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Investigation of Performance and Emission Characteristics on VCR Engine Utilizing Varied Injection Timing and Compression Ratio of Microalgae Biodiesel Blend

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Abstract

An analysis of the performance and emission parameters using varying injection timing and compression ratio with a Microalgae Biodiesel blend was done to optimize the input parameter using grey relational analysis and Taguchi analysis. For this the microalgae biodiesel blends were used as B10 (MB10+PD90), B20 (MB20+PD80) and B30 (MB30+PD70) and the compression ratios were used as 17:1, 19:1 and 21:1. Injection timing where used as 21° bTDC, 23° bTDC, 25° bTDC and load was varied as 3, 6 and 12 to optimize the blend. The purpose was to address numerous response optimization problems with a limited number of experimental runs using the Taguchi approach and L27 orthogonal analysis. To determine the best combination of four input parameters, the data from this experiment was further examined using the signal-to-noise ratio and grey relational analysis. The aim was to reduce emission parameters such as NOx, CO, HC and Smoke, as well as the Brake-Specific Fuel Consumption (BSFC) and Exhaust Gas Temperature (EGT) and to increase performance parameters, i.e. Brake Thermal Efficiency (BTE). From the above study, it was observed that B20 (MB20+PD80) has shown optimum results for performance and emission parameters at 21:1 compression ratio, 23° bTDC injection timing and 12kg load.

Keywords: *Diesel Engine, GRA, L27 Array, Microalgae Biodiesel, Taguchi Method*

1.0 Introduction

Crude oil is a fossil fuel that is widely used around the world to produce a variety of products, including gasoline, diesel, and other fuels, as well as chemicals and other products[1,2]. According to data from the International Energy Agency (IEA), the global consumption of crude oil has risen steadily over the past several decades, with the largest increases occurring in developing countries. In 2030, the global crude oil consumption was estimated to be around 105.8 million barrels per day[3]. The largest consumers of crude oil are typically the countries with the largest and most industrialized economies, such as China, the United States and India[4]. These countries are also some of the largest producers of crude oil, although they also import significant amounts from other countries. It is worth noting that while global crude oil consumption has increased over time, there has also been a trend towards

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the use of alternative energy sources and increased efforts to improve energy efficiency[5]. It has led to a slowdown in the growth of crude oil consumption in recent years. Biodiesel is a type of sustainable energy source that is generated from plant oils or animal fats and may be used in diesel engines as an alternative to traditional fossil fuels[6-8]. Biodiesel research has focused on several areas, including improving the efficiency and sustainability of biodiesel production. It includes studies on optimizing the feedback used to make biodiesel, such as vegetable oils and animal fats, as well as developing new methods for producing biodiesel from non-traditional feedstock, such as algae and waste oils[9-11]. Also, these are biodegradable and renewable and contain no hazardous chemicals. And other than NOx, it has a low emission profile[12,13]. There is also a debate on the production of biodiesel with edible sources as a country like India and China has a huge population, and to fulfil the need for food, edible crops cannot be utilized for biodiesel or ethanol production, potentially leading to higher food prices and food insecurity in some areas[14,15].

Bio-fuels can also be produced from non-food crops and agricultural waste, and the production of such crops will require land, which will reduce the land for food crop production[16]. Microalgae can be grown relatively quickly, and they do not compete with food crops for land or resources. In addition, the production of microalgae biodiesel has a lower carbon footprint than the production of fossil fuel, which can help cut down on greenhouse gas emissions and slow down climate change[17,18]. Microalgae biodiesel has good emission and combustion properties, such as low carbon monoxide and unburned hydrocarbon and smoke opacity emissions, which also improves the net heat release rate. It might be because biodiesel has a higher cetane number[19]. The impact of methyl ester on microalgae biodiesel in a diesel engine has been investigated, and an average 6% reduction was found in brake thermal efficiency. CO emissions were reduced by 9.4% when compared to diesel engines, while NOx emissions were reduced by 9.2%[20]. Two blends of microalgae biodiesel BD 20 and BD40 were taken for study in that BTE had lowered by 7.4to 16.7%, BSFC and NOx emission were found higher for both blends, HC emission had improved by 10 to 14% and CO emission was lowered by 9.3 to 13.9%[21]. Mixed culture algae biodiesel was prepared using transesterification and used on a CI engine. From that, CO emission was lowered by 66% to 70%, whereas CO_2 emission was lowered by 4% to 7%, NOx emission was higher by 43% to 58%, HC emission was lowered by 40-45%, and EGT was increased by 31% to 33%[22]. On the VCR engine, the effect of injection timing and compression ratio were investigated for Nahar Methyl Ester blend (NME40), and results revealed that NME 40/CR18 BTE was improved by 1.09%, lowered EGT by 2.98% at standard engine setting and reduced HC CO and smoke emission by 15.38, 21.5% and 0.5% for NME40/CR18 compared to NME40 at standard setting[23]. Optimization of engine response parameters was done using the grey-taguchi method. 3 input and eight output parameters were taken with an L25 orthogonal array. From that, it was observed that the B50 blend provided better results with CR 17 and 80% loading conditions[24]. The investigation was conducted to find optimized performance using Taguchi and Grey relational analysis. That, six inputs with five levels and seven output parameters were taken with L25 OA. From that injection, nozzle geometry was found to be the most significant parameter, i.e., 68.73%, to optimize performance and emission[25].

2.0 Material and Method

Petroleum Diesel was bought from a nearby fuel supplier. Indian biodiesel corporation Baramati, Pune, has supplied microalgae oil samples. Since algae oil contains glycerides, it must be transformed into algae biodiesel via the transesterification process before being utilized in diesel engines.

2.1 Transesterification

According to the literature review, Microalgae oil contains more than 2% Free Fatty Acid (FFA), which means that the first phase of transesterification must involve acid catalysis, and the second step must involve triglyceride transesterification in an alkaline solution[26]. H_2SO_4 1.5% wt was used as an acid catalyst during step 1 of esterification. Biodiesel was heated at 55° C for 90 minutes with methanol added in a 7:1 molar ratio along with H_2SO_4 before being allowed to cool for 180 minutes to settle. The solution was then separated with a separating funnel, and methanol was added once more along with KOH 3 wt. % in a 6:1 molar ratio before being heated at 60° C for 90 minutes. The mixture was then allowed

Table 1. Physical and Chemical properties of Microalgare Biodiesel Blend and PD

Sr No.	Test Description	ASTM 6751	Diesel	Algae Biodiesel		
			D100	B10	B20	B30
1	Density	0.800-0.900 gm/cc	0.831	0.833	0.834	0.836
2	Calorific Value	34-45 MJ/Kg	42.70	42.55	42.40	42.15
3	Cetane No.	41-55	49.00	49.11	49.36	49.46
4	Viscosity	3-6 mm2/sec	2.70	2.79	2.80	2.89
5	Moisture	0.05%	NA	NA	NA	NA
6	Flash Point	-	64˚c	66 ˚c	69 ˚c	71 ˚c
7	Fire Point	-	72 ˚c	74 ˚c	78 ˚c	80 ˚c

to settle for 150 minutes before being transferred to a separating funnel to separate glycerol from biodiesel. To eliminate contaminates, the biodiesel was washed twice with hot distilled water. Biodiesel has been heated in an oven at 100° C for 60 minutes to eliminate the moisture present[27,28].

2.2 Preparation of Algae Biodiesel Blend

Based on the literature review and India's current biofuel policy, PD was mixed with Algae biodiesel at different ratios, and different biodiesel blends were prepared. Blend 1 contains 90% PD and 10% ABD, i.e., B10 (PD90%+ABD10%); Blend 2 contains 80% PD and 20% ABD, i.e., B20 (PD80%+20%ABD); and Blend 3 contain 70% PD and 30% ABD, i.e., B30 (PD70%+30%ABD). Various chemical and physical properties of PD and different Blends were measured in the laboratory. Table 1 represents several of the chemical and physical characteristics of all blends and PD.

2.3 Experimentation

Experimentation was conducted at the Research Assistance Lab of Apex Innovation Sangali. The Experiments were done on Research Engine Test Setup Computerized (240PE).

Product code	240PE
Engine	Single cylinder 4 stroke water cooled CI Engine
Maximum Power	3.5 KW at 1500 rpm
Stroke x Bore	110 mm x 87.5 mm
Displacement	661 cc
CR	17.5:1
CR range	14-22
Injector opening pressure	210 bar
Start of IT	23°CA bTDC

2.4 Experimental Setup

The experiment was carried out using a single-cylinder, four-stroke, water-cooled diesel engine with variable compression ratio. A schematic representation of the engine is illustrated in Figure 1, and engine details are supplied in the above table. The engine output shaft is connected to the eddy current dynamometer to deliver the load. Engine soft was used to evaluate the engine performance of the Lab view-based performance evaluation software. AVL DiGas 444 analyzer was used to measure exhaust gases, i.e. CO, HC, CO_2, NOx and O_2. Also, an AVL 437 smoke meter was used to measure smoke at the exhaust of the engine.

3.0 Methodology

To determine the best blend of Microalgae Biodiesel and diesel depending on the VCR engine's performance and emission characteristics, four major input parameters, i.e., Blend (C1), Injection timing (C2), Compression ratio (C3) and Load (C4) were selected to be the main design parameter with 3 levels each for Taguchi L27 orthogonal array. Based on the previous finding, as revealed in the literature, the different levels of parameters and their

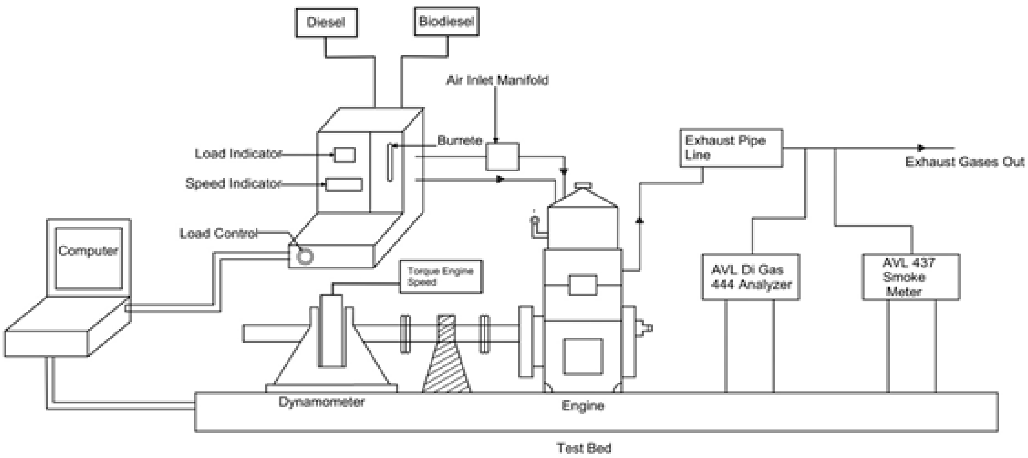

Figure 1. Schematic representation of experimental setup.

Table 2. Factors and their levels for blend with Microalgae Biodiesel

Experimental Factor				
Levels	**A=(Blend)**	**B=(IT)**	**C=(CR)**	**D=(Load)**
1	10	21	17	25
2	20	23	19	50
3	30	25	21	100

ranges were selected. Input parameter and their level are given in Table 2

These selected parameters and levels are supplied in Taguchi's Orthogonal Array (OA) so that optimization should take place in the fewest possible trials and tests[29-31]. Compared to an unplanned experiment, a well-designed experiment might generate significantly more data in fewer runs. Rather than altering one element at a time, all parameters are modified concurrently, and the response values are monitored in accordance with the design array. The Taguchi technique was used to investigate how different input factors affect response[32,33]. The conventional Taguchi method was used to find a single optimal parameter, but since multiple output parameters optimization was present in this case, Grey relation analysis was done to find a single response from different performance and emission parameters, these will be organized in a limited number of trials according to the factor and their levels (OA L27). These combinations and their research findings of responses are given in Table 3

3.1 Analysis of S/N Ratio

In the above parameter for BTE, larger is better as we aimed to maximize BTE, and for the rest of all other cases, i.e. BSFC, CO, NOx, HC, smoke, and EGT smaller is better. We aim to minimize specific fuel consumption and exhaust emissions. The equation for larger is better is shown by eq. 1

$$S/N = -10 \log \left[\frac{1}{r}\sum_{i=1}^{r}\frac{1}{yi^2}\right] \quad (1)$$

and for smaller is better is shown by eq. 2

$$S/N = -10 \log \left[\frac{1}{r}\sum_{i=1}^{r} yi^2\right] \quad (2)$$

In the above, for both equations, negative values indicate that the largest value determines the optimum

Table 3. Experimental results of orthogonal array

	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11
Sr. No	**Blend**	**IT**	**CR**	**Load**	**BTE**	**BSFC**	**CO**	**NOX**	**HC**	**Smoke**	**EGT**
1	10	21	17	25	15.58	0.62	0.04	376	11	0.55	153.64
2	10	21	19	50	22.32	0.45	0.06	572	17	0.8	173.75
3	10	21	21	100	30.76	0.35	0.21	836	29	1.6	244.92
4	10	23	17	50	22.91	0.46	0.05	539	16	0.8	183.71
5	10	23	19	100	31.2	0.33	0.19	812	25	1.5	247.91
6	10	23	21	25	17.13	0.58	0.04	394	10	0.3	155.9
7	10	25	17	100	30.98	0.34	0.23	836	27	1.4	274.74
8	10	25	19	25	15.89	0.6	0.06	407	12	0.35	160.95
9	10	25	21	50	22.45	0.44	0.08	600	15	0.56	175.03
10	20	25	17	25	15.96	0.64	0.04	457	11	0.45	162.22
11	20	25	19	50	22.56	0.43	0.05	661	14	0.65	198.22
12	20	25	21	100	30.36	0.35	0.2	947	24	1.1	251.09
13	20	21	17	50	22.72	0.47	0.07	595	13	0.9	194.82
14	20	21	19	100	30	0.36	0.17	897	24	1.5	271.36
15	20	21	21	25	16.2	0.65	0.03	440	9	0.35	129.4
16	20	23	17	100	29.74	0.38	0.16	853	23	1.5	255.38
17	20	23	19	25	16.93	0.59	0.03	399	8	0.37	151.24
18	20	23	21	50	22.86	0.44	0.05	598	13	0.7	171.77
19	30	23	17	25	16.59	0.66	0.04	390	8	0.4	159.39
20	30	23	19	50	23.64	0.47	0.05	607	14	0.7	181.45
21	30	23	21	100	29.47	0.34	0.14	926	23	1.2	248
22	30	25	17	50	22.36	0.48	0.07	618	15	0.6	180.11
23	30	25	19	100	29.4	0.37	0.18	927	21	1.2	257.11
24	30	25	21	25	16.96	0.67	0.04	487	8	0.2	163.93
25	30	21	17	100	28.02	0.37	0.16	886	22	1.5	262.42
26	30	21	19	25	14	0.69	0.04	434	12	0.4	159.3
27	30	21	21	50	22.62	0.47	0.04	635	15	0.6	187.45

value of the response element. Where r is the number of experiments performed in an OA at a certain level of control factor, and yi is the mean of the measured values of the response variable of the ith experiment[34].

4.0 Result and Discussion

4.1 Optimization of Parameter

In this experimentation, performance parameters, i.e., BTE, BSFC were measured on the VCR engine using Enginesoft software and emission parameters, i.e., CO, HC, NOx were measured on the Exhaust gas analyzer to optimize parameter two methods were used in the first single parameter optimization was done by using Taguchi method and to for multivariable analysis Grey relation analysis was done.

From the Figure 2, the optimum level of each different factor can be obtained in terms of BTE. The optimum level for BTE at a constant speed of 1500 rpm is A1-B2-C3-D3 s (Larger is better) Blend = 10%, IT = 23° bTDC, CR= 21, Load = 100%. As a result of experimental studies, it has been found that when different blends of biodiesel are used, Brake thermal efficiency has a small drop with an increase in biodiesel percentage. From the literature, it was also observed that with an increase in blend percentage, a drop in BTE occurred. This might be due to the lower heating value of biodiesel compared to PD[35]. The regression equation of BTE was represented by equation 3, and from this model, it has been found that the R-square value is 96.08%; that model has a linear nature in the curve and it is represented by Figure 3.

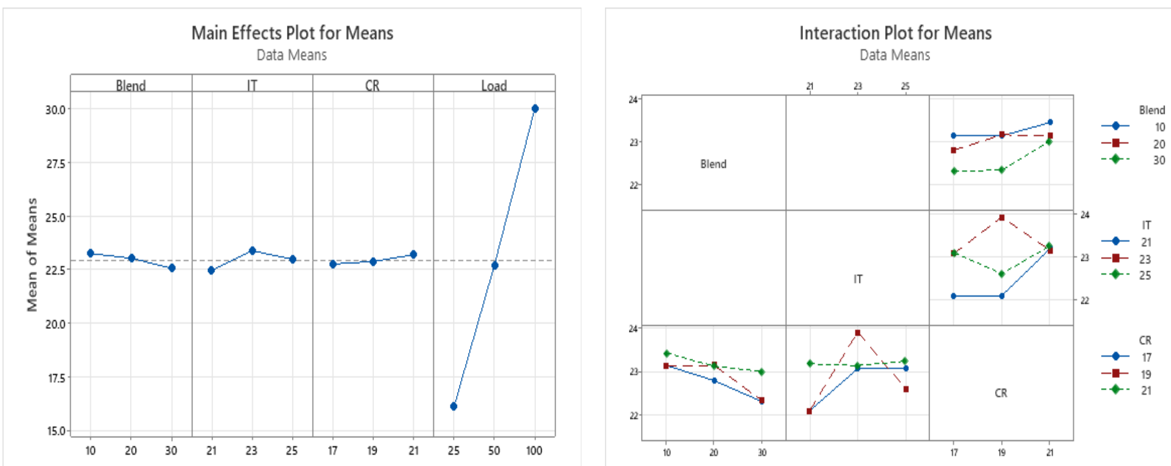

Figure 2. Taguchi Analysis: BTE versus Blend, Injection Timing, Compression Ratio, Load.

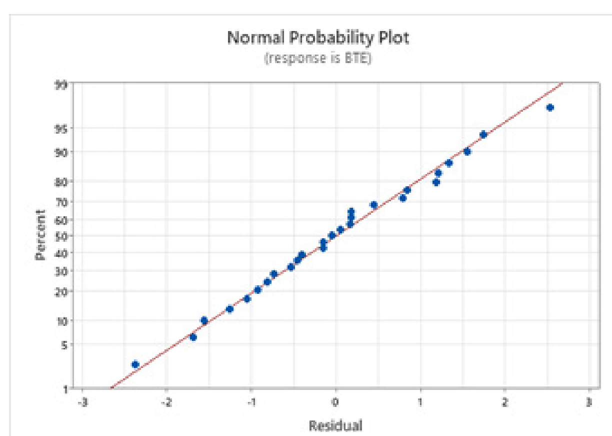

Figure 3. Curve fitting for Brake Thermal Efficiency.

4.2 Taguchi Method for Single Parameter Optimization

4.2.1 Brake Thermal Efficiency

The Table 3 reading of column C5 indicates BTE, and it was considered to find the optimum level of input parameter, i.e. Blend, IT, CR and Load, using Taguchi analysis. Figure 2 shows a graph of mean values of BTE versus blend, injection timing, compression ratio and load. From that, we can find the optimum level of each parameter.

Regression Equation

$$BTE = 8.10 + 0.131\ IT + 0.110CR + 0.17913\ Loads - 0.0342\ Blend \quad (3)$$

Model Summary

S	R-sq	R-sq(adj)	R-sq(pred)
1.25268	96.08%	95.37%	94.22%

4.2.2 Brake Specific Fuel Consumption

The Break-Specific Fuel Consumption (BSFC) values are taken from Table 3 for the C6 column, and then the graph is plotted with the mean values of BSFC vs. Blend, IT, CR and Load. From that, we can find the optimum level of each parameter.

Regression Equation

$$BSFC = 0.784 - 0.00306\ IT - 0.00361\ CR - 0.003479\ Load + 0.00194\ Blend \quad (4)$$

Model Summary

S	R-sq	R-sq(adj)	R-sq(pred)
0.0468761	87.09%	84.75%	81.04%

4.2.3 Exhaust Gas Temperature

For Exhaust Gas Temperature (EGT), the graph is plotted with mean values of EGT vs Blends, IT, CR and Load. From that, we can find the optimum level for the above parameter from the graph.

From the graph in Figure 6, the optimum level of each different factor can be obtained in terms of EGT.

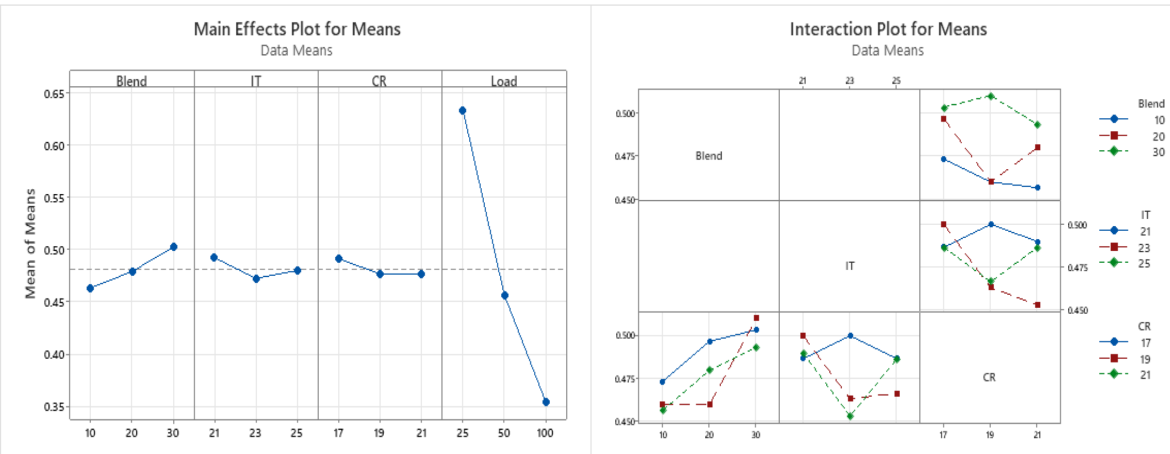

Figure 4. Taguchi Analysis: BSFC versus Blend, Injection Timing, Compression Ratio, and Load.

From the graph in Figure 4, the optimum level of each different factor can be obtained in terms of BSFC. The optimum level for BSFC at a constant speed of 1500 rpm is A2-B2-C3-D3 s (Smaller is better) Blend = 10%, IT 23° bTDC, CR 21, Load =100 %. As a result of experimental studies, it has been found that when different blends of biodiesel are used, BSFC has increased with an increase in biodiesel percentage. According to the study findings, BSFC increased as the blend percentage increased; this might be because biodiesel has a lower calorific value than diesel[36]. The regression equation of the BSFC is shown in equation 4, and we can determine from the model that if the R square value is less than 90%, the model demonstrates the nonlinear character of the curve, as seen in Figure 5.

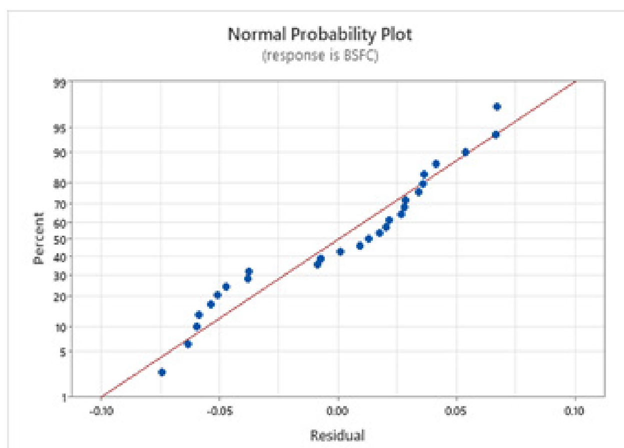

Figure 5. Curve fitting for Brake Specific Fuel Consumption.

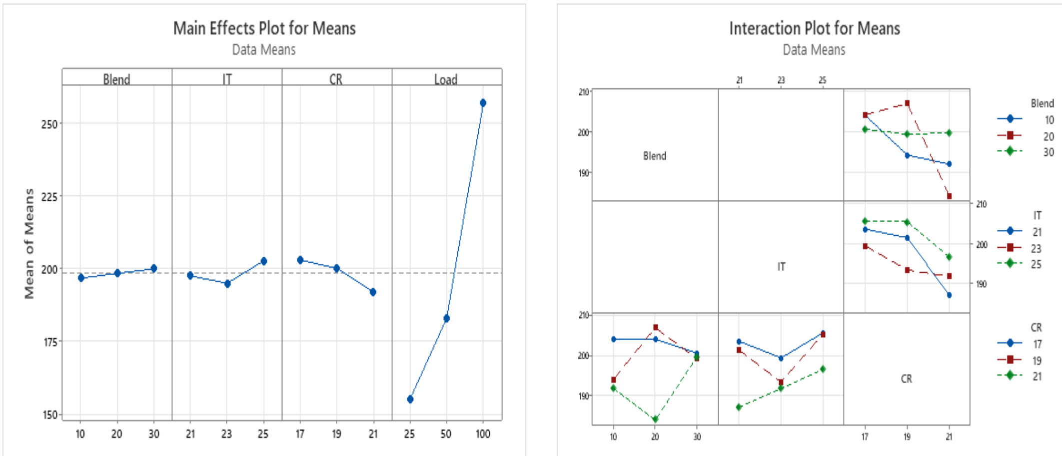

Figure 6. Taguchi Analysis: EGT versus Blend, Injection Timing, Compression Ratio, Load.

The optimum levels for EGT at a constant speed of 1500 rpm are A1-B2-C3-D1 (Smaller is better), Blend = 10%, IT = 23°bTDC, CR= 21, Load = 25%. As a result of experimental studies, it has been found that when different blends of biodiesel are used, EGT has increased with an increase in biodiesel percentage. From the literature, it has been observed that as the biodiesel percentage increases, oxygen content in biodiesel also increases, and it generates more heat in the combustion chamber; due to this, the exhaust gas temperature was higher[37]. The regression equation for EGT has been provided in eq. 5, and the R square value from the model was 96.25%, indicating that the model has a linear nature, as shown in Figure 7.

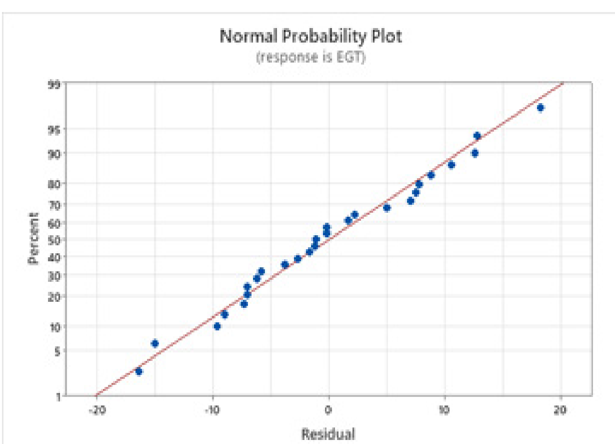

Figure 7. Curve fitting for Exhaust Gas Temperature.

$$EGT = 137.5 + 1.29\,IT - 2.75\,CR + 1.3760\,Load + 0.159\,Blend \quad (5)$$

Model Summary

S	R-sq	R-sq(adj)	R-sq(pred)
9.44360	96.25%	95.57%	94.31%

4.2.4 Carbon Monoxide Emission

The Carbon Monoxide (CO) emission graph is plotted with mean values CO vs Blend, IT, CR and Load; from that, we can find the optimum level of each parameter

From the graph in Figure 8, the optimum level of each different factor can be obtained in terms of CO emission. The optimum levels for CO at a constant speed of 1500 rpm are A3-B2-C3-D1 (Smaller is better), Blend = 30%, IT = 23°bTDC, CR= 21, Load = 25%. As a result of experimental studies, it has been found that when different blends of biodiesel were used, CO was reduced with an increase in biodiesel percentage. From the literature, it was found that with an increase in blend percentage, a decrease in CO emission occurred. It may be due to higher load oxygen content in microalgae biodiesel rising cylinder temperature, which reduces viscosity and advances oxidation. This element provides better combustion, which reduces emissions[38]. The regression equation of CO emission was given by eq.6, and from the model, the R square value has been above 91%,

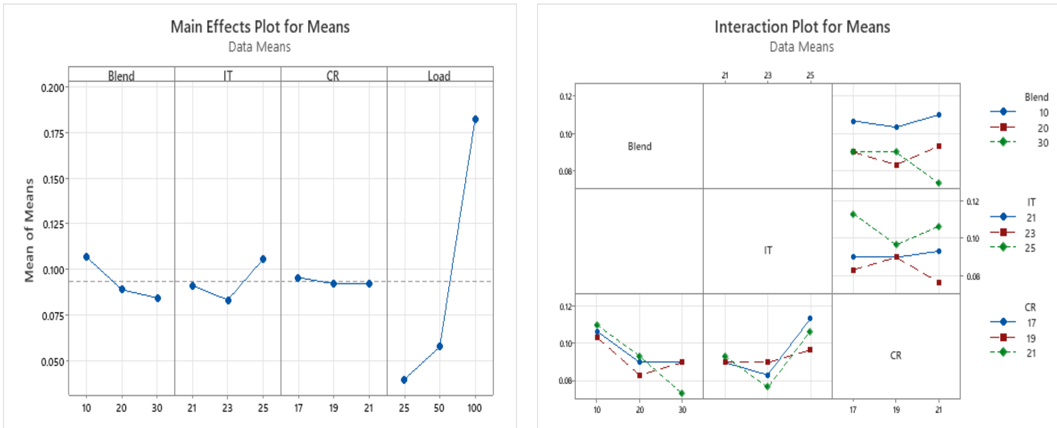

Figure 8. Taguchi Analysis: CO versus Blend, Injection Timing, Compression Ratio, Load.

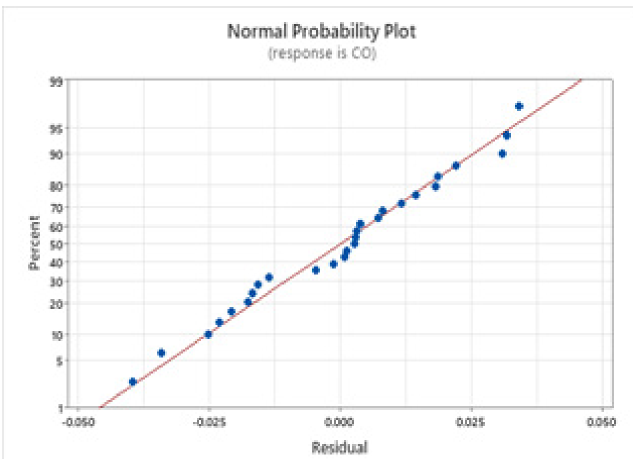

Figure 9. Curve fitting for Carbon Monoxide.

indicating that the model has a linear nature, as shown in Figure 9.

Regression Equation

CO = -0.0672 + 0.00361 IT - 0.00083 CR + 0.001981 Load - 0.001111 Blend (6)

Model Summary

S	R-sq	R-sq(adj)	R-sq(pred)
0.0215104	91.25%	89.66%	86.63%

4.2.5 Nitrogen Oxide Emission

The Nitrogen Oxide (NOx) emission graph is plotted with mean values NOxvs Blend, IT, CR and Load; from that,

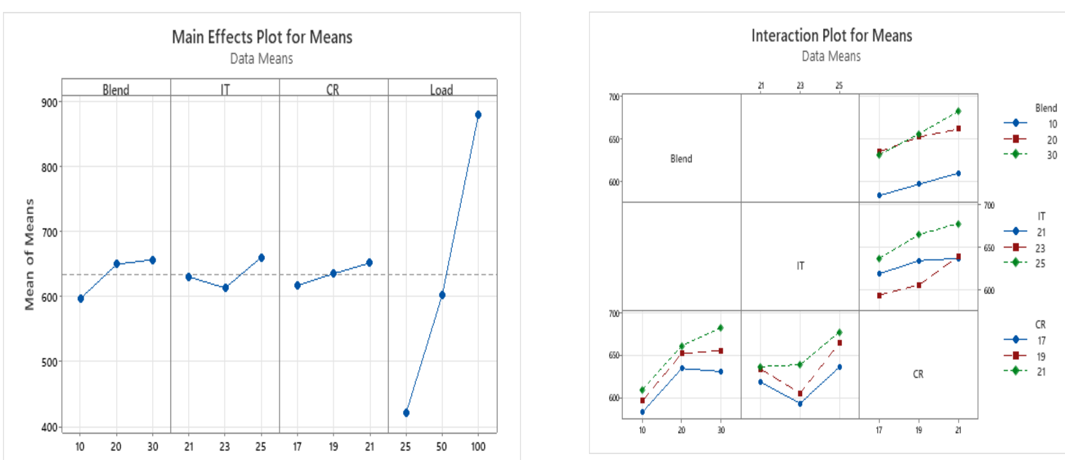

Figure 10. Taguchi Analysis: NOX versus Blend, Injection Timing, Compression Ratio, Load.

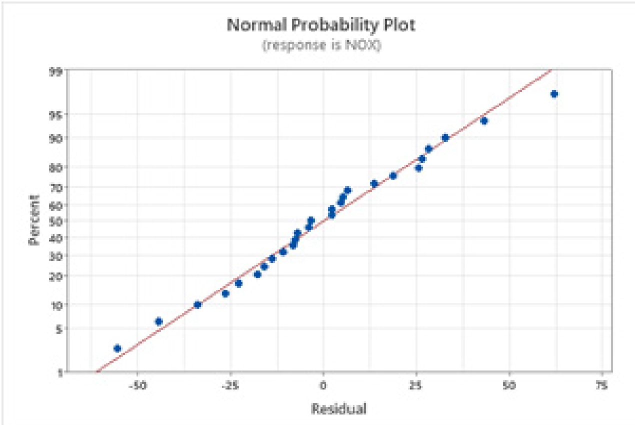

Figure 11. Curve fitting for Nitrogen Oxide.

we can find the optimum level of each parameter.

From the graph in Figure 10, the optimum level of each different factor can be obtained in terms of NOx emission. The optimum levels for NOx at a constant speed of 1500 rpm are A1-B2-C1-D1 (Smaller is better) Blend = 10%, IT = 23°bTDC, CR= 17, Load = 25%. As a result of experimental studies, it has been found that when different blends of biodiesel were used, NOx increased with an increase in biodiesel percentage. NOx emission has been generally produced due to the reaction of nitrogen and oxygen in the air at higher temperatures during combustion. As microalgae biodiesel contains more oxygen, it causes rapid heat release during combustion at the premixed burn phase, which produces more emissions[39]. The above eq. 7 represents the regression equation of NOx emission, and from the model, it has been identified that NOx emission has a linear nature, as shown in Figure 11.

Regression Equation

$$NO_x = -115 + 7.47\ IT + 8.69\ CR + 6.044\ Load + 2.989\ Blend \quad (7)$$

Model Summary

S	R-sq	R-sq(adj)	R-sq(pred)
28.6788	98.20%	97.87%	97.43%

4.2.6 Unburned Hydrocarbon Emission

For Unburned hydrocarbon emission graph is plotted with mean values HC vs Blend, IT, CR and Load from that we can find optimum level of each parameter.

From the graph in Figure 12 optimum level of each different factor can be obtained in terms of HC emission The optimum level for HC at a constant speed of 1500 rpm are A3-B2-C3-D1 (Smaller is better) Blend = 30%, IT = 23°bTDC, CR = 21, Load = 25%. As a result of experimental studies, it has been found that when different blends of biodiesel are used HC emissions have decreased as the amount of biodiesel has increased; this may be because biodiesel has a higher cetane number than diesel and this leads to improve ignition quality and complete oxidation of fuel. Another factor is that algal biodiesel has a higher

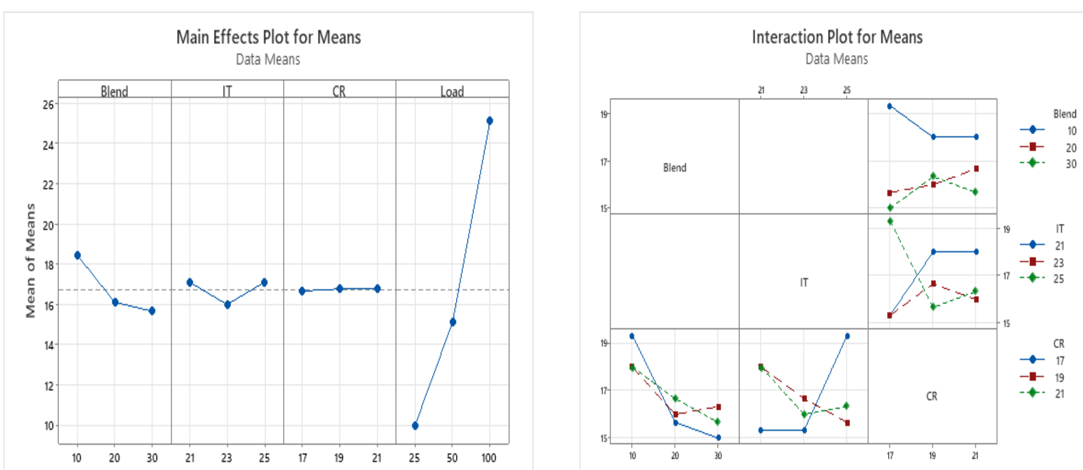

Figure 12. Taguchi Analysis: HC versus Blend, Injection Timing, Compression Ratio, Load.

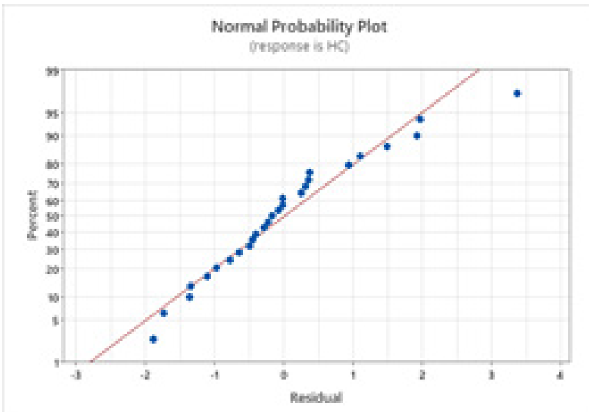

Figure 13. Curve fitting for Unburned Hydrocarbon.

4.2.7 Smoke Opacity Emission

The smoke emission graph is plotted with mean values Smoke vs Blend, IT, CR and Load; from that, we can find the optimum level of each parameter.

From the graph in Figure 14, the optimum level of each different factor can be obtained in terms of Smoke emission. The optimum levels for smoke at a constant speed of 1500 rpm are A3-B3-C3-D1 (Smaller is better), Blend = 30%, IT = 25° bTDC, CR = 21, Load = 25%. As a result of experimental studies, it has been found that when different blends of biodiesel were used, smoke was reduced with an increase in biodiesel percentage. The reason for this may be that microalgae biodiesel viscosity, which results in a longer ignition delay with complete fuel combustion[40]. The regression equation for HC emission was given by eq. 8, and the R square value more than 96.34% indicates that the model has linear, as shown in Figure 13.

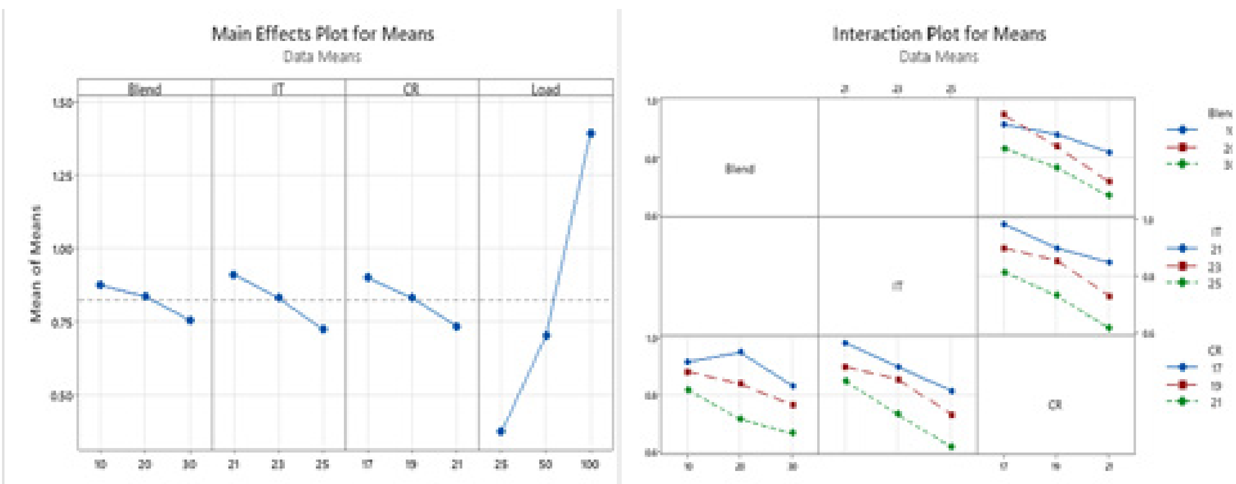

Figure 14. Taguchi Analysis: Smoke versus Blend, Injection Timing, Compression Ratio, Load.

Regression Equation

HC = 17.47 - 0.1889 Blend - 0.278 IT - 0.139 CR + 0.18794 Load (8)

Model Summary

S	R-sq	R-sq(adj)	R-sq(pred)
1.31385	96.34%	95.67%	94.19%

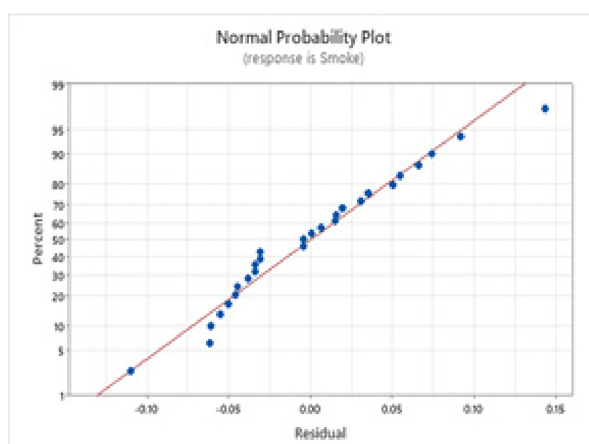

Figure 15. Curve Fitting for Smoke.

has a lower calorific value than diesel, which lowers the temperature and pressure of combustion and minimizes the amount of smoke that has been released. Another factor is that because algal fuel is partly oxygenated, oxidation processes are encouraged[41]. The above eq. 9 indicates the regression equation for the smoke emission. Also, we obtained an R square value of 98.43 from the model, indicating that the model was linear, as shown in Figure 15.

Regression Equation

Smoke =2.014 - 0.04694 IT - 0.04139 CR + 0.013559 Load - 0.00589 Blend (9)

Model Summary

S	R-sq	R-sq(adj)	R-sq(pred)
0.0611739	98.43%	98.15%	97.48%

4.3 Calculation of Grey Relational Grade

The multi-interdependent responses problem was solved using the GM optimization[33]. The initial step in this phase of optimization, known as grey relation generation, was to normalize the obtained S/N ratio between 0 and 1 linearly.

Using equations 10 and 11, the grey relation generation sij for trial i and response j has been computed. For determining the grey relational generation, equation 10 was used for larger the better responses, and equation 11 for smaller the better responses.

$$s_{ij} = \frac{\eta_{ij} - \min_j \eta_{ij}}{\max_j \eta_{ij} - \min_j \eta_{ij}} \quad (10)$$

$$s_{ij} = \frac{\max_j \eta_{ij} - \eta_{ij}}{\max_j \eta_{ij} - \min_j \eta_{ij}} \quad (11)$$

The grey relational generations for normalized S/N ratio:- All performance values are scaled upward between 0 and 1 when the grey relational generation has been determined. The optimum performance value for response j for experiment number i is if the performance value sij for response j is 1 or close to 1. These sorts of situations, however, are improbable; hence a reference sequence is given for comparability: X0 (best/ideal value) = (X01, X02,....) = (1, 1,.....).

4.4 Calculation of Grey Relational Coefficient

The grey relational generation calculated how near sij was to X0 by comparing it to the reference sequence. The grey relational coefficient, which was derived as shown in Equation 12, represents this closeness.

$$\omega_{ij} = \frac{\Delta_{\min} + \zeta.\Delta_{\max}}{\Delta_{ij} + \zeta.\Delta_{\max}} \quad (12)$$

$$\Delta_{\min} = Min\left(\Delta_{ij}, i = 1,2,....m; j = 1,2,...n\right)$$

$$\Delta_{\max} = Max\left(\Delta_{ij}, i = 1,2,....m; j = 1,2,...n\right)$$

The appropriate weighting factor for each response must be used when calculating the grey relationship grade. Because it has an impact on how trials are graded, the weighting factor is extremely important. As a result, the weighting factor in this study has been computed carefully and logically to prevent any errors in the performance calculation. The decision maker's opinion serves as the basis for the weights (wj). However, wj must equal 1.

The values of GRG from Figure 16, test number 25 is rated first and has the highest value when compared to the other tests. Similar to this, experiment numbers have been ranked in accordance with declining value of

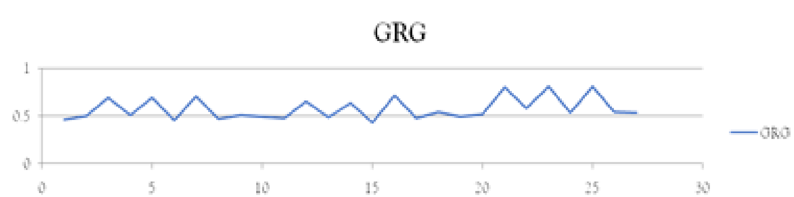

Figure 16. GRG vs Number of Experiment

GRG as shown in Figure 17. The fuel blend of B30 with CR17, IT21, and load 12 kg (100%) in operation number 25 provides the optimum performance characteristics for all Blends.

4.4.1 Grey Regression Grade

For grey regression grade graph is plotted with mean values GRG vs Blend, IT, CR and Load from that we can find the optimum level of each parameter.

From the above graph optimum level of each different factor can be obtained in terms of GRG The optimum level for GRG at a constant speed of 1500 rpm are A1-B3-C1-D3 (Smaller is better) Blend = 10%, IT = 25bTDC, CR = 17, Load = 100%. As a result of experimental studies, it has been found that when different blends of biodiesel are used GRG grade was higher for lower biodiesel percentage. As load increases the GRG grade was also increased.

4.5 Analysis of Variance for Means

Table 4 demonstrate the ANOVA, it has been identified that the relation between all parameters and output has been linear. From this analysis, engine load was found to be the most influencing parameter as it has the highest percentage contribution. Whereas CR has the list contribution and also has a minimum value in all parameter.

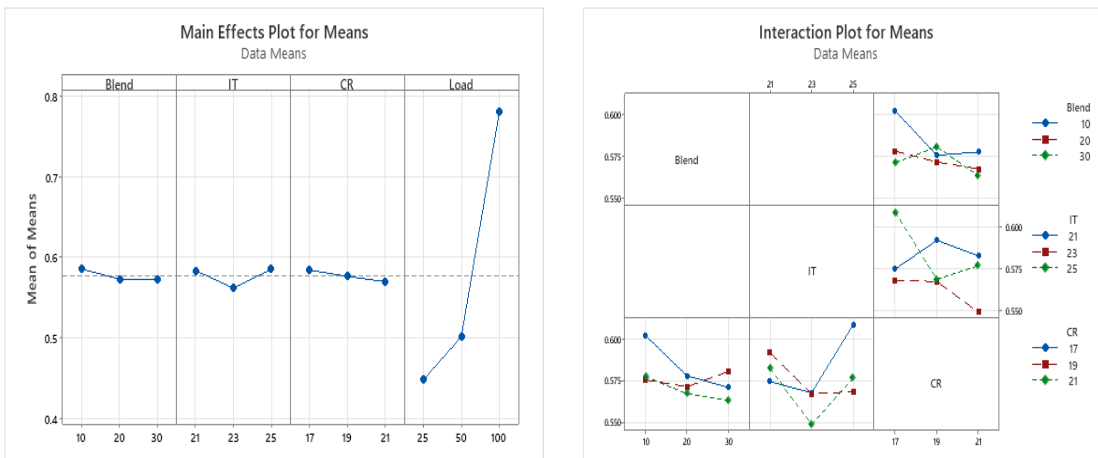

Figure 17. Taguchi Analysis: GRG versus Blend, IT, CR and Load.

Table 4. Analysis of variance for means

Source	DF	Adj SS	Adj MS	F-Value	P-Value	% Contribution
Blend	2	0.007414	0.003707	6.31	0.008	1.591961
IT	2	0.003468	0.001734	2.95	0.078	0.744661
CR	2	0.001181	0.000591	1.01	0.386	0.253589
Load	2	0.443075	0.221538	377.04	0	95.13866
Error	18	0.010576	0.000588			2.270917
Total	26	0.465715				100

5.0 Conclusion

In this investigation, the effect of Microalgae Biodiesel Blend on CI engines with different Compression Ratio (17, 19, 21), Injection timing (21° bTDC, 23° bTDC, 25° bTDC), Load (3, 6, 12) for engine performance and emission characteristics were reported. The optimization of the microalgae Biodiesel blend was done using the Taguchi and Grey relation analysis with an L27 orthogonal array. Based on the result achieved, the following conclusions are derived from Taguchi's analysis.

- Optimum level of BTE is A1-B2-C3-D3, i.e. Blend= 10%, IT= 23° bTDC, CR= 21, Load=100%
- Optimum level of BSFC is A1-B2-C3-D3 s (Smaller is better) i.e. Blend= 10%, IT= 23° bTDC, CR= 21, Load=100%.
- Optimum level of CO emission is A3-B2-C3-D1 (Smaller is better) Blend= 30%, IT= 23° bTDC, CR= 21, Load=25%.
- Optimum level of NOx emission is A1-B2-C1-D1 (Smaller is better) Blend= 10%, IT= 23° bTDC, CR= 17, Load=25%.
- Optimum level of HC emission is A3-B2-C3-D1 (Smaller is better) Blend= 30%, IT= 23° bTDC, CR= 21, Load=25%.
- Optimum level of Smoke opacity emission is A3-B3-C3-D1 (Smaller is better) Blend= 30%, IT= 25° bTDC, CR= 21, Load=25%.

From the above discussion, if we consider the performance, the B10 Blend is better. Still, if we consider emission, then the B30 blend is better as it improves one kind of result with high penalties with other results; considering both performance and emission, we can select the optimum blend as B20 for most of the cases CR 21 has shown better result so we can consider that CR 21 is optimum in CR. Also, IT 23 has shown better results, so we can select IT23 as optimum. From this, the B20 blend of Microalgae biodiesel can be widely used in Single-cylinder VCR engines without any modification. We can adjust the IT and CR of the engine to a particular setting, CR 21 and IT 23, which will improve the performance and minimize the emissions.

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Abbreviation

ABD	Algae biodiesel	BTE	Break Thermal Efficiency
VCR	Variable Compression ratio	BSFC	Break specific fuel consumption
IT	Injection timing	CO	Carbon Monoxide
CR	Compression ratio	HC	Hydrocarbon
ABD10	Microalgae biodiesel 10% vol. and Diesel 90% vol.	ABD30	Microalgae biodiesel 30% vol. and Diesel 70% vol.
ABD20	Microalgae biodiesel 20% vol. and Diesel 80% vol.	OA	Orthogonal array
GRA	Grey relational analysis	NOx	Nitrogen oxide
EGT	Exhaust gas recirculation	GRG	Grey relational grade
bTDC	Before top dead center	BD	Biodiesel
ANOVA	Analysis of variance	FFA	Free fatty acid
PD	Petroleum Diesel	CI	Compression Ignition
S/N ratio	Signal to Noise ratio		