Journal of Mines, Metals and Fuels, *73(6): 1749-1764; 2025. DOI: 10.18311/jmmf/2025/49023*

Print ISSN : 0022-2755

Journal of Mines, Metals and Fuels

Contents available at: *www.informaticsjournals.co.in/index.php/jmmf*

Optimizing the Factors Impacting on MPFI SI Engine Performance and Emissions Parameters using Taguchi Technique

Ravindra S. Deshpande[1]*, Mayur J. Gitay[2], Pramod B. Magade[3], Nitin Kardekar[4], Ajay D. Diwate[5], Pradip P. Patil[6] and Vijaya Patil[7]

[1]Department of Mechanical Engineering, Sinhgad College of Engineering (SCOE), Vadgaon (Bk.), Pune - 411041, Maharashtra, India; ravindra.deshpande8888@gmail.com
[2]Bhivrabai Sawant Polytechnic, Pune - 412207, Maharashtra, India
[3]Zeal College of Engineering and Research, Pune - 411041, Maharashtra, India
[4]JSPM Narhe Technical Campus, Pune - 411041, Maharashtra, India
[5]TSSM'S Bhivrabai Sawant College of Engineering and Research, Narhe, Pune - 411041, Maharashtra, India
[6]D. J. Sanghvi College of Engineering, Vile Parle, Mumbai - 400056, Maharashtra, India
[7]Prin. L.N. Welingkar Institute of Management Development and Research (PGDM), Matunga, Mumbai - 400019, Maharashtra, India

Abstract

Alcohol-related fuels are gradually becoming the most suitable alternative fuel. The two alcohols that seem to have the greatest potential for use as fuel are ethanol and methanol. This was accomplished by running the test engine under various conditions, including varied ratios of alcohol to gasoline blends (A_5, A_{20}, and A_{25}), compression ratios (10, 10.5, 11), and engine speeds (2100, 2800, and 3500 rpm). The Taguchi design of experiment (DoE) approach and one-way ANOVA were used to identify the optimal Factor Levels (FL) concerning performance (BP, BSFC, and BTE) as well as emissions (CO, CO_2, HC, and NO) parameters. The trials were carried out using the combinations provided in the L9 orthogonal arrays (OA), which were found to be appropriate according to the design of the experiment. From the results, the best performance conditions are an engine speed (3500 rpm), a CR (11:1), and a blend ratio of 25% alcohol to gasoline (A_{25}). The highest exhaust emissions from the blends were HC and CO_2, while the lowest were NO and carbon monoxide. According to the analysis, engine performance and emission parameters were used to identify the optimal levels of each factor.

Major Findings: *The Taguchi method optimizes factor levels to maximize BP and BTE while minimizing engine emissions and BSFC. The ANOVA indicate that speed has a significant impact on BP (96.44%). The compression ratio influences HC, with a percentage contribution of 69.87%.*

Keywords: *ANOVA, Emissions, Ethanol, Methanol, Performance, Taguchi*

1.0 Introduction

One of the major significant issues around the world today, particularly in developed countries, is the energy crisis. Energy shortages are mainly caused by increased industrialization, population, and improved transportation, with continuing usage of fossil fuels in various sectors. This signifies major challenges for human

**Author for correspondence*

beings to overcome[1]. Greenhouse gases, pollution, and increased global warming are all negative consequences of using oil. Biofuel has the potential to be one of the optimal alternatives for conventional fuels in this scenario because it has less adverse environmental effects, such as air pollution, increased carbon dioxide emissions, and global warming, and it can reduce the country's oil import bill, which will save foreign exchange and improve energy security[2]. The use of oxygenated biofuels is known to lower dependence on depleted fossil fuels and also minimize exhaust emissions[3]. Biofuel policies have been proposed and adopted to increase the production and consumption of biofuels. Biofuel policies include bending regulations, tax reductions and incentives, carbon-free or sustainable fuel requirements, fiscal incentives, and public funding[4]. The government of India announced a national biofuel policy in 2008 with a target of blending up to 20% ethanol into gasoline by 2017. Biofuel will boost alternative fuel sources, foster sustainable energy and environmental systems, and improve the rural economy, among other benefits[5]. Alcohol including methanol (M) and ethanol (E), have emerged as potential alternatives to conventional fuels due to their many physical and combustion characteristics that are comparable to those of pure gasoline[6]. Usman *et al.*,[7] tested the addition of dual alcohol to gasoline fuel at speeds between 1200 and 4400 rpm in a 4-cyl, 4-stroke spark ignition engine. They showed that when the blend percentage of ethanol and methanol fuel was boosted exhaust gases including carbon monoxide, NO_x, carbondioxide, and HC were much reduced, but BP, BTE, and BSFC dropped. Iorio *et al.*[8] evaluated the influence of dual-alcohol blends of turbocharged direct injection spark ignition engines for both performance as well as emissions analysis. When the percentage ratio of alcohol level in the mixtures is increased for different contributions at various phases of the cycle. Yusuf *et al.*,[9] effects of performance as well as emission parameters on SI engines. The findings demonstrated that ethanol-gasoline performed better than methanol-gasoline concerning exhaust pollutants, engine power, and torque output, particularly for low-speed engines. ÖRS *et al.*,[10] evaluated the performance as well as emission evaluation of fuel blends containing 10% methanol and ethanol in gasoline for single-cylinder SI engines. Their findings revealed that a mixture of methanol improved BSFC and decreased BTE while also reducing HC, CO, NO_x, and CO_2 pollutants in comparison to adding an equal quantity of ethanol. Zhang *et al.*,[11] examined the exhaust emissions of three passenger automobiles running on gasoline, ethanol, and methanol, as well as their mixtures. The outcomes revealed a decline in CO and HC exhaust gases from vehicles run by E7.5 or M7.5 compared to those gasoline fuel, E10, and M10, however, NO_x emissions increased by 7.5-25.8%. Li *et al.*,[12] presented a comparative evaluation of ethanol, butanol, and methanol-gasoline blends from exhaust emissions, combustion, as well as performance point of view on PFI SI engines with different loads, alcohol content, and equivalence ratios. Elfasakhany[13] evaluated ternary gasoline-alcohol fuel blends' emission, performance, and combustion properties; the results showed that BP and volumetric efficiency were significantly improved. However, for alcohol-gasoline ternary mixtures, the exhaust emission results were not very favorable. In low-temperature conditions, the amount of alcohol (ethanol and methanol) was limited to 10% even though the stabilizer addition is commonly used in alcohol-gasoline fuel mixtures. Elfasakhany[14] studied low rates (3 to 10 percent in volume) of both methanol and ethanol fuel blends into gasoline from performance as well as emissions analysis perspectives on SI engines, the findings have suggested utilizing dual fuel mixtures rather than neat gasoline. Iliev[15] in this paper results showed that gasoline-alcohol fuel blends were tested, BP dropped, and BSFC elevated related to pure gasoline though the amount of fuel mixtures rose by up to 30%, then concentrations of CO and HC declined, although NOx emissions enhance significantly. Balki *et al.*,[16] evaluated the impacts of using alcohol-gasoline fuel for exhaust emissions as well as the performance of a low-power 1-cylinder, 4-stroke, SI engine at 2KW rated power output. Higher BTE, BT, and BSFC were observed, although NO_x, CO, and HC have reduced and CO_2 has increased. Balki *et al.*[17] examined both gasoline and ethanol-methanol blended fuel-affected SI engines from the standpoints of performance, exhaust emissions, and combustion analysis at varying CRs (8:1, 8.5:1, 9:1.9.5:1). The outcomes indicated that using methanol

(M) and ethanol (E) instead of gasoline increased and decreased emissions at all CR's for CGP, BMEP, BTE, and BSFC. Varol *et al.*[18] in this study, ethanol (E),

methanol (M), and n- butanol are added to gasoline (by 10% volume) in 4-stroke, 4-cylinder spark ignition engines. Different alcohols in blended fuels appear to have decreased CO and hydrocarbon exhaust gases while enhanced fuel consumption and CO_2 related to gasoline. Altun *et al.*[19] the outcomes represented that M10 or E10 fuel mixtures with pure gasoline (G) are appropriate for operating conditions and the engine's existing design. Canakci *et al.*[20] reported the impact of adding both ethanol and methanol to regular gasoline on the MPFI SI engine was investigated from an emissions perspective. The results revealed that using methanol (M) and ethanol (E) blends in pure gasoline fuel reduced exhaust gases of unburned HC, CO_2, NO_x, and CO at speeds of 80 km/h for various powers (5, 10, 15, 20 kW). The A/F equivalence ratio raised about regular gasoline as the quantity of both methanol and ethanol in blended fuels increased. Eyidogan *et al.*[21] in this paper E5, M5, E10, and M10 blends were evaluated for an MPFI SI engine in comparison to pure gasoline, and they showed that employing EM fuel blends enhanced brake-specific fuel. The optimum design and operating parameters for MP FI SI engines fueled by alcohol-gasoline blends were not statistically examined, based on the literature review. Therefore, this work has filled this gap in the literature. According to this study, the least experiments are required to identify the best engine operating conditions concerning emissions as well as performance when statistical approaches are applied. The main objective is to determine the optimal performance and emissions values for alcohol- gasoline fuel blends under the best operating and design conditions. For this reason, the Taguchi and ANOVA statistical techniques are used to identify the optimum design and operating variables that result in the best engine performance values. The remaining part of the article is arranged as follows. The next section covers methodology of study which involves the experimental setup of a 4-cyl, 4-s, MPFI SI-engine system and the Taguchi design of experiment approach then followed by a discussion of results and a summary of conclusions at the end of the article.

2.0 Materials and Methods

The experiment test rig used to evaluate the engine's performance along with emission parameters is described thoroughly in this section. This also includes an outline that shows the order in which the experiments were conducted.

2.1 Test Rig and Fuel Blends Used

A computerized Maruti BS-VI 4-stroke, 4-cyl, 1197 cc, water-cooled, MPFI petrol engine was employed for the experiments. Ethanol, methanol, and regular gasoline were employed as fuel for the present research work. Both ethanol (E) and methanol (M) were procured from Impression Chemicals Enterprises (ICE), Sangli whereas gasoline fuel was supplied from the Indian Oil Corporation Limited petrol station in Sangli (I). To measure engine performance as well as exhaust emissions, they were blended in various quantities. Table 1 represents percentage ratio of each composition in the fuel blend.

A_{20}, A_5, and A_{25} are three distinct fuel blends resulting from combining gasoline with ethanol and methanol on a volume basis. The test in this experiment includes both performance and emissions measurements. Different operating conditions were used for the tests, which include speed (2100, 2800, and 3500 rpm) by varying mixtures. To analyze the different performance parameters like BSFC, BP, and BTE. The first fuel sample is named A_{20} (20% ethanol and 80% gasoline) and the other two samples are named A_5 (5 % methanol and 95% gasoline) and A_{25} (20% ethanol and 5% methanol with 75% gasoline). The engine was run on different fuel

Table 1. Percentage ratio of each composition in the fuel blend

Fuel Name	A_{20}	A_5	A_{25}
Gasoline (vol %)	80	95	75
Ethanol (vol %)	20	-	20
Methanol (vol %)	-	5	5

Table 2. Technical specifications of Exhaust gas analyzer[22]

Model	AVL DIGAS 444 Gas Analyzer
Measuring principle	NDIR
Weight	4.5kg
Measuring range	
O_2	0-22 (vol %)
CO_2	0-20 (vol %)
NO	0-4000 (ppm)
CO	0-15 (vol %)
HC	0-20000 (ppm)
Engine Speed	400- 6000 (rpm)
Lambda (λ)	0 - 9.999
Oil Temperature	- 30 -125 ^{0}C
Measuring principle	NDIR

blends during 2100-3500 rpm with a compression ratio of 11:1 at full throttle. The engine emissions were analyzed using the "AVL DIGAS 444N" exhaust gas analyzer. The NO (ppm), CO_2 (% vol), CO (% vol), and HC (ppm) gases can all be measured by the exhaust gas analyzer. Table 2 indicates technical specifications of exhaust gas analyzer.

For accurate measurement of exhaust gases, the gas analyzer's probe was directly connected to the exhaust manifold. Three experiments were conducted for each blend, and the average reading was obtained for analysis. A computerized data collecting system has compiled and analyzed all of the measurements. Table 3 shows basic properties of gasoline, ethanol, and methanol fuels.

2.2 Engine Setup and Procedure

Table 4 presents technical specifications of engine used in this study. Figure 1 (a) and (b) Computerized 4 cyl, 4 s, MPFI petrol engine set up and schematic arrangement was employed for the experimental trials in this research. The system includes an eddy current dynamometer with loading. It includes the tools required to measure crank angle and combustion pressure. Engine indicators transmit signals to computers for P θ-PV graphs. The interfaces with airflow, fuel flow, temperatures, and load measurement are additionally provided. A separate control panel, an air box, a fuel tank, a U-tube manometer, a fuel measurement unit, transmitters for monitoring fuel and airflow, engine indicators (EI), process indicators (PI), and load indicators (LI) are all components of the experimental test rig. Rotameters are used to monitor the flow of fluid in calorimeters as well as water systems.

Table 3. Basic properties of gasoline ethanol and methanol[22]

Properties	Gasoline	Ethanol	Methanol
Density (kg/m^3)	720-760	789	791
Heating value (MJ/kg)	42-44	27.0	19.5
Research Octane number (RON)	94	111	114
Motor octane number (MON)	88	94	96
Carbon content (% mass)	85-88	52.2	37.5
Hydrogen content (% mass)	15	13.1	12.5
Oxygen content (% mass)	0	34.7	50
Boiling point (^{0}C)	40-200	78	65
Auto ignition (^{0}C)	500	450	500
Vapor pressure (kPa)	80	21	52

Table 4. Technical specifications of the engine (Apex Innovation Pvt. Ltd.)

Item	Specification
Engine	Make Maruti, Type BS-VI, 4 Cylinder, 4 Stroke, Petrol (MPFI), water-cooled, Power 61 Kw @ 6000 rpm, Torque 113Nm @ 4200 rpm, bore 73 mm,
Dynamometer	Type Eddy current, water-cooled
Piezo powering unit	Make-Apex, Model AX-409
Temperature sensor	Type RTD, PT100 and Thermocouple, Type K
Data acquisition device	NI USB-6210, 16-bit, 250kS/s
Load indicator	Digital, Range 0-50 Kg, Supply 230VAC
Airbox	M S fabricated with orifice meter and manometer
Load sensor	Load cell, type strain gauge, range 0-50 Kg
Airflow transmitter	Pressure transmitter, Range (-) 250 mm WC
Software	"ICEngineSoft" Engine performance analysissoftware
Dynamometer	Type Eddy current, water-cooled
Piezo powering unit	Make-Apex, Model AX-409

"EngineSoft", a LabVIEW-based software program, can be used to evaluate online performance.

A_{20} (20 % E and 80 % G), A_5 (5 % M and 90 % G), and A_{25} (20 % E and 5 % M and 75 % G) GEM blends were used in this study's experiments to evaluate the performance as well as exhaust emission parameters on a 4-cyl 4-stroke MPFI SI engine. Tests were conducted using 99.9% pure industrial- grade methanol (M) and ethanol (E). Before being added to the fuel tank, the gasoline was blended with splashes of ethanol and methanol. During the tests, engine speeds between 2100 and 3500 rpm were varied while a constant compression ratio (CR) of 11:1, was used to identify the optimal blend using statistical analysis. The engine was running throughout the experiment at each speed until it reached a stable

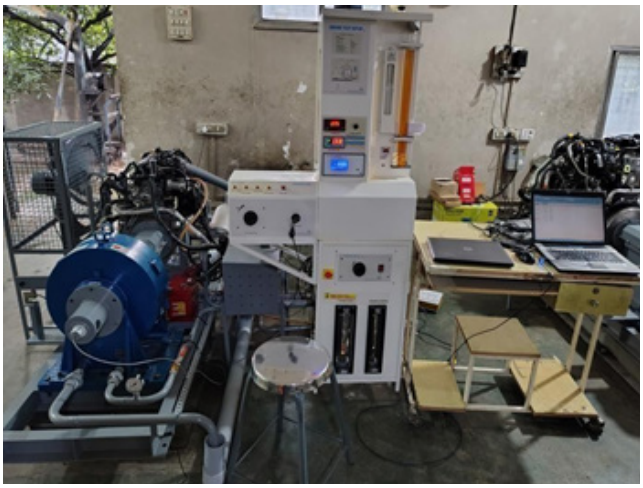


Figure 1. **(a)** Computerized 4 cyl, 4 s, MPFI Petrol engine set up.

Source:

Apex Innovations Pvt. Ltd.

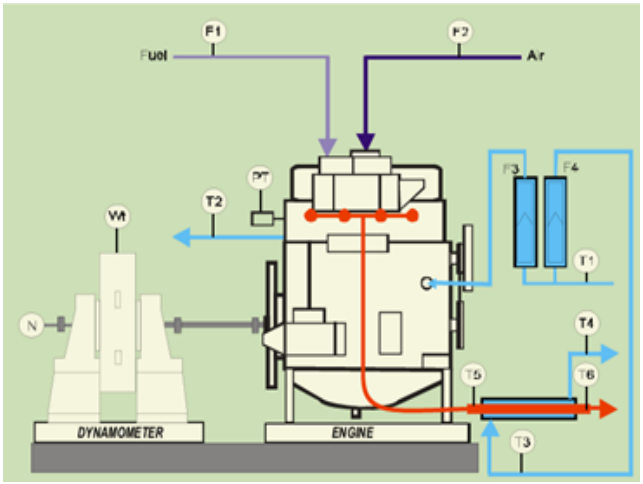


Figure 1. **(b)** Schematic arrangement Source: Apex Innovations Pvt. Ltd.

condition by adjusting the load and throttle position and maintaining a constant compression ratio condition. The "ICEngineSoft 9.1" software package, which is based on Lab View, was used to collect online performance data from the engine under various operational test conditions and pollutants including NO, CO, CO_2, and HC analyzed with an exhaust gas analyzer (EGA). Engine performance as well as emission data for each speed were obtained once steady operating conditions were achieved. The averages were used for test findings, and measurements were carried out approximately four times for each

test condition until the reproducibility was found to be correct.

Where,

T1- Inlet temperature of jacket water (^{0}C), T2- Outlet temperature of jacket water (^{0}C), T3- Inlet temperature of calorimeter water (^{0}K), T4- Outlet temperature of calorimeter water (^{0}K), T5-Inlet temperature of exhaust gas to calorimeter (^{0}K), T6- Outlet temperature of exhaust gas from calorimeter (^{0}K), F1- Fuel consumption (kg/hr), F2- Air consumption (kg/hr), F3- Jacket cooling water rate (kg/hr), F4- Calorimeter water flow (kg/hr)

2.3 Taguchi Design of Experiments (DoE) Approach

Taguchi is a Statistical Design (SD) approach developed by "Genichi Taguchi" to analyze the methods in which various parameters influence the Variance Of Performance (VOP) attributes that define the process's optimum operating conditions. Another advantage of the Taguchi technique of statistical design with the Orthogonal Array (OA) is that it reduces the number of tests. The Taguchi approach uses data obtained from experiments to estimate a SNR. This ratio determines the experimental level that produces the most effective results for the test variables. Furthermore, the ANOVA provides a statistical demonstration of the impact of test factors on the experiment results. Therefore, to identify the engine operating variables that will produce the best performance, the SNR and ANOVA can be employed. This research defined the optimal operating conditions for an SI engine in terms of engine performance using an L9 Orthogonal Array (OA). To construct DoE, Taguchi Design (TD) chooses an Orthogonal Array (OA) to estimate the minimum number of runs based on the selection of predictor variables and their control levels. To acquire valid results, the S/N ratio graph revealed the best combinations of operating parameters. The three I/P variables that are considered to be controlling factors are engine speed (rpm), CR, and blend (%), as well as their three levels: low, moderate, and high. The maximum

Table 5. Input parameters and their different levels

Code	Process parameters	Level 1	Level 2	Level 3
A	Engine speed (rpm)	2100	2800	3500
B	Compression ratio	10.0	10.5	11.0
C	Blend (%)	5	20	25

Table 6. L9 Orthogonal array for experiments

Run	Engine speed (rpm)	Compression ratio	Blend (%)
	A	B	C
1	1	1	1
2	1	2	2
3	1	3	3
4	2	1	2
5	2	2	3
6	2	3	1
7	3	1	3
8	3	2	1
9	3	3	2

25% bio-fuel blend with gasoline fuel was the main focus of the study[23]. Table 5 presents the input variables and their respective levels for test setup. Table 6. depicts L9 Orthogonal Array (OA) for experiments. The number of trials and parameters needed can be estimated using OA. The number of parameters and their variations define the OA selection[24]. Nine experiments with three repetitions were conducted in a random order.

Data from engine testing was used to estimate engine performance parameters, including BP, BSFC, and BTE, for each test phase. From the type of characteristics, there are a variety of SNR (signal-to-noise ratios) including "HTB", "LTB," and "NTB" (higher is the better, lower is the better, and nominal is the best). To determine the brake power, SFC, brake thermal efficiency, NO, hydrocarbon, CO_2, and carbon monoxide exhaust gases, the proper S/N ratio formulas were used. To meet the high level of outcomes required by brake power, BTE Taguchi's "Higher the Better" (HTB) formula was applied. Since the least values were selected, the "Lower the Better" (LTB) approach was also applied to engine emission characteristics and SFC. The formulas of SNR below are given by Equations (1) and (2)

Table 7. Experimental test data summary for responses

Run	Speed (rpm)	CR	blends (%)	BTE (%)	BSFC (kg/kWh)	BP (kW)	CO (%)	CO_2 (%)	HC (ppm)	NO (ppm)
1	2100	10	A_5	24.25	5.388	17.39	27.17	-17.16	-12.829	-19.63
2	2100	10.5	A_{20}	23.68	5.006	19.78	25.69	-19.79	-16.79	-19.69
3	2100	11	A_{25}	24.6	5.694	21.51	23.74	-19.14	-14.093	-23.06
4	2800	10	A_{20}	24.51	5.849	19.75	27.31	-18.84	-21.25	-29.48
5	2800	10.5	A_{25}	23.83	5.074	19.16	24.24	-17.92	-17.274	-15.87
6	2800	11	A_5	24.18	5.165	19.78	25.05	-19.33	-5.188	-17.04
7	3500	10	A_{25}	24.58	5.494	19.53	24.38	-20.02	-18.248	-23.98
8	3500	10.5	A_5	23.98	5.059	19.47	28.15	-17.13	-10.123	-21.7
9	3500	11	A_{20}	23.97	5.534	19.69	24.07	-18.94	-15.34	-16.7

Table 8. Optimal settings for responses

Sr. No.	A	B	C	Parameters	The optimum combination of factor levels
1	3500	11	A_{25}	BP	A_3-B_3-C_3
2	3500	10	A_{25}	BSFC	A_3-B_1-C_3
3	3500	10	A_5	BTE	A_3-B_1-C_1
4	2100	10	A_{20}	CO	A_1-B_1-C_2
5	2800	11	A_5	CO_2	A_2-B_3-C_1
6	2800	10	A_5	HC	A_2-B_1-C_1
7	3500	10	A_5	NO	A_3-B_1-C_1

S/N ratio for higher the better = $-10\ log_n^1 \sum \frac{1}{y^2}$ (1)

S/N ratio for smaller the better = $-10\ log_n^1 \sum y^2$ (2)

Where,

n = number of tests

S/N ratio = signal to nose ratio (dB) y = observed data for each response

For each emission as well as performance measurement, S/N ratios were evaluated. Based on the results, the optimal combinations were selected, and the percentage (%) contributions of the components were evaluated using ANOVA [25]. Table 7 and 8 indicates experimental test data summary for responses and optimal settings for responses (output).

3.0 Results and Discussion

3.1 Performance Parameters

Figures 2 indicates the optimal factor values that were found concerning performance characteristics as a result of tests using the Taguchi technique. By using the design of experiment (DoE), Figure 2 depicts that brake power

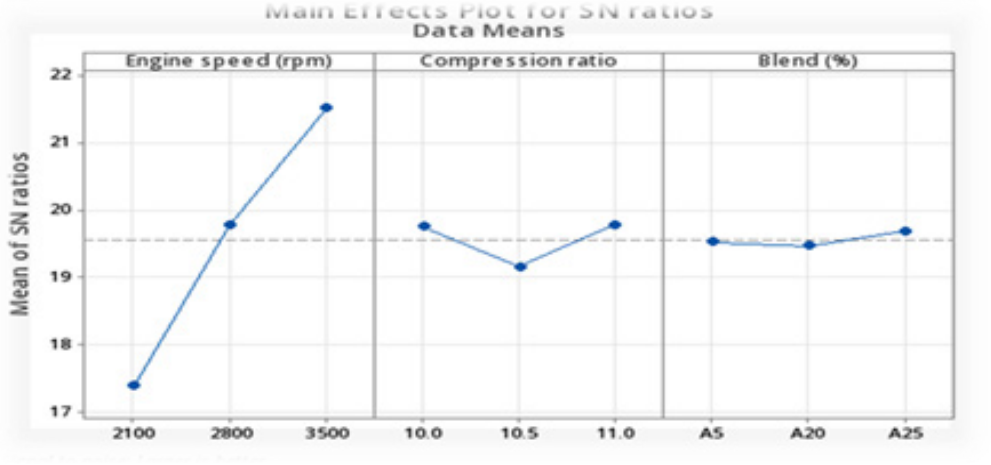


Figure 2. SNR of factor level with brake power.

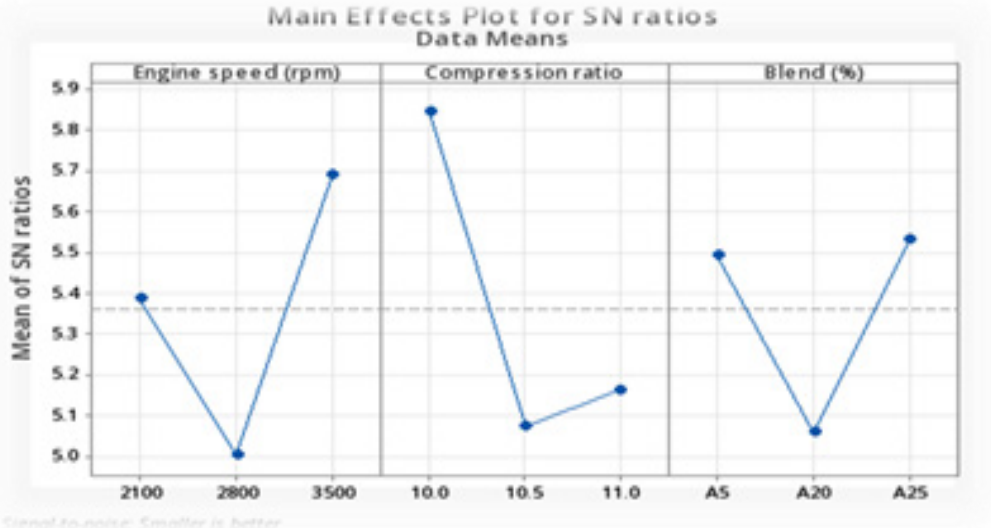


Figure 3. SNR of factor levels with Specific fuel consumption.

is affected by variations in factors and their levels. The engine speed (3500 rpm), BP, CR (11), and A_{25} blend are all present in the diagram along with the factor and optimal factor levels. "A_3-B_3-C_3" is the best combination of factors for brake power. It has been found that the increases up to A_{25}; hence, the amount of oxygen in alcohol is correlated to the optimal level of A_{25} fuel. The literature demonstrates that using alcohol blends raises BP due to their improved combustion efficiency. Alcohol in blended fuel approaches 20%, and the heating value of blended fuels diminishes as the ethanol content increases.

The predictor variables influencing engine SFC using the Taguchi method are presented in Figure 3. The SFC reached its optimum value at 3500 rpm at speed, 10 at CR, and an alcohol blend of A_{25}. The optimal combination is "A_3-B_1-C_3". When alcohol blends were used, SFC decreased when A20 was used, but increased significantly as A_{25} was used, to typical engine data. In this study, the minimum SFC at 2800 rpm was determined by taking these selected criteria into account. In the case of BSFC, the maximum SNR for speed was 3500 rpm, the blend ratio was 25%, and the CR was 10. In this research work, Minitab - 2022 software is used.

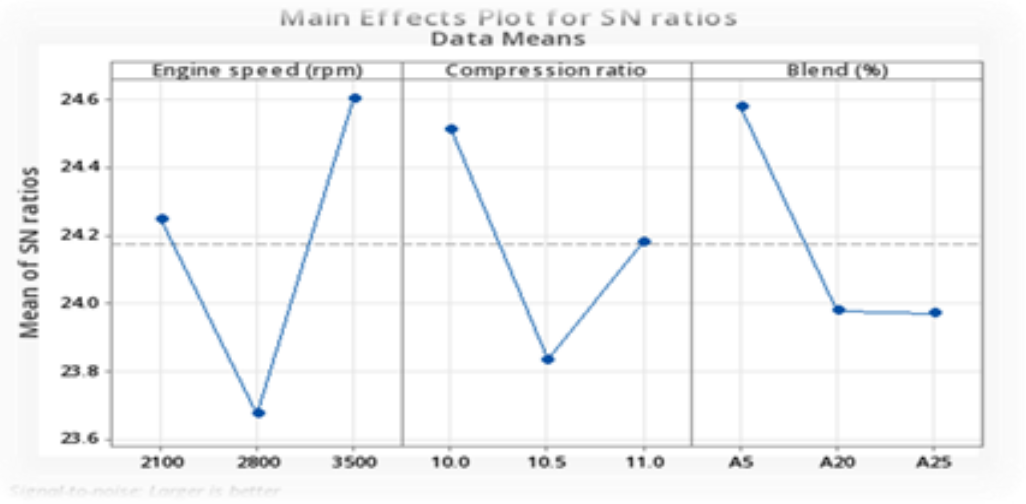


Figure 4. SNR of factor levels with brake thermal efficiency.

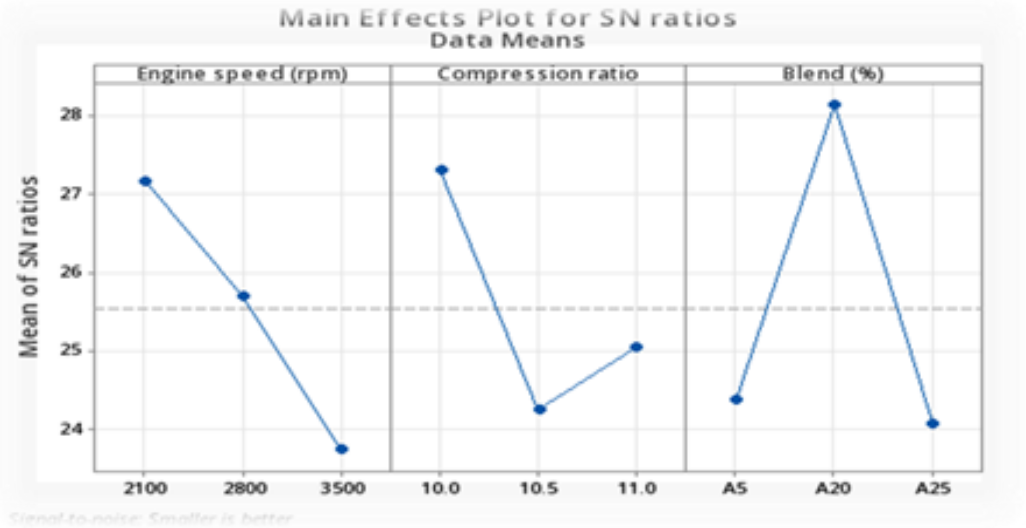


Figure 5. SNR of factor levels with carbon monoxide.

BTE peaked at 3500 rpm. Figure 4 depicts the variations in parameters and levels that impact engine brake thermal efficiency. For CR 10, speed, 3500 rpm, and an A_5 alcohol blend percentage, the BTE was optimized.

The most effective combination of factor levels is "A_3-B_1-C_1". It was found that for 3500 rpm at A_5 and CR 10, BTE has the highest S/N ratio. Furthermore, speed has a significant effect, but blend ratio has the least effect. The graph indicates that engine speed is ranked first, followed by CR and alcohol mixtures. As the alcohol blend level increased, the BTE decreased marginally.

3.5 Exhaust emission parameters

Figure 5 indicates the predictor factors and levels that affect CO emission, with the optimum value at 2100 rpm, CR 10, and A20 fuel blend. "A_1-B_1-C_2" is the optimal factor level combination.

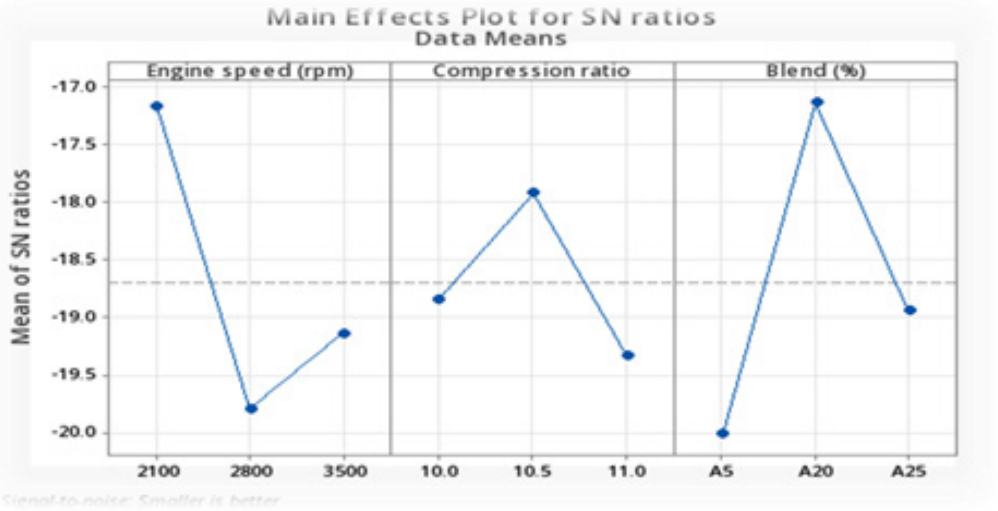


Figure 6. SNR of factor levels with carbon dioxide.

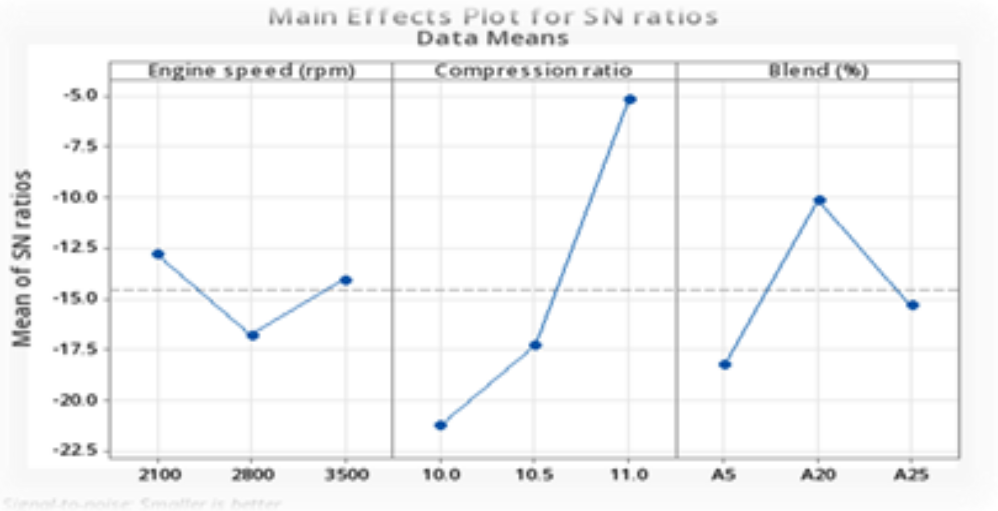


Figure 7. SNR of factor levels with hydrocarbon.

CO emissions were decreased by using alcohol blends as fuel. Alcohol's higher combustion effect because of its high oxygen content is considered to be the reason for this. To assess the best values of parameters, the Taguchi design technique uses the SNR. Three distinct types of SNR are employed in this research work. Lower the better (LB): To optimum I/P variables for carbon monoxide responses, this method was applied. Figure 6 indicates the factors and levels influencing CO_2 exhaust gas emissions. The carbon dioxide emissions were at their lowest at CR 11, 2800 rpm, and A_5 alcohol blend. "A_2-B_3-C_1" is the optimum combination.

To optimize the input parameters for CO_2 responses, the lower is better (LB) the approach was adopted. The Figure 6 indicates that the blend percentages rank first, followed by engine speed and compression ratio.

Figure 7 represents variations in the predictor parameters and levels that influence HC exhaust gas emissions. The optimum hydrocarbon emission value was found at 2800 rpm, CR 10, and A_5 (alcohol) fuel mixture. "A_2-B1-C_1" is the optimum factor level combination. The graph clearly shows that the compression ratio is ranked first, followed by the alcohol blend and engine speed. Lower is better (LB): It was employed to optimize the input variables for HC exhaust gas emission responses. The factors and levels that affect NO emissions are indicated in Figure 8. At 3500 rpm, CR 10, with an alcohol blend of A_5, the optimum NO emission value was found; "A_3-B_1-C_1" is the best combination.

NO emissions rise with engine speed, causing temperature increase. Figure 8 shows that the lowest engine speed resulted in the minimum NO. The experiment results showed that regular gasoline fuel produced the lowest NO. The minimal NO was obtained at the maximal level of CR in the study. The result clearly shows that CR is ranked first, followed by alcohol mixtures and engine speed. Using the concept "lower is better," NO was utilized to optimize the input parameters for responses. In Table 9, the outcomes of ANOVA analysis of experiment data are presented. These results demonstrate that the parameters for BP, BSFC, and BTE are effective at a 95% confidence level. As anticipated, the most important factor influencing brake power was engine speed variation, however, other factors also appeared a significant contribution. Blends of alcohol were demonstrated to be less effective for SFC and BTE. As seen in Table 9, the highest contribution of brake power of gasoline engines is the speed (96.44%), followed by compression ratio 2.57%). Because speed is always directly proportional to the engine performance, it has significantly affected brake power. The CR has some effect on the brake power. Alcohol fuel blends give the least or nearly no contribution at 0.24%. The cause for the very small percentage contribution to BP is that the

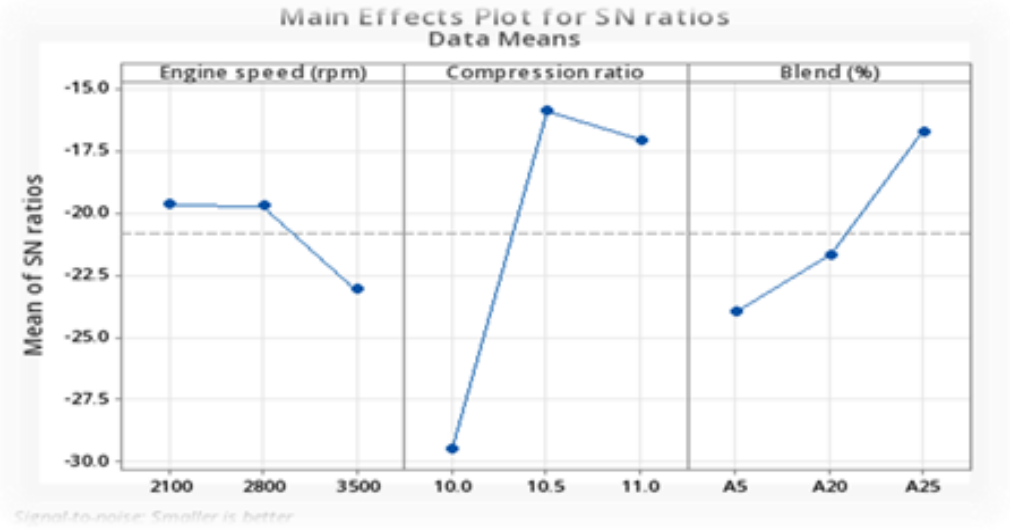


Figure 8. SNR of factor levels with nitrogen oxide.

Table 9 . ANOVA for performance parameters

Response parameters	Factors	Sum of Squares, [SS]	P-Value	Degree of Freedom [θ]	Squares Mean, [MS]	F_{factor}	Contribution
BP	A- Engine speed, rpm	30.3	0.000	2	15.15	81.29	96.44%
	B- Compression ratio	0.8065	0.925	2	0.4032	0.08	2.57%
	C- Alcohol blends, %	0.0755	0.993	2	0.03774	0.01	0.24%
	Error	63.0728		6	10.51221		0.75%
	Total	94.2548		12	26.10315		100.00%
BSFC	A- Engine speed, rpm	0.002822	0.586	2	0.001411	0.59	16.32%
	B- Compression ratio	0.004422	0.412	2	0.002211	1.03	25.58%
	C- Alcohol blends, %	0.001622	0.744	2	0.000811	0.31	9.38%
	Error	0.043001		6	0.007166		48.72
	Total	0.051867		12	0.011599		100.00%
BTE	A- Engine speed, rpm	4.473	0.302	2	2.236	1.47	32.89%
	B- Compression ratio	2.068	0.61	2	1.034	0.54	15.20%
	C- Alcohol blends, %	2.637	0.524	2	1.319	0.72	19.39%
	Error	31.621		6	5.27		32.52
	Total	40.799		12	9.859		100.00%

% 95 confidence level

Table 10. ANOVA for emissions parameters

Response parameters	Factors	Sum of Squares,[SS]	P-Value	Degree of Freedom[θ]	Squares Mean, [MS]	F_{factor}	Contribution
CO	A-Engine speed, (rpm)	0.000867	0.535	2	0.000433	0.7	18.84%
	B-Compression ratio, (CR)	0.001067	0.453	2	0.000533	0.91	23.19%
	C-Alcohol blends, (%)	0.001267	0.381	2	0.000633	1.14	27.54%
	Error	0.010599		6	0.001767		30.43%
	Total	0.0138		12	0.003366		100.00%
CO_2	A-Engine speed, (rpm)	7.727	0.463	2	3.863	0.88	22.62%
	B-Compression ratio, (CR)	1.22	0.897	2	0.61	0.11	3.57%
	C-Alcohol blends, (%)	9.207	0.39	2	4.603	1.11	26.95%
	Error	84.326		6	14.055		46.86
	Total	102.48		12	23.131		100.00%
HC	A-Engine speed, (rpm)	5.556	0.923	2	2.778	0.08	2.64%
	B-Compression ratio, (CR)	146.89	0.027	2	73.44	6.96	69.87%
	C-Alcohol blends, (%)	37.56	0.554	2	18.78	0.65	17.86%
	Error	440.667		6	73.451		9.63
	Total	630.673		12	168.449		100.00%
NO	A-Engine speed, (rpm)	98.67	0.874	2	49.33	0.14	4.40%
	B-Compression ratio, (CR)	1354.7	0.062	2	677.3	4.58	60.42%
	C-Alcohol blends, (%)	384	0.569	2	192	0.62	17.13%
	Error	4888.63		6	814.82		18.05
	Total	6,726		12	1,733.45		100.00%

% 95 confidence level

mixtures CV has not changed considerably, resulting in no improvement in BP or a low influence. However, the addition of gasoline to the alcohol engine improved exhaust emission characteristics. (The F-test, with 95% confidence, was performed to determine each variable's contribution to the output. A larger F value indicates a higher contribution. The percentage contribution (PRC) of each variable to the response is demonstrated in Table 9. Since determining the relative significance of parameters to response in this study was not significant, a one-way ANOVA method was used instead of a two-way one. Each response contributes to approximately 100% of the total percentage. Analysis of variance analysis was performed in this study with a 95% (0.95) confidence level (CI) and a 5% significance level. The results and P- values for process parameters are presented in Table 9, which emphasizes the significance of Control Factors (CL) in influencing trial outcomes. Total variance, SS (Sum of Squares), SMS (Sum of Mean Squares), and level average are among the factors that can be determined using the ANOVA. To separate the individual impacts from all control factors, a statistical design technique called ANOVA is used. The corresponding impact on the quality characteristic is determined using the % contribution of each Control Factor (CF). ANOVA outcomes for emission characteristics are presented in Table 10. Based on those results, there is a 95% Confidence Level (CL) that factors are useful in reducing exhaust emissions. The ANOVA-derived effect levels and significant value for each factor are seen when Table 10 is evaluated. Any factor's effect on the test results (CO, CO_2, HC, and NO) for various fuel blends. For instance, when factors are analyzed where the P value is less than

0.05. The variable contributes more to the output if its F value is higher. Significant effects on HC emissions were caused by the compression ratio, alcohol blends, and engine speed, which had the least effect. To identify the most significant components and measure their impact on emissions such as nitrogen oxides, CO, CO_2, and HC, an ANOVA was used. The PRC (percentage contribution) of each parameter to total variance, indicated in the last columns of the ANOVA table, signifies the degree of influence on the outcome. ANOVA and column effect techniques were used to analyze the impact of CR, engine speed, and alcohol mixtures. Taguchi uses the column effect a simplified ANOVA, to subjectively identify. Columns that significantly affect the response.

4.0 Conclusions

The influence of various alcohol blends on an MPFI SI engine working at various speeds was examined in the present study by using the Taguchi technique. Additionally, improvements in performance as well as emission parameters were also evaluated. Based on analysis and data obtained, it has been determined that different alcohol-gasoline mixtures, engine speed, and compression ratios have an impact on emissions and engine performance parameters. According to the Taguchi experimental design technique, determining the optimal factor levels is important for the maximization of BP and BTE while minimizing exhaust emissions and BSFC. In general, the following results were obtained. The optimal outcomes for SFC and CO emissions were obtained at 3500 rpm, CR 10, and A_{25}.

- At A_5, 3500 rpm, and CR 10, the optimum BTE results were achieved.
- The best results for BP were found at CR 11, A_{25} fuel blend, and 3500 rpm.
- The optimal CO emission results were found at 2100 rpm, CR 10, and an A20 fuel blend.
- In terms of CO_2 emissions, 2800 rpm, CR 11, and A_5 fuel blend produced the best results.
- The Analysis of Variance (ANOVA) shows that speed has a significant influence on BP. Engine speed has a 96.44% correlation with brake power. The BP rises in proportion to the speed.
- The compression ratio influences HC, with a PCR of 69.87%. Nonetheless, alcohol blends have no effect on brake power at a 95% reliability level.

With the least amount of experimentation, the current study intended to investigate the impacts of CR, engine speed, and alcohol blends on brake thermal efficiency, BP, BSFC, CO, CO_2, HC, and NO. The tests were constructed using L9 Orthogonal Arrays (OA) to minimize the experimental work. One useful technique for determining the best combinations was the Taguchi method. Future research may be extended to explore the effects of additional variables. The Taguchi Statistical Design (TSD) method was adopted in the present study, resulting in a 67%reduction in both time and costs. The

tests used a 95% CI (Confidence Interval). The technique can demonstrate the relationships between performance as well as exhaust emissions parameters.

5.0 References

1. Dhande DY, Sinaga N, Dahe KB. Study on combustion, performance and exhaust emissions of bioethanol-gasoline blended spark ignition engine. Heliyon. 2021; 7(3):1-11. https://doi.org/10.1016/j.heliyon.2021.e06380 PMid:33748464 PMCid:PMC7969905.
2. Nimje P, Dandotiya D, Banker ND. An experimental investigation of MPFI gasoline engine fuelled with ethanol and n-butanol. IJEST. 2022; 19(3):1165-74. https://doi.org/10.1007/s13762-021-03242-0
3. Waluyo B, Setiyo M, Saifudin, Wardana ING. Fuel performance for stable homogeneous gasoline-methanol-ethanol blends. Fuel. 2021;294. https://doi.org/10.1016/j.fuel.2021.120565
4. Ebadian M, van Dyk S, McMillan JD, Saddler J. Biofuels policies that have encouraged their production and use: An international perspective. Energy Policy. 2020;147. https://doi.org/10.1016/j.enpol.2020.111906
5. Sakthivel P, Subramanian KA, Mathai R. Indian scenario of ethanol fuel and its utilization in automotive transportation sector. Resources, Conservation and Recycling. Elsevier B.V.; 2018. p. 102-20. https://doi.org/10.1016/j.resconrec.2018.01.012
6. Balki MK, Sayin C, Sarikaya M. Optimization of the operating parameters based on Taguchi method in an SI engine used pure gasoline, ethanol and methanol. Fuel. 2016; 180:630-7. https://doi.org/10.1016/j.fuel.2016.04.098
7. Usman M, Ijaz Malik MA, Chaudhary TN, Riaz F, Raza S, Abubakar M, *et al.* Comparative assessment of ethanol and methanol-ethanol blends with gasoline in SI engine for sustainable development. Sustainability (Switzerland). 2023; 15(9). https://doi.org/10.3390/su15097601
8. Di Iorio S, Catapano F, Magno A, Sementa P, Vaglieco BM. The Potential of ethanol/methanol blends as renewable fuels for DI SI engines. Energies (Basel). 2023; 16(6). https://doi.org/10.3390/en16062791
9. Yusuf AA, Inambao FL. Progress in alcohol-gasoline blends and their effects on the performance and emissions in SI engines under different operating conditions. Int J Ambient Energy. Taylor and Francis Ltd.; 2021; 42:465-81. https://doi.org/10.1080/01430750.2018.1531261
10. Örs İ, Sayin B, Ciniviz M. A comparative study of ethanol and methanol addition effects on engine performance, Combustion and Emissions in the SI EngineInt. j. automot. sci. technol. 2020; 4(2):59-69. https://doi.org/10.30939/ijastech..713682
11. Zhang C, Ge Y, Tan J, Li L, Peng Z, Wang X. Emissions from light-duty passenger cars fueled with ternary blend of gasoline, methanol, and ethanol. J Energy Resour Technol, Transactions of the ASME. 2017; 139(6). https://doi.org/10.1115/1.4036932
12. Li Y, Gong J, Deng Y, Yuan W, Fu J, Zhang B. Experimental comparative study on combustion, performance and emissions characteristics of methanol, ethanol and butanol in a spark ignition engine. Appl Therm Eng. 2017; 115:53-63. https://doi.org/10.1016/j.applthermaleng.2016.12.037
13. Elfasakhany A. Performance and emissions of spark-ignition engine using ethanol- methanol-gasoline, n-butanol-iso-butanol-gasoline and iso-butanol-ethanol-gasoline blends: A comparative study. JESTECH. 2016;19(4):2053-9. https://doi.org/10.1016/j.jestch.2016.09.009
14. Elfasakhany A. Investigations on the effects of ethanol-methanol-gasoline blends in a spark-ignition engine: Performance and emissions analysis. JESTECH, an International Journal. 2015; 18(4):713-9. https://doi.org/10.1016/j.jestch.2015.05.003
15. Iliev S. A comparison of ethanol and methanol blending with gasoline using a 1-D engine model. In: Procedia Engineering. Elsevier Ltd; 2015. p. 1013-22. https://doi.org/10.1016/j.proeng.2015.01.461
16. Balki MK, Sayin C, Canakci M. The effect of different alcohol fuels on the performance, emission and combustion characteristics of a gasoline engine. Fuel. 2014; 115:901-6. https://doi.org/10.1016/j.fuel.2012.09.020
17. Balki MK, Sayin C. The effect of compression ratio on the performance, emissions and combustion of an SI (spark ignition) engine fueled with pure ethanol, methanol and unleaded gasoline. Energy. 2014; 71:194-201. https://doi.org/10.1016/j.energy.2014.04.074
18. Varol Y, Öner C, Öztop HF, Altun Ş. Comparison of methanol, ethanol, or n -butanol blending with unleaded gasoline on exhaust emissions of an SI engine. Energy Sources, Part A: Recovery, Utilization and Environmental Effects. 2014; 36(9):938-48. https://doi.org/10.1080/15567036.2011.572141
19. Altun S, Oztop HF, Oner C, Varol Y. Exhaust emissions of methanol and ethanol-unleaded gasoline blends in a

spark ignition engine. Thermal Science. 2013; 17(1):291-7. https://doi.org/10.2298/TSCI111207034A
20. Canakci M, Ozsezen AN, Alptekin E, Eyidogan M. Impact of alcohol-gasoline fuel blends on the exhaust emission of an SI engine. Renew Energy. 2013; 52:111-7. https://doi.org/10.1016/j.renene.2012.09.062
21. Eyidogan M, Ozsezen AN, Canakci M, Turkcan A. Impact of alcohol-gasoline fuel blends on the performance and combustion characteristics of an SI engine. Fuel. 2010; 89(10):2713-20. https://doi.org/10.1016/j.fuel.2010.01.032
22. Deshpande RS, Tadamalle AP, Katikar RS, Kadam PG, Biradar AK, Thipse SS. Performance and Emission Evaluation of Gasoline- Methanol Fuel Blend at Different Conditions in SI Engine. JMMF. 2024; 687-97. https://doi.org/10.18311/jmmf/2024/45290
23. Shrivastava K, Thipse SS, Patil ID. Optimization of diesel engine performance and emission parameters of Karanja biodiesel-ethanol-diesel blends at optimized operating conditions. Fuel. 2021; 293. https://doi.org/10.1016/j.fuel.2021.120451
24. Sathish Kumar R, Sureshkumar K, Velraj R. Optimization of biodiesel production from *Manilkara zapota* (L.) seed oil using Taguchi method. Fuel. 2015; 140:90-6. https://doi.org/10.1016/j.fuel.2014.09.103
25. Ayhan V, Çangal Ç, Cesur İ, Çoban A, Ergen G, Çay Y, *et al*. Optimization of the factors affecting performance and emissions in a diesel engine using biodiesel and EGR with Taguchi method. Fuel. 2020; 261. https://doi.org/10.1016/j.fuel.2019.116371