

Overall Performance Investigation and Optimization of a Multi-fuel Operated Compression Ignition Engine Using Coupled Taguchi and Grey Relational Analysis

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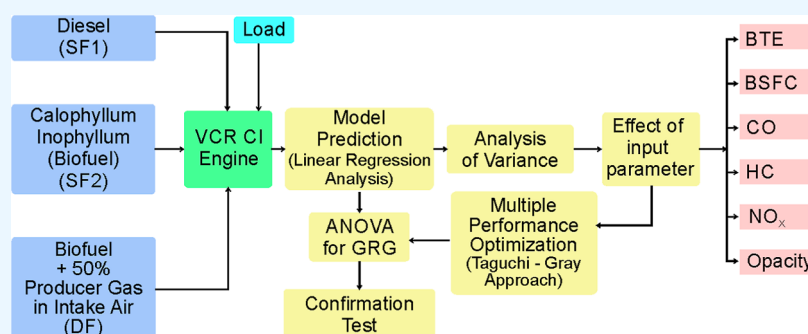


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ABSTRACT: Biofuels are regarded as the best diesel fuel substitute due to their low sulfur concentration, reduced aromatic hydrocarbon content, renewable nature, and higher oxygen content. In this research article, the impact of producer gas, Calophyllum inophyllum oil, diesel, and a blend of *C. inophyllum*–producer gas fuel on a variable compression ratio (VCR) compression ignition (CI) engine, and the performance and emission parameters are evaluated. Several test runs are undertaken at a constant speed of 1500 rpm to predict the performance and emission characteristics of the test engine by changing input parameters such as engine load, CR, and fuel mode of operation. The brake thermal efficiency, BTE, is considered the performance characteristic, and CO, HC, NO_x, and opacity are considered the emission characteristics for the present study. The biofuel, or producer gas, employed in this study is prepared from waste biomasses, such as leaves, small tree branches, vegetable waste, and cow dung, aiding waste management for a sustainable environment. In addition, a coupled Taguchi–Grey relational analysis technique is used to predict the best possible combination of control factors for optimizing the overall output responses. 12 kg load, a CR of 18, and diesel fuel are found to be the optimum input parameters of an engine toward optimum performance. A confirmation test is performed at the end to validate the outcome of the experiment. An enhancement in performance of 22.75% is observed with the considered Grey relational grade model.

1. INTRODUCTION

Nowadays, compression ignition (CI) engines are the primary source of public and private transportation. Compared to gasoline engines, CI engines or diesel engines reject a greater amount of NO₂, NO_x, and particulate matter. Mineral oils and fossil fuels used in diesel engines have recently hit their highest prices in history due to limited resources, supply, and a significant increase in demand, as well as an increase in the cost of refinement processes. Furthermore, the presence of NO_x and particulate matter contributes to the greenhouse effect and other forms of health hazards. The cost, as well as negative impacts on the environment, forces the researchers to think about alternate fuels. The amount of waste biomass collected from Mumbai city alone can fill a hole of 15 m diameter and 15 m depth in a single day. Those biomasses may be used for generating producer gas, methane gas, or other types of

combustible gases. These are the driving forces for the development of biofuels (liquid and gas), which are more environmentally friendly than fossil fuels.

Diesel engines in dual-fuel (DF) mode can run on two different types of fuel. One is known as pilot fuel, while the other is known as secondary fuel. To initiate the ignition, a little amount of diesel is utilized as pilot fuel. In a DF diesel engine, conventional fuel is made up of natural gas, biofuel, or a combination of both. In this engine, the supply of diesel ends

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once the engine starts, then the supply of natural gas or biofuel begins. Single fuel (SF) and DF were tested in one-cylinder diesel engines in SF and DF modes by introducing the exhaust gas recirculation (EGR) technique. The test revealed significant depletion in NO_x , CO emission, and smoke by utilizing the EGR technique.¹ 10% of chicken fat oil of was added with 90% of diesel in a single-cylinder direct injection (DI) diesel engine with a full load and 1800–3000 rpm speed variation. The result showed an increase of 5.2% in fuel consumption, 13% decrease in CO emission, and 13% decrease in smoke emission at the peak cylinder pressure.² Liquefied petroleum gas (LPG) was blended with methyl ester of Karanja oil used in a diesel engine. The outcomes were compared with the engine fueled with diesel fuel. The performance and emission characteristic of the engine were found to be improved as compared to diesel when fueled with a blend of 10 and 20% Karanja oil.³ Producer gas was used with diesel in a test rig to know the performance of the engine. A downdraft gasifier was connected with the engine. It was found that there was 75% diesel saving but with a decrease in the overall efficiency.⁴ The compressed natural gas (CNG)–diesel fuel blend was tested in a diesel engine to evaluate the emission behavior compared to diesel fuel at different blends and perfect pilot injection timing. Even at the peak load, CO emissions in DF mode were significantly greater than those of diesel fuel. In comparison to diesel mode, an average of 30% decrease in NO_x emission in DF operation was observed.⁵ The bio-oil from castor seeds and their blend starting from 0 to 40% were tested in a diesel engine. The performance and emission behaviors were evaluated and compared. Addition of 40% of castor oil in diesel (B40) gave less black smoke, but an increased percentage of castor oil increased the brake-specific fuel consumption (BSFC).⁶ The honge oil methyl ester (HOME) biodiesel blend with producer gas generated from different biomasses was used in a diesel engine. The performance and emission behaviors were investigated and compared with the engine running with a blend of diesel and producer gas. The break thermal efficiency (BTE) values of different blends of HOME biodiesel were found to be less than that of the blend of diesel and producer gas.⁷ Under different test conditions, the engine was tested with diesel, a blend of 10% neat oil with 90% diesel, and a blend of 20% neat oil with 80% diesel in different fuel modes, with a constant flow rate of producer gas. In the next step, DF was tested in the engine at a variable flow rate of gas. The results demonstrated that under all load circumstances, there was a reduction in the engine BTE and a better result of smoke and NO_x emissions than in SF mode operation.⁸ The blends of Mahua biodiesel and diesel were investigated in a variable compression ratio (VCR) CI engine. As compared to diesel, the blend of 15% Mahua oil with diesel showed better results in both performance and emission bases.⁹ Using diesel oil blended with heated coconut oil in an 80 hp marine diesel engine, it was found that BSFC and emission parameters were higher, except for the NO_x emission. The BTE was higher when the engine was fueled with coconut oil in heated conditions as compared to diesel oil.¹⁰ An investigation has been carried out on a diesel engine working with a blend of diesel oil and 5% vol of preheated palm oil, jatropha oil, and waste cooking oil. At different loading conditions and different speeds, the kit found that crude palm oil (CPO10) gave maximum brake power and a low emission rate.¹¹ Refined Polanga oil was blended with diesel in quantities of 20–100% by mass and was tested in a CI

engine under various loading conditions. Under certain loads, the thermal efficiency, BSFC, and emission results of 20 and 40% mixed fuels were found to be better than those of diesel.¹² The CO, CO_2 , NO_x , HC, and smoke emissions were assessed for a diesel engine running on alternative fuels such as Jatropha, palm, algae, and waste cooking oils, and the emission and performance parameters were compared to those of a diesel engine. The CO, HC, CO_2 , and smoke emissions were decreased for biodiesel blends B10 and B20, but NO_x emission was increased compared to diesel fuel.¹³ The crude *Calophyllum inophyllum* and palm oils were combined in a 50:50 volume percent ratio before being fueled in a CI engine. Over the whole range of speeds, the average results reveal that blended fuels have higher BSFC and NO_x emissions, but a lower BTE, with lower CO and HC emissions compared to diesel fuel.¹⁴ In a one-cylinder CI engine, a blend of ethanol and Jatropha biodiesel with *n*-butanol (co-solvent) was used. Due to the addition of ethanol, there was an increase in cylinder pressure and heat removal rate. When ethanol was added to JME fuel, the BSFC was reduced. With the addition of ethanol, there were reductions of 40, 40 and 40% in CO, HC, and NO_x emissions, respectively.¹⁵ The producer gas was introduced at the intake manifold during suction stroke, and biofuel was charged through the injector. The performance and emission characteristics were evaluated at different injection pressures. It was found that at a high injection pressure (200 bar), the fuel consumption rate was decreased with a minimum ignition delay.¹⁶ A diesel generator set was fueled with a producer gas–diesel blend, and the diesel saving ability was compared. The test was conducted in eight runs. It was concluded that there was a saving of diesel when the engine was run with the producer gas–diesel blend.¹⁷ The diesel engine was operated with Honge oil as the injected fuel and three types of gases (CNG, hydrogen-enriched CNG, and producer gas) as the induction fuel. When compared to a SF mode of operation, the results showed a lower BTE, less smoke, lower nitric oxide emission levels, and increased hydrocarbon and carbon monoxide emission levels. The hydrogen-enriched CNG operation produced overall better performance when compared to CNG–producer gas in DF operation.¹⁸

The nozzle geometry, injection pressure, and combustion chamber design have a greater impact on engine performance and emission characteristics, when the engine was fueled with biofuel as well as fossil fuel. Some related literature is described herewith. The goal of the research was to determine the ideal number of holes for diesel engine applications that would result in greater emissions and engine efficiency. The findings demonstrate that increasing the number of holes has a considerable impact on combustion, atomization, and evaporation.¹⁹ The engine used Honge oil methyl ester and producer gas induction while operating in DF mode. In the initial stage of the project, the injection pressure (which ranged from 210 to 240 bar in steps of 10 bar) and injector nozzle (three-, four-, and five-hole injector nozzles, each having 0.2, 0.25, and 0.3 mm hole diameter) were optimized. Then, in the following stage of the study, the combustion chamber was examined for the best performance. The best performance was demonstrated with a combustion chamber of the re-entrant type, 230 bar injection pressure, four holes, and a 0.25 mm nozzle aperture.²⁰ Investigations were conducted under various engine operating conditions, including an optimal ignition time (IT) of 27° BTDC and a variable injector opening pressure (IOP) with

nozzle geometry and combustion chamber morphologies. The engine's operational parameters were kept at 1500 rpm with a CR of 17.5. It was discovered that the diesel engine operated with a palm oil methyl ester fuel, an IT of 27° BTDC, an IOP of 240 bar, five-hole nozzle geometry, and toroidal re-entrant combustion chamber showed higher improvement in BTE with the least amount of emissions.²¹ Analyses were done on injector nozzles with various numbers and sizes of holes. Better performance and reduced emissions were obtained by operating Honge oil–producer gas with six holes and a 0.25 mm diameter nozzle that had four holes. In comparison to Honge oil–producer gas operation, the BTE for the diesel–producer gas operation was 4.5% higher with a four-hole nozzle and 0.7% higher with a 0.25 mm diameter six-hole nozzle. The HOME–producer gas operation showed an enhanced BTE of 5.8% and 15–30% lower emission levels than those of other geometries with an IOP of 240 bar, a six-hole nozzle, and a diameter of 0.25 mm.²²

The results of continuous research on biofuel are encouraging to develop newer types of biofuel. Some research personnel have used newer types of biofuel to improve the engine performance and emission characteristics. The waste plastic oil and diesel blend was used in the diesel engine to determine the performance and emission behavior by the response surface methodology technique. It was found that with 17 CR, 10% WPO–90% diesel blend, and full load, the engine showed the maximum efficiency and minimum emission.²³ Three types of newer biofuel (96% of lauric oil, 88% of oleic oil, and 89.5% ricinoleic oil) were used in a diesel engine. The rate of heat release, combustion pressure, and NO_x emission were evaluated and validated.²⁴ There was an increased value of brake power, an increased value of BSFC, and a decreased value of BTE, when a diesel engine was fueled with algal biofuel and its blend.²⁵ The use of hydrous ethanol, which resembles biofuel, can be substituted for by blending it with gasoline and diesel and adding other additives. Hydrous ethanol has been used into combustion processes like (GPI + EDI), HCCI, RCCI, and PCCI, lowering hazardous pollutants like NO_x and soot with good energy conversion efficiency. Cost savings from using hydrous ethanol as an engine fuel were found to be reasonable.²⁶ Four-part loads and three fuel injection pressures were evaluated with a blend of 80% diesel and 20% biodiesel made from waste cooking oil. According to the test results, opacity (84.4%), HC (71.8%), and CO (46.8%) were significantly decreased as compared to the basic diesel operating at a single injection and a lower fuel injection pressure. The thermal efficiency of the brakes was also increased by 4.46%.²⁷ Leather waste methyl ester was added with diesel at 10, 20, and 30% concentrations. The result showed that the BTE of the engine was reduced when fueled with all types of blends under every loading conditions, but the BSFC was increased. For 30% leather waste methyl ester–70% diesel blend, the engine showed minimum emission behavior.²⁸ For the purpose of facilitating the ignition pattern of a diesel engine powered by waste seed biodiesel, propane was induced with air at various liters per minute. The addition of propane at 6 lpm reduced HC by 0.04 g/kW h, CO by 0.5 g/kW h, and smoke emission by 0.4 BSU at all brake powers from neat waste seed biodiesel with 0.9 g/kW h higher NO_x.²⁹ Di-*tert*-butyl peroxide (DTBP) in orange peel oil (OPO) was used to make modified fuels, and its attributes were calculated and compared to diesel. When 90 and 80% by volume of OPO was blended with 10 and 20% by volume of DTBP, there was a

drop in emission parameters and increase in the performance of the engine in the case of 20% DTBP–80% OPO as compared to raw OPO.³⁰ The CRDI engine was run with different CRs and different EGR rates. The engine was fueled with a blend of diesel and sapota biodiesel. The result showed that at higher CRs, the ignition delay was reduced.³¹ An investigation was carried out on *Brassica oleracea* leaves, *Moringa oleifera* pods, *Citrullus lanatus* lunds, and *Annona squamosa* seeds to determine their properties for use as eco-friendly biofuel. After briquetting and addition of the binder, proximate and ultimate analyses were done.³²

Some distinct research work has been carried out by some researchers by adding different types of catalysts to reduce the diesel activation temperature and production of reactive oxygen species. Investigations have been done into the effects of adding two different metals (Ag or Cu) on the oxidation of soot in a catalytic CeO₂-based DPF. Two approaches were used for this work.³³ Regarding the regeneration dynamics of a catalytic particulate diesel filter (PDF), the combined effects of starting temperature and catalyst activity were studied. In order to do this, single-channel soot combustion simulations using computational fluid dynamics were carried out. The model made the assumption that the catalyst was in contact with all of the soot trapped inside the filter.³⁴

After reviewing the literature, it is determined that numerous studies on the performance and emissions of CI engines in single- and multiple-fuel modes have been carried out using alternative fuel like biomass oil, bioethanol, leftover cooking oil, natural gas, producer gas, various types of vegetable oils, and so forth. Although each of these alternative fuel has benefits, there are some drawbacks that limit their use. Some alternative fuel do not need any kind of blend at all. Due to their lower cetane number and lower calorific value, some biofuel are used as secondary fuel (mixed with pilot fuel) and cannot be used directly after chemical treatment. There are also similar restrictions on the usage of alternative fuel mixtures in diesel engines, but these alternative fuels have the potential to eventually replace fossil fuel. However, in order to contribute toward making the world a better and cleaner place for everyone, it is now necessary to use alternative fuels more frequently. In this regard, extensive research is going on. In this study, a similar approach of usage of alternative fuels separately or in blends in existing diesel engines to substitute fossil fuel without any modification is tested. For the current study, diesel, *C. inophyllum* oil, and *C. inophyllum* oil–producer gas blend are considered as the test fuel, and several test runs are carried out in SF and DF modes. *C. inophyllum* oil is chosen for the current research work for its abundant availability, higher production rate, restricted government policy toward the use of edible oil, and cheaper production process. In order to improve energy production and promote waste management, producer gas generated in a more affordable way from waste biomass such as leaves, small tree branches, vegetable waste, and cow dung is chosen for the study. Currently, functional investigation of the test engine is carried out concerning variation in key input parameters, that is, load, CR, and fuel mode of operation. Multiple performance characteristic optimizations are carried out using Taguchi and Grey relational analysis (GRA). The findings of this study will help encourage manufacturers and users on the use of alternative fuels in stationary engines. In the following, the performance study and optimization analysis are discussed.

2. MATERIALS AND METHODS

2.1. Biodiesel Preparation and Producer Gas Generation. **2.1.1. Methodology for Preparation of *C. inophyllum* Oil.** *C. inophyllum* is an evergreen tree. It belongs to the Clusiaceae family and is a non-edible oilseed crop. It thrives in coastal environments. Its fruit (ball nut) is spherical and 2–4 cm in diameter. It contains around 71% unsaturated fatty acids when fully ripe (oleic and linoleic acids). The fruit of the *C. inophyllum* tree is produced twice a year. One mature tree produces approximately 100 kg of fruits, which is equivalent to 18 kg of oil. Pre-treatment, alkali catalyzed transesterification, and post-treatment are the three stages of a bio-diesel production process from *C. inophyllum* seeds, as shown in Figure 1.

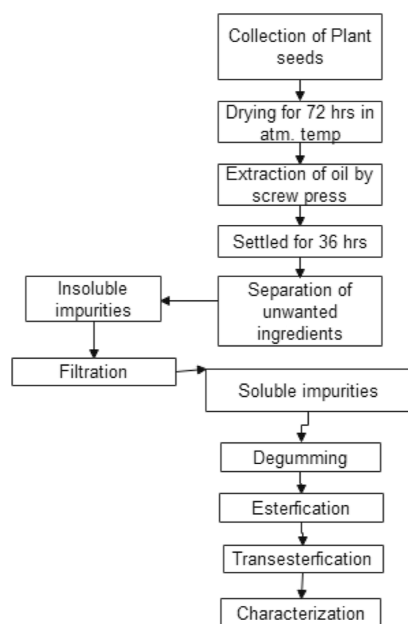


Figure 1. Preparation of *C. inophyllum* biodiesel.

2.1.2. Extraction of Biodiesel from *C. inophyllum* Seeds. The seeds were extracted from ripe fruits of *C. inophyllum*. To remove moisture from the seeds, they were dried in broad daylight for 2 days at an average temperature of 35 °C. Using an electrically operated oil press machine (screw type), the oil was physically extracted from the seeds, whose characteristics are listed in Table 1. The extracted oil was then filtered by a filter with a mesh size of 5 μm. After filtering, the oil color turned dark brown.

2.1.3. Refinement of *C. inophyllum* Oil. Insoluble impurities such as natural wax, fatty acids, phosphates, and

Table 1. Oil Extraction Press Specification

Sl. no.	properties	value
1	operating type	automatic
2	mechanical type	cold press
3	I/P voltage	220–240 V
4	motor power	0.25 HP
5	rpm	60
6	capacity	3 kg/h
7	weight	13 kg
8	size	20 (length) × 8 (width) × 10 (height) in.

mucilage were mostly separated by the filtration process, whereas soluble impurities like natural wax, fatty acids, phosphates, and mucilage were difficult to separate. In the chemical lab, 1250 mL of *C. inophyllum* oil was combined with 1.25 mL of H₃PO₄ in a flask (round-bottomed). The mixture was constantly stirred at 600 °C for up to 2 h. The pure oil was then collected from the upper layer once it had settled down.

2.1.4. Esterification of *C. inophyllum* Oil. Esterification is a chemical reaction that produces an ester and water as products. As a result, external heat is required to evaporate the water produced during the process. As a catalyst, the refined *C. inophyllum* oil was combined with 24 vol % CH₃OH and 1 volume % H₂SO₄. For elimination of water particles and excess CH₃OH, the mixture was continuously stirred and heated to 700 °C.

2.1.5. Transesterification of *C. inophyllum* Oil. The transesterification technique was used to convert *C. inophyllum* oil into usable biodiesel and lessen its viscosity. A 2 L round-bottomed flask with a separating valve at the bottom was filled with 1250 mL of esterified *C. inophyllum* oil. The transesterification unit is a complete unit. The oil was then heated to 700 °C to eliminate any remaining ester and KOH.

2.1.6. Characterization of Fuel Properties. Before using the *C. inophyllum* biodiesel in the CI engine, characterization was done for knowing the fuel properties. Many American Society for Testing and Materials methods were used to determine the above-mentioned properties. The details of the properties of *C. inophyllum* oil and mineral diesel oil are given in Table 2.

Table 2. Detailed Properties of Fuels Used in the Experiment

properties	<i>C. inophyllum</i> oil	diesel
density (kg/m ³)	858	826
viscosity at 40 °C	3.9	3.1
flash point	138 °C	48 °C
cetane number	59	52
heating value	41,300 MJ/kg	42,500 MJ/kg

2.1.7. Generation of Producer Gas. Gasification of solid/liquid fuels is commonly used to produce producer gas. Gases like CO, H₂, CH₄, and N₂ are the main ingredients of producer gas. Conversion from unused biomass to producer gas generally takes place in biomass gasification. Gasification requires a gasifier, which is a chemical reactor that performs a variety of physical and chemical processes such as drying, heating, pyrolysis, partial oxidation, and ultimate reduction. According to the direction of gas flow, the gasifier can be divided into three categories: updraft, downdraft, and cross draught.

For generating the producer gas for this experiment, a downdraft gasifier was used with the specifications mentioned in Table 3.

A downdraft gasifier is a fixed-bed-type gasifier with a throat. A good grade of coal mixed with waste dry wooden pieces (1:3 ratio) was the biomass introduced at the top of the gasifier. At the bottom, the hot producer gas was collected at about 490 °C. Then, the producer gas was passed through a counter flow heat exchanger, where it exchanged its heat with water, and the temperature of the producer gas was reduced to atmospheric temperature. It needed a minimum of 30 min to decrease the

Table 3. Details of Downdraft Gasifier

Sl. no	gasifier	specification
1	model	WBG-10
2	gas flow rate	25 Nm ³ /h
3	gasifier type	downdraft
4	average calorific value of gas	1000 kcal/Nm ³
5	temperature during gasification	1050–1150
6	fuel tank storage capacity	100 kg
7	ash removal method	manually
8	consumption rate	8–9 kg
9	gas composition	CO, H ₂ , CO ₂ , CH ₄ , N ₂

temperature of the producer gas. Properties of producer gas are detailed in Table 4.

Table 4. Properties of Producer Gas Obtained from the Gasifier

properties	values
methane (% by vol.)	3%
CO (% by vol.)	20%
CO ₂ (% by vol.)	10%
N (% by vol.)	49%
H (% by vol.)	21%
heating value (kJ/kg)	4100
density (kg/m ³)	1.29
octane number	103

2.2. Experimental Investigation. **2.2.1. Experimental Test Setup.** A VCR CI engine was considered for this study, whose specifications are mentioned in Table 5. The setup for

Table 5. Details of Diesel Engine Test Rig

particulars	specification
make	Kirloskar TV1
speed	1500 rpm
BHP	14 HP
no. of cylinder	1
compression ratio 3 port	11:1 to 18:1
diameter of the cylinder bore	87.5 mm
length of the stroke	110 mm
cooling type	water cooled
dynamometer	eddy current type
air drum orifice diameter	20 mm
swept volume	661 cm ³
peak pressure	77 kg/cm ²
connecting rod length	231 mm

testing consists of an engine, a generator, an eddy current dynamometer, a gasifier, a heat exchanger (cooler), a filter, a producer gas tank, an air tank, a C. inophyllum oil tank, and an exhaust gas analyzer (Figure 2). The variation of load and speed was managed by the eddy current dynamometer. The AVL analyzer was fitted with the exhaust pipe to determine the emission characteristics. Smoke emissions were measured by a NASSALCO-make smoke meter.

The producer gas collected from the gasifier was passed through a cotton column for absorbing moisture and suspended particles. For controlling the flow rate of gas, a valve was installed at the last portion of the cotton column, and the flow rate was measured by an orifice meter. In the intake

pipe, the biogas and air were mixed, and the mixture entered the engine cylinder through the inlet valve. Under various load circumstances, the performance and emission metrics were observed.

Two K-type thermocouples are fitted to the engine to estimate the temperature of the inlet air and exhaust gas. The flow meter linked to the engine test rig was used to measure the biofuel and diesel flow rates. For a multi-fuel system of operation, the intake system was modified. The pressure head of the gas was measured using a U-tube manometer.

2.2.2. Experimental Procedure. **2.2.2.1. Experimentation with Diesel Fuel.** Diesel was used to start the engine. To achieve a steady state, it is acceptable to run for 15–20 min. Readings were taken once the system reached a steady condition. Graduated tubes in the gasoline line to the engine were used to record fuel consumption rates at various loads. During this time, the engine only runs on diesel, with no producer gas or C. inophyllum oil. An emission recorder was used to keep track of the exhaust emissions. Exhaust emission data were recorded by an emission recorder. NO_x, CO, CO₂, and N₂ were recorded at different loads with the help of an eddy brake dynamometer.

2.2.2.2. Experiment with C. inophyllum Oil. As it is very difficult to start the engine fueled only with C. inophyllum oil, first, the engine was allowed to run with diesel in a steady state for some time. Afterward, the diesel line was cut off and the C. inophyllum oil line was fed to the engine. It was allowed to operate without load for 10–12 min to get a stable speed of 1500 rpm. Later, at 4–12 kg of load, exhaust emission, exhaust gas temperature, and fuel consumption were measured.

2.2.2.3. Experiment with DF Mode (C. inophyllum Oil and 50% Producer Gas in Intake Air). After 10 min of biomass charge, the gasifier produced producer gas. To achieve a steady state, the engine was first operated for 15 min with C. inophyllum oil without load. On reaching the steady state, the inlet valve was opened, and 50% producer gas with intake air was permitted to enter into the engine cylinder. The producer gas pressure head was allowed to stay at 40 cm. The readings were taken as previously described.

2.2.3. Data Reduction.

$$\eta_{\text{BTE}} (\%) = \frac{\text{Brake power (kW)} \times 3600}{\text{Fuel flow (kg/h)} \times \text{calorific value (kJ/kg)}} \times 100 \quad (1)$$

where η_{BTE} is the BTE in %

$$\text{Brake power} = \frac{\pi DN(W - S)}{60000} (\text{kW}) \quad (2)$$

where D = brake drum diameter in mm, W = given load in kg, S = spring scale reading in kg, and N = number of revolutions of engine shaft in rpm

$$\begin{aligned} \text{Brake specific energy consumption (BSEC)} \\ = \frac{m_{\text{fuel}} \times \text{CV}_{\text{fuel}}}{\text{Brake power}} (\text{kW}) \end{aligned} \quad (3)$$

where m_{fuel} = mass of fuel flow (kg) and CV_{fuel} = calorific value of the test fuel (kJ/kg).

2.2.4. Uncertainty Analysis. As measuring devices are always connected with a certain error, uncertainty or error analysis is crucial for the prediction of exact findings in experimental activity. In this study, eddy current dynamom-

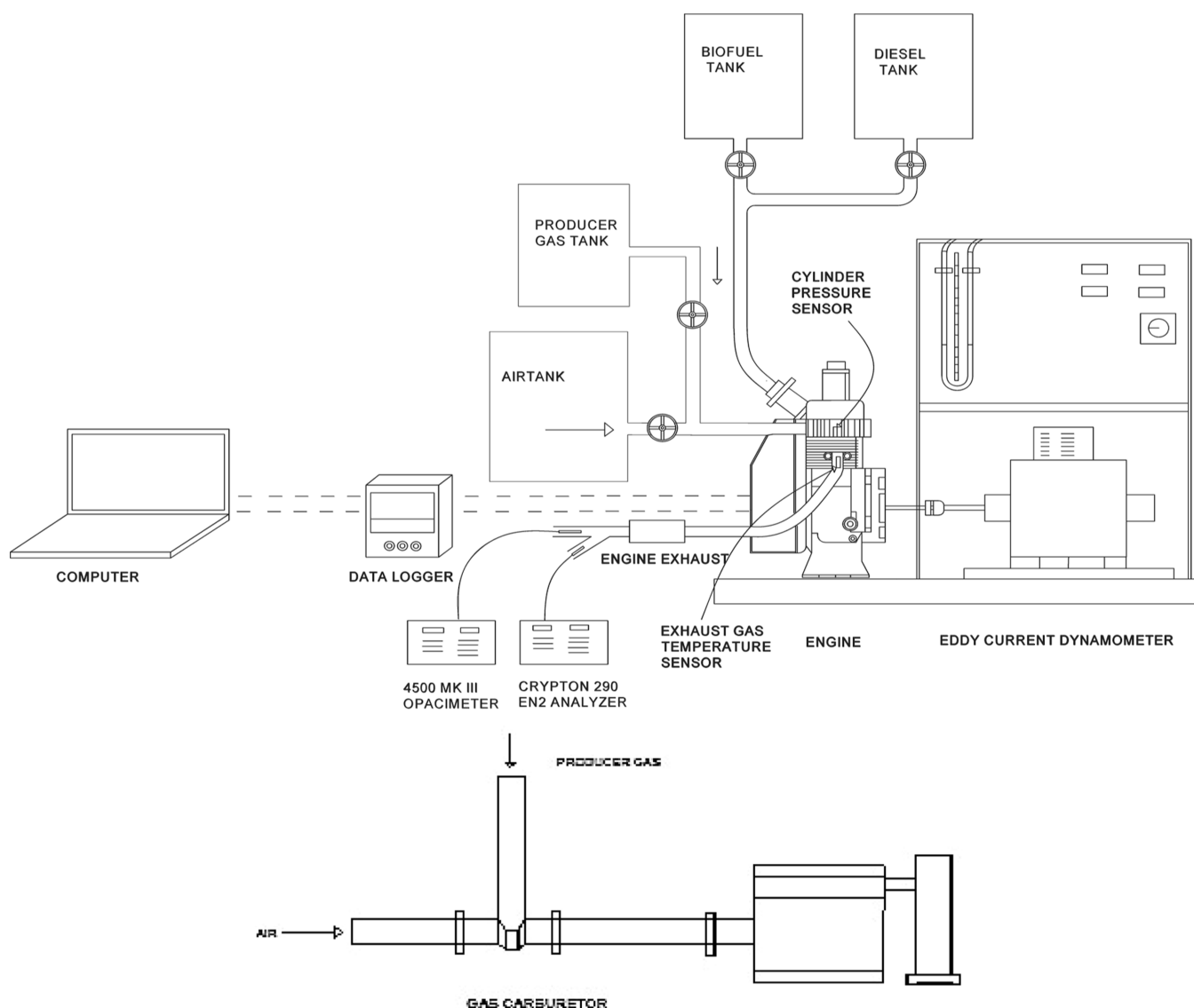


Figure 2. Schematic diagram of the test engine setup and gas carburetor.

eters, thermocouple wires, manometers, flow meters, exhaust gas analyzers, and opacity meters are used to monitor various parameters, including load, temperature, pressure, flow, and emissions. Therefore, it is necessary to assess the impact of inaccuracy on output from the aforementioned devices for the current study in order to obtain accurate data from the instruments. After going through various research articles on uncertainty analysis,^{26–32} the following uncertainty measurements were performed in this experiment and are shown in Table 6.

2.3. Taguchi Method. To improve the performance of CI engines, a variety of strategies were explored. Load, CR, injection pressure, cooling water temperature, fuel type, and engine cylinder temperature all affect the performance of CI engines. The performance of the CI engine can also be significantly increased by using proper optimization techniques.

The Taguchi technique was used to optimize the performance of a VCR DI CI (diesel) engine in this study. Based on Taguchi's "orthogonal arrangement," the optimum value of input control variables (load, fuel mode, and CR) was established for maximum performance and minimum emission.

Table 6. Uncertainty in Measuring Instruments

instruments	uncertainty
brake thermal efficiency	±2.5%
crank angle sensor (for measuring crank angle in degree)	±1
K-type thermocouple	±0.25
exhaust gas analyzer (CO, HC, NO _x)	±0.15, ±0.15, ±0.15
opacity meter	±0.2
fuel buret	±0.15
load indicator	±0.3

The signal-to-noise (S/N) ratio is the required output recording function, which is utilized as an optimized objective function to predict the best outcomes, and the "orthogonal array" gives a group of well-balanced (minimum) experiments. A diesel engine was used to test the blend of Jatropha oil and diesel. The Taguchi optimization approach was used to predict the influence of factors, such as load, mixing ratio, and CR, and their optimum values. The results revealed that the optimal parameter settings for the lowest BSFC were a mix ratio of 0%, a CR of 18, and an engine load of 10 kg.³⁵ The factors for

optimization in the experiment were the fuel mixing ratio, CR, fuel injection pressure, and intensity of load. The best parameter results for the highest BTE were found at a blending ratio of 0%, a CR of 18:1, a fuel injection pressure of 160 bar, and a load intensity of 9 kg.³⁶

According to the analysis, in a diesel engine fueled by a blend of *C. inophyllum* diesel, diesel, and *n*-butanol, greater performance was reported when 15% *n*-butanol was used. To predict the performance at full load, a study was done by taking input factors such as the blend ratio, injection, and pressure. The Taguchi approach was used to improve engine output parameters using numerous response characteristics of performance and emission results.³⁷ In a variable compression diesel engine, the engine performance and emission properties of Karanja oil blended with diesel methyl ester were examined. The multi-response optimization problem was solved using the Taguchi method with GRA. The grayscale and S/N ratio correlation levels were employed as performance indicators to predict a certain combination of input parameters that would result in optimal response characteristics. It was discovered that 50% of the mixture was best for diesel engines without altering the engine performance or emission characteristics considerably.³⁸ The CI engine performance was experimentally tested, and its multi-objective optimization was investigated using Taguchi and GRA. The GRG improvement in the performance at full load was noticed with the *Mangifera indica* biodiesel blend.³⁹

The Taguchi technique generates a good design of experiment (DOE) using the best combination of input parameters to yield the best output response. The performance and emission metrics employed in this study were BTE (%), CO emission (%), HC emission (%), and NO_x emission (ppm), which were analyzed using the Taguchi method.

For optimization analysis, the value of S/N ratio commonly used is 3. The S/N ratio is used to assess parameter variations. S stands for signal and represents mean, while N stands for noise and represents standard deviation. To analyze the S/N ratio, three sorts of quality criteria are defined: "larger is better," "nominal is best," and "smaller is better."

In this work, three control factors, namely, CR, change in load (kg), and fuel mode (single/dual), and their effect on the performance of the engine and emission characteristics of the test engine were evaluated by the Taguchi method. The BTE considered as the performance parameter for this study was analyzed with "larger is better" quality characteristics. The BSFC, CO, HC, and NO_x emissions, and opacity were analyzed with "smaller is better" quality characteristics.

This research work aims to determine the maximum engine performance in terms of BTE, minimum emission (CO, HC, and NO_x), BSFC, and opacity. The said optimization was carried out for three levels of CRs, that is, 14, 16, and 18, three levels of loads, that is, 4, 8, and 12 kg, and three levels of fuel modes, that is, SF1, SF2, and DF. SF1 is the SF mode 1, and the test was conducted with diesel fuel. Similarly, SF2 is the SF mode 2, and the test was conducted with *C. inophyllum* oil. DF is the operation in DF mode, and the test was conducted in a combination of *C. inophyllum* oil as the pilot fuel with producer gas. The control factors with corresponding levels are mentioned in Table 7.

Based on the control factors and their corresponding levels, a DOE is provided by the Taguchi method used for analysis. In this work, for three control factors (CR, load, and fuel mode)

Table 7. Control Factors with Levels

control factors	level 1	level 2	level 3
CR	14	16	18
load (kg)	4	8	12
fuel mode	SF1 (diesel fuel)	SF2 (<i>C. inophyllum</i> oil)	DF (<i>C. inophyllum</i> oil and producer gas)

and their respective levels, the L9 orthogonal array was presented as the DOE and are shown in Table 8.

Table 8. Orthogonal Array for Control Factors and Noise Factors

L16 orthogonal array for control factors			
no	load	CR	fuel mode
1	4	14	D100
2	4	16	P100
3	4	18	P100 & PG
4	8	14	P100
5	8	16	P100 & PG
6	8	18	D100
7	12	14	P100 & PG
8	12	16	D100
9	12	18	P100

The experiments were carried out according to the DOE provided by the Taguchi approach. The S/N ratio was used to calculate the effect of factors. The following formulae were employed for "larger is better" quality characteristics for BTE and "smaller is better" quality characteristics for CO, HC, and NO_x emissions.

$$\text{Larger is better: } \frac{S}{N} \text{ratio}_{\text{BTE}} = -10 \log \left(\frac{1}{n} \sum_{i=1}^n \frac{1}{y_i^2} \right) \quad (4)$$

$$\text{Smaller is better: } \frac{S}{N} \text{ratio}_{\text{CO, HC and NO}_x} = -10 \log \left(\frac{1}{n} \sum_{i=1}^n y_i^2 \right) \quad (5)$$

The better performance is associated with a higher S/N ratio, and the optimum value of various control parameters is determined related to a greater S/N ratio, as shown in Table 9.

From Taguchi analysis, the percentage contribution of each factor to the performance and emission characteristics was determined for the test engine and are given in Table 10. Delta is calculated for each factor. It is the difference between the maximum and minimum S/N ratio for a particular control factor. The contribution rate is the ratio between the individual delta of a factor and the total delta of all three factors.

2.4. Grey Relational Analysis. GRA is generally useful for evaluating the relationship degree between sequences and Grey relational grade (GRG). GRA is commonly used to integrate all of the performance characteristics that are analyzed into a single number, which is generally the solution to the optimization problem. There are two steps for solving GRA. In the first step, it is needed to convert the data into S/N ratio, and in the second step, the data is pre-processed by normalization of data in the range of zero and one.

An investigation used Taguchi's orthogonal L9 array to optimize the engine fueled with a blend of diesel, biofuel, and a small volume percentage of hexyl nitrate. Using the analysis of

Table 9. Experimental Response and S/N Ratio

run	control factors			experimental response						S/N ratio (dB)					
	load	CR	fuel type	BTE	BSFC	CO	NO _x	HC	opacity	BTE	BSFC	CO	NO _x	HC	opacity
1	4	14	D100	23	0.84	0.26	113	60	60	27.2346	1.7237	11.7	-41.06	-35.56	-35.417
2	4	16	P100	22.7	0.85	0.22	164	37	35	27.1358	1.4116	13.15	-44.3	-31.36	-32.041
3	4	18	P100 & PG	15.9	0.38	0.54	121	57	62	24.0279	8.4043	5.352	-41.66	-35.12	-33.979
4	8	14	P100	24	0.75	0.24	219	60	51	27.6042	2.4988	12.58	-46.81	-35.56	-33.064
5	8	16	P100 & PG	15	0.36	0.55	188	65	52	23.5218	8.8739	5.193	-44.71	-36.26	-34.32
6	8	18	D100	27.4	0.56	0.17	267	29	30	28.7391	5.0362	15.39	-49.07	-29.25	-32.465
7	12	14	P100 & PG	15.4	0.35	0.63	176	77	46	23.7729	9.1186	4.013	-45.8	-37.73	-34.964
8	12	16	D100	27.2	0.52	0.21	400	48	65	28.6914	5.3521	13.76	-51.6	-33.62	-33.625
9	12	18	P100	27.9	0.59	0.19	428	33	32	28.8996	4.583	14.42	-52.63	-30.37	-29.827

Table 10. Contribution of Control Factors to Experimental Performance

BTE (%)				BSFC (kg/kW h)				CO Emission (ppm)			
level	load	CR	fuel mode	level	load	CR	fuel mode	level	load	CR	fuel mode
1	26.13	26.2	28.22	1	3.847	4.447	4.037	1	10.068	9.431	13.619
2	26.62	26.45	27.88	2	5.47	5.213	2.831	2	11.054	10.703	13.385
3	27.12	27.22	23.77	3	6.351	6.008	8.799	3	10.734	11.723	4.853
delta	0.99	1.02	4.45	delta	2.505	1.561	5.968	delta	0.986	2.292	8.766
rank	3	2	1	rank	2	3	1	rank	3	2	1
contribution ratio %	15.32	15.78	68.88	contribution ratio %	24.96	15.55	59.47	contribution ratio %	8.18	19.03	72.78
NO _x emission (ppm)				HC emission (ppm)				opacity (HSU)			
level	load	CR	fuel mode	level	load	CR	fuel mode	level	load	CR	fuel mode
1	-42.34	-44.56	-47.24	1	-34.01	-36.29	-32.81	1	-33.81	-34.48	-33.84
2	-46.86	-46.87	-47.91	2	-33.69	-33.75	-32.43	2	-33.28	-33.33	-31.64
3	-50.01	-47.78	-44.06	3	-33.91	-31.58	-36.37	3	-32.81	-32.09	-34.42
delta	7.67	3.23	3.86	delta	0.33	4.71	3.94	delta	1.01	2.39	2.78
rank	1	3	2	rank	3	1	2	rank	3	2	1
contribution ratio %	51.96	21.88	26.15	contribution ratio %	3.67	52.45	43.87	contribution ratio %	16.34	38.67	44.98

Taguchi and Grey, the optimum value of BTE and BSFC was found.⁴⁰ The optimum combination of parameters was developed by GRA for a biodiesel fueled diesel engine. At 80% load and a speed of 1900 rpm, with a blend of 50% biodiesel at 15.50 BTDC and at 225 bar injection pressure, optimum values of the engine were obtained.⁴¹ For finding out the optimal value of input parameters like fuel ratio and load intensity, a diesel engine using a blend of diesel, Mahua biodiesel, and mixtures of methanol additives was optimized by GRA.⁴² An experiment using the Grey–Taguchi method was carried out to determine the value of input parameters for the best possible engine performance for a diesel engine using blended Karanja oil and methyl ester. It was concluded that the B50 blend was found to be the most suitable blend with a corresponding 17:1 CR and at 80% load.³⁸ The Taguchi–GRA was performed on a diesel engine fueled with a blend of Thumba biodiesel and diesel. A blend of 30% Thumba biodiesel at 14:1 CR, 250 bar fuel injection pressure, and 20° BTDC showed maximum possible performances with minimum emissions from the engine.⁴³

This normalized data is divided into two categories, one in which “larger is better” and in the other “smaller is better”. If the output answer falls into the “bigger is better” group, it is stated using eq 6 below.

$$C_i(e) = \frac{[x_i(e)_{\max} - x_i(e)]}{[x_i(e)_{\max} - x_i(e)_{\min}]} \quad (6)$$

where $x_i(e)$ is the original sequence. $C_i(e)$ is the sequence for comparing, $i = 1, 2, 3, 4, \dots, n$ ($Q_n =$ total number of experiments), and $e = 1, 2, 3, 4, \dots, m$ ($Q_m =$ total number of responses).

If the result falls in “smaller is better” category, then eq 7 may be considered

$$C_i(e) = \frac{[x_i(e) - x_i(e)_{\max}]}{[x_i(e)_{\max} - x_i(e)_{\min}]} \quad (7)$$

Following the normalization of the sequence, the deviation of the sequence for all outputs is determined, and the Grey relational coefficient (GRC) was calculated by using the relationship provided in eq 8.

$$\text{GRC} = \frac{d_{\min} + \psi d_{\max}}{d_{oi} + \psi d_{\max}} \quad (8)$$

where d_{oi} is the deviation of the sequences for all responses. d_{\max} and d_{\min} are the maximum and minimum deviations of all comparing sequences. ψ is the identification coefficient, whose value lies in between 0 and 1. Here, its value is considered as 0.5. Then, Grey relational grade (GRG) can be found using eq 9.

Table 11. Analysis of Variance

BTE (%)						BSFC (kg/kW h)					
source	DF	Adj SS	Adj MS	F-value	P-value	source	DF	Adj SS	Adj MS	F-value	P-value
regression	4	223.544	55.886	182.86	0	regression	4	0.298589	0.074647	71.66	0.001
load	1	13.083	13.0833	42.81	0.003	load	1	0.05415	0.05415	51.98	0.002
CR	1	12.528	12.5282	40.99	0.003	CR	1	0.02535	0.02535	24.34	0.008
fuel mode type	2	197.933	98.9663	323.81	0	fuel mode type	2	0.219089	0.109544	105.16	0
error	4	1.223	0.3056			error	4	0.004167	0.001042		
total	8	224.767				total	8	0.302756			
R-sq = 99.46%, R-sq(adj) = 98.91%, R-sq(pred) = 97.43%						R-sq = 98.62%, R-sq(adj) = 97.25%, R-sq(pred) = 92.43%					
CO emission (ppm)						NO _x emission (ppm)					
source	DF	Adj SS	Adj MS	F-value	P-value	source	DF	Adj SS	Adj MS	F-value	P-value
regression	4	0.26766	0.06692	168.16	0	regression	4	97611	24402.7	59.48	0.001
load	1	4 × 10 ⁻⁶	4 × 10 ⁻⁶	0.01	0.923	load	1	61004	61004.2	148.68	0
CR	1	0.00844	0.00844	21.2	0.01	CR	1	15606	15606	38.04	0.004
fuel mode type	2	0.25922	0.12961	325.72	0	fuel mode type	2	21001	10500.3	25.59	0.005
error	4	0.00159	0.0004			error	4	1641	410.3		
total	8	0.26925				total	8	99252			
R-sq = 99.41%, R-sq(adj) = 98.82%, R-sq(pred) = 96.81%						R-sq = 98.35%, R-sq(adj) = 96.69%, R-sq(pred) = 91.32%					
HC emission (ppm)						opacity (HSU)					
source	DF	Adj SS	Adj MS	F-value	P-value	source	DF	Adj SS	Adj MS	F-value	P-value
regression	4	1942.22	485.556	52.97	0.001	regression	4	586.833	146.708	81.88	0
load	1	6	6	0.65	0.464	load	1	32.667	32.667	18.23	0.013
CR	1	962.67	962.667	105.02	0.001	CR	1	228.167	228.167	127.35	0
fuel mode type	2	973.56	486.778	53.1	0.001	fuel mode type	2	326	163	90.98	0
error	4	36.67	9.167			error	4	7.167	1.792		
total	8	1978.89				total	8	594			
R-sq = 98.15%, R-sq(adj) = 96.29%, R-sq(pred) = 92.01%						R-sq = 98.79%, R-sq(adj) = 97.59%, R-sq(pred) = 92.78%					

$$\text{GRG} = \frac{\sum_{\ell=1}^m \text{GRC}}{m} \quad (9)$$

3. RESULTS AND DISCUSSION

3.1. Model Prediction and Analysis of Variance. The optimization software develops a linear mathematical model for different output responses using linear regression analysis as functions of input variables. The mathematical equations predicted for different responses are given below.

The predictive equations formed for the BP, SFC, CO, and NO_x emissions are as follows

$$\text{BTE} = C_{\text{Fuelmode}} + 0.3692 \text{ load} + 0.723 \text{ CR} \quad (10)$$

where the C values for different fuel modes are $C_{\text{SF1}} = 11.34$, $C_{\text{SF2}} = 10.35$, and $C_{\text{DF}} = 0.93$.

$$\text{BSFC} = C_{\text{Fuelmode}} - 0.02375 \text{ load} - 0.0235 \text{ CR} \quad (11)$$

where the C values for different fuel modes are $C_{\text{SF1}} = 1.35$, $C_{\text{SF2}} = 1.44$, and $C_{\text{DF}} = 1.073$.

$$\text{CO emission} = C_{\text{Fuelmode}} + 0.00021 \text{ load} - 0.01875 \text{ CR} \quad (12)$$

where the C values for different fuel modes are $C_{\text{SF1}} = 0.51$, $C_{\text{SF2}} = 0.5133$, and $C_{\text{DF}} = 0.8717$.

$$\text{NOx emission} = C_{\text{Fuelmode}} + 35.21 \text{ load} + 25.5 \text{ CR} \quad (13)$$

where the C values for different fuel modes are $C_{\text{SF1}} = -350.7$, $C_{\text{SF2}} = -339.3$, and $C_{\text{DF}} = -447.0$.

$$\text{HC emission} = C_{\text{Fuelmode}} + 0.25 \text{ load} - 6.333 \text{ CR} \quad (14)$$

where the C values for different fuel modes are $C_{\text{SF1}} = 148.0$, $C_{\text{SF2}} = 144.3$, and $C_{\text{DF}} = 168.0$.

$$\text{Opacity} = C_{\text{Fuelmode}} - 0.583 \text{ load} - 3.083 \text{ CR} \quad (15)$$

where the C values for different fuel modes are $C_{\text{SF1}} = 103.67$, $C_{\text{SF2}} = 92.67$, and $C_{\text{DF}} = 106.67$.

The R²-value shows the capability of the model to predict output responses, which vary from 0 to 1. The R²-value close to 1 or more than 90% shows a good model fit to relate the independent and dependent variables effectively. The present developed models for BTE, BSFC, CO emission, NO_x emission, and HC emission, and opacity with R²- values of 99.46, 98.62, 99.41, 98.35, 98.15, and 98.79%, respectively, are shown in Table 11.

3.2. Effect of Input Parameters on Output Responses.

3.2.1. Brake Thermal Efficiency. The effect of load, CR, and fuel mode on BTE is shown in Figure 3. It is observed in Figure 3 that the maximum BTE is achieved at the load of 12 kg, CR of 18, and in diesel fuel for “larger is better” quality characteristics. The contribution ratio of load, CR, and fuel mode for BTE is given in Table 10. The fuel mode contributes the most with a contribution percentage of 68.88%, followed by CR and load with contribution percentages of 15.78 and 15.32%, respectively. As a result, the fuel mode has a considerable impact on the BTE.

In Figure 4, the influence of input parameters on the BTE is also represented in the form of surface contour plots for better understanding and visibility. It is found from Figure 4 that the maximum BTE is obtained at a CR of 18 and a load intensity of 12 kg with diesel fuel, confirming the results of Figure 3. The BTE increases with an increase in load intensity and CR and decreases with fuel mode changes. Similar results have

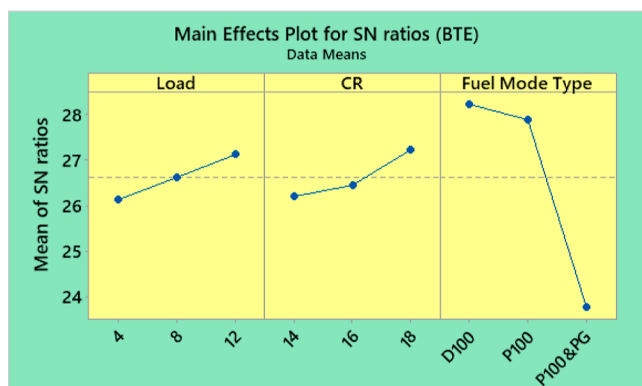


Figure 3. Effect of input parameters on BTE.

been observed in refs 44 and 45 for fuel mode type. The lower BTE achieved in the DF operation is due to the effects of residual gas, residual combustion gas, low combustion temperature, and higher fuel flow during test engine operation. The slower flame propagation rate causes the negative work of compression. This is another cause of lower engine performance in terms of BTE. With *C. inophyllum* oil in SF2 mode and *C. inophyllum* oil–producer gas blend in DF mode, the BTE falls by nearly 5 and 12.5%, respectively, as compared to diesel fuel. According to the findings, proposed alternative fuels are suggested to be used in stationary engines for electricity generation and as a substitute of diesel fuel but restricted for use in automotive engines for lower performance, that is, BTE.

3.2.2. Brake-Specific Fuel Consumption. The effect of load, CR, and fuel mode on BSFC is shown in Figure 5. It is observed from Figure 5 that the minimum BSFC is achieved at the load of 12 kg, CR of 18, and in DF mode for “smaller is better” quality characteristics. The contribution ratio of load, CR, and fuel mode for BSFC is given in Table 10. The fuel mode contributes the most with a contribution percentage of 59.47%, followed by load and CR with contribution percentages of 24.96 and 15.55%, respectively. As a result, the fuel mode has a considerable impact on the BSFC.

In Figure 6, the influence of input parameters on the BSFC is also represented in the form of surface contour plots for better understanding and visibility. It is found from Figure 6 that the minimum BSFC is obtained at a CR of 18 and a load

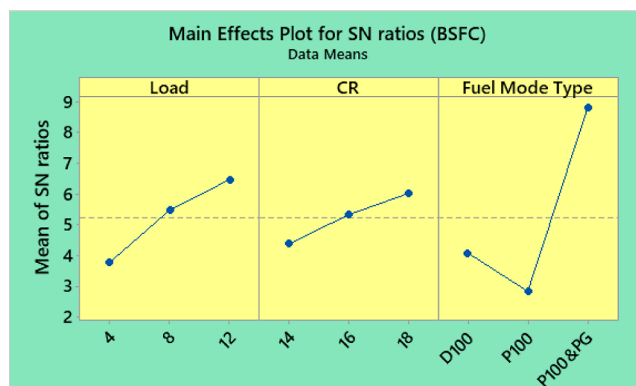


Figure 5. Effect of load, CR, and fuel mode on the BSFC.

intensity of 12 kg with DF confirming the results of Figure 5. The BSFC decreases with an increase in load intensity and CR; however, it initially decreases and later increases with fuel mode changes from SF1 to DF. Similar results have been observed for the fuel mode type in refs 46 and 47. Increasing the load and CR ensures better combustion with increasing cylinder pressure and temperature in the combustion chamber, thereby reducing BSFC in the test engine. Despite having a lower BTE in DF mode, the *C. inophyllum* oil–producer gas blend can be used in stationary engines as a diesel fuel substitute due to its superior fuel economy, although *C. inophyllum* oil in SF2 mode fails in that regard.

3.2.3. CO Emission. The effect of load, CR, and fuel mode on CO emission is shown in Figure 7. It is observed from Figure 7 that the minimum CO emission is achieved at the load of 8 kg, CR of 18, and in diesel fuel for “smaller is better” quality characteristics. The contribution ratio of load, CR, and fuel mode for CO emission is given in Table 10. The fuel mode contributes the most with a contribution percentage of 72.78%, followed by CR and load with contribution percentages of 19.03, and 8.18%, respectively. As a result, the fuel mode has a considerable impact on CO emissions.

In Figure 8, the influence of input parameters on CO emission is also represented in the form of surface contour plots for better understanding and visibility. It is found in Figure 8 that the minimum CO emission is obtained at a CR of 18 and a load intensity of 8 kg with diesel fuel confirming the

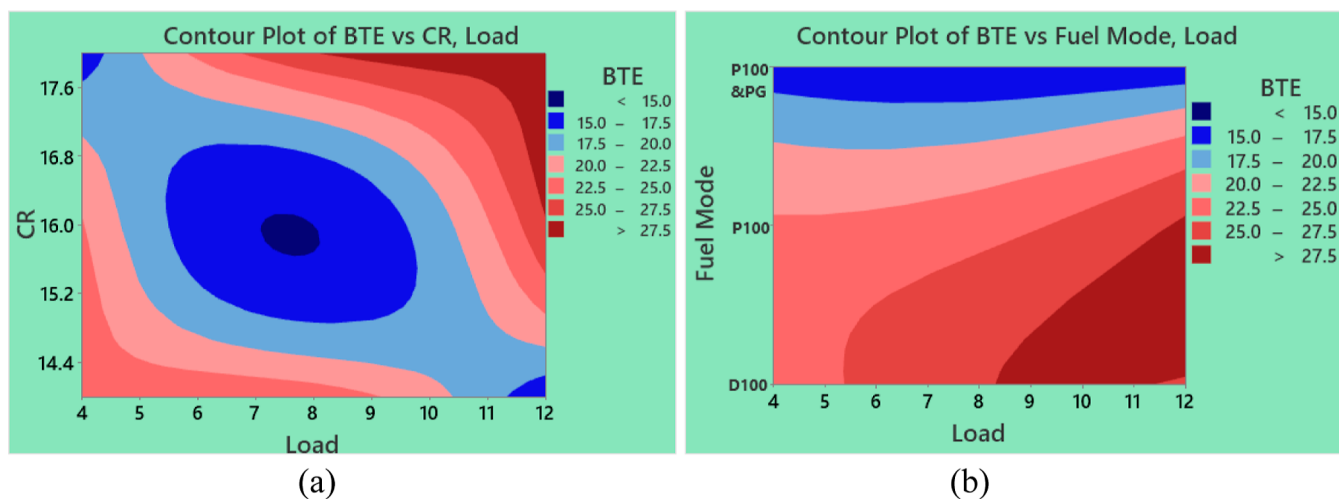


Figure 4. Contour plots of BTE: (a) CR and load; (b) fuel mode and load.

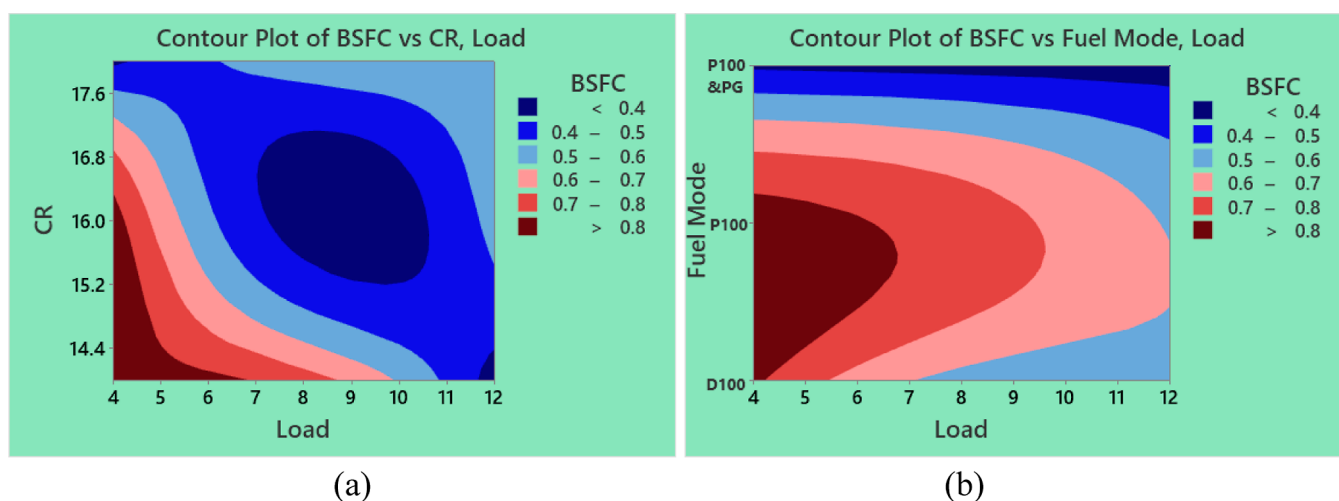


Figure 6. Contour plots of BSFC: (a) CR and load; (b) fuel mode and load.

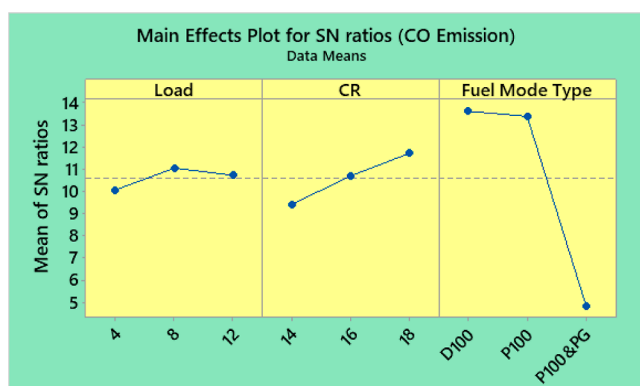


Figure 7. Effect of load, CR, and fuel mode on the CO emission.

results of Figure 7. The CO emission decreases with an increase in CR and increases with changes in fuel mode from SF1 to DF. With load increment, the CO emission initially decreases and afterward increases. *C. inophyllum* oil emits less CO in a SF mode than diesel fuel because *C. inophyllum* oil contains about 11% oxygen by weight, resulting in more

thorough combustion. Furthermore, *C. inophyllum* oil has a reduced stoichiometric requirement for air, allowing the mixture to burn efficiently. The trend found in this experiment is similar to the research article in ref 48. It also ensured that, under all test settings and CRs, the CO content in DF mode of operation is significantly higher than that in the SF mode of operation. This is because the addition of producer gas with *C. inophyllum* oil, rather than fresh air, increases the CO content in the mixture, as producer gas contains 20% CO (by vol. percentage). The reduced CO emissions produced by *C. inophyllum* oil in SF2 mode make it superior to diesel fuel; however, the higher CO emissions produced by the blend of *C. inophyllum* oil and producer gas in DF mode make it unsuitable for use in stationary engines.

3.2.4. NO_x Emission. The effect of load, CR, and fuel mode on NO_x emission is shown in Figure 9. It is observed in Figure 9 that the minimum NO_x emission is achieved at the load of 4 kg, CR of 14, and in DF for “smaller is better” quality characteristics. The contribution ratio of load, CR, and fuel mode for NO_x emission is given in Table 10. The load contributes the most with a contribution percentage of 51.96%, followed by fuel mode and load with contribution percentages

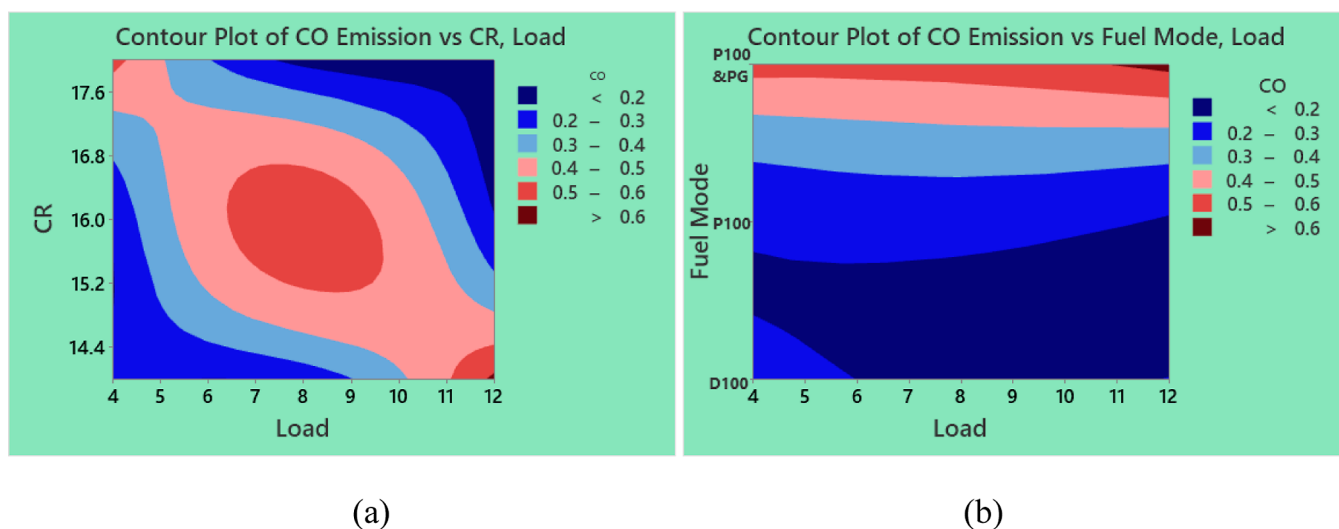


Figure 8. Contour plots of CO emission: (a) CR and load; (b) fuel mode and load.

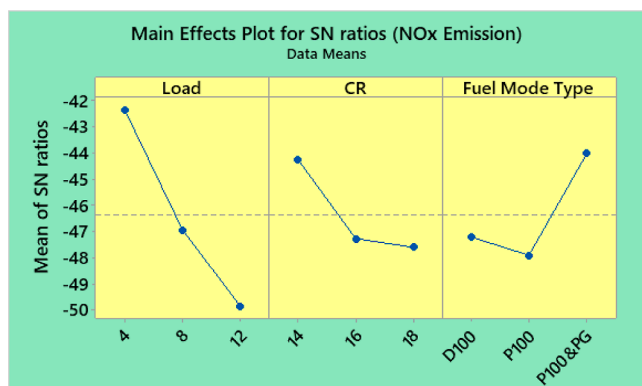


Figure 9. Effect of load, CR, and fuel mode on the NO_x emission.

of 26.15 and 21.88%, respectively. As a result, the load has a considerable impact on the NO_x emission.

In Figure 10, the influence of input parameters on NO_x emission is also represented in the form of surface contour plots for better understanding and visibility. It is found in Figure 10 that the minimum NO_x emission is obtained at the CR of 14 and load intensity of 4 kg with DF confirming the results of Figure 9. Similar findings^{49,50} show that when used in the SF mode, *C. inophyllum* oil releases greater amount of NO_x than diesel fuel. Faster injection and early injection characteristics of *C. inophyllum* oil lead to higher combustion pressure and higher temperature, which encourage more NO_x emissions to be produced. Due to the presence of CO_2 in the producer gas, the concentrations of NO_x emissions in the DF mode of operation are lower than in the SF mode of operation using *C. inophyllum* oil or diesel fuel. CO_2 dilutes the oxygen concentration in the *C. inophyllum* oil that is consumed. When compared with a SF mode of operation, CO_2 from the producer gas improves the specific heat capacity of the DF, delaying flame propagation and decreasing the combustion temperature. According to the findings, even if it may have a lower BTE in DF mode, the *C. inophyllum* oil–producer gas blend can effectively substitute diesel fuel in stationary engines due to its lower NO_x emission. However, due to its greater NO_x emission and ineffectiveness as a diesel fuel replacement,

C. inophyllum oil in SF2 mode is not recommended for the same.

3.2.5. *HC Emission.* The effect of load, CR, and fuel mode on the HC emission is shown in Figure 11. It is observed from

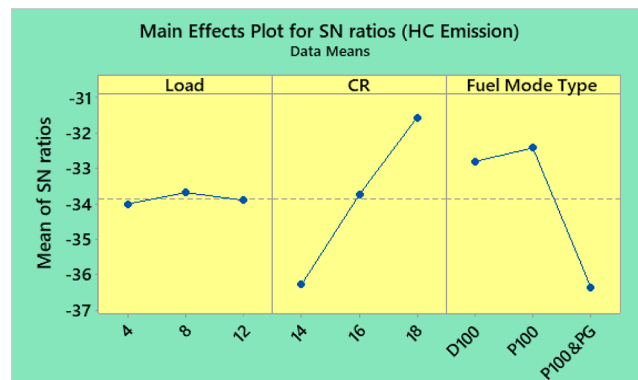


Figure 11. Effect of load, CR, and fuel mode on the HC emission.

Figure 11 that the minimum HC emission is achieved at the load of 8 kg, CR of 18, and in *C. inophyllum* oil for “smaller is better” quality characteristics. The contribution ratio of load, CR, and fuel mode for HC emission is given in Table 10. The CR contributes the most with a contribution percentage of 52.45%, followed by fuel mode and load with contribution percentages of 43.87 and 3.67%, respectively. As a result, the CR has a considerable impact on HC emissions.

In Figure 12, the influence of input parameters on HC emission is also represented in the form of surface contour plots for better understanding and visibility. It is found in Figure 12 that the minimum HC emission is obtained at the CR of 18 and load intensity of 8 kg with SF2, that is, *C. inophyllum* oil conforming to the results of Figure 11. The HC emission decreases with an increase in CR. It can also be noticed that HC emission initially decreases and later increases with an increase in load and changes in fuel mode from SF1 to DF. In a SF mode of operation, diesel fuel emits more HC than *C. inophyllum* oil. The HC concentration is lower because *C. inophyllum* oil contains more than 11% oxygen by weight, resulting in more complete combustion and fewer incomplete

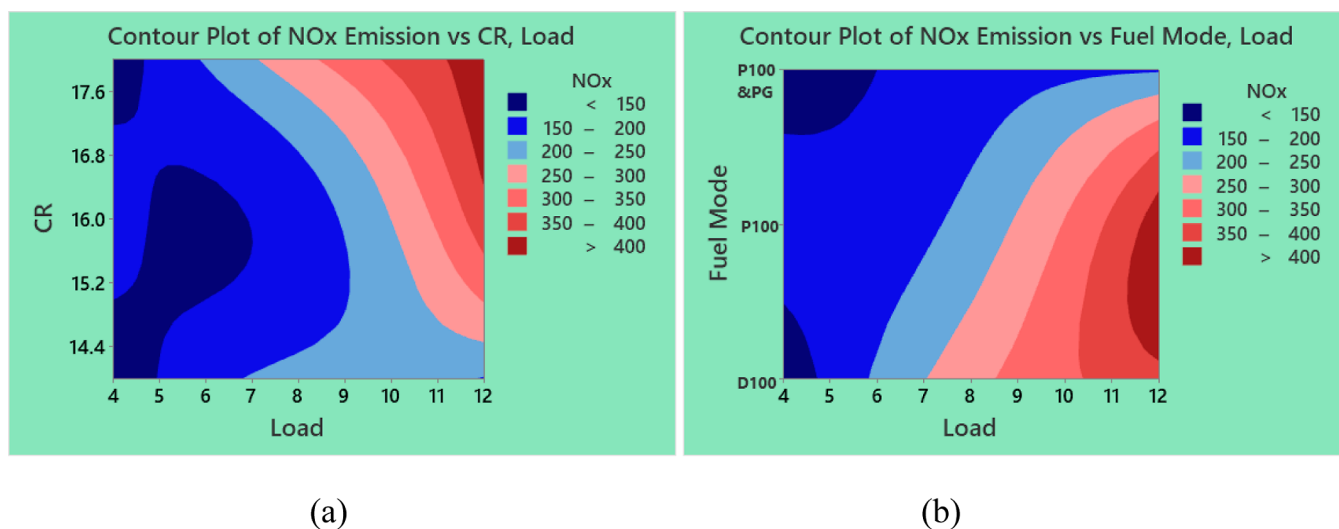


Figure 10. Contour plots of NO_x emission: (a) CR and load; (b) fuel mode and load.

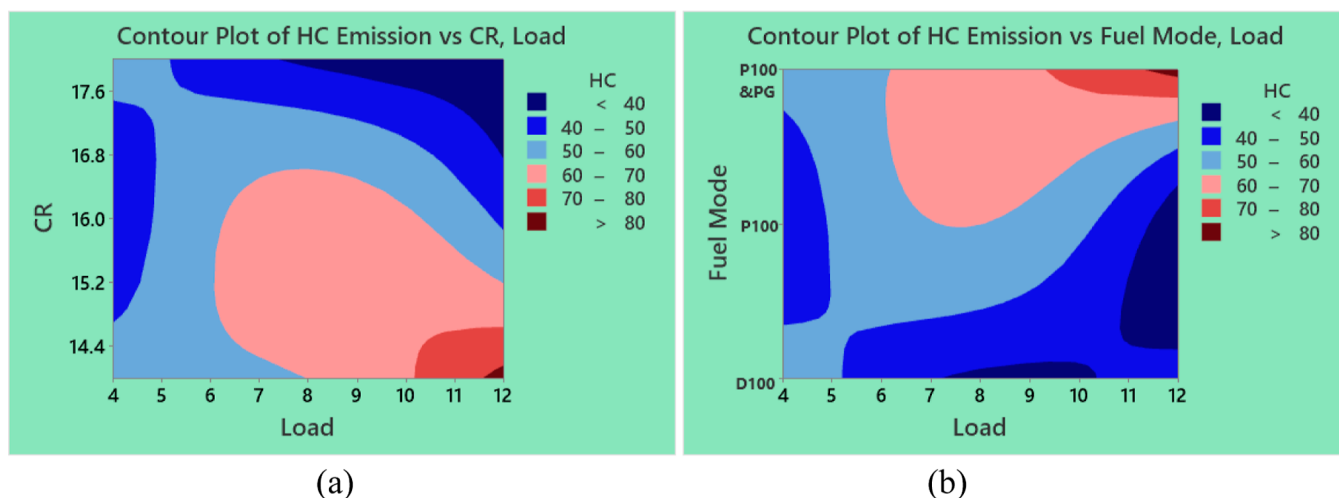


Figure 12. Contour plots of HC emission: (a) CR and load; (b) fuel mode and load.

combustion particles, as confirmed by similar published research works.^{39,49,50} *C. inophyllum* oil also has low stoichiometric requirement for air, resulting in more efficient combustion of the air–fuel mixture. In DF mode, the inclusion of producer gas in the combustion chamber increases the CO₂ content instead of fresh air, causing ignition delay when compared to diesel fuel. As a result of the unburned air–gas mixture, incomplete combustion occurs more frequently, resulting in increased HC emissions. The *C. inophyllum* oil in SF2 mode results in lower HC emissions and can replace diesel fuel used in the stationary engine; however, the higher HC emissions produced by the blend of *C. inophyllum* oil and producer gas in DF mode make it unsuitable for the same.

3.2.6. Opacity. The effect of load, CR, and fuel mode on opacity is shown in Figure 14. It is observed in Figure 14 that

minimum opacity is obtained at the CR of 18 and load intensity of 8 kg with SF2, that is, *C. inophyllum* oil conforming to the results of Figure 13. The current result is confirmed by similar findings^{50,51} that the opacity decreases with an increase in the CR, as a higher CR boosts the cylinder pressure and temperature inside the combustion chamber, ensures complete combustion, and reduces the test engine's opacity. At all CRs, the SF and DF modes of operation using *C. inophyllum* oil have lesser capacity than the SF mode of operation with diesel fuel. *C. inophyllum* oil contains about 11% oxygen and has a low stoichiometric requirement for air, resulting in more efficient combustion, complete combustion, and less soot formation. Producer gas also has a low sulfur content, resulting in low soot emissions. From aforementioned results, one can say that the *C. inophyllum* oil in SF2 mode can be used in stationary engines as a substitute of diesel fuel due to its lower opacity, whereas the blend of *C. inophyllum* oil and producer gas in DF mode fails in that regard due to its higher value.

3.3. Multiple Performance Optimization Using Taguchi–Grey Analysis. In this study, a multiple response optimization, that is, maximization of performance and minimization of engine emissions were performed using Taguchi–Grey analysis. In literature, numerous works using Taguchi–Grey analysis had been performed in fields of alternate fuels, thermal energy systems, and other for determining optimum conditions pertaining to the input parameters.

The transformation of data into the S/N ratio is shown in Table 9. Eqs 6 and 7 were used to pre-process the data into normalized values in two categories. Table 12 shows the normalized value and the deviation sequences.

After determining the deviation sequence, GRC was calculated for each response using eq 8, and GRG was determined using eq 9, as shown in Table 13.

The first rank, which is the sixth run of the experiment, is given to the S/N ratio with the highest value. The GRG response table was designed after the rankings were allocated. The average of the GRG of each factor at the given level was then calculated to obtain the mean of the GRG for each factor.

The ratings in Table 14 indicate the degree of correlation between the reference sequence and the GRG compatibility sequence. The stronger the correlation, the higher the mean

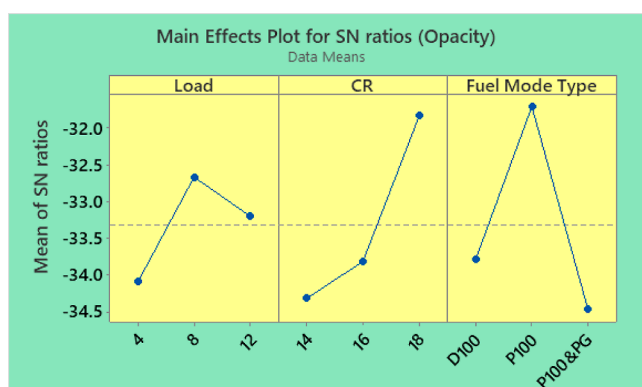


Figure 13. Effect of load, CR, and fuel mode on the opacity.

the minimum opacity is achieved at the load of 8 kg, CR of 18, and in SF2, that is, *C. inophyllum* oil for “smaller is better” quality characteristics. The contribution ratio of load, CR, and fuel mode for opacity is given in Table 10. The fuel mode contributes the most with a contribution percentage of 44.98%, followed by CR and load with contribution percentages of 38.67 and 46.34%, respectively. As a result, the fuel mode has a considerable impact on opacity.

In Figure 14, the influence of input parameters on opacity is also represented in the form of surface contour plots for better understanding and visibility. It is found in Figure 14 that the

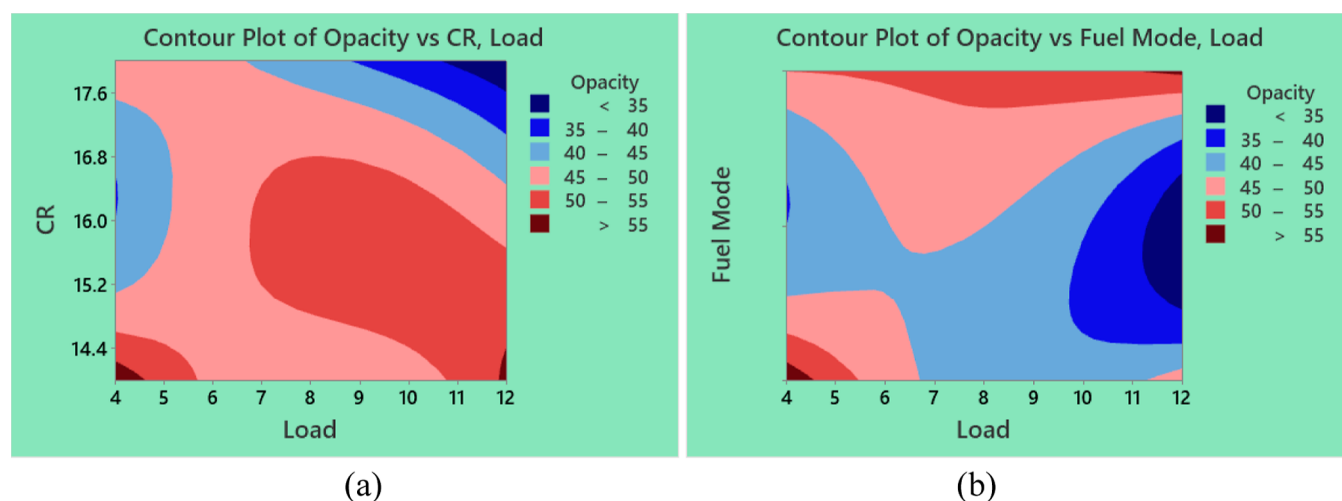


Figure 14. Contour plots of opacity: (a) CR and load; (b) fuel mode and load.

Table 12. Normalized and Deviation Sequences

run	normalized sequence						deviation sequences					
	BTE	BSFC	CO Emi.	NO _x Emi.	HC Emi.	opacity	BTE	BSFC	CO Emi.	NO _x Emi.	HC Emi.	opacity
1	0.622	0.020	0.804	1	0.354	0.143	0.378	0.980	0.196	0	0.646	0.857
2	0.602	0	0.891	0.838	0.833	0.857	0.398	1	0.109	0.162	0.167	0.143
3	0.070	0.940	0.196	0.975	0.417	0.086	0.930	0.060	0.804	0.025	0.583	0.914
4	0.700	0.200	0.859	0.663	0.354	0.400	0.300	0.800	0.141	0.337	0.646	0.600
5	0	0.980	0.174	0.762	0.250	0.371	1	0.020	0.826	0.238	0.750	0.629
6	0.960	0.580	1	0.511	1	1	0.040	0.420	0	0.489	0	0
7	0.034	1	0	0.800	0	0.543	0.966	0	1	0.200	1	0.457
8	0.949	0.660	0.924	0.089	0.604	0	0.051	0.340	0.076	0.911	0.396	1
9	1	0.520	0.957	0	0.917	0.943	0	0.480	0.043	1	0.083	0.057

Table 13. GRC and GRG

run	GRC							GRG	S/N ratio	rank
	BTE	BSFC	CO emission	NO _x emission	HC emission	opacity				
1	0.570	0.338	0.719	1	0.436	0.368	0.572	-4.8549	5	
2	0.557	0.333	0.821	0.755	0.750	0.778	0.666	-3.5335	3	
3	0.350	0.893	0.383	0.952	0.462	0.354	0.565	-4.9524	6	
4	0.625	0.385	0.780	0.598	0.436	0.455	0.546	-5.2514	7	
5	0.333	0.962	0.377	0.677	0.400	0.443	0.532	-5.4807	9	
6	0.927	0.543	1	0.506	1	1	0.829	-1.6261	1	
7	0.341	1	0.333	0.714	0.333	0.522	0.541	-5.3402	8	
8	0.907	0.595	0.868	0.354	0.558	0.333	0.603	-4.3988	4	
9	1	0.510	0.920	0.333	0.857	0.897	0.753	-2.4639	2	

Table 14. Response Table of GRGs

factors	level 1	level 2	level 3	delta	rank
load	0.601	0.6359	0.6321	0.0349	3
CR	0.553	0.6002	0.7159	0.163	1
fuel mode	0.6679	0.655	0.5461	0.1218	2
mean of GRG = 0.623011					

GRG values. Table 10 shows how the data can be used to generate a combination of optimal parameters that improve the overall response.

Level 2 of load, level 3 of CR ratio, and level 1 of fuel mode have the highest GRG, according to Table 14. As a result, the engine's best performance is achieved when the load is 8 kg, the CR is 18, and the fuel is common diesel.

3.3.1. Analysis of Variance for GRG. Analysis of variance for GRG was done to find out the percentage contribution of each factor to the output responses with a significance level of 5%. Table 15 shows that CR is the most significant factor with a contribution of 57.14%, followed by fuel mode and load with contributions of 37.38 and 3.71%, respectively. Also, the R^2 -value is more than 90%, which states that the GRG model has a good fit.

3.3.2. Confirmation Test. The final stage in the Grey analysis is to predict and verify the quality features using the equation below once the optimal condition is achieved.

$$\text{GRG}_{\text{predicted}} = \text{GRG}_{\text{mean}} + \sum_{i=1}^q (\text{GRG}_{\text{oi}} - \text{GRG}_{\text{mean}}) \quad (16)$$

Table 15. Analysis of Variance

source	DF	Adj SS	Adj MS	F-value	P-value	% contribution
load	2	0.002963	0.001481	2.12	0.32	3.719516789
CR	2	0.045505	0.022752	32.62	0.03	57.14142201
fuel type	2	0.029774	0.014887	21.34	0.045	37.38855263
error	2	0.001395	0.000697			
total	8	0.079637				
S	R-sq	R-sq(adj)	R-sq(pred)			
0.0264097	98.25%	92.99%	64.53%			

where q = quantity or no of factors, GRG_{oi} = maximum of average GRG, and GRG_{mean} = mean of GRG.

Validation of the outcome is required and a confirmation test is conducted. The predicted GRG is calculated by using eq 16. The initial condition parameters are taken by considering the mean of the GRG table and then finding out the value in the GRG in Table 14 which is nearest to the mean value.

From Table 16, it can be observed that the confirmation test result is in good agreement with the predicted values. Also, an

Table 16. Result of the Confirmation Test

initial design parameters	optimal design parameters	
	prediction	experiment
setting level L3 CR2 SF1 (diesel fuel)	L2 CR3 SF1 (diesel fuel)	L2 CR3 SF1 (diesel fuel)
GRG	0.60264	0.7736
improvement in GRG	28.38%	22.75%

improvement of 22.75% is observed in the GRG. The improvement results aim at the validity of the Taguchi method with Grey analysis for better performance of the CI engine under different loads, CRs, and fuel conditions..

4. CONCLUSIONS

The effect of producer gas–C. inophyllum oil–diesel blend on CI engine performance was investigated in this study. By altering the input factors such as engine load, CR, and fuel mode, several test runs were done at a constant speed of 1500 rpm to predict the performance and emission characteristics of the test engine. For this study, BTE and BSFC were regarded as performance features, while CO, HC, and NO_x emissions and opacity were considered as emission characteristics. To predict the optimum performance, the Taguchi method provided an L9 orthogonal array experiment design, which decreased the time and expense of running the experiments. Taguchi–GRA was used to determine the optimal value of input factors which helped in finding the optimum output responses. This study's findings can be summarized as follows:

- Considerable increase in BTE and NO_x emission, as well as decrement in BSFC, is noticed concerning load increment. Early decrement and later increment in CO emission, HC emission, and opacity are also observed related to a rise in load. Load is determined as the most promising factor for NO_x emission with a contribution of 51.96%.
- Considerable increase in BTE and NO_x emission, as well as decrement in BSFC, CO emission, HC emission, and opacity, is noticed with regard to a rise in CR. CR is determined as the most promising factor for HC emission with a contribution of 52.45%.

- Considerable increase in CO emission and decrement in BTE is noticed concerning changes in the fuel mode from SF1 to DF. Early increment and later decrement in BSFC and NO_x emission are also observed related to changes in the fuel mode from SF1 to DF. However, early decrement and later increment in HC emission and opacity are also observed related to changes in the fuel mode from SF1 to DF. The fuel mode is determined as the most promising factor for BTE, BSFC, CO emission, and opacity with contributions of 68.88, 59.47, 72.78, and 44.98%, respectively.

- In order to substitute fossil fuels, tested alternative fuels, such as C. inophyllum oil and C. inophyllum oil–producer gas blend, are recommended to retrofit in existing stationary unmodified diesel engines used for electricity generation; however, they are restricted for use in automotive engines because of their lower engine performance, that is, BTE.

- Despite having a lower engine performance, BTE in DF mode, the C. inophyllum oil–producer gas blend is best suited for stationary engines to replace diesel fuel because of its better fuel economy and lower NO_x emission. However, C. inophyllum oil in SF2 mode makes it preferable to diesel fuel due to its lower CO emission, HC emission, and smoke opacity.

- More experiments may be carried out by varying producer gas % in C. inophyllum oil–producer gas blend. Nanoparticles with different volume fractions may be added to C. inophyllum oil or C. inophyllum oil–producer gas blend for enhanced performance and reduced emission of the test engine. The addition of C. inophyllum oil in the test engine at different elevated temperatures may be experimented with. The effects of varying the injection pressure and injection angle of C. inophyllum oil inclusion on the test engine may be evaluated. These may be considered as the future scope of the current study.

- The overall performance optimization of the CI engine had been conducted using the Taguchi–GRA technique. 12 kg load, CR of 18, and diesel fuel were found as the optimum input parameters.

- A confirmation test was performed at the end to validate the outcome of the experiment. An improvement of 22.75% in performance was observed with the considered GRG model.

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Notes

The authors declare no competing financial interest.

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