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Determination of Optimum Operating Parameters in a Non-Road Diesel Engine Fueled with 1-Heptanol/Biodiesel at Different Injection Pressures and Advances

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Abstract: It is important to reduce the negative environmental effects of non-road diesel engines, which are increasingly used in many facilities and machines, without loss of performance. Biodiesel is used as an alternative to fossil-based diesel fuels to eliminate these effects and ensure sustainability in energy. This study focused on the optimization of the operating parameters of a non-road diesel engine operating with a waste frying oil biodiesel mixture at 50% load. Pure biodiesel, 1-heptanol, different injection advances and pressures were determined as input parameters for optimization. The tests were designed according to Taguchi's L16 orthogonal array. ANOVA analysis was performed to determine the importance of input parameters on engine performance and exhaust emissions. Optimization was made based on the highest brake thermal efficiency (BTE) in addition to the lowest values of brake-specific fuel consumption (BSFC), brake-specific hydrocarbon (BSHC), brake-specific nitrogen oxide (BSNOx) and smoke emissions. In the optimization carried out according to the response surface methodology (RSM), the optimum combinations to obtain the best engine characteristics were determined as 17.27% 1-heptanol, a 226-bar injection pressure, 27 CAD injection advance and B75. These optimization results were verified by engine experiments within the recommended error range.

Keywords: biodiesel; 1-heptanol; optimization; non-road diesel engine; engine performance; exhaust emissions; Taguchi; ANOVA; response surface methodology

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1. Introduction

Non-road diesel engines have become a vital part of today's society due to their static application energy needs. They are also considered a significant source of pollutant emissions that contribute to climate change. Non-road diesel engines are widely used in many areas such as agriculture, construction and mining, general industry, lawns and gardens, airport shuttle equipment, recreational/commercial marine vehicles, pumps/compressors, power generation and logging equipment [1,2]. The use of such tools and equipment has increased, especially during the pandemic period. Non-road engines are engines with high fuel consumption. The use of fossil-based fuels in these engines causes harmful emissions to increase. For this reason, it is important to use alternative fuels to fossil fuels in non-road engines. In this context, biodiesel comes to the fore.

As the urgency of environmental sustainability increases globally, researching alternative fuels for diesel engines has become crucial [3]. Biodiesel, a green and environmentally friendly oxygenated fuel, can effectively reduce the CO, NO_x and PM emissions of diesel engines. Moreover, it can reduce the increasing automobile emissions pollution trend as soon as possible [4]. Biodiesel is an alternative diesel engine fuel that contains oxygen, and is non-toxic, with high cetane, lubricating, biodegradable and renewable factors [5]. Raw materials used in biodiesel production can generally be divided into three generations. The first generation includes traditional vegetable oils and animal fats such as soybean, sunflower, palm, canola and animal oils. Second-generation raw materials are oil and oily substances obtained from waste and residues. These are raw materials such as restaurant waste oils, animal waste and agricultural waste. Third-generation biodiesel feedstocks generally contain oils and oily substances obtained from microorganisms such as algae. Such raw materials can reduce the need for agricultural land and can also be used in wastewater treatment [6]. These generations differ according to the sources, sustainability and environmental impact of the raw materials. The selection of raw materials for biodiesel production is important to minimize environmental impacts and observe sustainability principles. For this reason, the use of biodiesel obtained from waste frying oil was preferred in this study.

If biodiesel is used purely in engines, some exhaust emission values do not comply with EURO standards. At the same time, it may cause a loss of performance when used in naturally aspirated engines such as non-road engines. For this reason, alcohol is added as a blended fuel to minimize these negative effects of biodiesel [7]. The effect of biodiesel/alcohol blend on engine performance and emissions has been investigated for a long time. The most used types of alcohol are ethanol, methanol and iso-butanol [8–11]. Biodiesel and alcohol are obtained from renewable agricultural raw material sources. The physical–chemical properties of alcohols used as blended fuels are an important factor affecting performance and emissions [12]. Therefore, the properties of alcohol are important. Recently, researchers have focused on using higher alcohols instead of lower-chain alcohols such as ethanol and methanol. Long-chain alcohols with high molecular weight and more than three carbon atoms were defined as higher alcohols. For example, butanol (C_4H_9OH), pentanol ($C_5H_{11}OH$), hexanol ($C_6H_{13}OH$), heptanol ($C_7H_{15}OH$), octanol ($C_8H_{17}OH$), decanol ($C_{10}H_{21}OH$) and phytol ($C_{20}H_{39}OH$) are higher alcohols. Some properties, such as cetane number and the calorific values of higher alcohols, are better than those of lower alcohols. For this reason, they are preferred as a mixture of fuel [13,14]. Among the higher alcohols, propanol, butanol, pentanol, hexanol, heptanol and octanol are the most popular alcohols that can be blended with diesel fuel without any mixing problems [15,16]. Due to these properties, the use of heptanol among higher alcohols was preferred for the experimental study. There are some studies in the literature investigating the use of heptanol/biodiesel mixtures. In one such study, biodiesel obtained from algae was blended with commercially available diesel fuel and used as fuel in a diesel engine. In the tests carried out by adding heptanol to the algae biodiesel and diesel mixture to improve the ignition quality of the mixture, the performance and exhaust emission changes in the engine were examined. At full load, a maximum brake thermal efficiency (BTE) of 34.96% was achieved with a mixture fuel consisting of 10% heptanol, 20% biodiesel and 70% diesel. A general improvement was observed in emissions, except for smoke levels, and it was determined that the largest decrease was in NO_x emissions at 14.7% [17]. Doğan et al. analyzed the energy, exergy, exergoeconomics, environmental economics and sustainability of 1-heptanol/biodiesel mixtures (Hp0, Hp5, Hp10 and Hp20) blended at different rates in a compression ignition engine, depending on their performance and emission values. It was found that increasing the heptanol ratio in the mixture increased brake-specific fuel consumption (BSFC), CO, NO_x and HC and decreased CO_2. Energy and exergy efficiency resulted close to diesel. Additionally, exergy destruction was higher compared to diesel [18]. In another study using different ratios of heptanol/biodiesel mixtures, the effect of injection pressure on the engine was investigated. According to the results, it was seen that a mixture of 40% diesel + 40% biodiesel + 20% heptanol at high injection pressure significantly reduced CO and smoke emissions. The lowest value of NO_x emission was reached in the mixture fuel with a 40% heptanol addition. It was found that, at this mixture ratio, BSFC reached the lowest value, while thermal efficiency reached the maximum value [19]. In a study investigating the effect of ternary blends containing higher alcohols 1-heptanol and n-octanol in hybrid biodiesel on a compression ignition engine, experiments were carried out at different loads and constant engine speeds. Octanol and 1-heptanol were added into biodiesel separately at rates of 10% and 20%. 1-heptanol reduced BSFC compared to octanol. In general, BSFC increased as the mixing ratio increased. Thermal efficiency reached its maximum in fuel with a 10% 1-heptanol addition. It has been determined that the addition of 1-heptanol and n-octanol causes an increase in CO_2 and NO_x emissions while reducing CO and HC emissions compared to diesel fuel [20]. The effect of 10, 20 and 40% n-heptanol in biodiesel was examined by EL-Seesy et al. Due to the high calorific value and latent heat of evaporation of n-heptanol, it increased the combustion pressure and heat release rate compared to pure biodiesel. Additionally, the addition of 1-heptanol to biodiesel fuel also extended the ignition delay time. Smoke and NO_x levels are reduced compared to pure biodiesel [21]. In another study on the blending of different alcohols with diesel, n-heptanol was also used in the mixture at the 5% and 10% levels. In the study, it was determined that high alcohol-blended fuels had a negative effect on combustion performance compared to pure diesel [16]. Nour et al. obtained the test fuels by mixing n-butanol, n-heptanol and n-octanol separately with 10% each into B10 fuel, which was created by adding 10% biodiesel by volume to diesel. In experiments where the effect of these test fuels on a diesel engine was determined, it was reported that an improvement in exhaust emissions was achieved with n-heptanol fuel. With n-heptanol added to blend fuel, smoke opacity, NO_x, CO and CO_2 emissions decreased by 38%, 11%, 35% and 14%, respectively, compared to diesel. It was determined that BSFC and thermal efficiency are close to diesel in this fuel type [22]. The effect of mixing pure biodiesel with 10, 20, 30 and 40% n-heptanol by volume on the combustion and emission characteristics in a common rail diesel engine was investigated. According to the combustion and emission results, it was suggested that the optimum mixture ratio for n-heptanol should be 20% [23]. In a study where higher alcohols such as butanol, octanol and heptanol were blended with diesel, the changes in engine performance, combustion and exhaust emissions were examined. It has been observed that the 20% heptanol/diesel mixture increases the heat released per cycle compared to other fuel types. Additionally, the highest combustion efficiency was achieved. At the same time, the lowest smoke opacity was detected [24]. McCormick et al. studied the effect of adding 1-heptanol to biodiesel and found a 3% reduction in NO_x emissions with heptanol added to biodiesel [25].

Another way to benefit more from the physical and chemical properties of alternative fuels is to optimize some engine-operating parameters such as engine injection pressure [26,27] and advance [28,29]. For this purpose, engine tests must be carried out by changing the values given during the manufacture of the engine and optimizing diesel. There are many studies in the literature that focus on injection pressure and injection advance as test variables in experiments using biodiesel. In general, it has been emphasized that increasing the injection pressure and advancing the use of biodiesel in naturally aspirated non-road diesel engines is beneficial in terms of performance, combustion and emissions. The diversity in the results of tests with many variables in alternative fuel experiments makes it difficult to determine optimum operating conditions. By evaluating all the results in a single model, the most suitable fuel can be determined in terms of many criteria. Many optimization techniques are used for this [30]. In this paper, Taquchi's experimental design was chosen to reduce the number of experiments. The optimum heptanol mixture ratio and operating conditions in terms of performance and emission were determined using the response surface methodology (RSM).

When the literature is examined, it is seen that studies investigating the changes in performance and emissions for non-road diesel engines using a heptanol/biodiesel mixture are limited. Moreover, it is determined that there are not many studies on optimizing the use of biodiesel/heptanol at different injection pressures and advances in terms of performance and emissions. In this context, the optimization of operating conditions for a non-road diesel engine fueled with different ratios of heptanol/biodiesel at different injection pressures and advances constitutes the innovation side of this article. This innovative approach ensures that the most efficient operating parameters in terms of performance and emissions are achieved when using heptanol/biodiesel blends, from agricultural machinery to commercial vehicles and even individual machines. In conclusion, this article supports the principle of reducing environmental impact and sustainability by ensuring more effective use of biodiesels obtained from waste frying oil. Optimizing the heptanol/biodiesel blend has the potential to reduce the carbon footprint by reducing the use of fossil fuels. This can contribute to the protection of ecosystems and the fight against climate change by reducing the environmental impact in the long term.

2. Materials and Methods

The test equipment consists of a non-road diesel engine, eddy current dynamometer, control unit, exhaust gas analyzer and fuel consumption measurement system. A schematic view of the test setup is given in Figure 1. The technical specifications of the test engine are shown in Table 1. Non-road diesel engines used in fixed facilities generally operate at 50% engine load. For the test engine, a 50% load corresponds to 10 Nm. All tests were carried out at a load of 10 Nm and a constant engine speed of 2200 rpm for each test fuel.

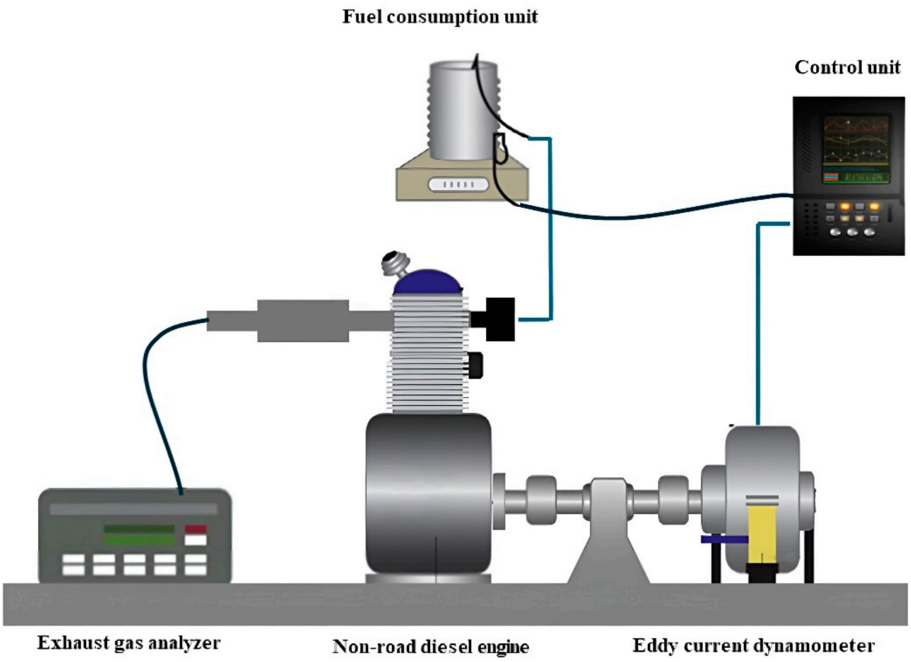

Figure 1. Schematic view of the experimental system.

Table 1. The technical specifications of the test engine.

Parameters	
Model	6LD 400
Number of cylinders	1
Bore and stroke (mm)	86 × 68
Displacement (cm^3)	395
Aspiration	Naturally aspirated
Cycle	4 strokes
Combustion system	Direct injection
Cooling system	Air
Compression ratio	18:1
Standard injection advance (CAD)	24
Standard injection pressure (bar)	200
Maximum power (HP/rpm)	8.5/3000
Maximum torque (Nm/rpm)	20/2200

The injection pressure of the test engine adapted to diesel was 200 bar (see Table 1). In the experiments, four different injection pressures were determined as 180 bar, 200 bar, 220 bar and 240 bar. In order to conduct experiments at different injection pressures, the injection pressure was increased with extra washers placed behind the injector and adjusted to 220 bar and 240 bar pressure. To reach 180 bar injection pressure, the existing washer in the injector was replaced with a thinner one. These adjusted injection pressures were verified with the injector pressure adjustment device.

The diesel-adapted injection advance of the test engine was 24 crank angle degrees (CAD) before the top dead center (see Table 1). Experiments were carried out at four different injection advances (22 CAD, 24 CAD, 26 CAD bar and 28 CAD). The static injection advance of the test engine was adjusted from the fuel pump pulley. For this purpose, the desired spray advance was adjusted by changing the position of this pulley. Since the original mark on the fuel pump pulley corresponded to the 24 CAD injection advance, a line was drawn through the center of the pulley at this point. Then, 26 CAD and 28 CAD injection advances were set by making two markings 2 degrees apart from this line in the direction of rotation, while 22 CAD was determined by marking 2 degrees in the opposite direction of rotation. Injection advances were adjusted by matching these points determined in the tests with the mark on the crankshaft. The accuracy of these adjusted values was verified from in-cylinder pressure curves in preliminary tests.

The waste frying oil methyl ester, called biodiesel in this study, was used as an alternative fuel in the tests. Biodiesel was purchased commercially from a company that produced biodiesel from waste frying oil in accordance with EN 14214 standard [31]. 1-heptanol as alcohol was purchased from MERCK (Darmstadt, Germany), and its purity was over 99%. Some physical and chemical fuel properties of biodiesel and 1-heptanol obtained from the supplier company and the literature are shown in Table 2.

Table 2. Some physical and chemical fuel properties of test fuels.

Fuel Properties	Diesel	Biodiesel (B100)	B75	1-Heptanol
Kinematic viscosity (cSt)	3.1	4.45	4.11	3.32 [18]
Density (kg/m^3)	830	885	865	822
Lower heating value (kJ/kg)	42,350	39,840	40,227.5	34,650 [18]
Cetane number	51	52.40	52.05	23 [18]

In the study, pure biodiesel was specified as B100, while the mixture of 75% biodiesel and 25% diesel was named B75. The blend fuels were obtained by adding 1-heptanol into B100 and B75 separately at 5, 10, 15 and 20% volumetric rates. For example, B75 fuel added with 15% 1-heptanol is designated B75H15.

The names and levels of the variables determined in the experiments are shown in Table 3. In these experiments, there are four factors, and three of them have four levels, while the biodiesel ratio has two levels. Taguchi's L16 (4ˆ3 2ˆ1) experimental design was used to make performance comparisons between the control factors and their interactions. The responses of the experimental design were BSFC, brake thermal efficiency (BTE) and exhaust emissions (HC, NO_x and smoke).

Signal/noise (S/N) analysis was performed using Minitab 17 software with the results of the experiments performed according to Taguchi's experimental design. The optimum values of the experimental variables and the optimum conditions that provided this value were determined. The effect levels of the variables under optimum conditions were determined by ANOVA analysis. Finally, the optimization was completed using the RSM.

Table 3. Control factors and their levels.

Code	Variables	Levels			
		1	2	3	4
A	1-heptanol (%)	5	10	15	20
B	Injection pressure (bar)	180	200	220	240
C	Injection advances (CAD)	22	24	26	28
D	Biodiesel (%)	75	100	-	-

3. Results and Discussion

The results of the experiments carried out according to Taguchi's experimental design at a constant engine load of 10 Nm (50% load) and an engine speed of 2200 rpm are presented in Table 4.

Table 4. Taguchi's L16 (4ˆ3 2ˆ1) orthogonal experiment design and responses.

Test No.	1-Heptanol (%)	Injection Pressure (bar)	Injection Advances (CAD)	Biodiesel (%)	BSFC (g/kWh)	BTE (%)	BSHC (g/kWh)	$BSNO_x$ (g/kWh)	Smoke (%)
	A	B	C	D	Y1	Y2	Y3	Y4	Y5
1	5	180	22	75	338.17	26.65	0.16	6.46	15.20
2	5	200	24	75	307.83	29.27	0.10	6.17	13.90
3	5	220	26	100	307.86	29.54	0.08	6.44	10.00
4	5	240	28	100	309.24	29.41	0.11	6.34	10.80
5	10	180	24	100	333.27	27.47	0.14	6.89	14.90
6	10	200	22	100	314.20	29.14	0.10	6.28	13.80
7	10	220	28	75	297.36	30.52	0.08	6.23	10.30
8	10	240	26	75	297.75	30.48	0.08	6.35	10.30
9	15	180	26	75	327.53	27.90	0.13	6.76	13.90
10	15	200	28	75	304.56	30.01	0.10	6.25	12.20
11	15	220	22	100	310.94	29.64	0.09	6.44	10.50
12	15	240	24	100	302.15	30.50	0.08	6.55	10.20
13	20	180	28	100	336.27	27.59	0.14	7.02	14.30
14	20	200	26	100	307.59	30.16	0.09	6.47	12.10
15	20	220	24	75	295.28	31.17	0.07	6.44	10.10
16	20	240	22	75	303.31	30.35	0.09	6.28	10.40

In the experimental design, engine performance and exhaust emissions were chosen as the response of the model. BSFC and brake thermal efficiency (BTE) were selected as engine performance, while brake-specific hydrocarbon (BSHC), brake-specific nitrogen oxide ($BSNO_x$) and smoke were determined as exhaust emissions.

Taguchis' is a powerful statistical approach that examines optimum operating parameters with a small number of tests, saving costly resources and time during experimentation [32].

First, S/N ratios were determined by Taguchi's analysis of the data obtained from the tests determined by the experimental design in Table 4. The S/N ratio determines the level of test variables that provide the best results for the response being examined. In the analysis, an analysis can be made such as 'Smaller is better', Larger is better' and 'Nominal is best' depending on the results expected from the experimental response [32]. S/N ratios for "larger is better" and "smaller is better" are determined by the equations below.

$$Larger\ is\ better: \frac{S}{N} ratio = -10 \cdot log \frac{1}{n} \left(\sum_{i=1}^{n} \frac{1}{y_i^2} \right) \tag{1}$$

$$Smaller\ is\ better:\ \frac{S}{N}ratio = -10 \cdot log\frac{1}{n}\left(\sum_{i=1}^{n} y_i^2\right) \quad (2)$$

The S/N ratio indicates the degree of importance of each variable in the results. In general, the larger the S/N ratio, the more consistent the result. Thus, the most appropriate parameter among the variables for the examined output is determined [33]. The S/N ratios obtained for engine performance and exhaust emissions with Equations (1) and (2) in different experimental variables are presented in Table 5.

Table 5. The S/N ratios (dB) for engine performance and exhaust emissions.

Variables	Level	BTE	BSFC	BSHC	$BSNO_x$	Smoke
1-heptanol (%)	5	29.16	−49.98	19.45	−16.06	−21.79
	10	29.36	−49.84	20.30	−16.17	−21.69
	15	29.40	−49.86	20.41	−16.25	−21.30
	20	29.48	−49.83	20.51	−16.32	−21.30
Injection pressure (bar)	180	28.75	−50.47	17.00	−16.62	−23.27
	200	29.44	−49.79	20.24	−15.98	−22.26
	220	29.60	−49.62	22.23	−16.11	−20.19
	240	29.59	−49.63	21.20	−16.10	−20.36
Injection advances (CAD)	22	29.22	−50.00	19.43	−16.07	−21.80
	24	29.42	−49.81	20.75	−16.27	−21.65
	26	29.40	−49.83	20.63	−16.26	−21.19
	28	29.36	−49.87	19.85	−16.19	−21.44
Biodiesel (%)	75	29.40	−49.79	20.38	−16.08	−21.50
	100	29.30	−49.97	19.95	−16.32	−21.54

In internal combustion engines, BSFC and exhaust emissions are desired at the lowest level, while BTE is desired to be high. Therefore, the models used in this study were "Larger is better" for BTE, while the "smaller is better" model was used for BSFC, BSHC, $BSNO_x$ and smoke responses. Thus, in multivariate experiments, experimental variables that could keep BTE at the highest value were sought. It is desirable to have a test condition that gives the lowest values in BSFC and exhaust emissions. The S/N ratio is used for this purpose. In both S/N models, the highest value among the values calculated according to Equations (1) and (2) represents the most suitable experimental condition for the response. In this context, when Table 5 is examined, it can be seen that the most suitable 1-heptanol ratio for BTE is 20%, which corresponds to 29.48 dB. Similarly, the most suitable injection pressure for smoke was determined to be 220 bar, corresponding to −20.19 dB. The variable most suitable for each experimental response can be found by looking at the S/N ratios in Table 5. Taguchi's analyses were examined separately as engine performance and exhaust emissions. Figure 2 presents the S/N ratios of engine performance data, including BTE and BSFC.

The best level of variables for the experimental results was determined by the highest S/N ratio [34]. While the dashed horizontal line in the S/N graphs shows the average S/N value, the blue dots indicate the S/N ratio corresponding to the levels of the variables. When Figure 2 is examined, it is clear that the operating parameters affecting BSFC are 20% of 1-heptanol, 220 bar of injection pressure, 24 CAD of injection advance and B75. It seems that the best results for BTE are achieved at the same test levels. The effect levels of the experimental variables on exhaust emissions are given in Figure 3.

It was seen from the S/N value that B75 was the optimum mixture compared to B100 in terms of exhaust emissions, as seen in Figure 3. The most ideal injection pressure for BSHC and smoke emissions was found to be 220 bar. While the optimum levels of injection advance for BSHC, BSNOx and smoke were 24 CAD, 22 CAD and 26 CAD, respectively, the optimal levels for 1-heptanol were determined to be 20%, 5% and 15%.

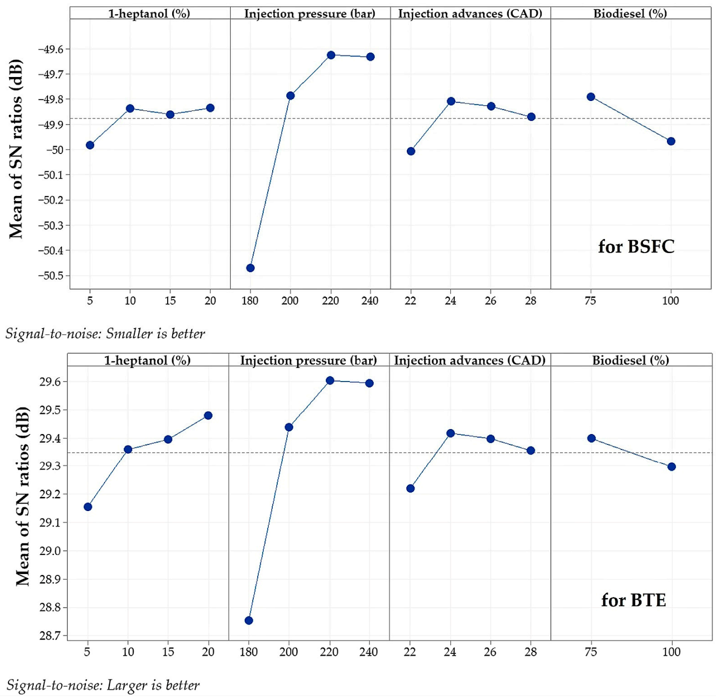

Figure 2. Main effect plots according to the means of S/N ratios for engine performances.

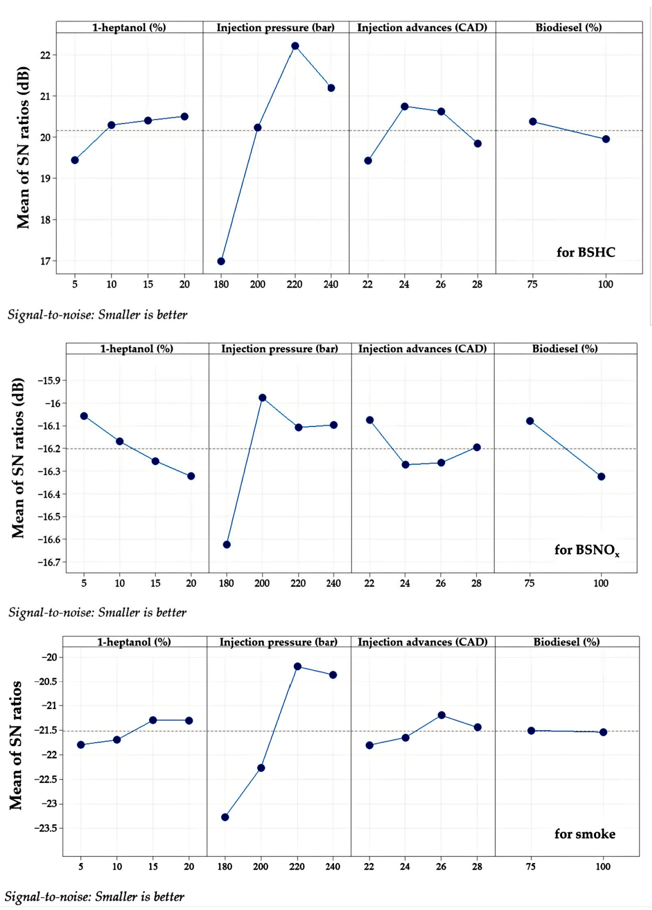

Figure 3. Main effect plots according to means of S/N ratios for exhaust emissions.

ANOVA is used to determine whether the results of data or analysis are significant. For this purpose, it determines the proportional effect of the variables and equalizes the mean of response variables at different factor levels to estimate the effect of one or more variables [32,35]. In ANOVA, *p* and F values needed to be examined to validate any quadratic model. A higher F value indicates stronger model reliability, while a lower *p* value indicates model significance. If the *p* value is less than 0.05, it means the relevant factor is more significant. Model terms with values greater than 0.1 are not significant [36]. While the sum of squares or quadratic sum is indicated by "SS" in the ANOVA table, the mean of squares or quadratic mean is indicated with MS. Mean squares (MS) are calculated by dividing the quadratic sum (SS) by the degrees of freedom (DF) of the variable of interest [37]. The variable that affects the result the most compared to other variables can be determined by the contribution output of ANOVA. If this value is high, it indicates that the experimental set is the most significant variable for the result.

The effects of different experimental variables on engine performance and emissions in a non-road diesel engine were examined using ANOVA. Table 6 shows the ANOVA analysis results for engine performance.

Table 6. Results of ANOVA analysis for engine performances.

Sources for Variance	Contribution (%)	Sum of Squares (SS)	Mean of Squares (MS)	F-Value	*p*-Value
Results of BSFC					
1-heptanol	2.5	74	24.667	14.43	0.007
Injection pressure	87.86	2600.37	866.791	507.20	0.000
Injection advances	4.13	122.37	40.790	23.87	0.002
Biodiesel	5.22	154.52	154.522	90.42	0.000
Error	0.29	8.54	1.709		
Total	100				
Results of BTE					
1-heptanol	10.10	2.58	0.86	39.17	0.001
Injection pressure	83.86	21.31	7.10	323.42	0.000
Injection advances	4.08	1.042	0.35	15.82	0.006
Biodiesel	2.04	0.52	0.52	23.70	0.005
Error	0.43	0.1098	0.02		
Total	100				

According to the ANOVA results in Table 6, it was determined that the highest effect on BSFC and BTE was caused by an injection pressure at 87.86% and 83.86%, respectively. When the sum of squares and mean of square values at the same time were examined, they were found to be 2600.37 and 866.791, respectively. Since these values are high, lower *p* values were achieved. This shows that the variable was meaningful for response. It was observed that 1-heptonol had the least effect on the change in BSFC, with a contribution of 2.5%. It is thought that due to the low cetane number and calorific value of 1-heptanol, more fuel is used to reach the same engine load. The use of 1-heptanol contributed 10% to the best result for BTE. In this study, parameters such as F value and *p* value obtained by ANOVA analysis and whether the experimental variables were statistically significant were evaluated. If the '*p*' value of any operating parameter is close to zero, it indicates that the variable has more influence on the output response. The fact that this value was less than 0.05 indicates that the model is significant. At the same time, the F value was expected to be high. When the *p* values of 1-heptanol, injection pressure, injection advance and biodiesel mixture were examined for BSFC and BTE, it was observed that they were less than 0.05, and F values remained at high values. According to the results, the test variables for BSFC and BTE were found to be statistically significant. In addition, while the R^2 value of the ANOVA model for BSFC was 0.9913, this value was found to be 0.9871 for BTE. Table 6 includes the ANOVA analysis results of the test variables for exhaust emissions.

When Table 7 is examined, it can be seen that the injection pressure is a very effective variable for BSHC, $BSNO_x$ and soot emissions. When the contribution values of injection pressure for BSHC, BSNOx and soot emission were examined, it was determined that they were 87.54%, 65.58% and 92.52%, respectively. As the sum of squares and mean of square values at the same points were examined, it was seen that the highest value was reached. Moreover, it was found that the parameter most affected by the use of 1-heptanol was $BSNO_x$. The use of biodiesel had an effect of 15.69% on $BSNO_x$ emissions. Apart from the injection pressure, the biggest impact on emissions was the injection advance of 6%. When evaluated in terms of p value, it was determined that 1-heptanol, injection pressure and advance were significant, remaining below 0.05 for all emissions. In these studies, the F value was also high. However, biodiesel was not statistically significant in terms of BSHC and smoke emissions. However, the p value did not exceed one and remained at an evaluable level. The R^2 value, which determines the accuracy of the model in the ANOVA analysis conducted for exhaust emissions, was found to be 0.9604, 0.9538 and 0.9778 for BSHC, $BSNO_x$ and soot emissions, respectively.

Table 7. Results of ANOVA analysis for exhaust emissions.

Sources for Variance	Contribution (%)	Sum of Squares (SS)	Mean of Squares (MS)	F-Value	p-Value
		Results of BSHC			
1-heptanol	4.44	0.00049	0.00016	5.61	0.047
Injection pressure	87.54	0.00962	0.00321	110.53	0.000
Injection advances	6.24	0.00068	0.00023	7.88	0.024
Biodiesel	0.45	0.00005	0.00005	1.71	0.248
Error	1.32	0.000145	0.00003		
Total	100				
		Results of $BSNO_x$			
1-heptanol	10.38	0.090	0.030	11.23	0.012
Injection pressure	65.58	0.571	0.1905	71.22	0.000
Injection advances	6.54	0.057	0.0189	7.07	0.030
Biodiesel	15.69	0.136	0.1362	50.92	0.001
Error	1.54	0.013	0.0027		
Total	100				
		Results of smoke			
1-heptanol	3.38	1.937	0.6456	7.63	0.026
Injection pressure	92.52	52.997	17.666	208.75	0.000
Injection advances	3.35	1.917	0.6390	7.55	0.026
Biodiesel	0.01	0.0056	0.0056	0.07	0.807
Error	0.74	0.4231	0.0846		
Total	100				

RSM can be defined as a method of finding the best operating conditions or optimized conditions that give the best possible results. Optimized parameters can be reached with this method when the maximum or minimum of the response surface is known [35]. Composite desirability represents a combined measure of the desirability values of different response variables. This helps us evaluate how good a solution is overall, taking all goals into account simultaneously. The closer this value is to one, the more the optimization is considered to be meaningful for all results. In RSM optimization, first the targeted levels of the experimental responses were determined. Optimization was made by targeting the maximum value for BTE, while targeting the minimum value for BSFC, BSHC and BSNOx. The optimization results are summarized in Figure 4.

As seen in Figure 4, the optimization approaches maximized BTE while minimizing BSFC, BSHC, $BSNO_X$ and smoke. In order to achieve this, it was determined that the optimum operating parameters should be 17.27% of 1-heptanol, 226 bars of injection pressure, 27 CAD of injection advance and B75. It was determined that the composite desirability value of optimization was 0.9709. This value close to 1 indicates that optimization is acceptable. The optimum parameters and the performance and emission results estimated by RSM for these parameters are given in Table 8.

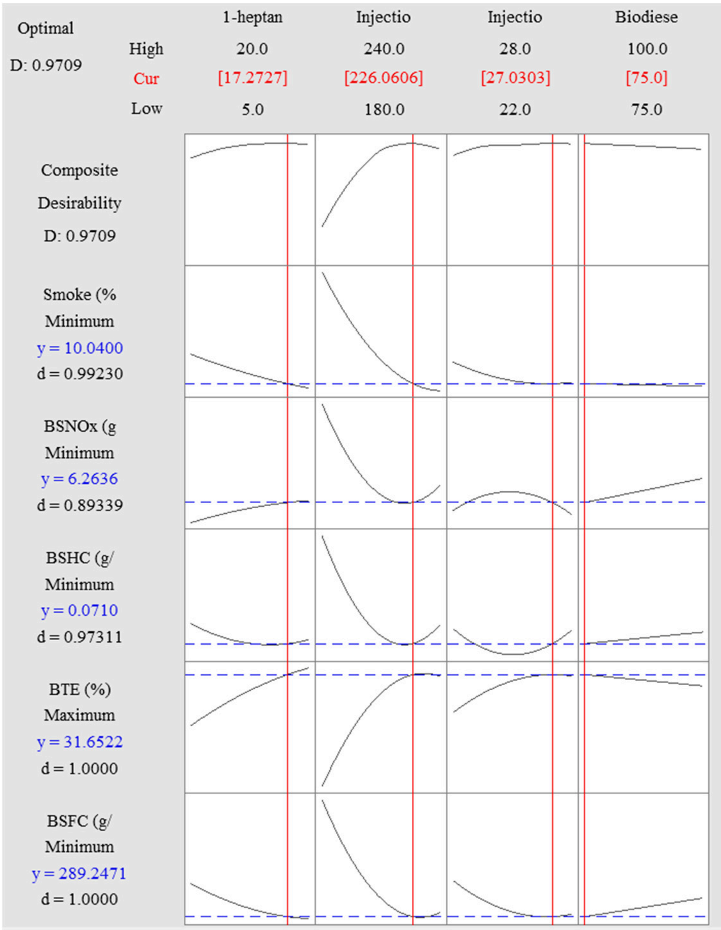

Figure 4. RSM optimization chart for engine performance and exhaust emissions.

Table 8. Summary of RSM optimization and predicted responses.

Optimum Test Parameters				
1-Heptanol (%)	**Injection Pressure (bar)**	**Injection Advances (CAD)**	**Biodiesel (%)**	**Composite Desirability**
17.2727	226.061	27.0303	75	0.970888

To evaluate the accuracy of the optimization results, validation testing must be performed in addition to optimization. For this purpose, the pressure value of the fuel injector was adjusted to 226 bar with the help of an additional washer, and the injector was verified with a pressure gauge. In order to reach the 27 CAD injection advance, the fuel pump pulley was marked and assembled according to this point. Its accuracy was checked by preliminary combustion analysis. The in-cylinder pressure and heat release rate curves obtained from the experiment, performed to verify the adjusted injection advance, are presented in Figure 5. When fuel is injected into the cylinders, it causes the temperature inside the cylinder to decrease slightly. This can be followed according to the heat release rate by combustion analysis. The point where the heat release rate drops to a negative value is considered the fuel injection moment. When an arrow is drawn downwards from the moment the heat release rate drops to a negative value, it corresponds to 27 CAD, see Figure 5.

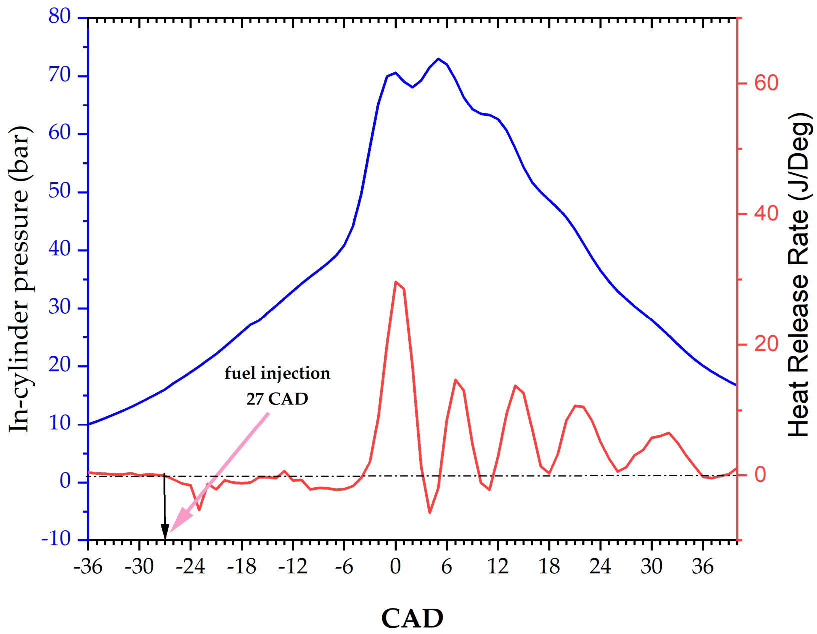

Figure 5. In-cylinder pressure and heat release rate curves for injection advance verification.

A test was carried out for verification using the values of the optimized engine parameters obtained through optimization. For experimental results, an average of three experiments was examined. The test results for validation with optimized results and the error percentage between both are shown in Table 9.

Table 9. Results of validation test and % error.

Engine Response	Predicted Value with RSM	Experimental Value	% Error
BTE (%)	31.6522	31.25	1.29
BSFC (g/kWh)	289.247	302.157	4.27
BSHC (g/kWh)	0.0710143	0.0746	4.81
$BSNO_x$ (g/kWh)	6.26362	6.021	4.03
Smoke (%)	10.04	10.15	1.08

When Table 9 is examined, it can be observed that the highest error is 4.8%. Accordingly, it has been found that the optimum levels of the test conditions determined by Taguchi's experimental design-based RSM application are sufficient to achieve the best engine performance and exhaust emissions in non-road diesel engines. According to optimization, non-road diesel engines can be used by adding 17.27% 1-heptanol into B75 fuel under 10 Nm load conditions. It has been determined that when using this fuel, the injection pressure of the engine should be set to 226 bar, and the injection advance should be set to 27 CAD.

4. Conclusions

In this study, the optimum levels of four operating parameters were determined for a non-road diesel engine: biodiesel obtained from waste frying oil, 1-heptanol from higher alcohols, injection pressure and injection advance. Taguchi's experimental design-based RSM optimization results for the best results of BSFC, BTE, BSHC, $BSNO_x$ and smoke emissions are presented below.

- According to the ANOVA analysis conducted for engine performance and exhaust emissions, the *p* value of the variables selected for the experiments was generally found to be lower than 0.05 and found to be significant. It was observed that the *p* values found for BSHC and smoke emissions of the biodiesel experiment variable were greater than 0.05. Therefore, it was seen that the use of biodiesel was not statistically significant on BSHC and smoke emissions compared to other variables. This was due to the use of biodiesel as B75 and B100.
- It was found that the most effective variable on performance and emission results for non-road diesel engines was injection pressure. According to the results, it has been determined that the injection pressure and advance should be increased in non-road diesel engines.
- It was observed that the addition of 1-heptanol into biodiesel had the most impact on engine responses to $BSNO_x$ emissions.
- According to the RSM results, it was determined that 1-heptanol, injection pressure, injection advance and biodiesel type should be optimized to 17.27%, 226 bar, 27 CAD and B75, respectively, in order to achieve the best engine characteristics. According to the verification tests performed under these conditions, the RSM model was verified.
- The results showed that Taguchi's experimental design can be used successfully in such comprehensive analyses with fewer experiments. Moreover, it showed that optimum experimental conditions can be determined with the help of RSM and ANOVA.
- By performing this test method separately for different loads and engine speeds, operating strategies for non-road diesel engines can be determined.
- If a non-road diesel engine is used under optimized test conditions, higher efficiency can be achieved in terms of performance and emissions compared to conventional diesel. In this way, it contributes to the fight against climate change.

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