Experimentation and Performance Parametric Optimization of Soybean-Based Biodiesel Fired Variable Compression Ratio CI Engine Using Taguchi Method

Prasheet Mishra[*], [***], Taraprasad Mahapatra[**], Biranchi N. Padhi[***], Sudhansu S. Sahoo[****]‡, Sudhansu S. Mishra[*****]

[*]School of Maritime Studies, Centurion University, Bhubaneswar, India
[**]Department of Mechanical Engineering, C V Raman Global University, Bhubaneswar, India
[***]Department of Mechanical Engineering, IIIT Bhubaneswar, India
[****]Department of Mechanical Engineering, Odisha University of Technology and Research (Formerly CET), Bhubaneswar, India
[*****]Department of Mechanical Engineering, Government College of Engineering, Keonjhar, India
(prasheetmishra@gmail.com, tpmohapatra@cgu-odisha.ac.in, biranchi@iiit-bh.ac.in, sudhansu@cet.edu.in, sudhansumishra_fme@gcekjr.ac.in)

‡Corresponding Author, Sudhansu S. Sahoo, PhD, Odisha University of Technology and Research (Formerly CET), Bhubaneswar, India, Tel : +91 9337645056, sudhansu@cet.edu.in

Received: 01.10.2022 Accepted: 15.12.2022

Abstract- In this study, the performance of a variable CR-type CI engine is investigated experimentally and optimized using Taguchi methods. Fuels consist of Common Diesel Fuel (CDF), 10%, and 20% mixes of soybean biodiesel. A novel single-step transesterification method is employed in this work to create biodiesel. Investigations are conducted on the engine's entire performance, including the braking power (BP), specific fuel consumption (SFC), CO, and NOx emissions. The results show that the kinds of fuel have the most impact on braking power, contributing 62.25% and that the load, types of fuel, and load have the largest impacts on SFC, CO, and NOx emission, contributing 89.7%, 49.62%, and 57.54%, respectively. With CDF, SOYA B10, and SOYA B20, respectively, SFC and CO emission percentage decreases of 60%, 50%, and 45% and 66.66%, 4%, and 6.7% have been observed. 3.66 kW of braking power, 0.34 kg/kWh of SFC, 0.028% of CO emission, and 182 ppm of NOx emission are the optimal performances that are attained when providing BP more weight. 2.62 kW of brake power, 0.91 kg/kWh of SFC, 0.04% of CO emission, and 28 ppm of NOx emission are the optimal performance results obtained when NOx is given greater weight.

Keywords: Variable compression ratio CI engine; Transesterification; Biodiesel; Performance analysis; Optimization; Taguchi method

1. Introduction

Diesel engines or compression ignition engines are widely used in various sectors like transport, agriculture, construction, etc. due to their higher fuel efficiency. However, the emission of gases from the exhaust of diesel engines is one of the major concerns. Hence, researchers are keenly interested in an alternative to diesel fuel that can be used in diesel engines for the same power output with reduced emissions. Biodiesel is one of the promising answers for the above-said alternation.

A sustainable and biodegradable fuel, biodiesel may be made in a variety of methods. They are thermal cracking (pyrolysis), microemulsions, direct usage and mixing, and the transesterification process. The most popular way to make biodiesel is by using animal fats and vegetable oils. The process of making biodiesel may be done in a variety of ways. They are divided into the first, second, third, and fourth generations. The first generation of biodiesel is created using edible oil, the second generation uses non-edible oil, the third generation uses waste oil and algae, and the fourth generation uses synthetic biology (advanced solar cells)[1]. The availability of feedstock, the molar ratio of oil to alcohol, catalyst type and concentration, reaction temperature, reaction time, mixing intensity, water content during purification, and agitation speed are the main limitations in the manufacture of biodiesel [2]. The most common type of homogenous catalysts used is sodium hydroxide, sodium methoxide and potassium hydroxide. The optimal temperature range for the reaction lies in the range of 50^0C – 60^0C[3]. The more the agitation speed more the reaction intensifies but it leads to saponification i.e excess formation of soap which is checked during the purification of biodiesel. The purification is required to remove the excess soap formation, the glycerol produced and the remaining catalyst. The purification is done by methods like wet washing, dry washing, membrane extraction, precipitation, complexation and simultaneous biodiesel synthesis. But mostly the wet washing purification method is practiced due to its simple procedures. Still, the excess usage of water and sometimes distillations or evaporation is required to remove excess alcohol increases the cost of production[4].

The mechanical parameters are almost coming the same as common diesel fuel as compared to biodiesel. But still, it is not extensively used because of the reason that is the higher cost of production[5]. Blends of biodiesel B10 and B20 of Mahua oil and Simarouba are used as fuel in a direct injection CI engine and it was found that blend B10 is good for long-term use. There has been an increase in specific fuel consumption and a decrease in the CO and HC emission [6]. Indonesia has already implemented the use of B30 in the year 2020 and has made it a mandate in its policy and regulations and they were already ready with the road test for B40 [7]. An experimental four-cylinder, direct-injection diesel engine with a turbocharger has been used to create biodiesel from used cooking oil using the transesterification method. [8].The effects of varying injection pressure have been explored in connection to the operation and emission characteristics of a four-cylinder, four-stroke, compression ignition direct injection engine using mineral diesel fuel and mixes of 20%, 40%, and 60% waste cooking oil biodiesel [9].

There have been tremendous efforts made by the researchers to get a better result in the performance of an engine by varying the input parameters like type of fuels used, compression ratio, load, injection pressure and others through the experimental approach without modifying the engine parameters greatly. The higher the no of experiments conducted with varying input parameters more is the more refinement of the result being observed. But going conducting such a large number of experiments will cost one dearly capital as well as time. Hence, researchers shifted their focus to using some optimization technique by which they can get maximum overall output response by conducting a minimum number of experiments. Venkatanarayana et.al. used the Taguchi Approach and Analysis of Variance to optimize outcome responses of a diesel engine fueled with Karanja biodiesel blend[10]. The result showed that the compression ratio contributed the maximum to the outcome response, brake-specific fuel consumption. Similarly, engine load contributed the maximum to the output response, CO emission. The Taguchi-Grey analysis is used to get the overall optimized result of the performance parameters and it was found that the combination of the compression ratio of 18 engine speed of 2100 rpm, 10 percent of blends of water to the fuel, equivalence ratio of 0.8, 10 percent fraction of residual gas and with an injection pressure of 100 kPa are the optimum parameters [11]. An experiment work using the Taguchi method taking Polanga biodiesel and the optimal value of the factors taken was found to be B30 for a blend of biodiesel, 200 bar injection pressure, 32.59% of brake thermal efficiency and 551 ppm of NOx emission[12]. The characterization and analysis of biodiesel formed due to the transesterification of non-edible seed oil for biodiesel production have been carried out[13]. Biofuel blends produced from Jatropha curcas and Pongamia pinnata oil were evaluated for their combustion properties [14]. The combined effect of using biodiesel and gas dual fuelling associated with emissions and depletion of fossil fuels has been addressed [15]. The effect of mixed nano additive added in diesel–water emulsion on the performance, combustion and emission of a single-cylinder diesel engine under varying load conditions have been obtained using experimentation[16]. The combustion characteristics of biofuel blends made from Pongamia pinnata oil and Jatropha curcas oil were assessed [17].NOx is one element that needs serious attention as this is the only parameter that is adverse in the use of biodiesel as fuel in CI engines. Dual blends of fuel along with the help of Artificial Neural Network analysis have been used to predict the emission of NOx specifically[18]. Along with the experiment and emission analysis, cost analysis is also required which increases the feasibility of the research work [19]. Governments of various countries have now become serious and they have their specific targets to achieve the implementation of renewable systems in place [20], [21]. Also, various optimization techniques are applied on top of that to enhance the results [22], [23].

From the extensive literature survey, it can be stated that various work has been done in CI engines related to experimental investigation and performance optimization using a suitable optimization technique. However, this present study is fairly different from others concerning biodiesel production in a novel single-step transesterification process and its usage in the variable compression ratio CI engine without any modification in the engine set-up, whose performance parameters are optimized using the Taguchi-based optimization technique which allows performing a minimum number of experiments runs and finding out the optimum output response.

2. Materials and Methods

2.1 Biodiesel Preparation

The biodiesel production method i.e., the single-step transesterification process is the novelty of this present study. Five litres of edible Soybean oil is bought from the market. The oil-to-methanol ratio is taken over a wide range of 3:1 to 15:1. Sodium Hydroxide is taken as the catalyst in the range varying between 0.3% to 1.2% concerning oil. The biodiesel is produced in batches. In each batch 100 g of soybean is taken and the production process is carried out. The set-up includes a sonicator vessel to attain the desired temperature in the range between 60^0–65^0C.

Ultrasonic energy was used to carry out the reaction and after 15mins the reaction stops. After the end of the reaction, a 500ml separating funnel is taken and the product formed is transferred to it. Deep brown color glycerol being heavy settles down at the bottom leaving the Fatty Acid Methyl Ester

(FAME) or biodiesel produced from soybean oil at the top which is pale yellow. The conventional methods of purification are water washing or vacuum distillation. This leads to a partial loss of biodiesel and a total loss of homogenous catalyst. It requires a huge amount of water and is also water treated. All of these make the entire biodiesel production affair costly.

Table 1. Fuel properties of Common Diesel Fuel and Soyabean oil and Soyabean Biodiesel (FAME)

Sl No	Properties of Fuel	CDF	Soyabean Oil	Soyabean FAME
1	Kinematic Viscosity (cSt)	2.5-5.5	35-65	5.0-8.0
2	Calorific Value (kj/kg)	42000	39000-48000	30000-39477
4	Flash Point (^{0}C)	38	200	130-175
5	Cetane Number	45	40-50	40-58

A novel process of purification is adopted in this work. The FAME is treated with dilute sulphric acid which nullifies the alkali content of the product. It is then washed with a counter-current water supply which removes the unreacted alcohol and residual glycerol. This reduces water usage to a large extent and also helps recover 90% of the methanol which used to get lost during the conventional method of purification. The waste of FAME which results from small usage of water is also recovered by reusing that as washing fluid. After this process, it is dried. It is then treated with silica gel under ultrasonication for 15-20 minutes[24], [25], [26].

Blends of biodiesel are prepared by taking common diesel fuel (CDF) and mixing it with biodiesel by some volume fraction. Here, the SOYA B10 biodiesel blend is prepared by mixing, 900 ml of CDF with 100ml of biodiesel. Similarly, the SOYA B20 blend is prepared with 800 ml of CDF and 200 ml of biodiesel. The properties of fuel are measured as per ASTM 6751 and are shown in the table 1 [27].

2.2 Engine Description and Working

For this study, a Kirloskar makes single-cylinder, VCR, fully computerized compression ignition engine has been used. An eddy current dynamometer is connected to the CI engine test rig toward a variation of load.

Table 2. Engine Specification

PARAMETERS	DESCRIPTION
Make	Kirloskar Oil Engines
Model	TV1
Type	Research Diesel Engine
Displacement	661.5
Max.Engine Power (kW)	3.5
Max. engine torque (Nm)	22.3
Bore x Stroke (mm)	87.5 x 110
Compression Ratio	12:1 – 18:1
Injection Pressure (bar)	240
Max.Speed (rpm)	1500
Cylinder Bore (mm)	87.5
Stroke (min)	110
ConnectingRod Length(mm)	234
Stroke Type	4 Stroke
Number of Cylinder	1
Speed Type	Constant
Cooling Type	Water
Fuel	Diesel
Swept Volume (m^3)	661.5

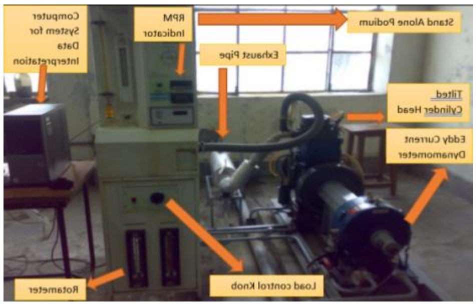


Fig. 1. Variable Compression Engine Used With Labeling

This is a variable compression ratio CI engine as shown in figure 1(c). To change the compression ratio, it is required to loosen six numbers of Allen bolts present on both sides of the cylinder block. The lock nut of the adjuster is loosened and is rotated with the help of a spanner for tilting the cylinder block. There is a compression ratio indicator that has got a scale of different compression ratios. Each rotation of the adjuster gives a 0.5 compression ratio variation. After setting the required compression ratio, the lock nut needs to be tightened along with all six numbers of Allen bolts.

After the desired compression ratio is set, then the starting of the engine is started with the help of a decompression lever. There are auxiliary units with the engine set up like a piezo powering unit (PPU), dynamometer loading unit (DLU), load indicator and voltmeter on the test rig. On the computer, all the parameters like speed, temperature and manometer reading and other mechanical parameters are also displayed on the screen and this is possible by the use of software called, “engine soft”. All these units require a power supply. The loading of the engine is done with the help of DLU.

An exhaust gas analyzer is used to detect exhaust emissions. It detects the percentage of the various gas present in the exhaust. It gives the reading of gases like CO_2, CO, HC, NOx, and Particulates in ppm. Then the same is repeated for a load of 4 kg and 7 kg for the compression ratio of 14 and 18 for common diesel fuel and all the blends of SOYA.

2.3 Data Reduction

It is important to measure the performance of the engine by using the biodiesel produced from the novel process. The parameters such as brake power, and specific fuel consumption are calculated in this work using the following equation:

The correlation between IP, BP and FP is given below:

$$BP = IP - FP \quad (1)$$

Also, brake power can be obtained from the following equation:

$$BP = \frac{2\pi N\tau}{60} \quad (2)$$

τ = Torque

N = speed of crankshaft in rpm

Specific Fuel Consumption:

It is the ratio of the amount of fuel consumed per unit of power produced.

$$SFC = \frac{fuel\ flow(kg/hr)}{Power(kW)} \quad (3)$$

3. Taguchi Method

The Taguchi technique provides the ideal set of input parameters to get the ideal output response. This is accomplished by creating an appropriate design of the experiment (DOE) that chooses the best parameters to be used as input to obtain the best outcome.

Taguchi method incorporates the design of experiments (DOE) in the form of orthogonal arrays based on the number of factors and their levels are considered in the study. In this work, Minitab 20.3 software is used for Taguchi mixed design and a DOE with L9 orthogonal array is formed to conduct the experiments which will reduce time.

4. Results and Discussions

The three control factors (load, compression ratio and types of fuel) and their respective levels, L9 orthogonal array are shown in table 3. After the orthogonal array is designed, the experiment was conducted. It gives us an idea about which parameters are to be considered as inputs for conducting the experiment which will reduce the time and also will give the optimum results.

Table 3. L9 Orthogonal array for control factors

No	load	CR	Fuels
1	2	14	B0
2	2	16	B10
3	2	18	B20
4	4	14	B10
5	4	16	B20
6	4	18	B0
7	7	14	B20
8	7	16	B0
9	7	18	B10

The effect of factors is calculated by the S/N ratio as mentioned below for

Larger the better = $-10\log_{10}(1/Y^2)$ (4)

Smaller the better = $-10\log_{10}(Y^2)$ (5)

Here Y stands for the output parameter. For the brake power, the larger the better is used and for other parameters like SFC, NOx and CO, the smaller the better is employed. These are chosen based on the requirement as brake power needs to be maximized and other parameters need to be minimized. The higher the value of the S/N ratio, high will be the performance quality characteristics. Hence, the optimum levels of various design parameters obtained corresponding to the higher value of S/N ratio and optimum parameters based on smaller the better are presented in Table 4.

4.1 Predicted Model and ANOVA Analysis

A linear predictive mathematical model has been developed by the optimization software using linear regression analysis for the variables BP, SFC, CO and NOx emission as functions of load, CR and types of fuel.

The predictive equations formed regarding load, *l*, compression ratio, *cr*, and blend, *bl* for the BP, SFC, CO and NOx emissions are as follows:

BP = 0.952 + 0.2129 l + 0.0667 CR - 0.1098 bl (6)

SFC = 1.107 - 0.0975l - 0.0058 CR +0.0005 bl (7)

CO emission = 0.156 - 0.004 l - 0.0058 CR - 0.0018 bl (8)

NOx emission = -128.1 + 26.05 l +8.33 CR + 2.050 bl (9)

The coefficient of determination R^2 talks about the capability of the model. It varies from 0 to 1. The model whose R^2 value is near about 1 like more than 90% then there is a good fit between the independent and dependent variables. The present work has developed models for BP, SFC CO and NOx emissions with R^2 values as 95.75%, 92.05%, 91.27%, and 97.76% respectively which is shown in table 5.

4.2 Contribution of Input Parameters On The Performance

According to Taguchi Analysis, Table 6 shows the percentage contribution of each aspect to the performance, including braking power, specific fuel consumption, CO and NOx emission. Each factor has a delta that is computed. It is the difference between that factor's S/N ratio's highest and minimum values. The contribution ratio measures how much each factor's delta contributes to the combined delta of all three components. Fig. 2 shows the contribution ratio of each factor such as BP, SFC, CO and NOx emission in the form of a Pie chart.

Table 4. S/N ratio of output response of BP, SFC, CO and NOx Emission

Load	CR	Blend	BP	SFC	CO Emission	NOx Emission	SNR (BP)	SNR (SFC)	SNR (CO Emission)	SNR (NOx Emission)
2	14	0	2.48	0.91	0.08	31	7.89	0.82	22.16	29.83
2	16	10	1.08	0.84	0.03	88	0.67	1.51	30.46	38.89
2	18	20	0.46	0.86	0.01	102	-6.74	1.31	41.51	-40.17
4	14	10	1.3	0.54	0.03	125	2.28	5.35	30.75	41.94
4	16	20	0.93	0.57	0.01	158	-0.63	4.88	40.63	43.97
4	18	0	3.12	0.54	0.03	128	9.88	5.35	30.46	42.14
7	14	20	1.28	0.39	0.01	204	2.14	8.18	41.21	46.19
7	16	0	3.66	0.34	0.03	182	11.27	9.37	31.06	45.20
7	18	10	2.28	0.37	0.01	230	7.16	8.64	42.16	47.23

Table 5. ANOVA and Model Summary for BP, SFC, CO and NOx Emission

(a) Brake Power

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Regression	3	9.07	3.02	37.57	0.00
Load	1	1.72	1.72	21.41	0.01
CR	1	0.11	0.11	1.33	0.30
Blend	1	7.24	7.24	89.98	0.00
Error	5	0.40	0.08		
Total	8	9.47			

S	R-sq	R-sq(adj)	R-sq(pred)
0.28	95.75 %	93.20%	88.15%

(b) Specific Fuel Consumption

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Regression	3	0.36	0.12	19.31	0.00
Load	1	0.36	0.36	57.77	0.00
CR	1	0.00	0.00	0.13	0.73
Blend	1	0.00	0.00	0.02	0.88
Error	5	0.03	0.01		
Total	8	0.39			

S	R-sq	R-sq(adj)	R-sq(pred)
0.08	92.05 %	87.29 %	71.70%

(c) CO Emission

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Regression	3	0.004	0.001	17.430	0.004
Load	1	0.001	0.001	11.730	0.019
CR	1	0.001	0.001	11.630	0.019
Blend	1	0.002	0.002	28.920	0.003
Error	5	0.000	0.000		
Total	8	0.004			

S	R-sq	R-sq(adj)	R-sq(pred)
0.01	91.27 %	86.03%	65.63%

(d) NOx Emission

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Regression	3	29980	9993.40	72.87	0.00
Load	1	25792	25792.10	188.06	0.00
CR	1	1666	1666.70	12.15	0.02
Blend	1	2521	2521.50	18.39	0.01
Error	5	685	137.10		
Total	8	30666			

S	R-sq	R-sq(adj)	R-sq(pred)
11.71	97.76 %	96.42 %	90.88%

Table 6. Contribution of Design Parameters on Performance

(a) Brake Power (BP)

Level	load	CR	Fuels
1	0.6042	4.104	9.6806
2	3.8439	3.7693	3.3687
3	6.8575	3.4323	-1.7437
Delta	6.2533	0.6717	11.4242
Rank	2	3	1
Contribution Ratio %	34.079	3.66	62.26

(b) Specific Fuel Consumption (SFC)

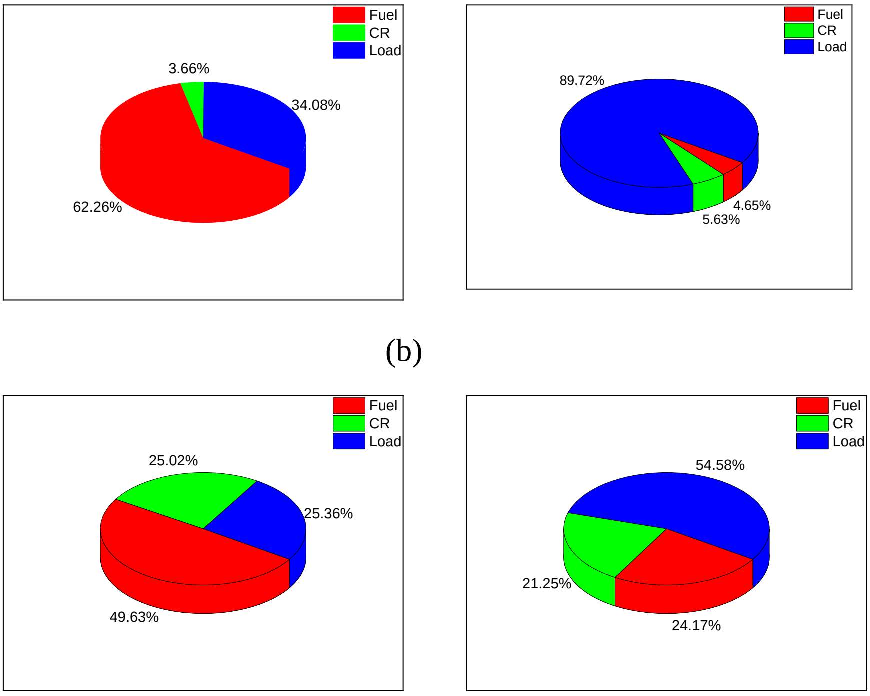
Level	load	CR	Fuels
1	1.215	4.783	5.181
2	5.196	5.256	5.168
3	8.728	5.099	4.79
Delta	7.514	0.472	0.39
Rank	1	2	3
Contribution Ratio %	89.708	5.63	4.65

(c) CO Emission

Level	load	CR	Fuels
1	31.38	31.37	27.89
2	33.95	34.05	34.46
3	38.14	38.04	41.12
Delta	6.76	6.67	13.23
Rank	2	3	1
Contribution Ratio %	25.35	25.018	49.62

(d) NOx Emission

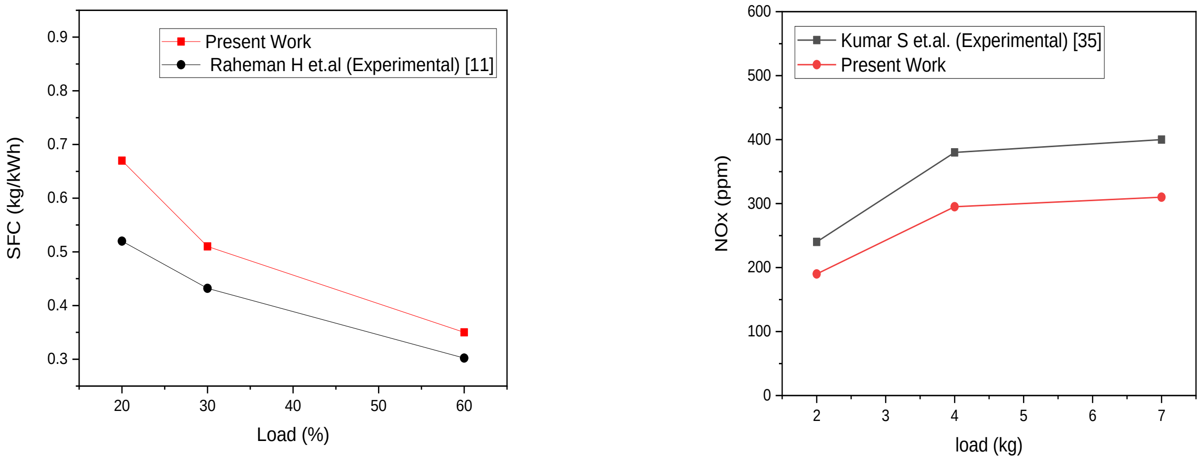
Level	load	CR	Fuels
1	-36.3	-39.32	-39.06
2	-42.69	-42.69	-42.69
3	-46.21	-43.18	-43.45
Delta	9.91	3.86	4.39
Rank	1	3	2
Contribution Ratio %	54.57	21.25	24.174



(c) (d)

Fig.2. Contribution ratio of factors (a) BP (b) SFC (c) CO(d) NOx

4.3 Verification and Validation



(a) **(b)**

Fig. 3. (a) Validation for SFC **(b)** Validation curve for NOx emission

The result of the present work is verified by the literature [28], [6]for the output response, specific fuel consumption and NOx emission of the test engine. The verification is carried out for the parameters, load (in %) and load (in kg) for SFC and NOx emissions respectively. The difference in results between the present work and the literature are calculated as +13% to +15% for SFC and -29% to -26.3% for the NOx emission respectively. The observed deviation in the results may be due to different engine parameters taken and different climatic conditions at the respective locations. It is observed that the present work reasonably matches the literature and is thus validated.

4.4 Effect of Design Parameters on Brake Power

As per the DOE framed in the Taguchi method, 9 experiments have been conducted which is depicted in table 3 concerning compression ratios 14, 16 and 18. Figures 4 (a), (b) and (c) show the performance of CI engines relating to compression ratios 14, 16 and 18 respectively.

The brake power of CDF increases with an increase in the compression ratio. Also, with the increase in the load, the brake power increases within each compression ratio. The brake power of the blends of biodiesel is found to be less as compared to CDF but if a particular blend is considered the brake power also increases with the increase of load and compression ratio, showing a similar trend to CDF. However, with the increase of blend percentage, the brake power went on decreasing. This might be with higher blends the viscosity increases decreasing the atomization of the fuel and leading to less effective combustion.

There is a 48% increase in the brake power of CI engines using CDF as fuel from lower compression ratio and load to higher compression ratio and load. Also, for fuel SOYA B10 and SOYA B20, there has been a 28.1 % and 23.7% increase in the brake power going from low compression ratio and load to higher compression ratio and load. Though the percentage increase in biodiesel blends of fuel is less as compared to the CDF, they follow the same increasing trend as CDF.

4.5 Effect of Design Parameters On Specific Fuel Consumption

Specific fuel consumption is defined by the ratio of the mass of fuel consumed in kg per hour to the engine output power. It is observed in Fig. 5(a), (b) and (c) that, in all the fuels there is a decrement in the SFC with an increment of load from 2kg to 7 kg.

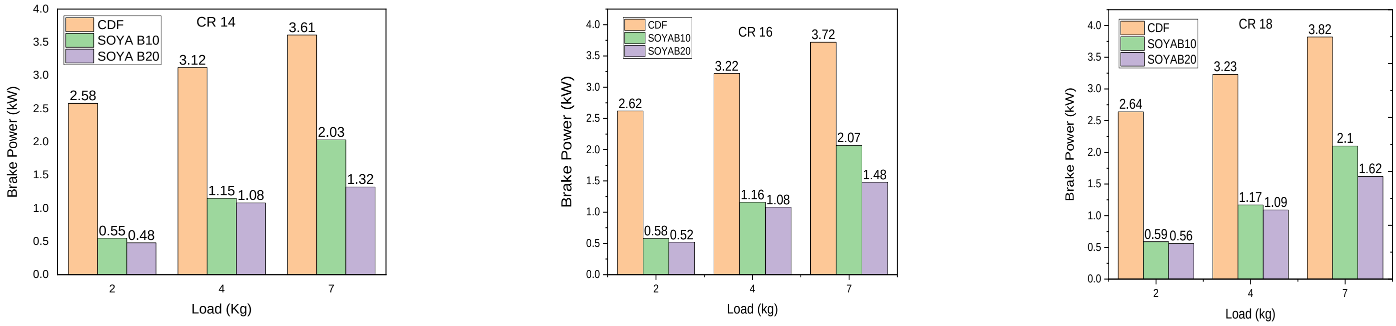
The SFC of CDF is less compared to the blends of biodiesel. This may be because CDF has a higher calorific value and the higher the calorific value, the lower will be the consumption of fuel to produce the required amount of power. Also, in biodiesel blends, the oxygen content is more so the consumption of fuel with biodiesel will be more as compared to CDF.

The specific fuel consumption decreases by 60%, 50% and 45% going from lower compression ratio and loads to higher compression ratio and load for CDF, SOYA B10 and SOYA B20 respectively. The biodiesel blends follow a similar trend to that of CDF which shows that this can be a good alternative for CDF.

4.6 Effect of Design Parameters on NOx Emission

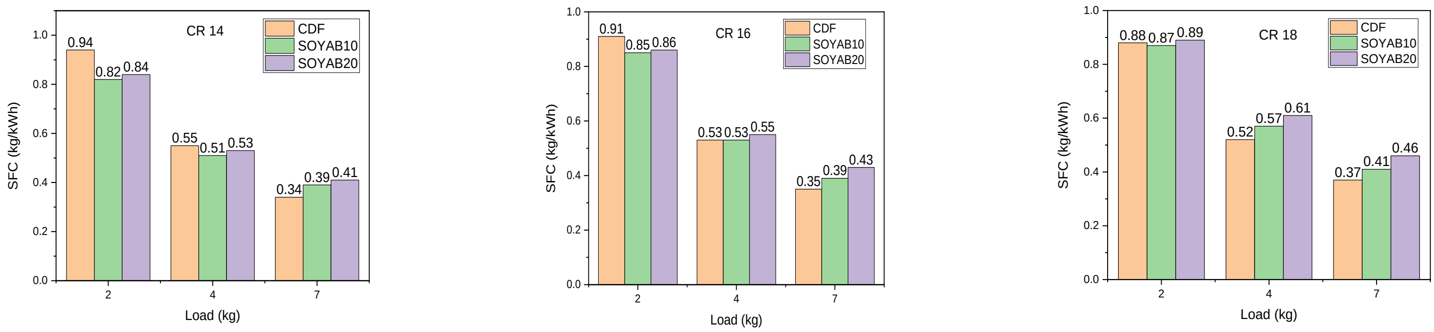
Figure 6 illustrates that; NOx emission is more in the biodiesel blends as compared to the CDF. It also increases with an increase in loads as well as compression ratio across all fuels. So, all the fuels follow a similar trend.

As biodiesel has a higher cetane number it leads to advanced combustion in the pre-mixed region with increases in the combustion time and also the in-cylinder temperature. The more the combustion time, the more will be the emission of NOx as it will get more time to react with the oxygen content of the biodiesel blends fuel[29]. Hence, biodiesel blends have more NOx formation as compared to CDF. It can be observed that the NOx emission increases with the increase in the compression ratio from 14 to 18. This may be because, nitrogen is not so active below 1000°C, when the engine cylinder temperature crosses this temperature limit, nitrogen reacts with oxygen and form oxides. So, when the compression ratio increases, the temperature in the cylinder increases as the brake mean effective increases causing more NOx formation. The more the temperature inside the engine cylinder, the more efficient the combustion and the more will be the formation of the NOx.



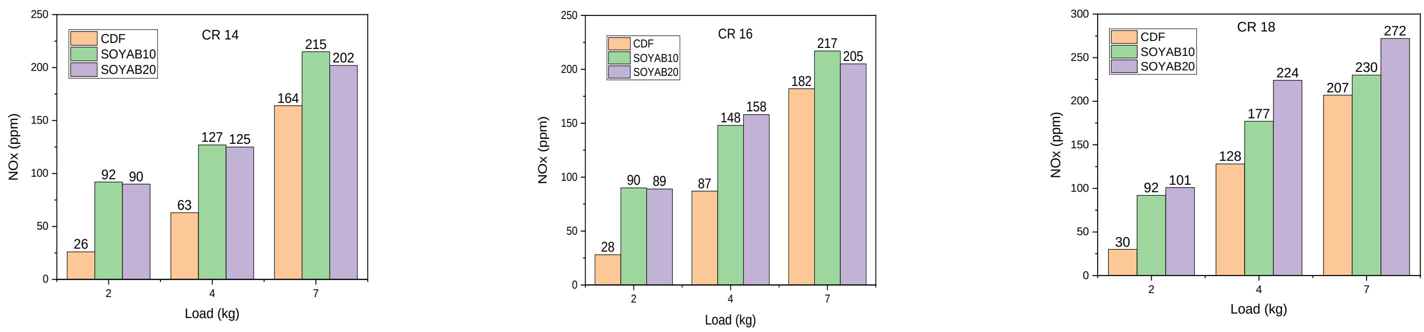
(a) (b) (c)

Fig.4. Effect of load and compression ratio on Brake Power (a) CR=14 (b) CR=16 (c) CR= 18



(a) (b) (c)

Fig.5. Effect of load and comp. ratio on Specific Fuel Consumption (a) CR=14 (b) CR=16 (c) CR = 18



(a) (b) (c)

Fig. 6. Effect of load and compression ratio on NOx Emission (a) CR=14 (b) CR=16 and (c) CR = 18

The percentage increment in NOx emission is observed as 475%, 152% and 202% for variation in types of fuel with CDF, SOYA B10 and SOYA B20 respectively from lower load to higher load across all compression ratios.

4.7 Effect of Design Parameters on CO Emission

As shown in Figures7(a), (b) and (c), the CO emission is more for CDF as compared to all the blends of biodiesel across all loads and compression ratios. This may be because of the higher oxygen content of biodiesel which reacts with the CO produced and gives out CO_2. Also, there is higher fuel consumption at high loads of biodiesel. The CO emission decreases by 66.66% with CDF as fuel and the decrease in CO emission is 4% and 6.7% with SOYA B10 and SOYA B20 respectively.

4.8 Optimum Performance Condition

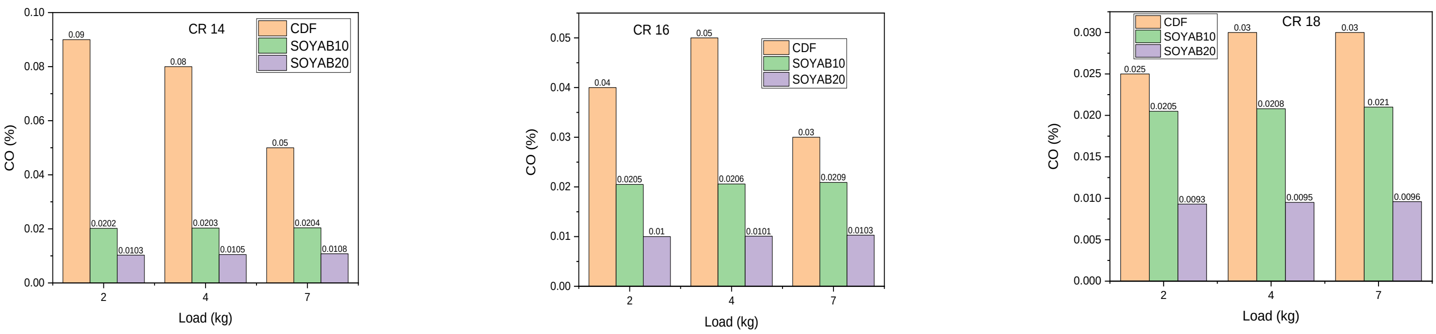
Three parameters i.e.Load, Compression Ratio and types of fuel were taken and how these factors affect the performance of the engine has been studied using the Taguchi method. The effects of each factor on the performance are recorded in Table 6 and are also plotted in the graph (Figure 8) produced by using the Taguchi method. The largest value of the S/N ratio for the combination of the control factors gives the optimum condition.

The effect of each design parameter (load, CR and types of fuel) on the brake power is shown in Fig. 8. The optimum value of the load, CR and types of fuel for the design parameter for the maximum brake power are 7 kg, CR 18 and CDF according to “larger is better” quality characteristics. The contribution ratio of each factor on the brake power is shown in Table 6 and Fig. 2. It is clear from the table and figures that type of fuel contributes maximum with a contribution percentage of 62.25% and that is why it is the most effective factor on brake power after which load contributes 34.07% followed by compression which contributes 3.66% respectively. Hence it is observed that the types of fuel and load have a significant effect on the brake power.

The effect of each design parameter (load, CR and types of fuels) on specific fuel consumption are shown in figure 9. The optimum value of the control factors load, CR and types of fuels for the design parameter for minimum specific fuel consumption are 7kg, CR 18 and CDF according to, the “smaller is better” quality characteristic. The contribution ratio of each factor on SFC is as shown in table 6 and Fig. 2. It is clear from the table and the figure that the load contributes maximum with a contribution percentage of 89.70% and that is why is the most effective factor followed by a contribution of 5.63% by the compression ratio and 4.65% by types of fuel and are that’s why the factors which affect the SFC least possibly.

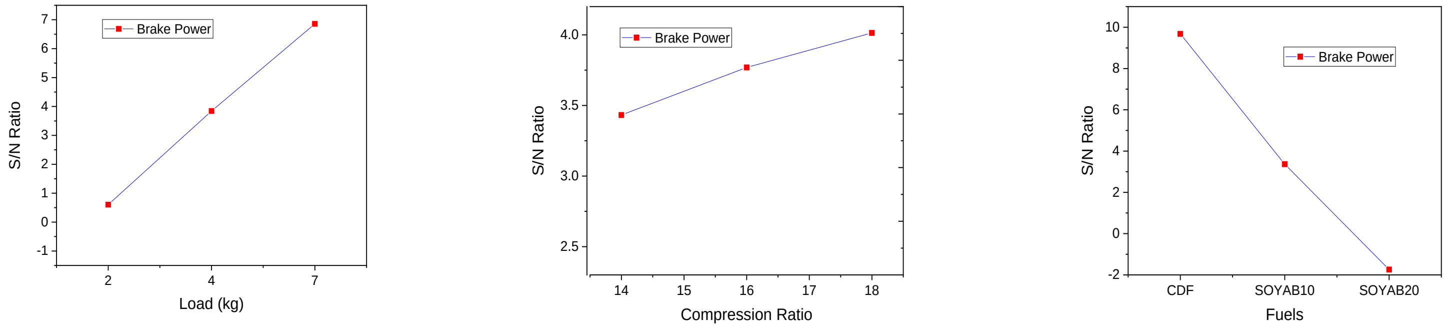
Fig. 10 shows the effect of each input factor on the NOx emission. The optimum value of these input factors for minimum NOx emission is obtained for 2kg load in the load, CR14 in the compression ratio category and CDF in the types of fuel category according to the “smaller is better” quality characteristic.

The contribution ratio of each parameter on the NOx emission is shown in Fig 2 and Table 6. It is clear from the figure and table that, the load is the most effective factor in the NOx emission with a contribution ratio of 54.57% followed by the type of fuels and compression ratio with a contribution ratio of 24.17% and 21.25% respectively. The results show that load and types of fuel are having a significant effect on NOx emission.



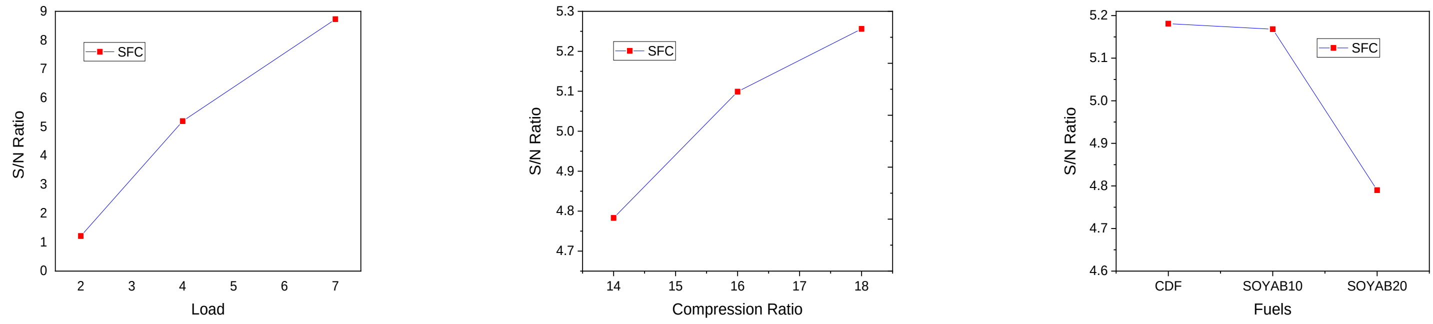
(a) **(b)** **(c)**

Fig.7. Effect of load and compression ratio on CO Emission (a) CR=14 (b) CR=16 and (c) CR = 18



(a) **(b)** **(c)**

Fig.8. Effect of each design parameter on the brake power (a) Load (b) CR (c) Fuels



(a) **(b)** **(c)**

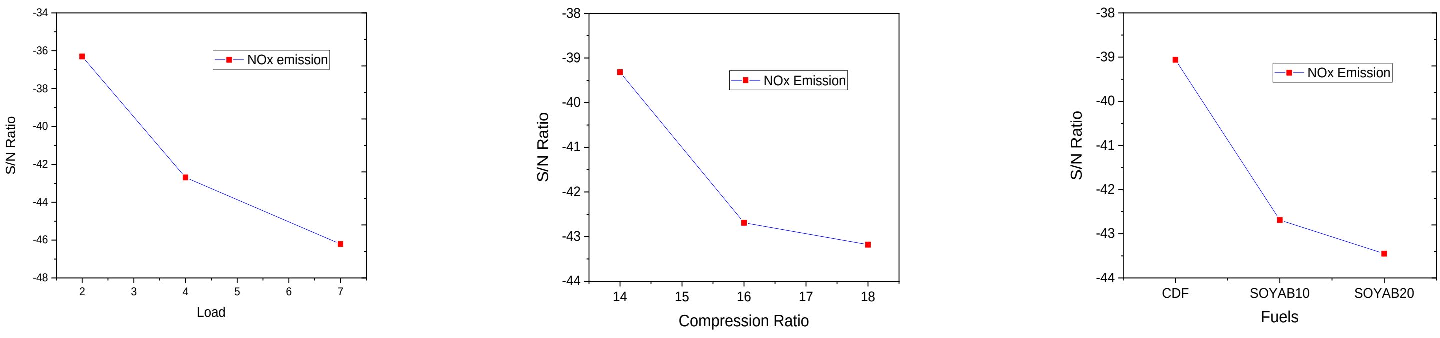
Fig.9. Effect of design parameter on the SFC (a) Load (b) CR (c) Fuels

The effect of each design parameter (Load, CR and types of fuel) on CO emission are shown in Fig. 11. The optimum value of the

control factors Load, CR and types of fuel for the design parameter for minimum specific fuel consumption are 7 kg, CR 18 and SOYA B20 according to, the “smaller is better” quality characteristic. The contribution ratio of each factor to CO emission is shown in Table 6 and Fig 2. It is clear from the table and the figure that the type of fuel used contributes the maximum with a contribution percentage of 49.62% and that is why is the most effective factor followed by a contribution of 25.35% by the load and 25.01% by the compression ratio. It is observed that types of fuel and load have a significant effect on the design parameters.

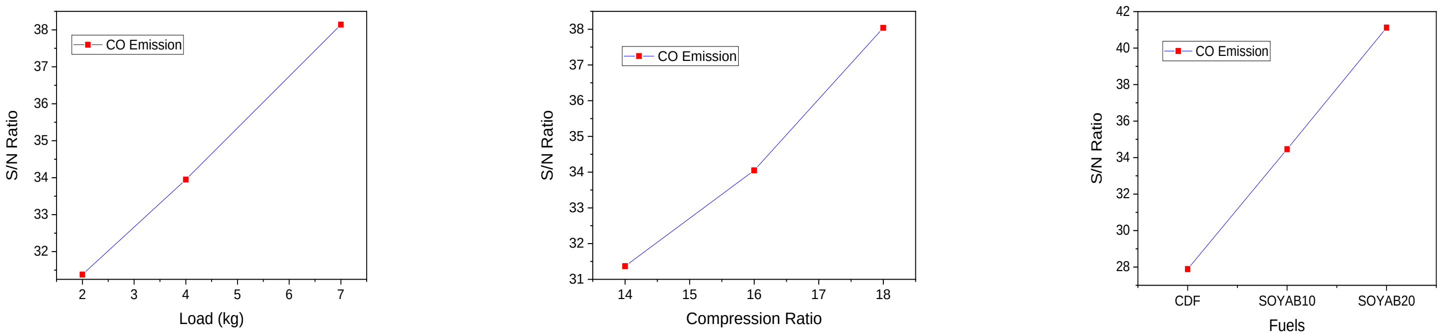
Afterward overall optimization is carried out for the performance of the engine as per the technique applied by Mohapatra et al. [30]. For the overall optimization, it is needed to bring together all the variations in the effects of each goal concerning the levels of importance of each parameter. The optimum condition of Brake Power, Specific Fuel Consumption, NOx Emission and CO Emission are determined as $[(load)_3]^b$, $[(CR)_2]^c$, $[(types\ of\ fuel)_1]^a$, $[(load)_3]^a$, $[(CR)_2]^b$, $[(types\ of\ fuel)_1]^c$, $[(load)_3]^b$, $[(CR)_3]^c$, $[(types\ of\ fuel)_2]^a$, $[(load)_1]^a$, $[(CR)_1]^c$, $[(load)_1]^r$espectively. Here 1,2 and 3 denote levels of input factors concerning the maximum SN Ratio and a, b, c denotes the ranking order of the input factors concerning their contribution ratio as mentioned in Table 5.

From Table 6, we can visualize that we have got four combinations of multi-response optimization (MRO I, II, III and IV). If we give more weightage to the brake power then the MROIII is considered the optimum condition for the CI engine and if we give more weightage to the NOx emission MRO II is considered the optimum condition for the CI engine.



(a) (b) (c)

Fig.10. Effect of design parameter on the NOx emission (a) Load (b) CR (c) Fuels



(a) (b) (c)

Fig.11. Effect of design parameter on the CO emission (a) Load (b) CR (c) Fuels

5. Uncertainty Analysis

Uncertainty analysis is important for experimental research as the instruments used to measure various entities are proneto errors occurring naturally due to the condition of instruments, laboratory calibration of instruments, environmental conditions and measurement of readings.

Thus, to reduce the probabilities of errors in different equipment while conducting experiments or to find out the uncertainties in the final value of various parameters measured by their respective instruments a mathematical expression named the propagation of errors is used which is as follows:

Total percentage uncertainties =

$$= \sqrt{\begin{Bmatrix} (BP)^2 + (SFC)^2 + (CO)^2 + (NO_x)^2 + (Temp.Ind)^2 + (TorqueInd)^2 \\ + (\Pr essuresensor)^2 + (fluidflow.Ind)^2 \end{Bmatrix}}$$

$$= \sqrt{\{(0.1)^2 + (3.1)^2 + (0.1)^2 + (0.01)^2 + (0.1)^2 + (0.2)^2 + (0.1)^2 + (0.12)^2\}}$$

$$= \pm 3.1 \tag{11}$$

Table 6. Optimum condition of design parameters and magnitude of performance parameters

Engine Parameters		Parameters			Output Responses			
		Load	Compression Ratio	Types of Fuel	Tested Brake power	Tested SFC	Tested CO Emission	Tested NOx Emission
Brake Power	Optimum Level	3[b]	2[c]	1[a]	3.66	0.34	0.028	182
	Optimum Value	7	16	B0				
SFC	Optimum Level	3[a]	2[b]	1[c]	3.66	0.34	0.028	182
	Optimum Value	7	16	B0				
CO Emission	Optimum Level	3[b]	3[c]	2[a]	2.28	0.37	0.0078	230
	Optimum Value	7	18	B10				
NOx Emission	Optimum Level	1[a]	1[c]	1[b]	2.48	0.91	0.078	31
	Optimum Value	2	14	B0				
General	Optimum Level	1	2	2	1.08	0.84	0.03	88
MRO - I	Optimum Value	2	16	B10				
	Optimum Level	1	2	1	2.62	0.91	0.04	28
MRO - II	Optimum Value	2	16	B0				
	Optimum Level	3	2	1	3.66	0.34	0.028	182
MRO - III	Optimum Value	7	16	B0				
	Optimum Level	3	2	2	2.07	0.39	0.0209	217
MRO - IV	Optimum Value	7	16	B10				

Table 7. List of instruments and their uncertainty analysis

Instrument	Measured Entity	Range	Units	Accuracy	Uncertainties
Temperature Indicator	Temperature	0-1200	^0C	$\pm 1^0 C$	±0.1
Torque Indicator	Torque	0-100	N-m	±0.1	±0.2
Pressure Sensor	Pressure	0-100	bar	±1	±0.1
Fuel Flow Indicator	Mass flow rate	0-99	k/h	±0.02	±0.12
Gas Analyser	CO	0-100	%	±0.03	±0.1
	NOx	0-10000	ppm	±25	±0.01
Calculated Results					

BP	-	-	kW	-	±0.1
SFC	-	-	kg/kWh	-	±3.1

6. Conclusions

In this study, different soybean biodiesel blends along with Common Diesel Fuel (CDF) i.e.,SOYAB10 and SOYAB20 are taken for performance analysis of the CI engine. The soybean biodiesel obtained from the single-step transesterification process which is different from the conventional method reduces the cost of production by reducing the number of steps involved in its production. The performance of the engine is optimized using the Taguchi method with the appropriate design of the experiment of L9 orthogonal array, which in turn reduces the time and cost of conducting the experiments. The results of this study may be summarized as follows:

i. There is a 48% increase in BP in CDF, 28.1% and 23.7% increase in the brake power for SOYA B10 and SOYA B20 while going from a lower load and compression ratio to a higher load and compression ratio. The specific fuel consumption shows a decreasing trend and that is by 60%, 50% and 45% going from lower compression ratio and load to higher compression ratio and load for CDF, SOYA B10 and SOYA B20 respectively. The CO emission also shows a decreasing trend and that is by 66.66% with CDF as fuel and 4% and 6.7% with SOYA B10 and SOYA B20 respectively. But there is a percentage increase in NOx emission for CDF, SOYA B10 and SOYA B20 and those are 475%, 152% and 202% respectively from lower compression ratio and load to higher compression ratio and load. Hence, we conclude that the biodiesel blends of Soybean oil show similar trends as a CDF and it can be a promising alternative to CDF.

ii. It may be concluded that types of fuel and load are the control factor that contributes significantly to the performance of all parameters. The types of fuel contribute significantly to BP and CO emissions whereas load contributes significantly to SFC and NOx emissions.

iii. The optimization method gave four combinations of optimized conditions MRO I, II, III and IV. If the focus is on enhancing brake power, then MRO III is the optimized condition. If the focus is on reducing the NOx emission, then MRO II is the optimized condition. The optimized value of MRO III gives 3.66 kW of brake power, 0.34 kg/kWh of specific fuel consumption, 0.028% of CO emission and 182 ppm of NOx emission. The optimized value of MRO II gives 2.62 kW of brake power, 0.91 kg/kWh of specific fuel consumption, 0.04% of CO emission and 28 ppm of NOx emission.

iv. There is a scope of taking higher blends of more than 20%, but that will require modification in the engine cylinder set-up. Triple fuel blends can be considered for future studies, which may give us enhanced performance. There has been some work by taking the gaseous fuel in literature. Waste oil can be taken and tested in the CI engine with proper blends as this will give a scope of utilizing the oil which would have been wasted by any means. This can be explored in future studies.

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