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# Enabling a Sustainable Diesel Future: Emission Control and Performance Enhancement with $B_2O_3$ Nanoparticles via RSM Optimization

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Research Article

## Abstract

Today, the energy required is constantly increasing. Diesel engines are one of the important energy production methods. Diesel engines will continue to be used for many years due to their efficiency and long life. However, fossil fuels used in diesel engines have disadvantages such as being harmful to the environment and decreasing reserves. In this work, boron oxide ($B_2O_3$) nanoparticles were added to diesel fuel and their effects on emissions and engine performance were examined in an effort to prevent these drawbacks and improve the sustainability of diesel fuel. Three distinct $B_2O_3$ concentrations (10, 20, and 30 ppm) were added to diesel fuel for the investigation. Six distinct loads, ranging from 0.5 to 3 kW, were used to test the fuels while a four-stroke, single-cylinder diesel engine ran at a steady 3000 rpm. Response surface methodology (RSM) was used to optimize the experimental study's results in order to determine the ideal operating parameters. The findings of the study showed that 1.5 kW load and 9 ppm $B_2O_3$ added fuel were the ideal operating conditions. Carbon monoxide (CO) was estimated to be 0.0459%, hydrocarbon (HC) to be 24.2915 ppm, carbon dioxide ($CO_2$) to be 5.0699%, nitrogen oxide ($NO_x$) to be 522.5814 ppm, brake specific fuel consumption (BSFC) to be 384.7523 g/kWh, and brake thermal efficiency (BTE) to be 22.96% at these operating conditions. When these values are compared with D100, CO decreased by 39.61%, HC by 13.17%, and BTE by 14.14%, while $CO_2$ increased by 11.68%, $NO_x$ by 15.87%, and BSFC by 23.33%. In the RSM study, the minimum correlation coefficient ($R^2$) value belongs to BSFC with 91.34%. All error rates in the study are below 10% and vary between 1.69% and 6.47%.

*Keywords*: Boron oxide nanoparticles; Response Surface Methodology (RSM); Sustainability; Engine performance and emission

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## 1. Introduction

The need for energy is constantly growing as a result of global modernity, population growth, industrialization, and the rise in the number of fossil fuel-powered vehicles [1]. This energy requirement is supplied by a number of sources. The most important of these sources is fossil-based fuels. Approximately 80% of the world's energy needs are provided by fossil fuels. Diesel engines, which produce energy using fossil fuels, are frequently preferred due to their efficiency and long life. However, CO, $CO_2$, HC and $NO_x$ emissions, which arise from the combustion of fossil fuels in diesel engines and are detrimental to both the environment and human health. [2]. Researchers have made modifications on the engine, systems such as exhaust gas recirculation (EGR) [3] and selective catalytic reduction (SCR) [4] studies on fuel to reduce these emissions. Due to the advantages of the diesel engine, the fact that diesel engines cannot be abandoned, the reserves of fossil resources are limited in certain regions and the price changes and reserves decrease due to political events, alternative fuel and fossil fuel development studies have increased in recent years [5]. Researchers have conducted various alternative fuel studies that can be used instead of fossil fuels. Simple alcohols such as methanol [6] and pentanol [7], biofuels obtained from vegetable [8,9] and animal oils [10], liquefied natural gas [11], biogas [12] and hydrogen [13] are some of the alternative fuel studies.

In one of these studies, Fernandez et al. [14] performed engine performance and emission tests by adding 10%, 15%, 20% and 25% pentanol to diesel by volume, respectively. In the tests, they determined that the addition of alcohol improved engine performance and that pentanol added up to 25% mixture could be used without making any changes to the engine. In another study, Ince et al. [15] produced test fuels by combining diesel and biodiesel made from leftover vegetable oil in two distinct volume ratios (10% and 20%). At a given speed of 1800 rpm, the acquired test fuels were evaluated at six different loads with a fixed ratio ranging from 0% to 100%. In the experiment, while the added biodiesel decreased BSFC at low loads, it increased compared to diesel at high loads. In addition, while CO and HC emissions decreased in 10% blended fuel, $CO_2$ and $NO_x$ emissions increased in 10% and 20% blended fuels. They contend that the high oxygen component of biodiesel raises the temperature at which it burns. Simsek [16] investigated what Biodiesel produced from a mixture of waste oil, canola, and safflower had an impact on emissions and engine performance. The author considered biodiesel as a renewable alternative fuel due to its high cetane number, lack of sulphur and oxygen content. At six different loads (500W, 1000W, 1500W, 2000W, 2500W, and 3000W) at a constant speed of 3000 rpm, the study examined seven different fuels that were produced by adding 0%, 10%, 20%, 30%, 50%, 75%, and 100% biodiesel to diesel by volume. The study found that because biodiesel has a low calorific value, its BSFC increased in all fuel types when compared to diesel, and its BTE value climbed up to 75% bio-diesel mixture, but declined when compared to 100% bio-diesel mixture. It was determined that biodiesel use increased $NO_x$ emissions while reducing CO and HC emissions. When the studies were examined, biodiesel has disadvantages such as low calorific value and high viscosity [17]. To minimize these disadvantages and ensure fuel sustainability, some researchers added additives such as nanoparticles to fuels [18].

The nanoparticles added to fuels are generally 1-100 nm in size. These nanoparticles reduce the ignition delay and deliver flawless combustion while improving the surface area/volume ratio, heat transport, and combustion quality [19,20]. In one of the studies conducted in this context, Sanjeevarao et al. [21] performed engine tests by adding $Al_2O_3$ nanoparticles to cottonseed biodiesel. In the study, four distinct fuels were produced by mixing 20% and 50% by volume of diesel with 50 and 100 ppm $Al_2O_3$ nanoparticles. Engine tests were conducted at a fixed 1500 rpm with loads of 0, 5, 10, 15, and 20 kg. The use of nanoparticles enhanced the bio-diesel's low calorific value, bringing it nearly equal to that of diesel. They found an increase in the BSFC value compared to diesel, and an improvement in the BTE value in the 20% fuel mixture with 100 ppm $Al_2O_3$ addition. They also observed an increase in $NO_x$ emissions. In another study, Reddy and Wani [22] obtained a fuel by mixing biodiesel produced from palm oil with diesel at a volume rate of 20% (B20). They prepared different fuels by adding 60 ppm $CeO_2$ (B20CO), 60 ppm $TiO_2$ (B20TO), and 60 ppm of two nanoparticles (B20COTO) to this fuel. They found that while the BSFC value increased in B20 fuel, the BSFC value decreased with the addition of nanoparticles, and the lowest BSFC value was in B20COTO. They noticed that the high oxygen content and high cetane number of biodiesel led to an increase in the entire combustion rate and a decrease in HC and CO emissions. B20 fuel was shown to have higher $NO_x$ emissions, but B20COTO fuel showed lower $NO_x$ emissions. Studies have demonstrated that adding nanoparticles improves fuel combustion. Numerous researchers have examined the effects of directly adding these nanoparticles to biodiesel and diesel fuel.

Çelik and Uslu [23] added 4 different amounts of $CeO_2$ nanoparticles to diesel fuel, namely 25, 50, 75 and 100 ppm. They found that the added nanoparticle positively affected the performance by the oxygen storage capacity and thermal properties, and that there was a 12.08% decrease in BSFC and a 13.73% increase in BTE in the fuel with 100 ppm addition compared to pure diesel. In terms of emission values, they observed that HC emissions decreased by 15.49%, smoke emissions by 17.65% and CO emissions by 13.26%, while $NO_x$ emissions increased by 7.56% in the fuel with 100 ppm addition compared to diesel. In the study, they determined that the nanoparticle positively affected combustion and that $CeO_2$ could be an additive for diesel fuel. In another study, three different concentrations of TiO2 nanoparticles 25, 50, and 75 ppm were introduced to pure diesel fuel by Koca et al. [24]. Experiments were conducted in the study at four distinct loads—25%, 50%, 75%, and 100%—while maintaining a steady speed of 1800 rpm. It was found that the engine's performance and emission characteristics were enhanced by the additional nanoparticles. In comparison to diesel, the fuel with 25 ppm $TiO_2$ added had a 13.36% drop in the BSFC value at low load and a 15.12% increase in the BTE value at 25% load. Emission data showed that $TiO_2$'s catalytic activity enhanced combustion, increasing $CO_2$ and $NO_x$ emissions while decreasing CO and HC emissions. When the studies were examined, it was determined that the added nanoparticles did not continuously improve combustion, performance and emissions, and after a certain point, the amount of added nanoparticles negatively affected the fuel density, disrupted fuel atomization and worsened combustion [25]. In order to determine the amount of nanoparticles that gave the lowest emission and highest performance value, experiments should be carried out at every interval. However, experiments cannot be done because they are time consuming and costly. Instead, optimization studies are carried out using mathematical and statistical approaches [26]. Optimization studies are carried out using techniques such as artificial neural networks and RSM to determine the best output values under ideal operating conditions. These algorithms use statistical and mathematical techniques to determine ideal values. Since RSM has a low error rate compared to other approaches, it is generally selected for engineering applications [27].

In one of the studies conducted in this context, Canan [28] investigated the effect of $B_2O_3$ addition to 3$^{rd}$ Generation biodiesel on engine emissions and performance. In the experiment, 3 different $B_2O_3$ (25, 50, and 75 ppm) were added to a mixture of 10% biodiesel and 90% diesel by volume. In the optimization study, engine load and nanoparticle amount were determined as input values, and CO, HC, smoke, $NO_x$, $CO_2$, BSFC, and BTE were determined as output values. The ideal operating parameters were identified as a 1378.68 W load and a 49.34 ppm $B_2O_3$

nanoparticle addition after the optimization study. Under these conditions, BTE was determined as 17.99%, BSFC as 458.68 g/kWh, CO as 0.027%, $CO_2$ as 4.84%, $NO_x$ as 443.99 ppm, HC as 6.42 ppm and smoke as 18.83%. In another study, Uslu [29] investigated the impact of adding $B_2O_3$ nanoparticles to the waste cable pyrolysis oil/diesel mixture on emissions and engine performance, as well as identifying the best operating parameters. In the investigation, a mixture of 20% biodiesel and 80% diesel by volume was mixed with three different concentrations of nanoparticles (20, 40, and 60 ppm). The amount of nanoparticles and engine load were approved as input elements, whereas BTE, BSFC, CO, $CO_2$, HC, and $NO_x$ were accepted as outcome metrics. The study found that the ideal working parameters were a 1500 W load and a 22 ppm nanoparticle level, with the goal of maximizing the BTE value and minimizing all other values. In these operating conditions, BSFC was found as 387.533 g/kWh, BTE as 24.5755%, CO as 0.0413%, $CO_2$ as 5.2072%, HC as 23.7139 ppm, and $NO_x$ as 523.141 ppm. When literature sources are examined, it is seen that the addition of nanoparticles has an effect on engine performance and emissions. Researchers have done tests by adding different nanoparticles to diesel and biodiesel.

The impact of adding $B_2O_3$ nanoparticles to diesel fuel, which have been shown in the literature to enhance engine performance and emissions, will be investigated in this study. Although they are limited, investigations on the impact of $B_2O_3$ nanoparticles on various biodiesels and the effects of various nanoparticles added to diesel fuel are available in the literature. However, no study was found on the case of adding $B_2O_3$ nanoparticles to diesel fuel. In this study, the optimum operating conditions of the amount of added nanoparticles and engine load will be determined and the values that give the least emission and the highest performance will be determined. These situations will reveal the innovative aspect of the current study and fill the gap in the literature.

## 2. Material and Method

The effects of adding three distinct quantities of $B_2O_3$ nanoparticles (10, 20, and 30 ppm) to diesel fuel on emissions and engine performance will be investigated in this study. Six distinct loads (between 0.5 kW and 3 kW) will be applied to the engine during the study, all while maintaining a steady speed of 3000 rpm. The best operating conditions will be identified by using RSM to optimize the data gathered from the experiments.

### 2.1. Preparation of test fuels

Figure 1 shows the schematic representation of the addition of nanoparticles to diesel. First, $B_2O_3$ nanoparticles were measured on a precision balance, and the desired level of nanoparticles were prepared. In order to mix the nanoparticles homogeneously in the fuel, they were mixed for 1 hour with a magnetic stirrer and then for 2 hours with an ultrasonic mixer. As a result of the fuel preparation, 4 different test fuels were obtained: D100 (100% Diesel), D100B10 (100% Diesel + 10 ppm $B_2O_3$), D100B20 (100% Diesel + 20 ppm $B_2O_3$), and D100B30 (100% Diesel + 30 ppm $B_2O_3$). The properties of the fuels are shown in Table 1. The surface characteristics and morphology of $B_2O_3$ nanoparticles, which are about 50 nm in size, are depicted in Figure 2 scanning electron microscopy (SEM) image. The Electron High Tension (EHT) value employed was 10.00 kV, and the image was acquired at a magnification of 30,000 times.

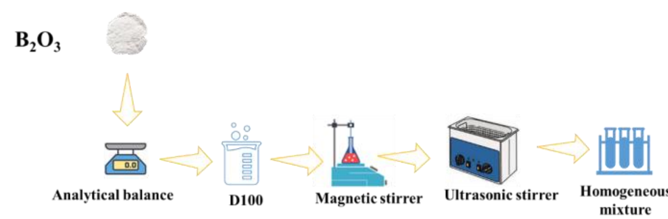


Figure 1. Schematic representation of the addition of nanoparticles

Table 1. Fuel properties of test fuels

| Properties | Unit | D100 | D100B10 | D100B20 | D100B30 |
|---|---|---|---|---|---|
| Calorific value | MJ/kg | 43.200 | 43.089 | 43.118 | 43.192 |
| Viscosity (40 ºC) | $mm^2/s$ | 4.24 | 4.50 | 5.09 | 5.14 |
| Density (15ºC) | $kg/m^3$ | 831.60 | 831.40 | 831.38 | 831.28 |

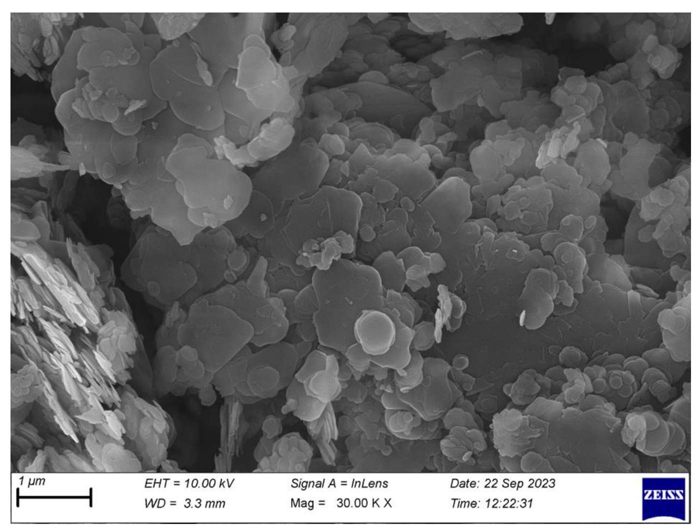


Figure 2. SEM of $B_2O_3$

### 2.2. Experimental Procedure

A 4-stroke, single-cylinder, air-cooled diesel engine was used in the investigation. Table 2 displays the engine specifications, whereas Table 3 displays the emission device specifications. The model of the test engine is Lutian 3GF-ME, and the emission device model is Bilsa Mod 2210 WINXP-K. Figure 3 displays the schematic depiction of the engine test setup. For the duration of the test, the engine was run at a steady 3000 rpm. To achieve basic equilibrium and offer identical circumstances for all test fuels, the engine was run for 30 minutes. Fuels were tested starting between 0.5 kW and 3 kW load with the engine loading unit. As a result of the experiments, the engine was operated for another 10 minutes to clean the remaining fuels in the fuel system. The tests were repeated 3 times in order to minimize and verify the errors in the experiments. The Kline and McClintock approach (equation 1) was used to calculate the uncertainty of the measured values. The uncertainty values of CO, HC, $NO_x$, $CO_2$, BSFC, BTE and Load are ±1.7, ±1.2, ±2.8, ±1.3, ±0.9, ±0.6 and ±0.8, respectively. It is found that the overall uncertainty is 3.96%.

Table 2. Lutian 3GF-ME engine specifications

| | |
|---|---|
| **Rated power** | 3.2 kW |
| **Swept Volume** | 296 $cm^3$ |
| **Fuel Type** | Diesel, 4-stroke, single cylinder, air-cooled |

Table 3. Technical standards for emission gas analyzers

| Parameter | Measurement Range | Sensibility |
|---|---|---|
| $CO_2$ | 0 - 20% vol | 0.01% |
| $NO_x$ | 0-5000 ppm | ± 1 ppm |
| CO | 0 - 10% vol | 0.01% |
| HC | 0-10000 ppm | ± 1 ppm |

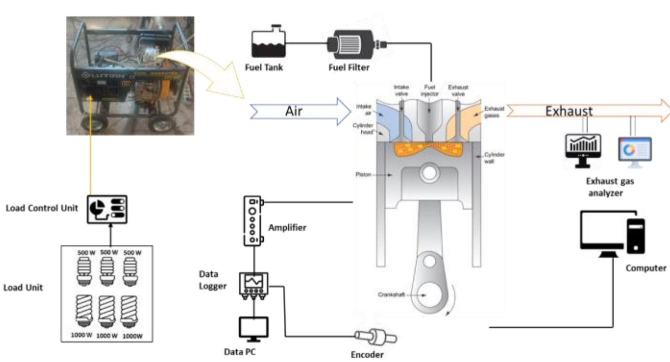


Figure 3. Schematic representation of the engine test

$$U_{overall} = \sqrt{[(U_{CO})^2 + (U_{HC})^2 + (U_{Load})^2 + (U_{BTE})^2 + (U_{BSFC})^2 + (U_{CO_2})^2 + (U_{NO_x})^2]} \quad (1)$$

## 2.3. Optimization with RSM

Determining intermediate values is challenging since experimental research is costly and time-consuming. The ideal process conditions are found by solving this problem using optimization techniques like ANN, RSM, and Taguchi [30,31]. With benefits like fewer tests, a low error rate, data visualization, and the capacity to ascertain the impact of independent factors on answers, RSM stands out among these methods [32]. It offers great benefits, particularly when it comes to complex system optimization. RSM can be used as a guidance approach while designing new systems, in addition to improving current ones. Equation 2 is used by RSM, a second-degree polynomial, to model complex systems.

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

The expected response is represented by the β coefficient y, the regression coefficients by $\beta_i$ and $\beta_j$, the model's order by k, the constant by $\beta_0$, the random error by ε, and the individual variables by $x_i$ and $x_j$.

This optimization study aims to determine the values that provide the lowest emission and highest performance values depending on the amount of $B_2O_3$ nanoparticles added to diesel fuel and engine load. Central Composite design was used in the RSM study. While determining the amount of $B_2O_3$ and engine load as inputs in the study, the values of these factors are shown in Table 4. The RSM design table from which experimental results were obtained is shown in Table 5. In our study, optimization studies were conducted at a 95% confidence interval and under 'full quadratic' conditions.

Table 4. Factor levels used to the RSM design

| Factors | Levels | | | | | |
|---|---|---|---|---|---|---|
| $B_2O_3$ (ppm) | 0 | 10 | 20 | 30 | - | - |
| Load (W) | 500 | 1000 | 1500 | 2000 | 2500 | 3000 |

Table 5. Design table

| $B_2O_3$ (ppm) | Load (kW) | CO (%) | HC (ppm) | $CO_2$ (%) | $NO_x$ (ppm) | BSFC (g/kWh) | BTE (%) |
|---|---|---|---|---|---|---|---|
| 0 | 1 | 0.091 | 20 | 3.84 | 271 | 389 | 21.41 |
| 0 | 2 | 0.061 | 39 | 5.608 | 577 | 298 | 27.97 |
| 0 | 2.5 | 0.070 | 50 | 6.476 | 694 | 300 | 27.78 |
| 0 | 3 | 0.081 | 60 | 7.644 | 781 | 337 | 24.69 |
| 10 | 1 | 0.055 | 15 | 4.408 | 407 | 600 | 13.92 |
| 10 | 2 | 0.035 | 34 | 6.224 | 656 | 327 | 25.53 |
| 10 | 3 | 0.046 | 51 | 8.584 | 873 | 360 | 23.21 |
| 20 | 1 | 0.053 | 14 | 4.46 | 413 | 498 | 16.75 |
| 20 | 2 | 0.034 | 31 | 6.168 | 663 | 316 | 26.41 |
| 20 | 2.5 | 0.030 | 38 | 7.164 | 792 | 300 | 27.83 |
| 30 | 0.5 | 0.086 | 5 | 4.008 | 341 | 685 | 12.18 |
| 30 | 1.5 | 0.050 | 25 | 5.352 | 536 | 343 | 24.31 |
| 30 | 2 | 0.041 | 35 | 6.236 | 667 | 310 | 26.90 |
| 30 | 3 | 0.049 | 52 | 8.704 | 775 | 360 | 23.15 |

## 3. Result and Discussion

### 3.1. Statistical analysis

As a result of RSM analysis, $R^2$ values of all output parameters were found to be above 90%. $R^2$ values of CO, HC, $NO_x$, $CO_2$, BTE, and BSFC were found to be 97.46%, 99.68%, 99.07%, 99.33%, 92.66%, and 91.34%, respectively. Regression equations created for each response are shown in Table 6. These equations can predict output values depending on input values in relation to real values.

Table 6. Regression equations*

| | Equations |
|---|---|
| *CO* | $0,13783 - 0,003816*B - 0,06660*L + 0,000106*B^2 + 0,01556*L^2 - 0,000096*B*L$ |
| *HC* | $0,01 - 0,878*B + 21,27*L + 0,02448*B^2 - 0,552*L^2 - 0,0334*B*L$ |
| *$CO_2$* | $3,031 + 0,0596*B + 0,496*L - 0,001408*B^2 + 0,3643*L^2 + 0,00394*B*L$ |
| *$NO_x$* | $-75,1 + 17,80*B + 379,0*L - 0,3021*B^2 - 29,0*L^2 - 3,065*B*L$ |
| *BSFC* | $869,3 + 8,70*B - 537,0*L - 0,221*B^2 + 120,2*L^2 - 0,74*B*L$ |
| *BTE* | $-0,82 - 0,300*B + 25,82*L + 0,01085*B^2 - 5,693*L^2 - 0,0225*B*L$ |

* L: Load, B: $B_2O_3$, $L^2$: $Load^2$, $B^2$:$B_2O_3{}^2$, B*L: $B_2O_3$*Load

### 3.2. Emission

Figure 4 shows the contour and surface graphs of CO emission depending on $B_2O_3$ amount and load. When the graphs are examined, CO emissions decreased up to a certain value depending on the increasing load, and increased after this value. CO emissions, which are the by-products of incomplete combustion, increased because there was insufficient time for homogeneous combustion due to the increasing load [33]. The addition of nanoparticles improved combustion and reduced CO emissions by increasing the amount of heat transfer with an increase in the surface area-volume ratio [34]; the lowest CO emission value in the experiments was 0.030% in D100B20 fuel at 2.5 kW load, while the highest CO emission value was 0.105% in D100 fuel at 0.5 kW load. Compared to D100 fuel, the average CO emission values of D100B10, D100B20, and D100B30 fuels decreased by 39.97%, 44.71%, and 34.10%, respectively. According to the graphs, the lowest CO emission value was observed in the fuel with 15-25 ppm $B_2O_3$ addition under a load of approximately 2.5 kW.

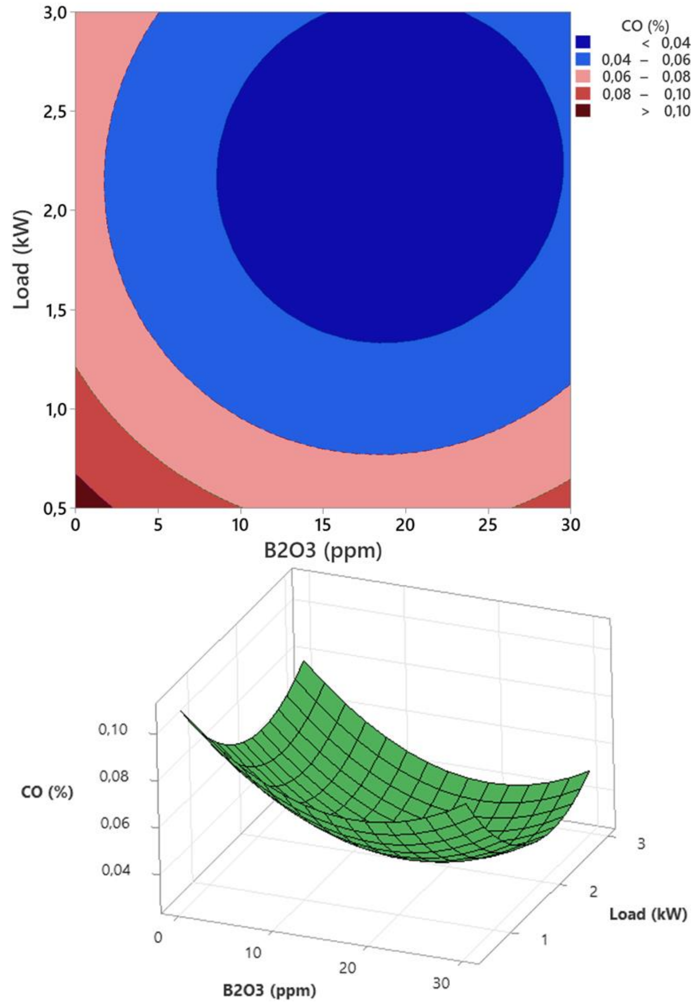


Figure 4. CO variation with nanoparticle and load

Contour and surface graphs of HC emissions, which are another incomplete combustion product, and their changes depending on the amount of $B_2O_3$ and load are shown in Figure 5. HC emissions increased with increasing load for all test fuels. Because the use of nanoparticles improved combustion, HC emissions dropped [35]. However, as the amount of nanoparticles added increases, it becomes difficult for them to be distributed homogeneously in the fuel, and the particles tend to cluster. This increases the viscosity of the fuel, negatively affecting the atomization process, and thus reducing combustion efficiency [36] and increasing HC emissions. The investigations revealed that the highest HC emission value was 60 ppm in D100 fuel at a 3 kW load, while the lowest HC emission value was 5 ppm in D100B30 fuel at a 0.5 kW load. The average HC emission values of D100B10, D100B20, and D100B30 fuels were 21.92%, 23.58%, and 22.66% lower than those of D100 fuel, respectively. When Figure 5 is examined, it is determined that the lowest HC emission in the experiments was at approximately 15-25 ppm $B_2O_3$ addition and approximately 2.5 kW load.

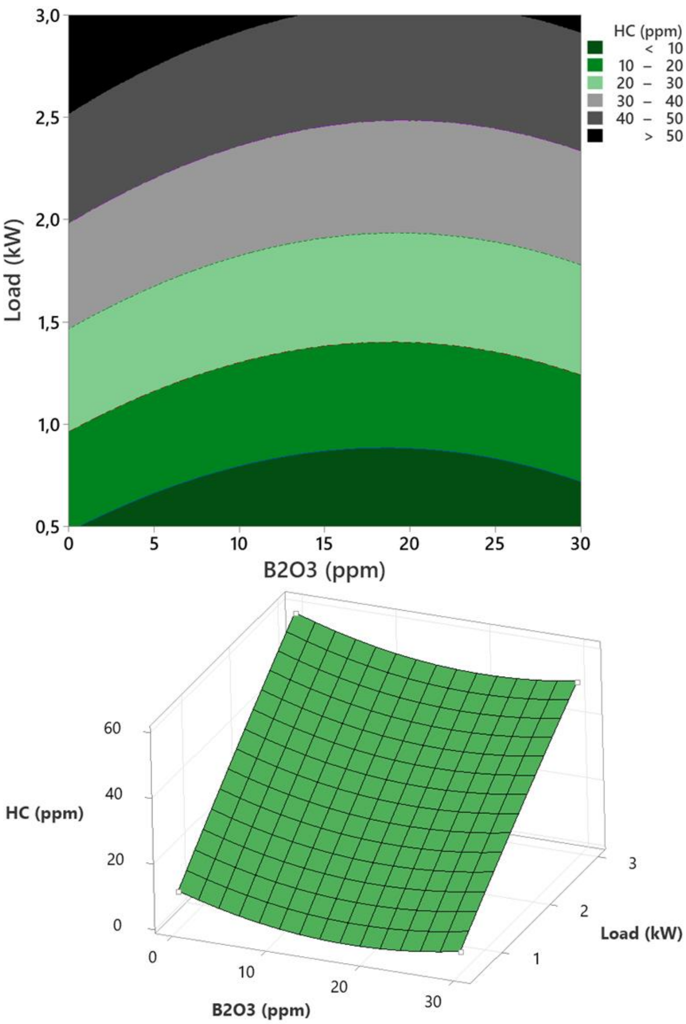


Figure 5. HC variation with nanoparticle and load

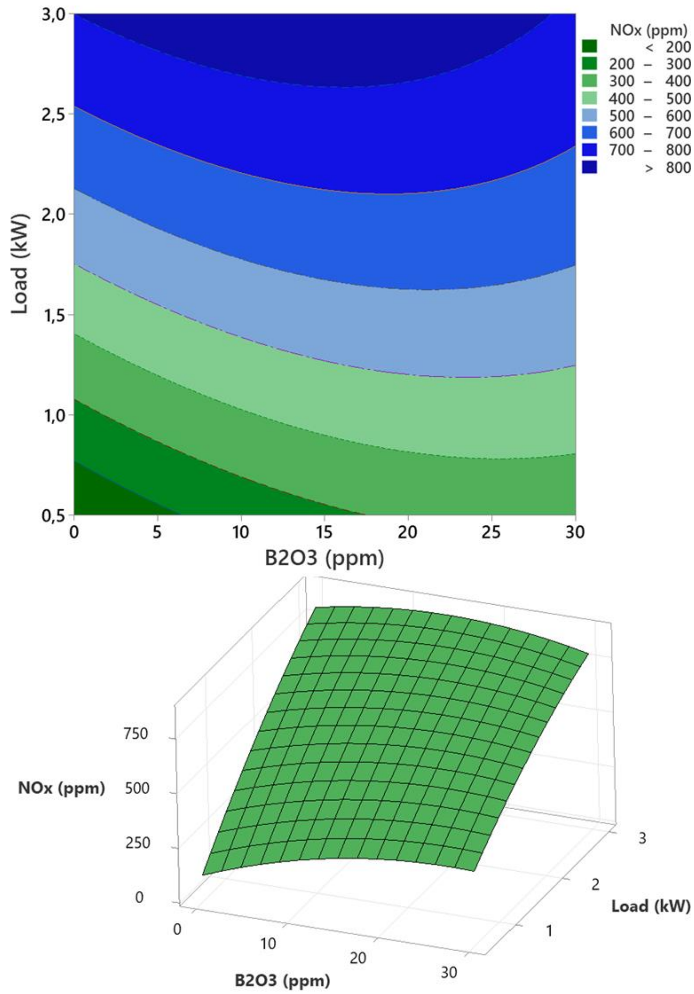


Figure 6. $NO_x$ variation with nanoparticle and load

The reaction of ambient nitrogen and oxygen during high temperature combustion in the engine produces $NO_x$ emissions, which are extremely detrimental to the environment. The contour and surface graphics of $NO_x$ emissions based on load and $B_2O_3$ quantity are displayed in Figure 6. At a 0.5 kW load, the $NO_x$ emission value was the lowest at 222 ppm in D100 fuel, and at a 3 kW load, it was the highest at 889 ppm in D100B20 fuel. $NO_x$ emissions for D100B10, D100B20, and D100B30 fuels rose by 22.20%, 23.25%, and 25.54%, respectively, in comparison to D100 fuel. $NO_x$ emissions increased with increasing load in all test fuels. With increasing load, in-cylinder temperature increases, which in turn increases $NO_x$ emissions. The additional nanoparticle raised $NO_x$ emissions, raised the in-cylinder temperature, and enhanced combustion [37]. The fuel with a 0–5 ppm $B_2O_3$ additive at 0.5 kW load had the lowest $NO_x$ emission value when the graphs were analyzed.

Unlike CO emission, $CO_2$ emission occurs as a result of complete combustion. The contour and surface graphics showing the effect of $B_2O_3$ amount and load change on $CO_2$ emission are shown in Figure 7. Depending on the rising load, $CO_2$ emissions rose in all test fuels as the in-cylinder temperature rose and combustion improved. At a load of 0.5 kW, the lowest $CO_2$ emission value was 3.42% in D100 fuel, while at a load of 3 kW, the highest $CO_2$ emission value was 8.704% in D100B30 fuel. D100B10, D100B20 and D100B30 $CO_2$ emission values increased by 12.51%, 11.72% and 15.47%, respectively, compared to D100 fuel. Combustion was improved, and $CO_2$ emission values increased with the nanoparticle added to D100 fuel. When the graphs were examined, the lowest emission value in the study was determined between 0.5 and 1 kW load and 0-15 ppm $B_2O_3$ addition.

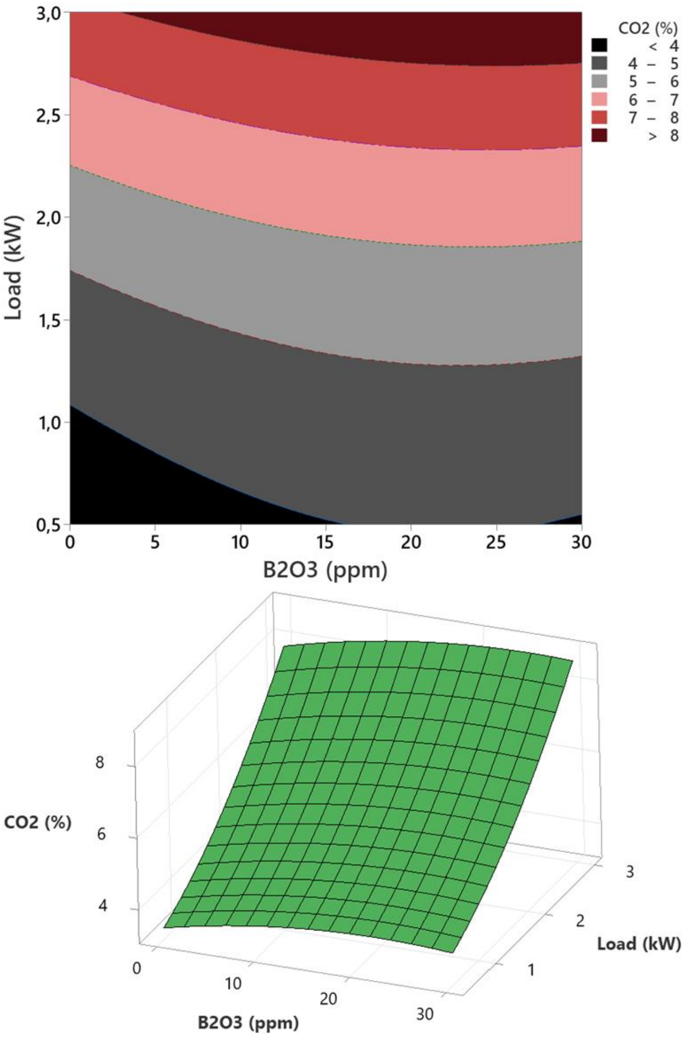


Figure 7. $CO_2$ variation with nanoparticle and load

### 3.3. Performance

The unit of BSFC, which is one of the performance parameters, is g/kWh. It shows the amount of fuel that must be burned in grams to produce 1 kW power in 1 hour. Contour and surface graphics showing the change of BSFC according to the amount of nanoparticles and load are shown in Figure 8. While BSFC decreased up to a certain load in all test fuels, after a certain load, BSFC value increased due to insufficient time for complete combustion. While the lowest BSFC value in the experiments was measured as 298 g/kWh in D100 fuel at 2 kW load, the highest BSFC value occurred as 900 g/kWh in D100B10 fuel at 0.5 kW load. Compared to D100 fuel, the average BSFC value increased by 23.18%, 10.10%, and 9.41% for D100B10, D100B20, and D100B30 fuels, respectively. The added nanoparticles improved combustion up to a certain value and reduced the BSFC value [38]. According to the graphs, it was determined that the addition of 0-5 ppm $B_2O_3$ and the load range of 2 -2.5 kW gave the lowest BSFC value.

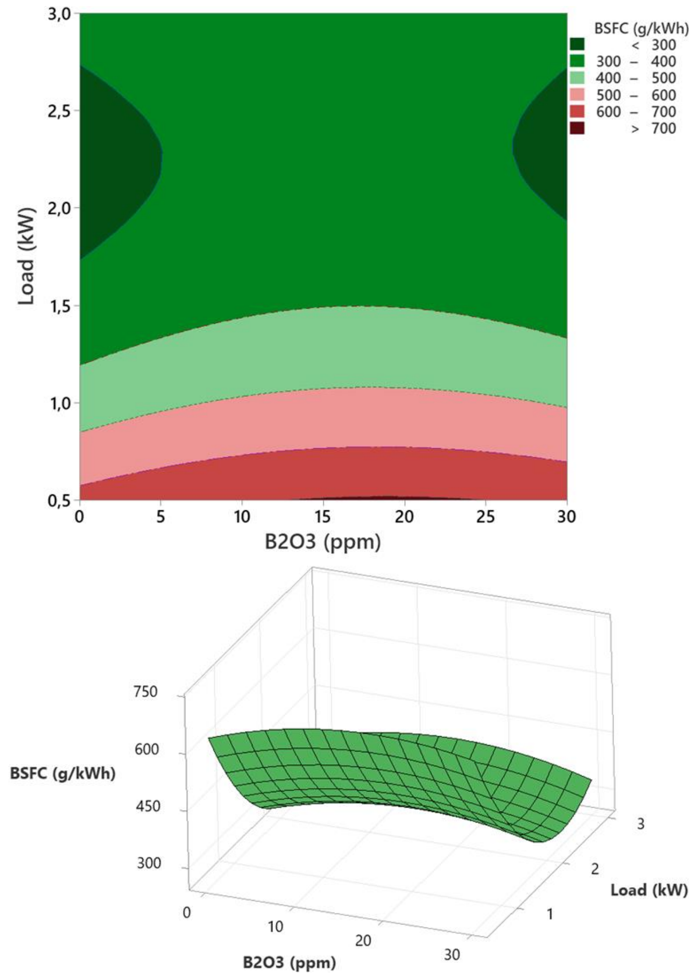


Figure 8. BSFC variation with nanoparticle and load

The BTE value indicates how much of the power obtained from the fuel is converted into useful work. In all test fuels, combustion improved and the BTE value increased with the increase in in-cylinder temperature depending on the increasing load. After a certain load, the BTE value decreased due to the insufficient time for complete combustion. Figure 9 shows the BTE change depending on the B2O3 amount and load. The lowest BTE value was measured as 9.28% in D100B10 fuel at 0.5 kW load, and the highest BTE value was measured as 27.97% in D100 fuel at 2 kW load. The average BTE value decreased by 17.16%, 8.21%, and 8.23% in D100B10, D100B20, and D100B30 fuels, respectively, compared to D100 fuel. The increase in the amount of added nanoparticles increases fuel density and viscosity, disrupts fuel atomization, and decreases the BTE value. According to the graphs, the highest BTE value is achieved with 10-20 ppm $B_2O_3$ addition and 2-2.5 kW load range.

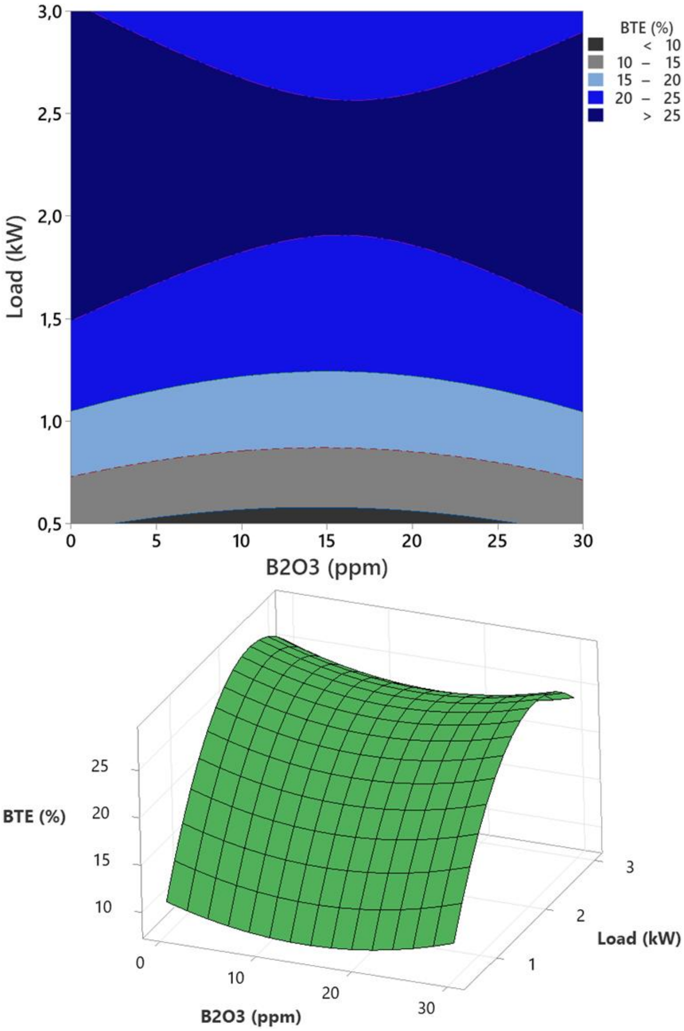


Figure 9. BTE variation with nanoparticle and load

### 3.4. Optimization with RSM

The error rate data between the output parameters estimated using regression equations and the actual output parameters are shown in Figures 10,11, and 12. The lowest error rate in the output parameters belongs to $CO_2$ emissions with 1.69%, while the highest error rate belongs to BSFC with 6.47%. In the RSM study, all error rates of the output parameters were below 10%, and a successful convergence was achieved. In the optimization study, the maximum value was targeted for the BTE and the minimum value for all other output parameters.

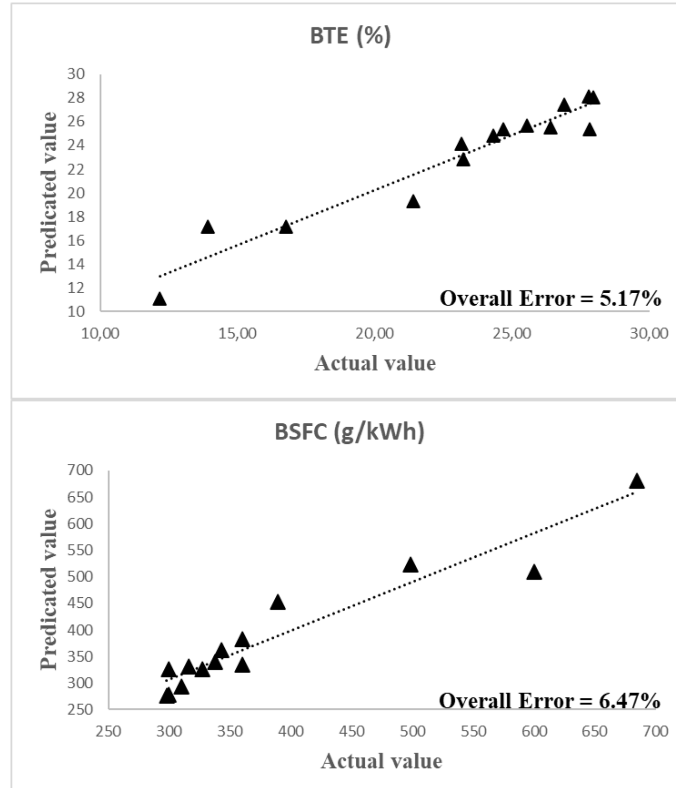


Figure 10. Error rates of BTE and BSFC

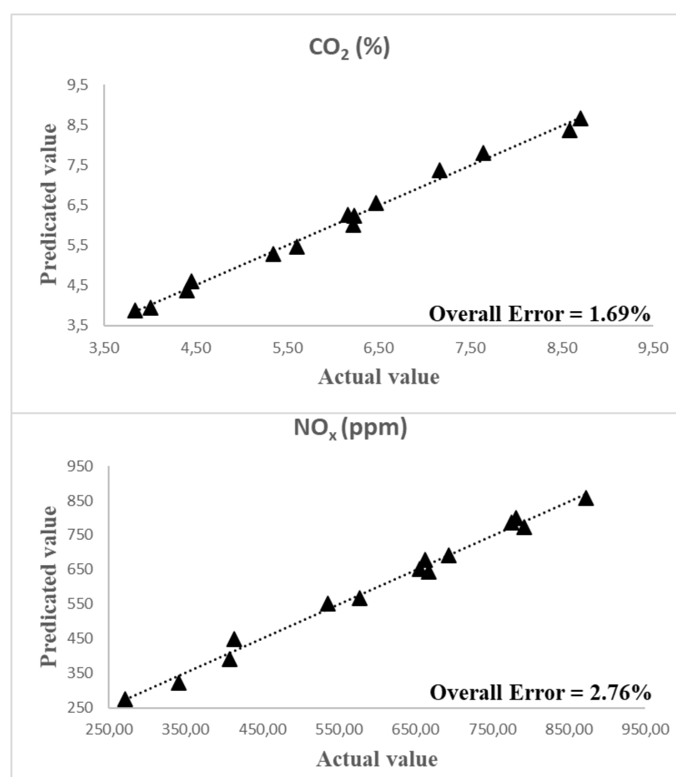


Figure 11. Error rates of $CO_2$ and $NO_x$

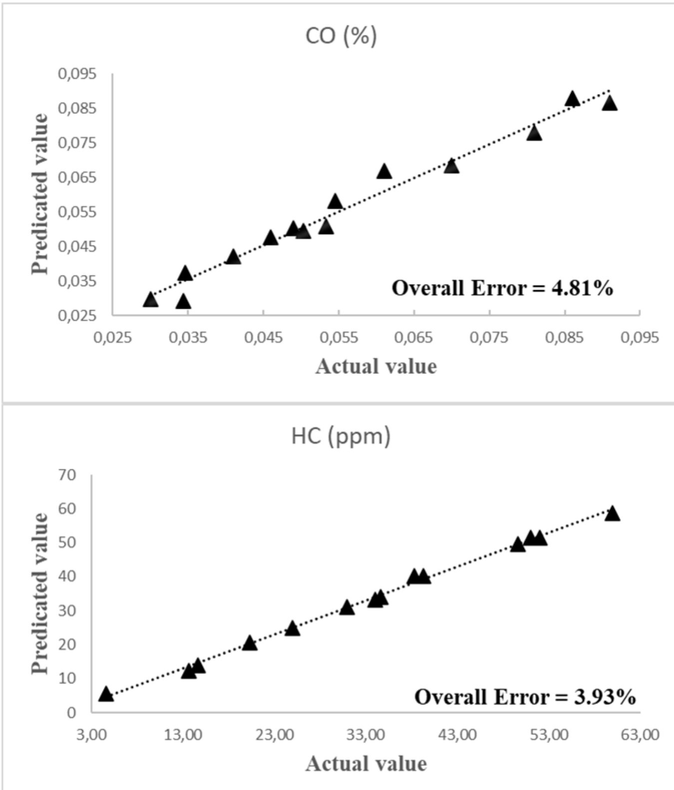


Figure 12. Error rates of CO and HC

The optimum $B_2O_3$ amount and load values are shown in Figure 13. At these values (9 ppm $B_2O_3$ and 1.5 kW load), the output parameter values were found to be 22.97% for BTE, 384.75 for BSFC, 552.58 ppm for $NO_x$, 5.07% for $CO_2$, 24.29 ppm for HC, and 0.046% for CO. In order to determine the accuracy of these values, a fuel was prepared by adding 9 ppm $B_2O_3$ to diesel fuel. The experiment was repeated by operating this fuel under 1.5 kW load. The comparison of the data obtained as a result of the experiment with the optimization data is shown in Table 7. The error rates in the optimization study vary between 0.30% and 5.99%.

Table 7. Comparison of RSM and experimental data

| | CO (%) | | $CO_2$ (%) | | HC (ppm) | |
|---|---|---|---|---|---|---|
| | RSM | Test | RSM | Test | RSM | Test |
| | 0.0481 | 0.0459 | 5.07 | 5.241 | 24.29 | 25.3 |
| Error | **4.59%** | | **3.26%** | | **3.99%** | |
| | $NO_x$ (ppm) | | BSFC (g/kWh) | | BTE (%) | |
| | RSM | Test | RSM | Test | RSM | Test |
| | 552.58 | 526 | 384.75 | 363 | 22.97 | 23.04 |
| Error | **5.13%** | | **5.99%** | | **0.30%** | |

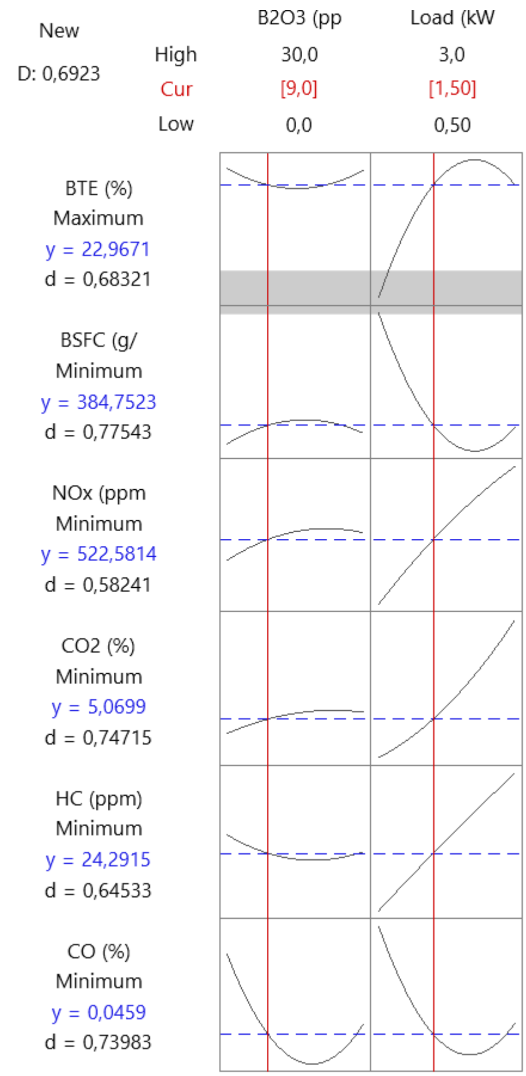


Figure 13. Optimization

## 4.Conclusion

In this study, the effect of $B_2O_3$ nanoparticle added to diesel fuel on engine performance and emissions was investigated. The experimental results were optimized with RSM to determine the optimum operating conditions.

D100B10, D100B20, and D100B30 fuels had average CO emission levels that were 39.97%, 44.71%, and 34.10% lower than D100 fuel, respectively. The typical HC emission values of D100B10, D100B20, and D100B30 fuels were 21.92%, 23.58%, and 22.66% lower than those of D100 fuel, respectively. $NO_x$ emissions for D100B10, D100B20, and D100B30 fuels rose by 22.20%, 23.25%, and 25.54%, respectively, in comparison to D100 fuel. In comparison to D100, the $CO_2$ emission values of D100B10, D100B20, and D100B30 increased by 12.51%, 11.72%, and 15.47%, respectively.

When comparing D100B10, D100B20, and D100B30 fuels to D100 fuel, the average BSFC value rose by 23.18%, 10.10%, and 9.41%, respectively, in terms of performance criteria. In comparison to D100 fuel, the average BTE value dropped by 17.16%, 8.21%, and 8.23% for D100B10, D100B20, and D100B30 fuels, respectively.

All of the output parameters $R^2$ values in the optimization research were determined to be greater than 90%. BSFC has the lowest $R^2$ value, at 91.34%. The optimization study's error rates range from 1.69% to 6.47%. The ideal operating parameters were found to be 1.5 kW load and 9 ppm All of the output parameters $R^2$ values in the optimization research were determined to be greater than 90%. Under these operating conditions, the results showed that the BTE was 22.97%, the BSFC was 387.75g/kWh, the $NO_x$ was 552.58 ppm, the $CO_2$ was 5.07%, the HC was 24.29 ppm, and the CO was 0.046%. The maximum error rate, as determined by the verification investigation, was 5.99%.

These results demonstrate the promising potential of nanoparticle integration in diesel engine applications, offering a solution to lower hazardous emissions and enhance engine efficiency. $B_2O_3$ nanoparticles have the potential to significantly contribute to the development of cleaner and more effective combustion processes by improving fuel economy and emissions control. As a result, it was discovered that incorporating $B_2O_3$ nanoparticles into diesel fuel was both feasible and enhanced engine performance and emissions. RSM was employed well in this investigation, yielding excellent $R^2$ values and low error rates.

Future research could look more closely at how various nanoparticle kinds interact with various fuel compositions and how these interactions affect engine performance and durability over the long run.

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## Nomenclature

| | |
|---|---|
| *BSFC* | : brake specific fuel consumption |
| *BTE* | : brake thermal efficiency |
| *CO* | : carbon monoxide |
| *$CO_2$* | : carbon dioxide |
| *D100* | : %100 Diesel |
| *D100B10* | : 100% Diesel+10 ppm $B_2O_3$ |
| *D100B20* | : 100% Diesel+20 ppm $B_2O_3$ |
| *D100B30* | : 100% Diesel+30 ppm $B_2O_3$ |
| *HC* | : hydrocarbon |
| *$NO_x$* | : nitrogen oxide |
| *$R^2$* | : correlation coefficient |
| *RSM* | : response surface methodology |

## Conflict of Interest Statement

The authors declare that they have no known competing financial interests or personal ties that could have seemed to affect the work reported in this study.

## CRediT authorship contribution statement

**Arif Savaş:** Writing – original draft, Software, Investigation, Methodology, Writing – review & editing, Conceptualization.

**Samet Uslu:** Supervision**,** Writing – review & editing, , Software, Methodology, Software

**Şule Saral:** Writing – original draft, Investigation, Methodology, Software.

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