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Optimization of VCR Diesel Engine Input Parameters Fueled with Maize Biodiesel Blends Using Taguchi Method

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Abstract. This study utilizes the Taguchi approach to optimize diesel engine characteristics, such as the compression ratio (CR), engine speed (ES), and the maize biodiesel combination ratio (MB), for better performance. Among the studied parameters, there are five levels of CR, ES, and MB. The output parameters include emissions of hydrocarbons (HC), carbon monoxide (CO), nitrogen oxide (NOx), brake thermal efficiency (BTE), and brake-specific fuel consumption (BSFC). Using an L25 orthogonal array provided an efficient experimental setup to examine how these features affect engine performance. The study applies the Taguchi technique to identify the optimal set of input parameters to enhance engine efficiency and reduce emissions. An ANOVA test was conducted on the performance variables to assess the influence of each intake parameter and to quantify its percentage contribution. The results revealed that MB had the most significant effect on BSFC, ES had the most important effect on NOX and CO emissions, and CR had the most significant effect on HC emissions and BTE

Keywords: Taguchi method, ANOVA, Maize biodiesel, compression ratio, engine speed.

1. Introduction

It is necessary to switch from fossil fuels to alternative sources of energy for numerous of reasons. One of the primary contributors of greenhouse gases, fossil fuels have major effects on global warming and environmental damage [1,2]. Fossil fuels are limited and are rapidly running out, which means they cannot be sustained over time. A steadier and environmentally friendly energy future can be assured by switching to renewable energy sources like solar, wind, and bioenergy because they are plentiful and renewable [3,4]. By reducing dependence on fossil fuels and minimizing exposure to price fluctuations and geopolitical crises, renewable energy additionally promotes the safety of energy. Growing technological advancements have made renewable energy sources more economical and effective than ever before, providing cleaner and occasionally better substitutes for conventional fuels [5,6]. Hence, switching to

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alternative energy is essential to preserving the environment, maintaining economic stability, and ensuring a more sustainable future. The availability of maize oil and its relatively suitable fatty acid composition for biodiesel production make it an attractive choice among possible options for biodiesel. By combining maize biodiesel with diesel, certain disadvantages of pure biodiesel can be prevented, giving a well-balanced fuel choice that capitalizes on the emissions advantages of biodiesel while preserving diesel's performance attributes [7,8]. Engine parameters must be tuned while utilizing biodiesel mixes in order to achieve better efficiency and lower emissions. Variables like BTE, BSFC, and emissions of NOx, HC, and CO are all impacted by combustion dynamics, which are greatly affected by factors such as CR, ES, MB. A recognized statistical strategy for optimizing complicated steps, the Taguchi method offers a systematic structure for finding out the ideal engine parameter values. This approach is economical and successful since it makes use of orthogonal arrays to analyse the effects of several variables with few experimental runs [9,10]. The Taguchi approach finds the parameter settings that produce reliable performance even in the face of operational condition variability through analysis of the signal-to-noise (S/N) ratio.

Applying RSM, Singh, Sinha, and Choudhary [11] analysed the engine's optimal operating parameters relative to the emissions and performance of the CI engine fuelled by Jatropha biodiesel. Utilizing the optimization strategy, BP and BTE are achieved while NOx and HC emissions are minimized. The thermal performance of a single-cylinder diesel engine has been analyzed by studying the effects of various factors such as injection pressure (IP), compression ratio (CR), and engine load.18 CR, 180 bar IP, and 8.11 kg engine load were the ideal engine requirements according to the optimization. For BP, BTE, HC, and NOx, the optimal responses under these conditions were 2.21 kW, 28.24%, 25.3 ppm, and 174.6 ppm, respectively. For better performance exhaust emissions, Sharma et al. [12] modified the input parameters of diesel engines powered by Polanga biodiesel. IT, IP, Polanga biodiesel blend, and engine load concerning BTE, BSFC, HC, smoke opacity, and NOx emission are the input parameters considered for optimization. Experiments were carried out using Taguchi's L_{16} orthogonal array, and Taguchi-based multi-objective optimization by ratio analysis was used to find the ideal combination of input parameters. It was determined that the best set of input variables for both highest performance and the lowest exhaust emissions was engine load at 60%, IT at 27° bTDC, IP at 220 psi, and biodiesel combination B40. These optimal parameters have been identified to be NOx emission (690.987 ppm), smoke opacity (80.925 HSU), hydrocarbon emission (2.193 ppm), BTE (36.351%), and BSFC (0.322 kg/kW-hr). Mohamed et al. [13]applied an optimization strategy to directly inject warm palm oil into a diesel engine with the main objective of excelling the standard engine. Torque, IP, CR, IT, and warmed palm biodiesel blend were the input variables. The opacity of smoke emissions and torque conditions through IP and IT had more influence on CO. IT had more impact than the others. Silver nanoparticles at a concentration of 50 ppm were consistently incorporated into different biodiesel blends, namely B10, B20, B30, and B40. Among these, the B30 blend with 50 ppm of silver nanoparticles exhibited the minimum S/N ratio for smoke opacity emissions and achieved the best overall performance. With a S/N ratio of 9.7, the combination of B30 & 50 ppm silver nanoparticles revealed the lowest value among all blends. All the response optimal factors had respective BSFC, CO emission, and smoke opacity of 0.288 kg/kWh, 0.32%, and 46.77 ppm.

To determine the performance and emissions of a single-cylinder diesel engine fuelled by diesel and propylene glycol additives, Karimmaslak et al. [14] provided the hybrid machine learning approach of artificial neural network genetic algorithm response surface methodology (ANN-GA-RSM). For BSFC, BTE, CO, CO2, NOx, and SO2, the most effective model for forecasting the dependent variables is ANN-GA, which has mean square error values of 0.0398, 0.0368, 0.0529, 0.0354, 0.0509, and 0.0409 and coefficient of correlation values of 0.988, 0.987, 0.977, 0.994, 0.984, and 0.990, respectively. The recommended hybrid model minimizes CO, NOx, and BSFC by 11.32%, 21.32%, and 30.82%, respectively. Furthermore, when contrasted to a single RSM at the optimal level of independent variables, the model enhances engine efficiency and CO2 emissions by 17.29% and 31.05%, respectively. The Bees Algorithm (BA) was implemented by Ahmad and Sunthiram [15] under specified engine load, engine speed, and biodiesel proportions in the fuel combination. Achieving the finest BP and braking torque as well as the lowest BSFC is the goal of this work to enhance the CI engine's condition when employing biodiesel fuel. The results demonstrated that the ideal parameters were 200.29 kW/h of BSFC, 58.33 kW of BP, and 310.33 Nm. of braking torque. The results obtained from BA were improved compared to those from other algorithms in terms of range, BSFC, and fine BP. Based on the optimum levels of BP, brake torque, and BSFC, this result suggested that the BA may be applied to achieve the best performance of diesel engines.

The impacts of engine CR of 16, 17, and 18; a load of 25%, 50%, and 75% torque; and biofuel mixture on emissions, combustion, and performance were studied by Wiangkham et al. [16]. Among the evaluated biofuel variations were mixes of 30% biokerosene with 70% biodiesel, 50% biokerosene with 50% biodiesel, and neat biodiesel and neat biokerosene. According to the studies, greater CR improves BTE, decreases BSFC, and enhances combustion efficiency—but it also increases NOx emissions. Because they have more oxygen, biofuels increase BTE. Biodiesel's higher viscosity, however, may prevent fuel atomization and raise emissions. On the other hand, biokerosene reduces emissions and allows for early combustion, which increases BTE. While load has a significant effect on performance, both load and the volume of biokerosene affect emissions. The results of optimization indicate that the best biokerosene blends, with ratios between 20% and 40%, for all CRs and loads between 50% and 75%, offer significant data to improve sustainable fuel use in automobiles.

Utilizing Xanthium strumarium biodiesel, Pawar, Hole, and Bankar [17] implemented the Taguchi optimization of engine intake variables such as CR, IT, EGr, and IP. Applying Taguchi Design L_9 orthogonal array for highest BTE, lowest BSFC, and minimal pollutants like CO, HC, smoke, and NOx, seed oil biodiesel (B20) is utilized in variable compression ratio diesel engines. The most suitable specifications for B20 are CR-18, IP-210 bar, IT-190bTDC, and EGR-10%, whereas for Diesel they are CR-18, IP-240 bar, IT-250bTDC, and EGR-5%, based on a 50:50 weighting of thermal performance and emissions. It has been reported that the B20 blend can be utilized as fuel efficiently without making any adjustments to the engine.

This work aims to better the performance and emission characteristics of a diesel engine operated on blends of maize biodiesel by optimizing the three main intake parameters, CR, ES, and MB. The objective of this work is to find the ideal values of each parameter and evaluate how each one impacts important performance indicators, such as exhaust emissions, BSFC, and BTE, using the Taguchi strategy combined with ANOVA. This paper extends to the variety of feed stocks in biodiesel research by focusing on maize biodiesel, a less frequently studied biofuel source that is less frequently studied. This methodology sets this work above other single-parameter investigations. It improves the study of parameter relationships by allowing an accurate evaluation of the three variables' combined influence on engine performance. When utilizing blends of maize biodiesel, ANOVA also makes it achievable to calculate statistically the significance of every aspect, revealing which factors best improve engine efficiency and emissions. This study gives helpful information that may assist in the growth of effective and environmentally friendly biofuel solutions with a combination of statistical analysis and optimization.

2. Experimental setup

A conventional diesel engine with a computerized variable compression ratio (VCR) is a distinctive engine type that enables real-time compression ratio variations while operating. When monitoring alternative fuel combinations, VCR engines are particularly helpful since they can adjust the compression ratio [18]. This is because various fuel types may operate effectively with various compression settings. A VCR diesel engine runs on the conventional four-stroke diesel cycle, which consists of the intake, compression, power, and exhaust strokes [19]. A single-cylinder, four-stroke diesel engine, and an eddy current dynamometer were picked for the current experimental studies [20]. Table 1 gives the specifications of the test setup, and Fig. 1 shows an arrangement of the engine test setup. Engine operational circumstances are modified to mitigate HC, CO, and NOx emissions, improve BTE, and reduce BSFC. Engine speed (ES), maize biodiesel combination (MB), and compression ratio (CR) are the chosen operating parameters. The ES changed between 1300 and 1500 rpm, the MB changed between 10 and 50%, and the CR changed between 14 and 18. AVL 444N exhaust gas analyzer was utilized for measuring exhaust emissions, including NOx, CO, and HC [21].

The biofuel made from corn oil is called maize biodiesel. Although maize is typically produced for food and to produce bioethanol, it can also be used to make biodiesel [22]. This oil can then be transformed into biodiesel by a chemical process called transesterification, in which the oil undergoes a reaction with an alcohol, typically methanol, with the help of a catalyst to create fatty acid methyl esters, which are the chemical compounds that, as a by-product, produce biodiesel and glycerine [23]. The table 2 displays the characteristics of biodiesel.

Table 1. Test engine specifications.

Engine type	4-Stroke VCR engine
Engine Make	Kirloskar
Number of cylinders	Single cylinder
Loading	Eddy current
Stroke Length (mm)	110
Bore (mm)	87.5 mm
Capacity (cc)	661 cc
Power (kW)	3.5
RPM	1500
Compression ratio	12-18

Table 2. Properties of fuel

Fuel	Kinematic viscosity (mm^2/s) @ 40°C	Calorific value (kJ/kg)	Density (kg/m^3) @ 15°C	Flash point (°C)	Cetane number
Diesel (D100)	3.35	45600	827	68.5	51
B100	5.26	38840	880	125	56
B10	2.74	43570	834	55	48
B20	2.88	43240	838	60	50
B30	3.12	42550	842	70	52
B40	3.42	42150	846	80	54
B50	3.63	41800	850	90	55

3. Optimization approach

The Taguchi is a statistical approach for process optimization that requires experimenting with the available resources [24]. Minitab software was utilized in this work to carry out the Taguchi design process, taking into account three input parameters: engine speed (ES), compression ratio (CR), and blends of maize biodiesel (MB) [25]. Table 3 depicts the standardized Taguchi orthogonal array L25 on which five levels have been fitted and allocated for low, middle, and higher-level values and table 4 depicts the experimental values. The technique of Taguchi evaluates the significance of process parameters using a statistical performance indicator called signal-to-noise ratio (S/N), which accounts for both the mean and the variability [26]. Improving BTE and lowering additional responses, including those related to BSFC, HC, CO, and NOx levels, were essential phases in the process of identifying the best settings.

Equations 1 and 2, respectively, display the stated S/N ratio for higher is better or lower is better conditions [27].

Fig. 1. VCR diesel engine experimental setup

The S/N ratio for the "higher is better" criterion was applied to evaluate the brake thermal efficiency (BTE).

$$-10ln_{10}\frac{1}{n}\sum_{i=1}^{n}\frac{1}{Y^2} \tag{1}$$

The S/N ratio for the "smaller is better" criterion was applied to evaluate BSFC, HC, CO, NOx.

$$-10ln_{10}\frac{1}{n}\sum_{i=1}^{n}Y^2 \tag{2}$$

Table 3. Taguchi design levels and variables

Variable	Symbol	Levels				
		1	2	3	4	5
Compression ratio	CR	14	15	16	17	18
Engine speed	ES	1300	1350	1400	1450	1500

(rpm) Biodiesel blend (%)	MB	10	20	30	40	50

Table 4: Experimental Values (L_{25})

Trail	CR	Speed (rpm)	Blend (%)	BTE (%)	BSFC (kg/kWh)	HC (ppm)	CO (%)	NO_x (ppm)
1	14	1300	10	19.64	0.41	29	0.042	438
2	14	1350	20	19.29	0.49	30	0.044	360
3	14	1400	30	20.51	0.42	32	0.048	310
4	14	1450	40	23.24	0.32	33	0.041	486
5	14	1500	50	21.27	0.3	28	0.039	680
6	15	1300	20	29.21	0.39	30	0.046	627
7	15	1350	30	28.27	0.35	34	0.051	510
8	15	1400	40	29.13	0.33	35	0.056	500
9	15	1450	50	29.52	0.36	33	0.052	540
10	15	1500	10	28.29	0.42	32	0.039	664
11	16	1300	30	26.18	0.34	34	0.042	810
12	16	1350	40	25.32	0.37	32	0.039	720
13	16	1400	50	25.98	0.41	35	0.042	715
14	16	1450	10	26.29	0.44	33	0.039	832
15	16	1500	20	27.52	0.46	35	0.041	790
16	17	1300	40	29.53	0.39	33	0.037	980
17	17	1350	50	28.65	0.36	39	0.047	39
18	17	1400	10	28.27	0.37	34	0.046	784
19	17	1450	20	29.12	0.42	35	0.042	860
20	17	1500	30	29.45	0.44	38	0.037	960
21	18	1300	50	26.75	0.43	34	0.036	1030
22	18	1350	10	27.25	0.39	36	0.053	806
23	18	1400	20	28.14	0.37	37	0.057	898
24	18	1450	30	29.49	0.42	38	0.039	1080
25	18	1500	40	30.52	0.45	39	0.036	1039

4. Results and Discussions

The current study employs a Taguchi L25 orthogonal array to optimize the intake parameters of diesel engines which operate on combinations of maize biodiesel. The CI engine may initially run at full load on diesel fuel, then blends of biodiesel. Then, under full load operating conditions, studies were conducted in diesel engines for several combinations of compression ratios (14, 15, 16, 17, 18), engine speeds (1300, 1350, 1400, 1450, 1500 rpm), and blends of maize biodiesel (10, 20, 30, 40, 50%). Lastly, ANOVA results were compared with all of the biodiesel blends' experimental outcomes.

Table 5. Response Table for S/N Ratios

Response	Level	CR	Speed (rpm)	Blend (%)
BTE	1	26.34	28.3	28.21
	2	29.21	28.13	28.42
	3	28.38	28.37	28.48
	4	29.25	28.76	28.76
	5	29.07	28.69	28.39
	Delta	2.91	0.63	0.55
	Rank	1	2	3
BSFC	1	8.366	8.161	7.845
	2	8.667	8.201	7.458
	3	7.925	8.436	8.138
	4	8.071	8.194	8.655
	5	7.723	7.761	8.656
	Delta	0.944	0.675	1.198
	Rank	2	3	1
HC	1	-29.64	-30.08	-30.3
	2	-30.31	-30.64	-30.44
	3	-30.57	-30.77	-30.91
	4	-31.06	-30.72	-30.71
	5	-31.31	-30.67	-30.53
	Delta	1.67	0.69	0.62
	Rank	1	2	3
CO	1	27.39	27.86	27.23
	2	26.3	26.65	26.81
	3	27.83	26.11	27.31

4	27.62	27.46	27.69
5	27.26	28.32	27.37
Delta	1.54	2.21	0.89
Rank	2	1	3
1	-52.83	-57.41	-56.74
2	-55.03	-50.47	-56.56
3	-57.75	-55.57	-56.49
4	-53.57	-57.23	-57
5	-59.69	-58.2	-52.09
Delta	6.86	7.73	4.91
Rank	2	1	3

Table 6. Analysis of Variance for SN ratios

O/P Parameter	Source	DF	Seq SS	Adj SS	Adj MS	F	P	Contribution
BTE	CR	4	30.3076	30.3076	7.57691	110.02	0	**90.84**
	Speed (rpm)	4	1.4334	1.4334	0.35834	5.2	0.011	4.30
	Blend (%)	4	0.7964	0.7964	0.1991	2.89	0.069	2.39
	Residual Error	12	0.8264	0.8264	0.06887			2.48
	Total	24	33.3638					100
BSFC	CR	4	2.765	2.765	0.6913	0.48	0.749	10.39
	Speed (rpm)	4	1.19	1.19	0.2975	0.21	0.93	4.47
	Blend (%)	4	5.417	5.417	1.3543	0.94	0.472	**20.36**
	Residual Error	12	17.238	17.238	1.4365			64.78
	Total	24	26.61					100
HC	CR	4	8.578	8.578	2.1444	9.87	0.001	**61.73**
	Speed (rpm)	4	1.569	1.569	0.3923	1.81	0.192	11.29
	Blend (%)	4	1.143	1.143	0.2857	1.32	0.319	8.23
	Residual Error	12	2.606	2.606	0.2172			18.75
	Total	24	13.896					100
CO	CR	4	7.011	7.011	1.7527	2.39	0.108	20.66
	Speed (rpm)	4	16.109	16.109	4.0272	5.5	0.009	**47.47**
	Blend (%)	4	2.027	2.027	0.5067	0.69	0.611	5.97
	Residual Error	12	8.785	8.785	0.7321			25.89

	Total	24	33.932					100
NOx	CR	4	166.42	166.42	41.61	1.42	0.287	20.84
	Speed (rpm)	4	194.06	194.06	48.51	1.65	0.225	**24.30**
	Blend (%)	4	85.6	85.6	21.4	0.73	0.589	10.72
	Residual Error	12	352.38	352.38	29.36			44.13
	Total	24	798.46					100

The BTE value of an engine shows how well it can convert fuel's chemical energy into mechanical power, a higher BTE value results in better fuel economy and fewer emissions. The S/N ratio, following the "higher is better" approach, was considered when evaluating the brake thermal efficiency (BTE). [28,29]. Figure 2 presents the major response graph of the S/N ratio for the BTE parameter. It shows that CR 14 to 15 swings significantly but stays relatively high from CR levels 15 to 18, indicating that BTE increased as engine rpm and biodiesel blend increased. For the BTE, a CR of 17, an ES of 1450 rpm, and an MB blend of 40% are the optimum values. Table 5 presents the response table for the S/N ratios of the brake thermal efficiency (BTE) performance parameters. Table 6 presents the results of an ANOVA in which the contributions of each intake parameter are assessed. With a contribution of 90.84%, it is discovered that CR significantly affects BTE and is more important than other variables.

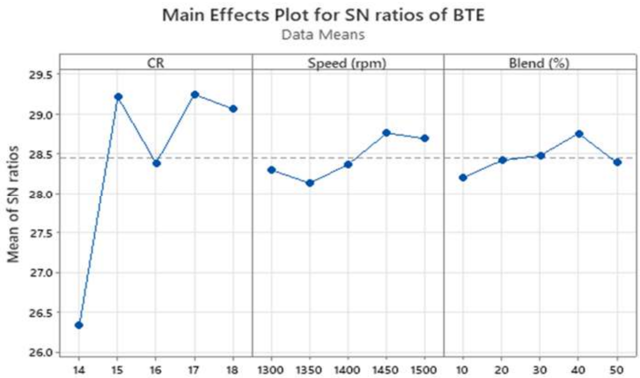

Fig. 2. S/N ratios for BTE

The total quantity of fuel used per unit of power production over time is known as the engine's BSFC, and it is a measure of fuel efficiency. When analyzing the BSFC using the SN ratio, the "lower is better" criterion is applied. [30,31]. Figure 3 shows the main response graph of the SN ratio for the BSFC. It shows that BSFC decreases when CR increases 15 to 18, and engine speed 1400 to 1500 rpm, but increases when the blend percentage increases. It indicates that BSFC rises as the MB blend % rises but falls as CR rises by 15 to 18 and ES rises by 1400 to 1500 rpm. The optimum values for the BSFC are CR 18, ES 1500 rpm, and MB blend 20%. The BSFC values obtained from each experiment, along with their SN ratio values, are presented in Table 5. From the Table 6 ANOVA values, it is clear that the MB blend is highly influenced by BSFC with a contribution of 20.36%. The SN ratio with lower is best value has been taken into consideration when assessing exhaust HC emissions [32]. S/N ratios for all response parameter indices are determined with the experimental results, as shown in Figure 4. It reveals that when ES rises from 1300 to 100 rpm, MB blend rises from 10% to 30%, and CR rises from 14 to 18 rpm, HC emissions decrease. For the HC emissions, a CR of 18, an ES of 1400 rpm, and an MB blend of 30% are the optimum values. The related ANOVA results, which assess the contributions of each intake parameter separately, are shown in Table 6. It is evident from the tabulated numbers that CR contributes the most, at 61.73%. Exhaust CO and NOx emissions have been assessed via the SN ratio, with a less value is better [33,34].

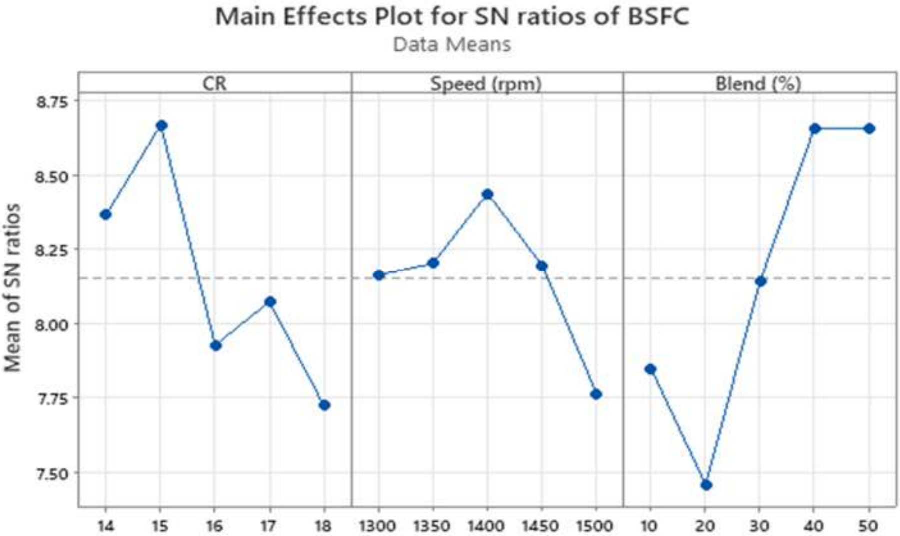

Fig. 3. S/N ratios for BSFC

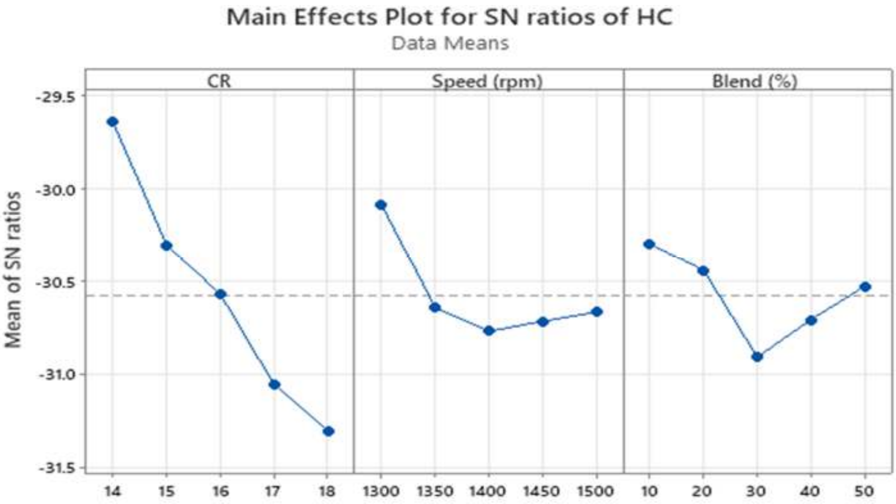

Fig. 4. S/N ratios for HC emissions

The experimental data are used to calculate S/N ratios for CO and NOx emissions of all response parameter indices, as depicted in Figures 5 and 6. Table 6 provides the corresponding ANOVA results, which evaluate each intake parameter's contributions independently. For the CO emissions, a CR of 15, an ES of 1400 rpm, and an MB blend of 20% are the optimum values. ES is the largest contributor, accounting for 47.47% of CO emissions and 24.30% of NOx emissions, respectively, according to the tabulated data. For the NOx emissions, a CR of 18, an ES of 1500 rpm, and an MB blend of 40% are the optimum values.

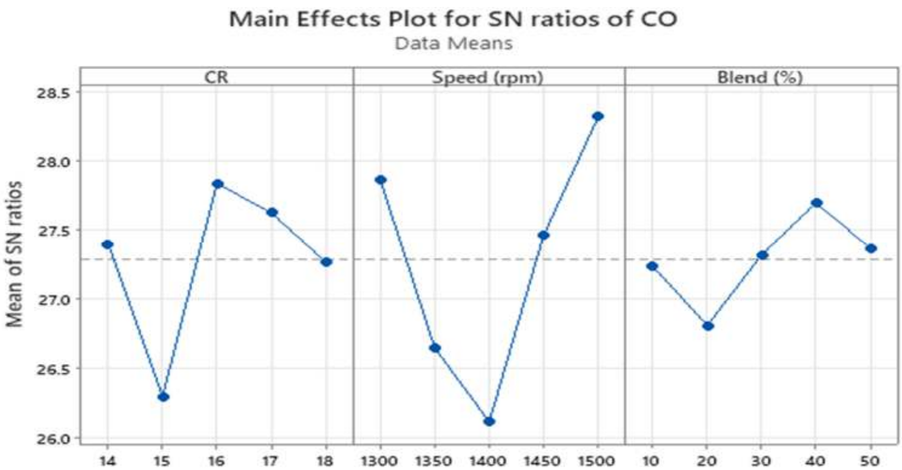

Fig. 5. S/N ratios for CO emissions

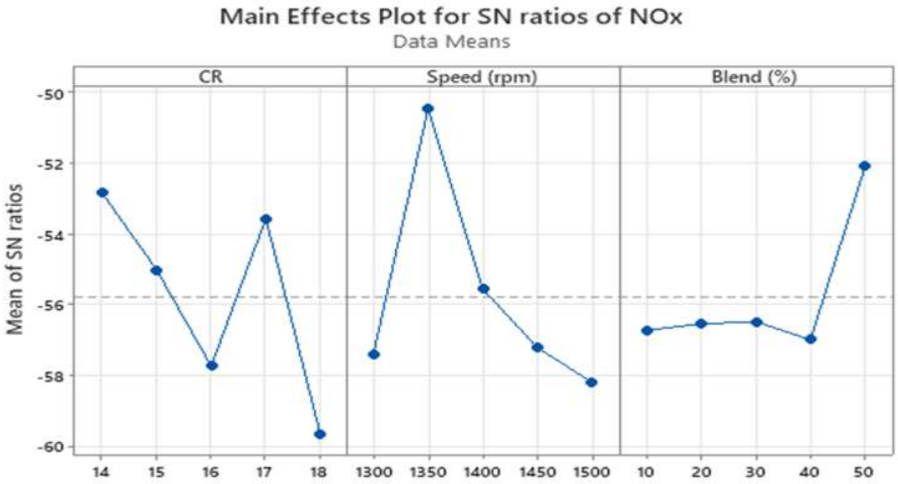

Fig. 6. S/N ratios for NOx emissions

5. Conclusions

Utilizing the Taguchi approach, this study effectively illustrates how to optimize a diesel engine's emissions and performance when operating multiple combinations of maize biodiesel. Through the analysis of three important input parameters, engine speed (ES), compression ratio (CR), and maize biodiesel blend% (MB), the study reveals the ideal variables that enhance brake thermal efficiency (BTE) while reducing pollutants and brake-specific fuel consumption (BSFC). BTE increases substantially, and HC emissions are reduced with an increased compression ratio, especially CR 18. The engine's speed has a major effect on CO emissions; 1500 rpm is a desirable rate to lower CO levels. BSFC is greatly affected by the quantity of the biodiesel blend; the best fuel efficiency is attained with a 20% maize biodiesel blend. An ideal setting for the BTE-MB blend (40%), ES (1450 rpm), and CR (17), and for the BSFC-MB blend (20%), ES of 1500 rpm, and CR (18). The ideal parameters for the HC emissions-MB blend of 30%, an ES of 1400 rpm, and a CR of 18, for the CO emissions-MB blend of 20%, an ES of 1400 rpm, and a CR of 15, and for NOx emissions-MB blend of 40%, an ES of 1500 rpm, and a CR of 18.

Disclosure of Interests. The authors have no competing interests to declare that are relevant to the content of this article.

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