aluminum oxide (Al_2O_3)
Appearance (Color)	White
Appearance (Form)	powder
Average particle size (TEM)	11 ± 2 nm
Shape (TEM)	Spherical - like Shape

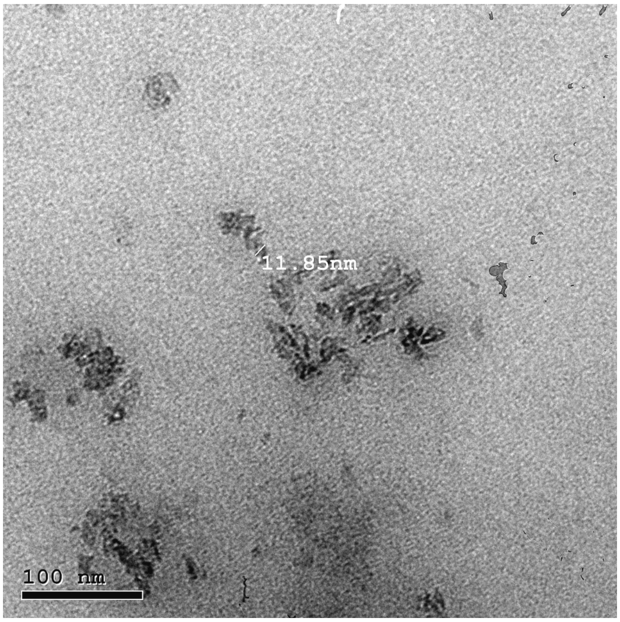


Fig. 1. The TEM images of AL_2O_3 nanoparticles.

Fig. 2. Fuel preparation stages. a) Stirrer setup; b) Sonicator setup.

2.4. Test procedure

The engine could keep running for 10 min for warm-up and achieve steady conditions. The experiment was carried out at varying the load using an electric load bank at 0.9 kW, 1.8 kW, and 2.7 kW and at a rated speed of 3000 revolutions per minute (rpm). The engine's performance and exhaust emission data were recorded once it had stabilized in working condition. Before switching to a different fuel blend, the fuel burette had to be drained of the previous fuel and refilled with freshly tested fuel. All runs were measured in triplicate and the average values were directly fed to the design expert software.

2.5. Response surface methodology (RSM)

RSM is a mathematical and statistical method that is used in conjunction with numerical experiments to model experimental responses. It offers a method for constructing and optimizing the model through experimentation. The RSM model uses a quadratic polynomial model to estimate the response surface, which is provided in Eq. (1):

$$Y=\beta_0+\Sigma_{i=1}^{n}\beta_i x_i+\Sigma_{i=1}^{n}\beta_{ii}x_i^2+\Sigma_{i>j}^{n}\beta_{ij}x_i x_j+e \tag{1}$$

where Y is predicted output response, $\mathbf{n}$ is the number of factors, β_0 constant, β_i,β_{ii}, and β_{ij} are linear, quadric and interaction coefficients, respectively, x_i and x_j are independent factors and e is error [33].

To investigate the link between the responses and a collection of experimental variables, a central composite design (CCD) was used. Nanoparticle concentration and engine load were employed as two independent variables to create prediction models of NOx, HC, CO_2, CO, BSFC, BTE and EGT at three levels $(-1,0,1)$. The input variables and their levels are displayed in Table 5. To assess the pure error, CCD consists of 13 experimental runs with four axial points, four factorial points, and five duplicated centre points. In Eq. (2), the number of experimental runs was calculated

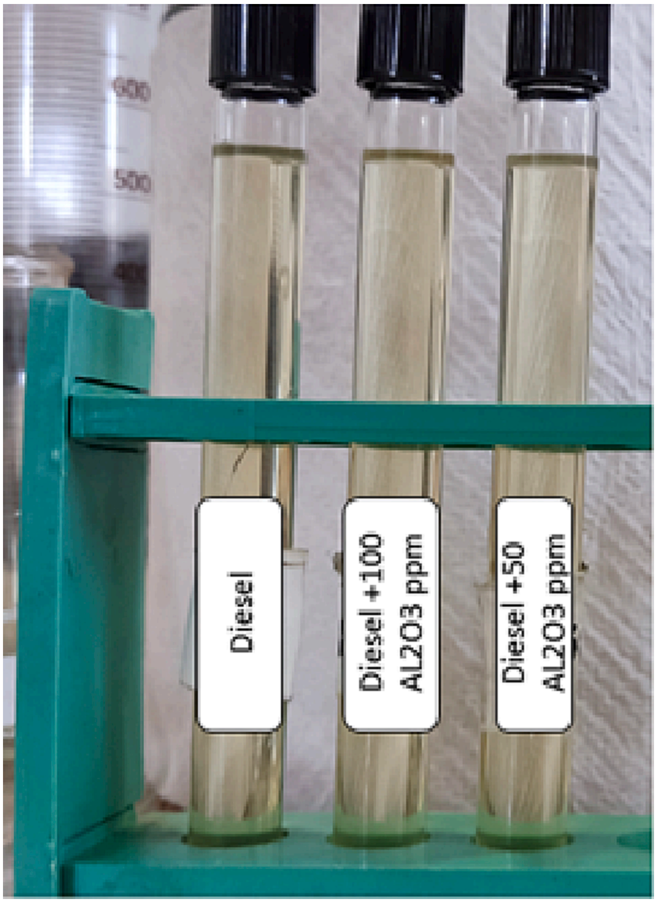


Fig. 3. Physical appearance of neat diesel fuel and nanodiesel fuels after preparation.

Table 2
Egyptian diesel fuel characteristics in accordance with ASTM standards [32].

Property	Value	Method
Cetane Number	45	ASTM D-13
Heating Value	42,000 kJ/kg	ASTM D-224
Kinematic Viscosity at 40°C	2.8 $mm^2/s(cst)$	ASTM D-445
Flash Point	75°C	ASTM D-93
Density at 15.56°C	829 kg/m^3	ASTM D-4052

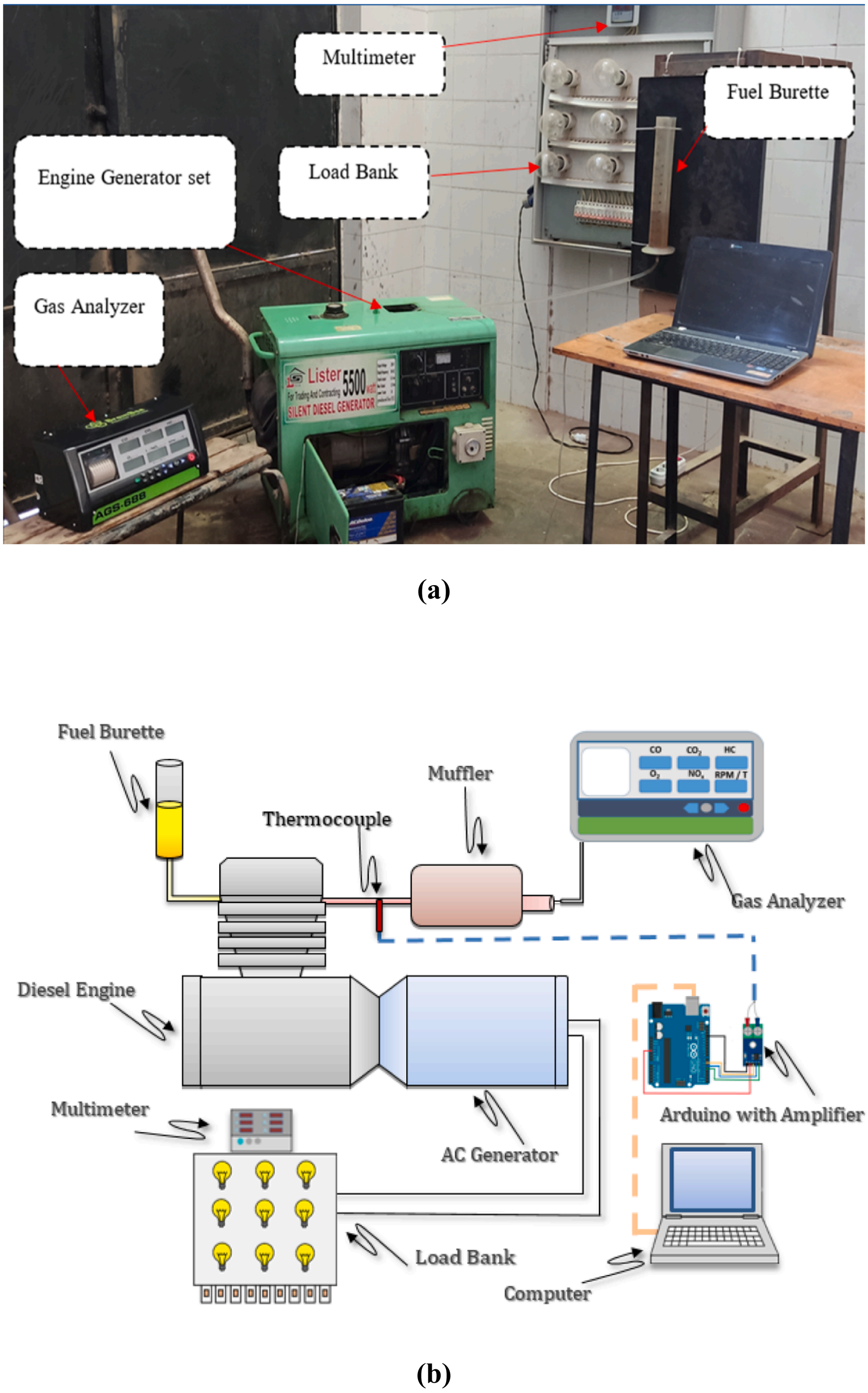
$$N=2^k+2^*k+NC \tag{2}$$

where NC is the number of center points and k is the number of independent variables [33]. The experiment design matrix is tabulated in Table 6.

3. Results and discussions

3.1. Evaluation and analysis of the model

The significance test for emissions parameters and engine performance was evaluated in this study using the analysis of variance



(a)

(b)

Fig. 4. Test rig. (a) Real view of test rig; (b) Schematic diagram of test rig.

Table 3
A list of the engine-generator set's technical specifications.

Generator	Type	Two-poles AC generator
	Voltage	220 VAC
	Rated output (kW)	5 kW
	Maximum output (kW)	5.5 kW
	Frequency (Hz)	50Hz
Engine	Model	5GF-SKM2 (Lister)
	Type	4-stroke diesel engine, Air-cooled
	Rated output	9hp/3000rpm
	Bore / stroke	86 mm/70 mm
	Displacement	406 cc

Table 4
The exhaust gas analyzers' technical specifications.

Emissions	Range	Unit	Accuracy
NO_X	0–5000	ppm	1
CO	0 –9.99	% vol	0.01
HC	0 –9999	ppm	1
CO_2	0 –19.9	% vol.	0.1

(ANOVA). If the p-value at the 95% confidence level is less than 0.05, the model is considered significant [34–37]. Table 7 demonstrates that all models are significant since their p-values are less than 0.05, indicating

Table 5
Experimental variables and their levels.

Variables	Symbols	Levels		
		−1	0	1
Nanoparticles concentration (ppm)	A	0	50	100
Engine load (kW)	B	0.9	1.8	2.7

that they can account for 95% of the response variability. The predicted R^2 and adjusted R^2 for the models are in reasonable consensus as their values are within 0.20 of each other. The obtained signal-to-noise ratios (Adequate Precision) for the models are greater than ideal. The lack of fit (F-value) for all models implies that it is insignificant relative to the pure error. No significant lack of fit is adequate for the model fit. Therefore, second order regression models that have been constructed are appropriate for predicting output responses [38]. The final empirical models for NOx, HC, CO_2, CO, BSFC, BTE and EGT in terms of coded factors are given by Eqs. (6)–(11), respectively, in Table 8. The correlation between predicted and actual values is shown in Fig. 5. It demonstrates how well the actual and expected data values match up. This indicates that the model is significant. The plots also show that most points are concentrated around the 45° line. This demonstrates how successfully the models predict the output responses.

3.2. Exhaust emissions analysis

3.2.1. NOx emissions

The response surface profile for a quadratic model of NOx emissions for engine load and all tested fuels is shown in Fig. 6 as a three dimensional (3D) plot. It reveals a steady increase in NOx emissions with respect to engine load. As a result, according to Zeldovich's thermal NOx mechanism, higher loads are associated with increased burning temperatures in the combustion chamber, which promote higher NOx emissions [16]. In addition, it was discovered that the NOx level and exhaust gas temperature were directly correlated.The figure clearly depicts a remarkable decrement in NOx level with the addition of nanoparticles to pure diesel. The amount of NOx emission is even less with addition of nanoparticles than it would be with pure diesel fuel because of the oxygenated additives and the combustion enhancement [15,20,29]. The cause of this reduction is the thermal stability and catalytic activity of nanofuels, which allow reaction completion and generate the final products from the HC compounds with the lowest thermal breakdown, resulting in a reduction in active radicals to form NOx [39]. Also, nanofuels with shorter ignition delays have lower adiabatic flame temperatures, earlier combustion, and hence reduced NOx emissions [29]. At the final load of 2.7 kW, the NOx emission

Table 8
The regression equations developed for different responses in terms of coded factors.

Eq.(6)	$\textbf{Sqrt (NOx)} = 8.55–0.7002 * A + 0.8714 * B - 0.1705 * AB + 0.9669 * A^2 - 0.0422 * B^2$
Eq.(7)	$\textbf{HC} = 15.31–1.33 * A + 2.67 * B + 0.2500 * AB + 3.41 *A^2 + 0.4138 * B^2$
Eq.(8)	$\textbf{Sqrt (CO}_\mathbf{2}\textbf{)} = 2.20 + 0.0000 * A + 0.2751 * B + 0.0000 * AB -0.0278 * A^2 + 0.0009 * B^2$
Eq.(9)	$\textbf{CO} = 0.0379–0.0067 * A - 0.0017 * B + 0.0025 * AB + 0.0072 * A^2 + 0.0022 * B^2$
Eq. (10)	$\textbf{Sqrt (BSFC)} = 21.40–0.1256* A - 3.71 * B - 0.0417 * AB + 0.3746 * A^2 + 0.8418 * B^2$
Eq. (11)	$\textbf{BTE} = 18.71 + 0.2369 * A + 5.90 * B + 0.1615 * AB - 0.6173 * A^2 + 0.0936 * B^2$
Eq. (12)	$\textbf{EGT} = 250.62–3.67 * A + 44.00 * B - 0.7500 * AB + 4.83 * A^2 - 4.17 * B^2$

Table 6
The experiment design matrix.

Run	Nanoparticles concentration (ppm)	Load (kW)	NOx (ppm)	HC (ppm)	CO_2 (% vol.)	CO (% vol.)	BSFC (g/kWh)	BTE (%)	EGT (°C)
1	50	2.7	86	18	6.1	0.04	345.417	24.8148	290
2	50	1.8	74	16	4.8	0.04	460.556	18.6111	251
3	100	2.7	91	21	6	0.04	350.899	24.427	291
4	50	1.8	74	15	4.8	0.04	460.556	18.6111	250
5	50	1.8	73	16	4.8	0.03	454.247	18.8696	250
6	50	0.9	59	13	3.7	0.04	669.899	12.7951	203
7	0	1.8	104	20	4.7	0.05	480.58	17.8356	259
8	100	0.9	65	15	3.6	0.04	690.833	12.4074	204
9	0	0.9	83	18	3.6	0.06	698.105	12.2781	210
10	0	2.7	127	23	6	0.05	362.404	23.6516	300
11	50	1.8	72	15	4.9	0.04	454.247	18.8696	251
12	50	1.8	74	15	4.9	0.04	460.556	18.6111	251
13	100	1.8	77	17	4.7	0.04	467.042	18.3526	252

Table 7
Model evaluation.

Model	**NOx** Quadratic	**HC** Quadratic	**CO_2** Quadratic	**CO** Quadratic	**BSFC** Quadratic	**BTE** Quadratic	**EGT** Quadratic
Transformation	Square Root	None	Square Root	None	Square Root	None	None
p-value	< 0.0001	< 0.0001	< 0.0001	0.0091	< 0.0001	< 0.0001	< 0.0001
Lack of Fit (F value)	2.93 Not Signficant	0.5089 Not Signficant	0.1390 Not Signficant	0.2807 Not Signficant	0.6488 Not Signficant	0.6024 Not Signficant	0.9432 Not Signficant
Std. Dev.	0.0707	0.4867	0.0099	0.0037	0.0745	0.1290	0.5410
Mean	8.98	17.08	2.19	0.0423	21.96	18.47	250.92
R^2	0.9967	0.9829	0.9985	0.8465	0.9995	0.9994	0.9998
Adjusted R2	0.9943	0.9707	0.9974	0.7368	0.9992	0.9991	0.9997
Predicted R^2	0.9775	0.9439	0.9970	0.5439	0.9981	0.9977	0.9991
Adeqate Precision	74.5086	29.7318	86.1234	8.0401	155.5690	142.6398	264.5781

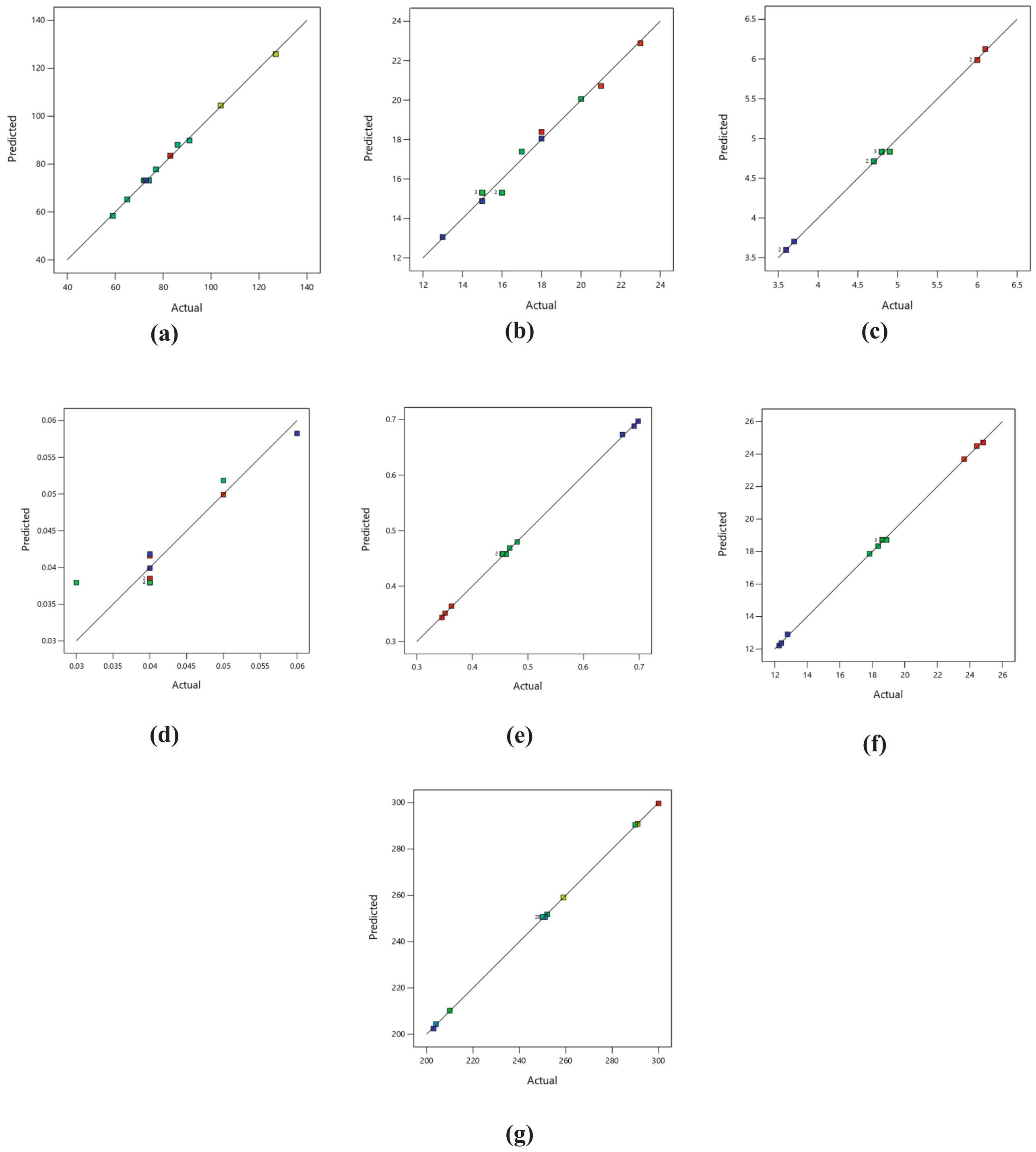


Fig. 5. Actual response versus predicted response for (a) NOx; (b) HC; (c) CO_2; (d) CO; (e) BSFC; (f) BTE; (g) EGT.

magnitude is found to be 127 ppm for pure diesel, compared to 86 and 91 ppm for D + 50AL_2O_3 and D + 100AL_2O_3, respectively.

3.2.2. HC emissions

Because there is less oxygen available close to the fuel particles, incomplete combustion of the fuel results in unburned HC emissions from the engine. The air–fuel ratio, air–fuel mixing, atomization of fuel particles, and cylinder wall temperature all affect how much oxygen is produced [23]. As shown in Fig. 7, HC emissions increase as the load increases for all tested fuels. As nanoparticles are added to neat diesel fuel, HC emissions decrease for all the loads because adding nanoparticles to pure diesel lowers the carbon's activation temperature and enhances combustion [29,40]. The maximum HC emission values for pure diesel, D + 50AL_2O_3, and D + 100AL_2O_3 are 23 ppm, 18 ppm, and 21 ppm, respectively, at the final load of 2.7 kW.

3.2.3. CO_2 emissions

CO_2 emissions are not regulated and are influenced by the fuel's carbon content. If complete combustion takes place in an engine, these emissions will be higher [41]. Fig. 8 shows a (3D) plot of a quadratic model of CO_2 emissions with respect engine load and all tested types. For all of the tested fuels, it was found that CO_2 raised linearly with the load. This is because higher loads result in higher combustion temperatures, which aid in full fuel combustion. [42]. Additionally, it was found that

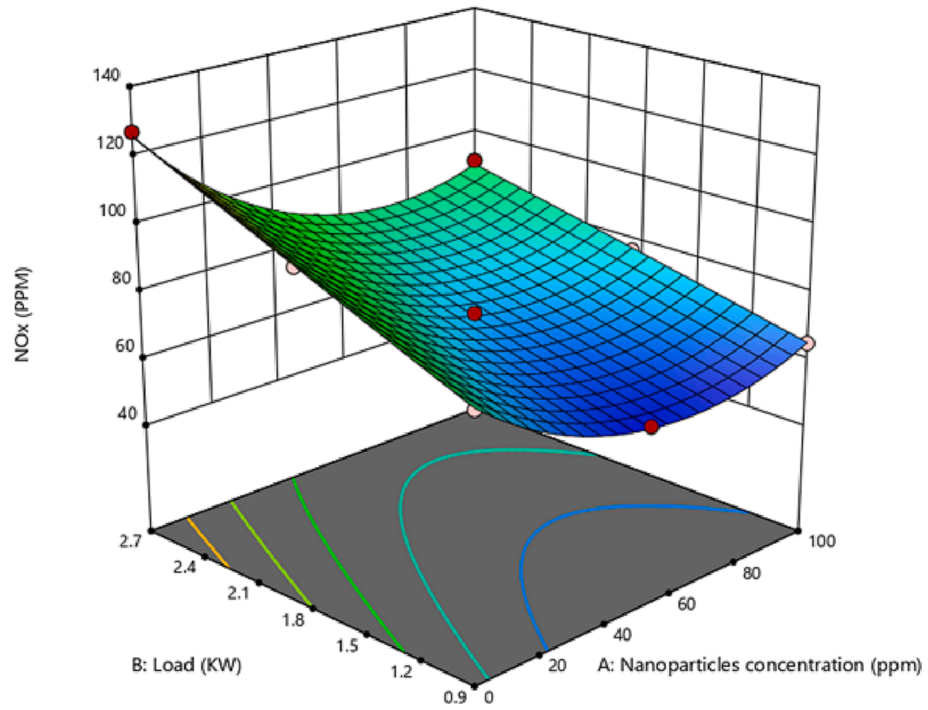


Fig. 6. Impact of engine load and nanoparticles concentration on NOx emissions.

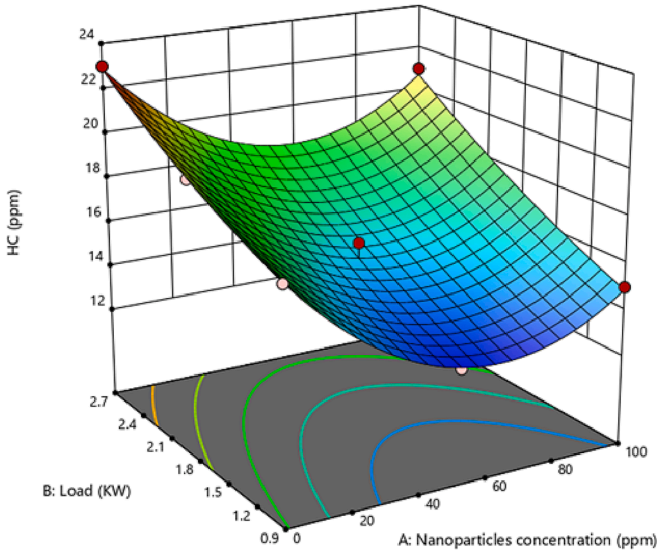


Fig. 7. Impact of engine load and nanoparticles concentration on HC emissions.

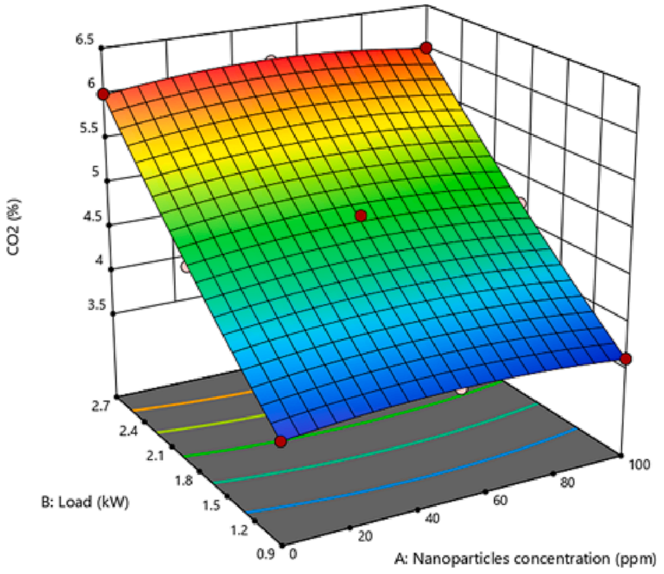


Fig. 8. Impact of engine load and nanoparticles concentration on CO_2 emissions.

the CO_2 emissions of pure diesel fuel and nanodiesel fuels did not differ much. Furthermore, due to the complete combustion process, the $D + 50AL_2O_3$ fuel produced more CO_2 emissions at all load conditions [40].

3.2.4. CO emissions

CO’s absence of color, flavor, and taste is well known. Its density is greater than that of the surrounding air. Additionally, CO is extremely poisonous and significantly impacts human health in the environment [43]. Furthermore, a small amount of CO may cause headaches and shortness of breath. Several factors, including injection timing, fuel type, air–fuel ratio, injection pressure, and engine speed, can affect the production of CO emissions in internal combustion engines. [43]. Fig. 9 shows a (3D) contour plot representing the interactions between nanoparticles concentration and load for CO emissions. As engine load increased, CO was seen to increase after initially decreasing with the load. All of the tested fuels showed this pattern. Additionally, it has been noted that using aluminum oxide nanoparticles in pure diesel fuel reduced CO emissions. This trend could be explained by several factors, such as improved combustion characteristics, ignition delay shortening, higher surface contact area, and higher chemical reactivity [29]. The value of CO emission is 0.05 % vol. for pure diesel, whereas it is 0.04 % vol. and 0.04% vol. for the $D + 50AL_2O_{3,}$ $D + 100AL_2O$ at the final load of 2.7 kW respectively.

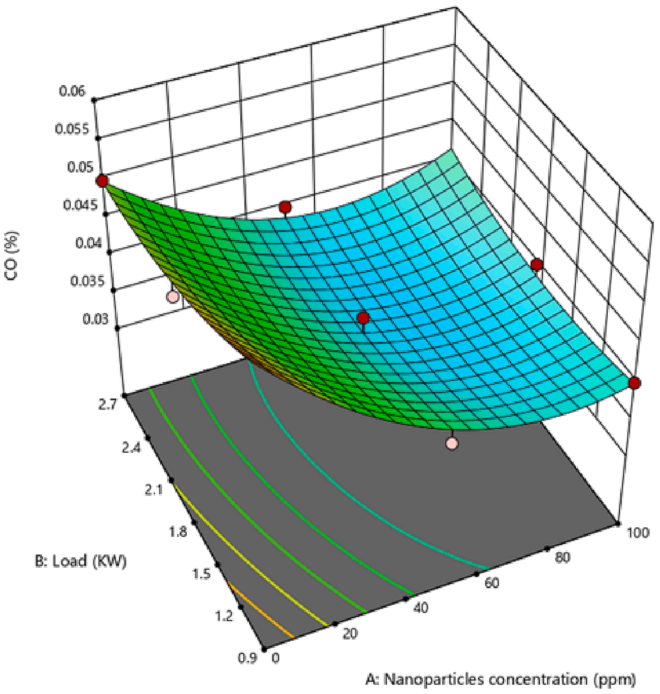


Fig. 9. Impact of engine load and nanoparticles concentration on CO emissions.

3.3. Engine performance analysis

3.3.1. BSFC

The term “BSFC” refers to the quantity of fuel consumed by an engine per unit of power production and its relationship to the heating content of the fuel, cetane number, viscosity, and density. To calculate BSFC **(**g/kWh**)**, the following equation is used,

$$\mathbf{BSFC} = \frac{\dot{m}_{fC}}{P_e} \tag{13}$$

where $\dot{\mathbf{m}}_{\mathbf{fC}}$ is actual measured fuel consumption $(\mathbf{g}/\mathbf{h})$ and P_e is brake power (kW) [44].

Fig. 9 illustrates how engine load and nanoparticle concentration affect BSFC. For all tested fuels, it should be noted that the BSFC decreased as the load was raised. The main reason for this might be that higher loads result in a smaller proportion of heat losses, so the percentage increase in fuel required to run the engine is less than the percentage increase in brake power [45]. With the addition of nanoparticles, there is also a slight decrease in BSFC. This is likely due to the beneficial characteristics of the nanoparticles in the mixture, such as a larger surface-area-to-volume ratio and high oxygen content. In fact, nanoparticles act like a catalyst which enhance the combustion process [15,16,29]. Also, the existence of an oxide nanoparticle can potentially cause a secondary atomization reaction following the micro-explosion phenomenon [15]. When using D + 50AL2O3 and D + 100AL2O at a final load of 2.7 kW, respectively, the magnitude of BSFC is 345.417 g/kWh and 350.899 g/kWh, compared to 362.404 g/kWh for pure diesel.

3.3.2. BTE

BTE can be defined as the output or work performed by the working substance in the cylinder of the engine at a given time to the input or heat energy of the fuel provided at that same time [46]. Simply, BTE is the inverse of the BSFC and fuel’s lower calorific value product [44]. To calculate BTE, the following equation is used,

$$\mathbf{BTE} = \frac{3600 * P_e}{\dot{m}_{fc} * LHV} \times 100 \tag{14}$$

where $\boldsymbol{LHV}$ is the lower heating value of the tested fuels (kJ/kg), $\dot{m}_{fC}$ is actual measured fuel consumption $(\mathbf{kg}/\mathbf{h})$ and P_e is brake power (kW).

BTE rises as the load rises for all tested fuels, as seen in Fig. 10. This is because there are fewer heat losses and more power when the load increases [47]. It is observed that the nanodiesel fuels gave the higher BTE than the neat diesel fuel for all load conditions. This may be related to nanoparticles’ improved combustion features, such as their higher surface-area-to-volume ratio, allowing more fuel to react with the air and increasing burning efficiency [16]. The maximum values of BTE at the final load condition of 2.7 kW are 23.6516 %, 24.8148 % and 24.427 %, respectively, for the pure diesel, D + 50AL$_2$O$_3$ and D + 100AL$_2$O$_3$.

3.3.3. EGT

The exhaust gas temperature significantly influences exhaust emissions. EGT is influenced by engine running conditions, including injection pressure and compression ratio as well as fuel qualities like heating value, cetane number, density, and viscosity [48]. The effect of nanoparticles concentration and engine load on EGT is plotted in Fig. 11. Due to the requirement for more fuel at higher loads to overcome the load, which increases the quantity of heat generated with combustion gases, it was found that the EGT increased with rise the in load for all tested fuels. [49]. Additionally, it was found that the EGT is reduced by the use of nanoparticles. This is likely brought on by the presence of nanoparticles, which have shorter ignition properties, in the mixture [16]. At the final load of 2.7 kW, the maximum EGT for pure diesel is 300° **C**, while it is 290° **C** and 291° **C** for the D + 50AL$_2$O$_3$ and D + 100 AL$_2$O$_3$, respectively.

3.4. Cost analysis

For the industry professionals and policymakers to decide whether a proposed process is valid, they must check its economic feasibility. In this paper, we have conducted a preliminary cost analysis. The estimation of diesel cost due to adding aluminum oxide nanoparticles was considered. The current price of one liter of diesel in the USA is about 1.199 $, while the price of Al$_2O_3$ nanoparticle was considered 185 $/kg as per Nouri et al. [47]. In the present study, the optimum nanoparticles concentration of 50 ppm (0.05 g) contributed to an additional cost of 0.00925 $ per liter of diesel. At the same time, the average fuel consumption in our proposed study was reduced by 4.3%. Such reduction contributed to a cost benefit of 0.052 $/ per liter of diesel. Based on the previous calculations, the net specific cost-benefit considering the addition of the nanoparticles and the reduced fuel consumption is

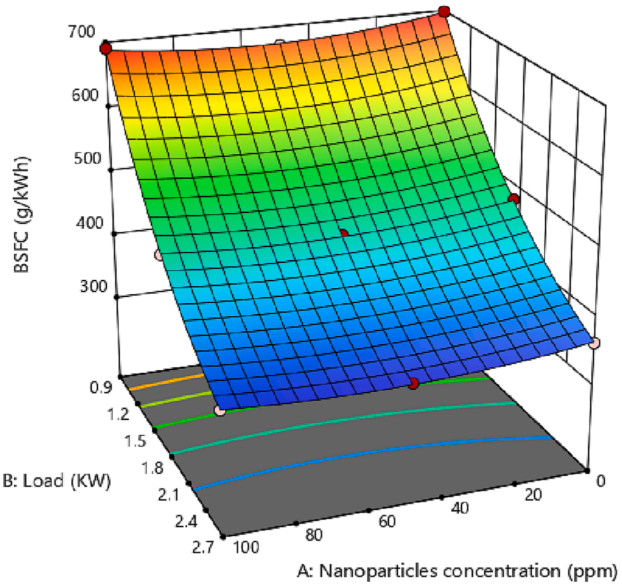


Fig. 10. Impact of engine load and nanoparticles concentration on BSFC.

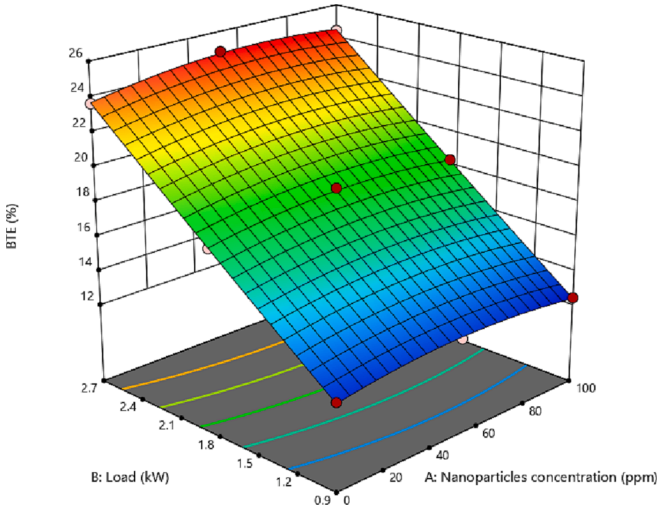


Fig. 11. Impact of engine load and nanoparticles concentration on BTE.

0.0427 $ per liter of diesel. In addition, the positive environmental advantages of using the proposed nano based fuel contribute toward mitigating harmful emissions, fulfilling the requirements of the sustainable development goals (Fig. 12).

4. Conclusions

In this work, the impact of mixing pure diesel with two different small-sized Al_2O_3 nanoparticle concentrations (50 and 100 ppm) was studied on engine emissions and performance parameters. The following are the major conclusions that can be drawn from the study's findings:

- With p-values less than 0.05, the developed response models were regarded as stable.
- The difference between the “Adjusted R^{2}″ and the ”Predicted R^{2}″ is less than 0.2, indicating good agreement between the experimental and predicted results.
- The coefficient of determination of R^2 for NOx, HC, CO_2, CO, BSFC, BTE and EGT were 0.9967, 0.9829, 0.9985, 0.8465, 0.9995, 0.9994 and 0.9998 respectively.
- The inclusion of Al_2O_3 nanoparticles significantly reduced the NO_X emissions from pure diesel. The lowest reduction of NO_X content at the final load condition with pure diesel and 50 ppm of Al_2O_3 nanoparticles was 32.28%. In addition, HC and CO concentrations were reduced when nanoparticles were used with pure diesel fuel.
- For D + 50 Al_2O_3 at final load condition, the best reduction in HC and CO emissions was 21.74 % and 20%, respectively.
- D + 50 Al_2O_3 produced the lowest reduction in BSFC. Furthermore, compared to pure diesel fuel, D + 50 Al_2O_3 produced the highest increase in BTE at final load condition, 4.92%. The engine performance improves with the addition of 50 ppm of Al_2O_3 nanoparticles to pure diesel.
- For the best improvements in engine emissions and performance, Al_2O_3 nanoparticle concentration is recommended to be 50 ppm, and it is also permissible to utilize it as an additive to fuel in diesel engines.
- This study showed that the combination between pure diesel and small-sized nanoparticles had positive synergistic effects on emissions characteristics and engine performance.

In this work, a small-sized (11 nm) low concentration (50 ppm) of Al_2O_3 nanoparticle (mixed with neat diesel) revealed a positive technical, environmental, and economic perspective on implementing the proposed nanofuel in practical application. In addition, the RSM's advantage contributed to analyzing the proposed model with few experimental runs. Furthermore, RSM could be successfully used to predict diesel engine-out emissions and performance. Future works may consider measuring the combustion characteristics, such as in-cylinder pressure and heat release rate. In addition, other tests can be performed at different conditions, such as different injection timings.

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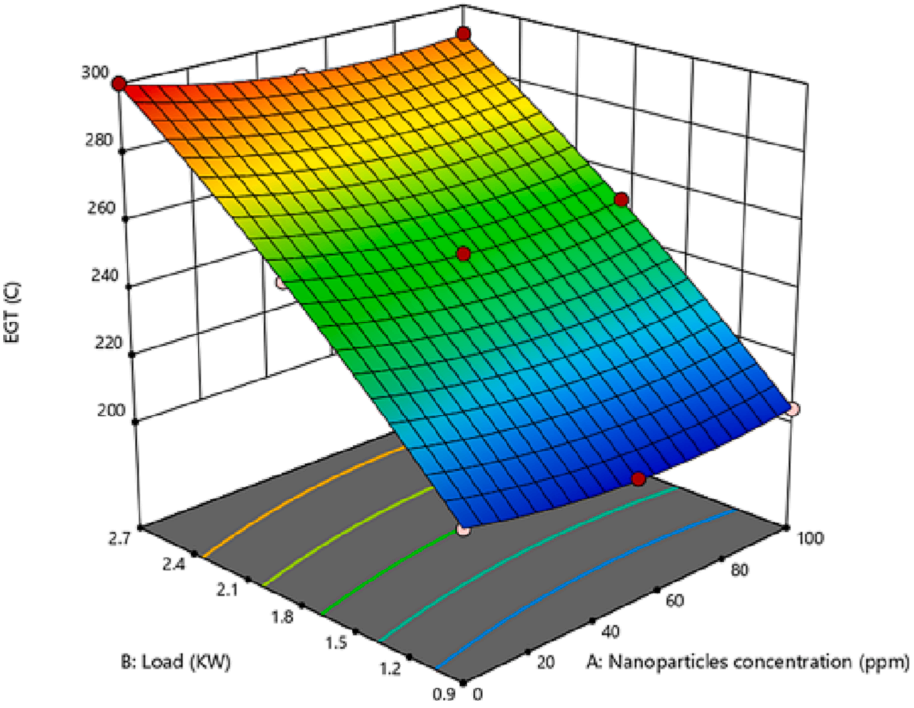

Fig. 12. Impact of engine load and nanoparticles concentration on EGT.

CRediT authorship contribution statement

A. Mostafa: Conceptualization, Methodology, Software, Formal analysis, Data curation, Writing – original draft, Supervision. **M. Mourad:** Conceptualization, Formal analysis, Resources, Data curation, Writing – review & editing, Supervision. **Ahmad Mustafa:** Methodology, Software, Investigation, Writing – review & editing. **I. Youssef:** Validation, Investigation, Resources, Writing – review & editing, Visualization, Supervision.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

References

[1] Yilmaz N, Atmanli A, Hall MJ, Vigil FM. Determination of the optimum blend ratio of diesel, waste oil derived biodiesel and 1-pentanol using the response surface method. Energies 2022;15(14):5144.

[2] Selvanayagam BF, et al. A review on nanoparticles blended with diesel to improve combustion characteristics and reduction in emission of diesel engine. Mater Today: Proc 2022;66:1031–7.

[3] Saxena S, Bedoya ID. Fundamental phenomena affecting low temperature combustion and HCCI engines, high load limits and strategies for extending these limits. Prog Energy Combust Sci 2013;39(5):457–88.

[4] Abomohra A, Faisal S, Ebaid R, Huang J, Wang Q, Elsayed M. Recent advances in anaerobic digestion of lipid-rich waste: challenges and potential of seaweeds to mitigate the inhibitory effect. Chem Eng J 2022;449.

[5] Dubey A, et al. Combined effects of biodiesel− ULSD blends and EGR on performance and emissions of diesel engine using Response surface methodology (RSM). Energy Nexus 2022;7:100136.

[6] Bui VG, Bui TMT, Hoang AT, Nižetić S, Nguyen Thi TX, Vo AV. Hydrogen-enriched biogas premixed charge combustion and emissions in direct injection and indirect injection diesel dual fueled engines: A comparative study. J Energy Res Technol 2021;143(12).

[7] Abdelmoez W, Tayeb AM, Mustafa A, Abdelhamid M. Green approach for biodiesel production from jojoba oil supported by process modeling and simulation. Int J Chem React Eng 2016;14(1):185–93.

[8] Ibrahim SM, Mustafa A. Synthesis and characterization of new bifunctional SnZrSi oxide catalysts for biodiesel production. J Mol Liq 2022;354:118811.

[9] Afzal A, et al. Characterization of biodiesel based on plastic pyrolysis oil (PPO) and coconut oil: Performance and emission analysis using RSM-ANN approach. Sustainable Energy Technol Assess 2023;56:103046.

[10] Faisal S, Zaky A, Wang Q, Huang J, Abomohra A. Integrated marine biogas: a promising approach towards sustainability. Fermentation 2022;8(10):520.

[11] Xiong M, et al. Evaluation of bio-oil/biodiesel production from co-pyrolysis of corn straw and natural hair: A new insight towards energy recovery and waste biorefinery. Fuel 2023;331:125710.

[12] Mostafa A, et al., Assessment of performance and emissions characteristics of diesel engine using water diesel emulsion: a review; 2022.

[13] Yilmaz N, Vigil FM, Atmanli A, Donaldson B. Detailed analysis of PAH formation, toxicity and regulated pollutants in a diesel engine running on diesel blends with n-propanol, n-butanol and n-pentanol. Energies 2022;15(17):6487.

[14] Shams Z, Moghiman M. An experimental investigation of ignition probability of diesel fuel droplets with metal oxide nanoparticles. Thermochim Acta 2017;657:79–85.

[15] Alex Y, et al. Study of engine performance and emission characteristics of diesel engine using cerium oxide nanoparticles blended orange peel oil methyl ester. Energy Nexus 2022;8:100150.

[16] Sadhik Basha J, Anand R. Effects of nanoparticle additive in the water-diesel emulsion fuel on the performance, emission and combustion characteristics of a diesel engine. Int J Veh Des 2012;59(2/3):164–81.

[17] D'Silva R, Binu K, Bhat T. Performance and Emission characteristics of a CI Engine fuelled with diesel and TiO2 nanoparticles as fuel additive. Mater Today: Proc 2015;2(4–5):3728–35.

[18] Abdel-Rehim AA, Akl SY. An experimental investigation of the effect of aluminum oxide (Al 2 O 3) nanoparticles as fuel additive on the performance and emissions of a diesel engine. 2016, SAE Technical Paper.

[19] Chen AF, Akmal Adzmi M, Adam A, Othman MF, Kamaruzzaman MK, Mrwan AG. Combustion characteristics, engine performances and emissions of a diesel engine using nanoparticle-diesel fuel blends with aluminium oxide, carbon nanotubes and silicon oxide. Energ Conver Manage 2018;171:461–77.

[20] Gumus S, Ozcan H, Ozbey M, Topaloglu B. Aluminum oxide and copper oxide nanodiesel fuel properties and usage in a compression ignition engine. Fuel 2016;163:80–7.

[21] Khatri D, Goyal R. Effects of silicon dioxide nanoparticles on the performance and emission features at different injection timings using water diesel emulsified fuel. Energ Conver Manage 2020;205:112379.

[22] Backiyaraj A, Parthasarathy M, Murugu Nachippan N, Senthilkumar PB, Kumaran T. Influence of nano AL2O3 on compression ignition engine characteristics fuelled with Mahua biodiesel. Mater Today: Proc 2023;72:2238–44.

[23] Kaushik Y, Verma V, Saxena KK, Prakash C, Gupta LR, Dixit S. Effect of Al2O3 nanoparticles on performance and emission characteristics of diesel engine fuelled with diesel-neem biodiesel blends. Sustainability 2022;14(13):7913.

[24] Hosney H, Al-Sakkari EG, Mustafa A. Kinetics and gibbs function studies on lipase-catalyzed production of non-phthalate plasticizer. J Oleo Sci 2020;69(7):727–35.

[25] Hosney H, Al-Sakkari EG, Mustafa A, Ashour I, Mustafa I, El-Shibiny A. A cleaner enzymatic approach for producing non-phthalate plasticiser to replace toxic-based phthalates. Clean Techn Environ Policy 2020;22(1):73–89.

[26] Hosney H, Mustafa A. Semi-continuous production of 2-ethyl hexyl ester in a packed bed reactor: Optimization and economic evaluation. J Oleo Sci 2020;69(1):31–41.

[27] Mustafa A, et al. Selective synthesis of alpha monoglycerides by a clean method: Techno-economic and environmental assessment. Sustain Chem Pharm 2022;27:100690.

[28] Mustafa A, Niikura F. Green synthesis of isopropyl palmitate using immobilized Candida antarctica lipase: process optimization using response surface methodology. Clean Eng Technol 2022;8:100516.

[29] Gad MS, Abdel Razek SM, Manu PV, Jayaraj S. Experimental investigations on diesel engine using alumina nanoparticle fuel additive. Adv Mech Eng 2021;13(2).168781402098840.

[30] Khulief S, Aboul-Fotouh TM. Experimental investigation of upgraded diesel fuel with copper oxide nanoparticles on performance and emissions characteristics of diesel engine. J Energy Power Eng 2017;11:541–52.

[31] Ebrahiem EE, et al. Improvement of diesel fuel to enhance engine performance and emissions using zinc oxide nanoparticle additive. Egypt J Chem 2022;65(2):349–55.

[32] Abed KA, Gad MS, El Morsi AK, Sayed MM, Elyazeed SA. Effect of biodiesel fuels on diesel engine emissions. Egypt J Pet 2019;28(2):183–8.

[33] Özgür C. Optimization of biodiesel yield and diesel engine performance from waste cooking oil by response surface method (RSM). Pet Sci Technol 2021;39(17–18):683–703.

[34] Adam IK, Aziz ARA, Yusup S. Determination of diesel engine performance fueled biodiesel (rubber seed/palm oil mixture) diesel blend. Int J Automot Mech Eng 2015;11:2675.

[35] Khatri D, Goyal R, Jain A, Johnson AT. Modeling and optimization of stability aspects for water diesel emulsified fuel using response surface methodology. Energy Sources Part A 2022;44(2):3055–78.

[36] Chen AF, Adzmi MA, Adam A. Optimization evaluation of various type nanoparticles-diesel blended fuels on diesel engine combustion characteristics, performances and exhaust emissions. Int J Mech Eng Robotics Res 2020:212–7.

[37] Dubey A, Prasad RS, Singh JK. An analytical and economical assessment of the waste cooking oil based biodiesel using optimized conditions on the process variables. Energy Sources Part A 2020:1–16.

[38] Singh A, et al. Optimization of performance and emission characteristics of CI engine fueled with Jatropha biodiesel produced using a heterogeneous catalyst (CaO). Fuel 2020;280:118611.

[39] Nouri M, Isfahani AHM, Shirneshan A. Effects of Fe2O3 and Al2O3 nanoparticle-diesel fuel blends on the combustion, performance and emission characteristics of a diesel engine. Clean Techn Environ Policy 2021;23(8):2265–84.

[40] Ghanbari M, et al. Effect of alumina nanoparticles as additive with diesel–biodiesel blends on performance and emission characteristic of a six-cylinder diesel engine using response surface methodology (RSM). Energy Convers Manage: X 2021;11:100091.

[41] EdwinGeo V, et al. Experimental analysis to reduce CO2 and other emissions of CRDI CI engine using low viscous biofuels. Fuel 2021;283:118829.

[42] Dębowski M, Michalski R, Zieliński M, Kazimierowicz J. A comparative analysis of emissions from a compression–ignition engine powered by diesel, rapeseed biodiesel, and biodiesel from chlorella protothecoides biomass cultured under different conditions. Atmos 2021;12(9):1099.

[43] Yesilyurt MK, Yilbasi Z, Aydin M. The performance, emissions, and combustion characteristics of an unmodified diesel engine running on the ternary blends of pentanol/safflower oil biodiesel/diesel fuel. J Therm Anal Calorim 2020;140(6):2903–42.

[44] Atmanlı A, Ileri E, Yüksel B. Experimental investigation of engine performance and exhaust emissions of a diesel engine fueled with diesel–n-butanol–vegetable oil blends. Energ Conver Manage 2014;81:312–21.

[45] Godiganur S, Murthy CS, Reddy RP. 6BTA 5.9 G2–1 Cummins engine performance and emission tests using methyl ester mahua (Madhuca indica) oil/diesel blends. Renew Energy 2009;34(10):2172–7.

[46] Syu J-Y, Chang Y-Y, Tseng C-H, Yan Y-L, Chang Y-M, Chen C-C, et al. Effects of water-emulsified fuel on a diesel engine generator's thermal efficiency and exhaust. J Air Waste Manag Assoc 2014;64(8):970–8.

[47] Mallikappa D, Reddy RP, Murthy CS. Performance and emission characteristics of double cylinder CI engine operated with cardanol bio fuel blends. Renew Energy 2012;38(1):150–4.

[48] Baweja S, Trehan A, Kumar R. Combustion, performance, and emission analysis of a CI engine fueled with mustard oil biodiesel blended in diesel fuel. Fuel 2021;292:120346.

[49] Kumar N, Raheman H. Thermal and environmental performance of CI engine using CeO2 nanoparticles as additive in water–diesel–biodiesel fuel blend. Int J Environ Sci Technol 2022;19(4):3287–304.