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Processing on *Curcuma longa* waste oil-diesel blends for using as better alternative to diesel fuel

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Abstract. Technology advancements are growing in an exponential rate. Automobile sector is getting developed day by day where modern innovations are viewed with different features for the human society. Inspite of having various renewable energy sources, the demand for the fossil fuels still exists for meeting out the requirements of the growing application sides. In the present work, different blends of *Curcuma longa* waste neat oil samples have been prepared and mixed with diesel at different volume fractions. Nano metal oxide particles such as cerium oxide and Nano Egg Shell Powder (NESP) have been added with the prepared fuel samples in order to achieve better evaporation, atomization, better air-fuel mixing, considerable reduction in ignition delay and best flame sustainability nature. The prepared waste oil samples have been tested under four different loading conditions such as 30, 60, 90 and 120 N. The performance characteristics such as Brake Thermal Efficiency (BTE), Brake Specific Fuel Consumption (BSFC), Exhaust Gas Temperature (EGT), % of carbon monoxide emission, % of carbon dioxide emission, % of hydrocarbon emission and % of NO_X emission have been measured for the tested blends. From the results, the optimal sample which exhibits improved desirable characteristics has been suggested. Grey Relational Analysis (GRA) has also been used as a multi objective optimization tool in order to find out the best composition of the *Curcuma longa* waste oil – diesel blend in order to achieve better desirable properties. ANOVA technique has been used to identify the most influencing input factor in achieving better characteristics for the oil blends.

Keywords: Renewable energy sources, Alternative fuels, *Curcuma longa*, Diesel, Performance characteristics, Grey Relational Analysis.

1 Introduction

Energy demand increases sharply due to the increase of population density, rising trend of global industrialization, engine vehicles, etc., [1]. Conventional energy resources (petroleum products based fuels) are used to fulfill the daily needs (LPG for cooking, diesel and petrol to run IC engines, coal for power production in thermal power plants, etc.,) of human society [2, 3]. The petroleum products are nature's gift to OPEC countries because they provide more revenue in exporting such products. India is the developing country that highly depends OPEC countries for its nation-wide energy needs. However numerous research works have been carried out on alternative fuels till date because the conventional fuels are less available, take more time to reproduce (for example, petroleum has been produced by degradation of botanical material under high pressure and heat but it takes millions of years to get produced naturally), the conventional fuels like petroleum products are poisonous to the environment because they emit carbon dioxide, carbon monoxides, oxides of nitrogen, hydrocarbons, sulphur oxides, etc., and also they lead to climate changes and greenhouse effect. So it is essential to continue the research work in this field to find the suitable alternative fuel to meet the future energy demands.

Comparatively, the petroleum products are much used than other available conventional fuels. Hence in this study it has been planned to focus on alternatives to petroleum products. Vegetable oils are renewable, commonly available, bio-degradable, less toxic, friendly to environment, better lubricant, etc. On the other hand, they have some disadherent properties like poor cold flow properties, low volatility, high density, high viscosity and high surface tension [4, 5]. Because of the inefficient oxidation reaction

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in the fuel cells, cost prohibitive barriers in production, problems with transportation and storage, and hydrogen separation needs additional electric energy. One most important thing to be considered is why biodiesel fuel is better than fuel cell powered vehicles. Fuel cells can be better alternative for bio-fuels only if green energy resources are used for hydrogen production. During the year 2017–2018, India imported crude oil of 220.43 MMT which costs 5 65 951 core Indian rupees. During the year 2016–2017, which was about 213.93 MMT which costs 4 70 159 core Indian rupees. This statistics provided by the *Government of India* indicates that the quantity of the imported crude oil got increased by 3.04%, and 20.37% in 2017–2018 over 2016–2017 respectively. Also Indian economy is agriculture based economy because more than 50 percent of people involves in agricultural activities. *Central and State governments of India* are supporting the researchers in finding alternate fuels to conventional petroleum fuels through DST [6].

Karthik *et al.* had studied about the performance and emission characteristics of jatropha bio diesel blends added with nano cerium oxide/nano zinc oxide. They found that the nano cerium oxide added blends had shown more Brake Thermal Efficiency (BTE) and less NO_X than nano zinc oxide added blends [7]. Sivakrishna *et al.* had conducted a study on performance characteristics of IC engine fuelled with palm oil blends, and reported that the various toxic emissions were reduced when using the palm diesel fuel compared with conventional diesel fuel [8]. Maawa *et al.* had studied the performance and emission characteristics of IC engines fuelled with emulsified palm oil biodiesel; and they stated that the NO_X and the emission of particulate matter were reduced significantly with the usage of emulsified biodiesel [9]. Baranitharan *et al.* had studied the performance and emission characteristics of IC engine fueled with Aegle marmelos seed cake pyrolysis oil – TBHQ-diesel blends. They recommended that the 20% Aegle marmelos oil in diesel fuels yielded better reduction in emission and provided maximum efficiency [10]. Naik *et al.* had investigated the performance, combustion, and emission characteristics of a single-cylinder diesel engine fuelled with ternary blends of diesel, WCSO biodiesel and DEE. The ternary blends considerably minimized the CO, NO_X and smoke emissions, but an increase in the hydrocarbon emission was noticed [11]. Gowthaman and Thangavel had investigated the performance characteristics, combustion behavior and emission behaviour of Coconut Shell Oil (CSO) – diesel blends at different loading conditions. The blend of CSO20 (20% CSO) was observed to produce lower pollutants in comparison with that of other blends, and which was nearer to the values of diesel fuel [12].

From the literature survey, it was found that there was no research work carried out with the *Curcuma longa* waste oil for preparing diesel blends. Therefore, the objective of the present study has been set to test the suitability of using *Curcuma longa* waste oil – diesel blends as the alternative for diesel fuel. Engine output parameters such as performance characteristics, combustion, and emission characteristics have been tested with the different concentration of diesel blends fueled in the engine. Also, the improvement of engine operating characteristics using nano additives like nano Cerium oxide and Nano Egg Shell Powder (NESP) (50 ppm) has been analyzed.

2 Materials and methods

In the present study, partially dried *Curcuma longa* leaves (collected from Punnam village, Erode) have been chosen as the botanical material for the neat fuel oil preparation. In Erode, people cultivate *Curcuma longa* in huge amount than other potential crops for food and medicinal purposes. The *Curcuma longa* roots are used for foods and some other uses, while the leaf and stems of *Curcuma longa* plant are not used for food and medicinal uses in India. Hence they are used as fertilizers by either burning or land filling. The leaves and stems of the *Curcuma longa* are considered as wastage, and they have been considered for fuel oil preparation in the proposed work. To improve the engine operating characteristics, Nano Cerium Oxide Powder (NCOP) and NESP have been used in the present study. Nano metal oxides are preferred as better additives for fuel combustion due to their heterogeneous combustion kinetics and ignition acceleration. Nano metal oxide particles oxidize the fuel and they have high surface area – volume ratio and high reactive surface area. Hence the nano metal oxide particles make the earlier start of combustion and better combustion by their catalytic effect.

2.1 Nano cerium oxide and Nano Egg Shell Powder preparation

For nano cerium oxide preparation, the macro cerium oxide particles were powdered using ball milling process. The balls rotated inside the container with high energy and then they fall on the macro cerium oxide particles and crushed egg shell particles. From which the particles got converted into nano sized (size less than 100 nm at least in one dimension). The required size of nano material was obtained by repeated loading and unloading at a suitable interval. For the current investigation, nano particle of size 50 nm was considered. The size of the particles has been confirmed using SEM analysis.

2.2 *Curcuma longa* leaf oil preparation

The *Curcuma longa* waste oil was prepared using the conventional steam distillation setup. The conventional steam distillation setup has (a) boiler unit, (b) separator, (c) condensing unit, and (d) oil precipitation unit. The waste stem and leaves of *Curcuma longa* were first dried under shadow and they were crushed to the smaller size, fed into the boiler unit where the waste botanical material was heated up to the boiling point. After reaching the boiling point the crushed *Curcuma longa* botanical material released the steam along with the vegetable oil. The steam was then condensed; and the vegetable oil was separated from water–oil mixture through fractional distillation. For 1000 kg of semi dried leaves, 50 L of vegetable oil yield was obtained. Many authors reported that oil yield can be increased by solvent extraction methods.

Table 1. Properties of *Curcuma longa* diesel blends as per ASTM-D-6751 standards.

Property	Unit	ASTM D6751 diesel	CLO100	CLO10D90	CLO20D80	CLO30D70
Kinematic viscosity	mm^2/s	2.5	1.2	2.37	2.24	2.11
Density	kg/m^3	0.843	0.855	0.8538	0.8526	0.8514
Calorific value	MJ/kg	44	41.936	43.143	43.588	43.794
Cetane number	–	42	51	42.9	43.8	44.7
Flash point	°C	70	65	69.5	69	68.5
Fire Point	°C	78	90	88.8	87.6	86.4

Table 2. Test engine specifications.

Type of engine	Single cylinder, 4 stroke, VCR, vertical, naturally aspirated, water cooled, direct injection engine
Rated power (diesel mode)	3.5 KW
Cylinder bore/ stroke length	87.5 mm/110 mm
Type of ignition	CI
Injection pressure	210 bar (standard)
Injection timing	23_bTDC (standard)
Rated speed	1500–2500 rpm
Dynamometer	Eddy current dynamometer, Make – *Technomech Pvt. Ltd.*, TEMC 10, water cooled
Fuel flow measurement	FCM model differential pressure transmitter, Make: *Broiltech*
Air flow measurement	Make: *Wika* (SL1)
Stroke length	110 mm
Connecting rod length	234 mm

2.3 Experimental procedure

2.3.1 Curcuma longa waste oil-diesel fuel blend preparation

The *Curcuma longa* oil has the tendency to mix with diesel fuel due to its low density and kinematic viscosity. Hence the *Curcuma longa* waste oil was not subjected to transesterification process. It was directly mixed with the diesel fuel on volume basis by 10%, 20%, and 30%. The prepared nano additives of 50 ppm quantity were mixed with each *Curcuma longa*-diesel blends. The prepared blends are as follows, CLO (X vol.%) – D (Y vol.%) – NA. X represents the volume percentage of *Curcuma longa* oil which was varied as 10%, 20%, and 30% whereas Y represents the volume percentage of diesel which was varied as 90%, 80%, and 70%. NA represents the nano additives such as Cerium Oxide (CeO_2) and NESP. The prepared blends are represented using the above mentioned designations as follows: CLO10D90CeO_2, CLO10D90NESP, CLO20D80CeO_2, CLO20D80NESP, CLO30D70CeO_2, and CLO30D70NESP.

2.3.2 Curcuma longa waste material vegetable oil properties

The various fuel properties of *Curcuma longa* leaf oil were checked as per ASTM-D-6751 standards and are presented in Table 1. The kinematic viscosity of the prepared diesel blends was measured using redwood viscometer. Density was predicted using hydrometer. The calorific values of the blends were predicted with the help of bomb calorimeter apparatus. With the aid of closed cup apparatus, the flash point and fire point values of the blends were found out.

2.3.3 Test engine specifications

The test engine specifications are detailed in Table 2 and the experimental set up is as shown in Figure 1. Each subcomponent present in the test engine set up is detailed in the Figure 2.

The engine performance, emission and combustion characteristics were measured by filling the fuel blends in the fuel tank. The engine was made to run for 10 min to avoid the effect of previously used fuel. After 10 min of time, the loads were applied and various characteristics were measured for each fuel blend.

3 Results and discussion

3.1 Performance characteristics

The chemical energy of the fuel was converted into most useful form of work in the diesel engines which can be measured by BTE, Brake Specific Fuel Consumption (BSFC), and mechanical efficiency [9, 10].

Fig. 1. Test engine set up.

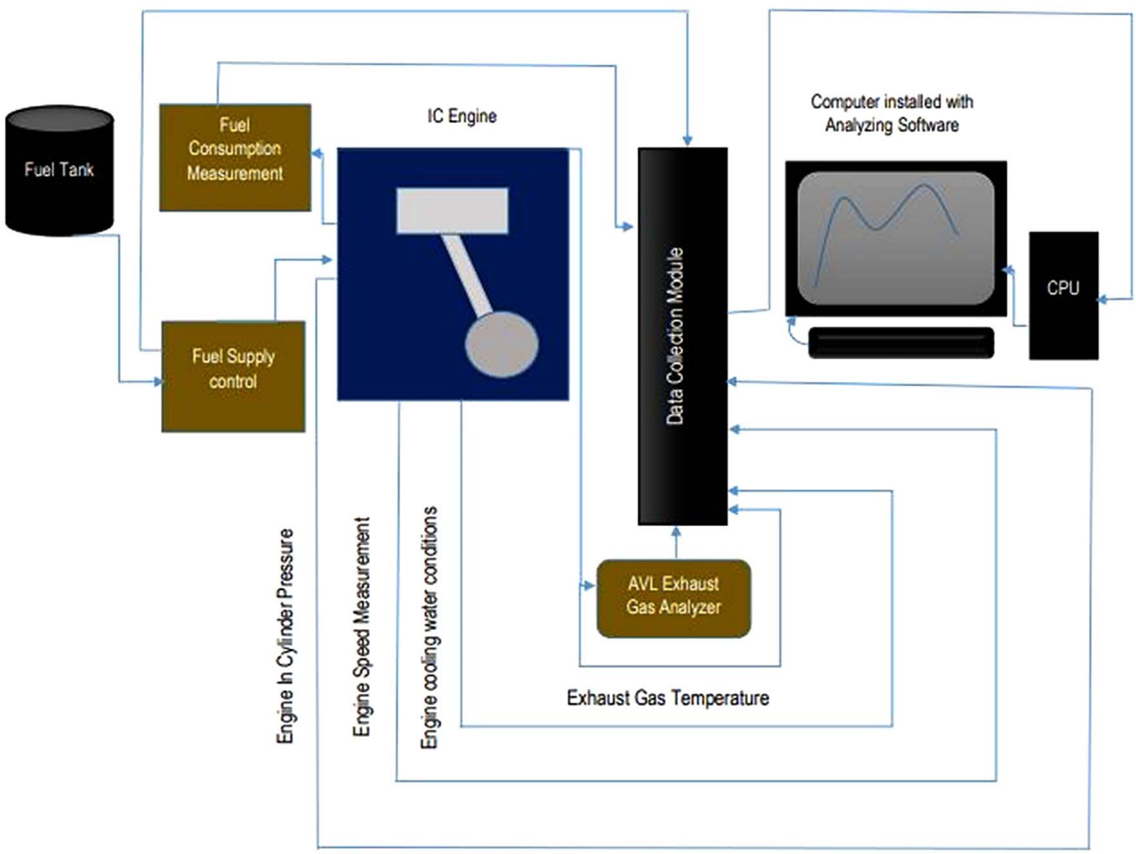


Fig. 2. Components description of the test engine setup.

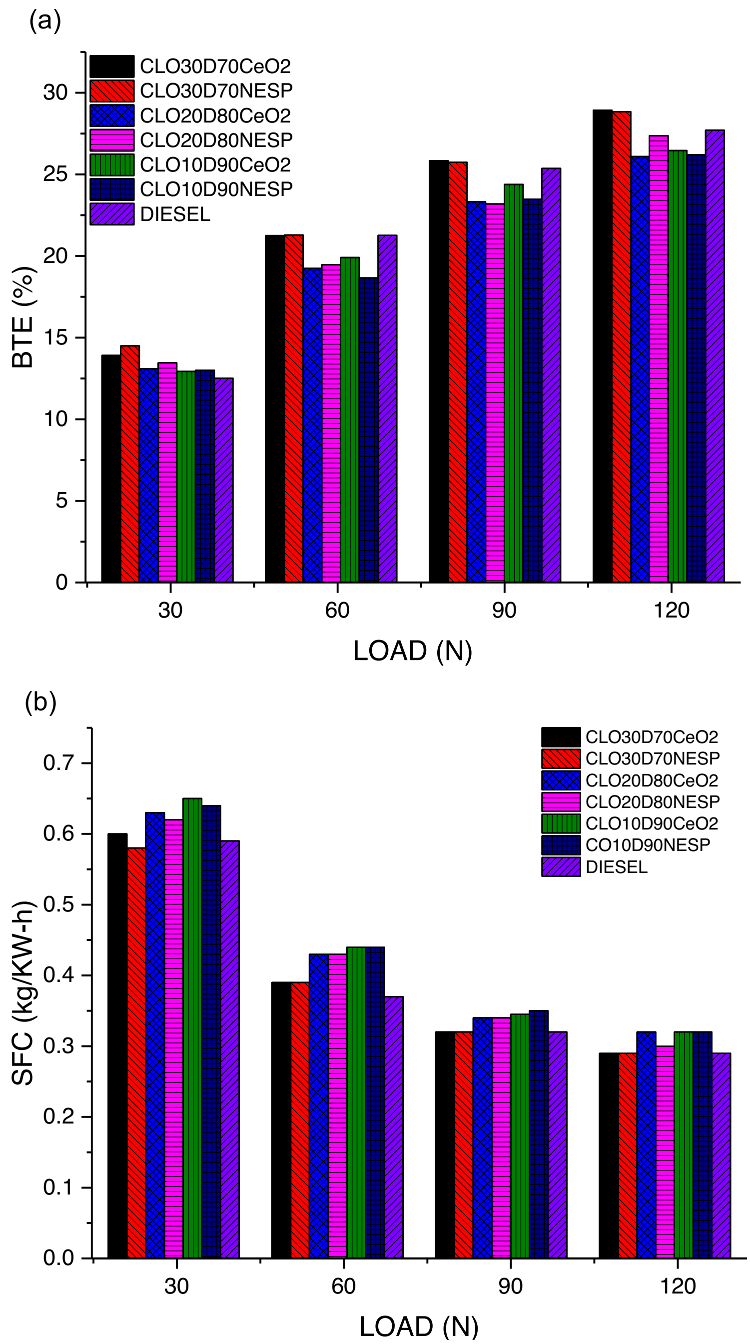


Fig. 3. (a) Break thermal efficiency *versus* Load plot. (b) Specific fuel consumption *versus* Load plot. (c) EGT *versus* Load plot. (d) Carbon monoxide emission *versus* Load plot. (e) Carbon dioxide emission *versus* Load plot. (f) Hydrocarbon emission *versus* Load plot. (g) NO_X emission *versus* Load plot.

3.1.1 Brake Thermal Efficiency

It is the measure of how much amount of heat energy of fuel has been utilized to produce the brake power output. BTE will get increased by enhancing the combustion [13]. The combustion enhancement depends upon the amount of oxygen present in the fuel [14]. To supply enough amount of oxygen during combustion, nano metal oxides were used with the oil blends. Nano cerium oxide (50 ppm) and NESP (50 ppm) mixed with *Curcuma longa* plant waste oils blended with diesel were used in this work. Figure 3a shows the variation of BTE for various loading conditions. The *Curcuma longa* leave oil has less viscosity, and also it enhances the auto ignition temperature, atomization and fuel spray features. More the load values more will be the BTE because of enhanced combustion for the period of power stroke by increased temperature and mean effective pressure during the peak loads. BTE depends on fuel

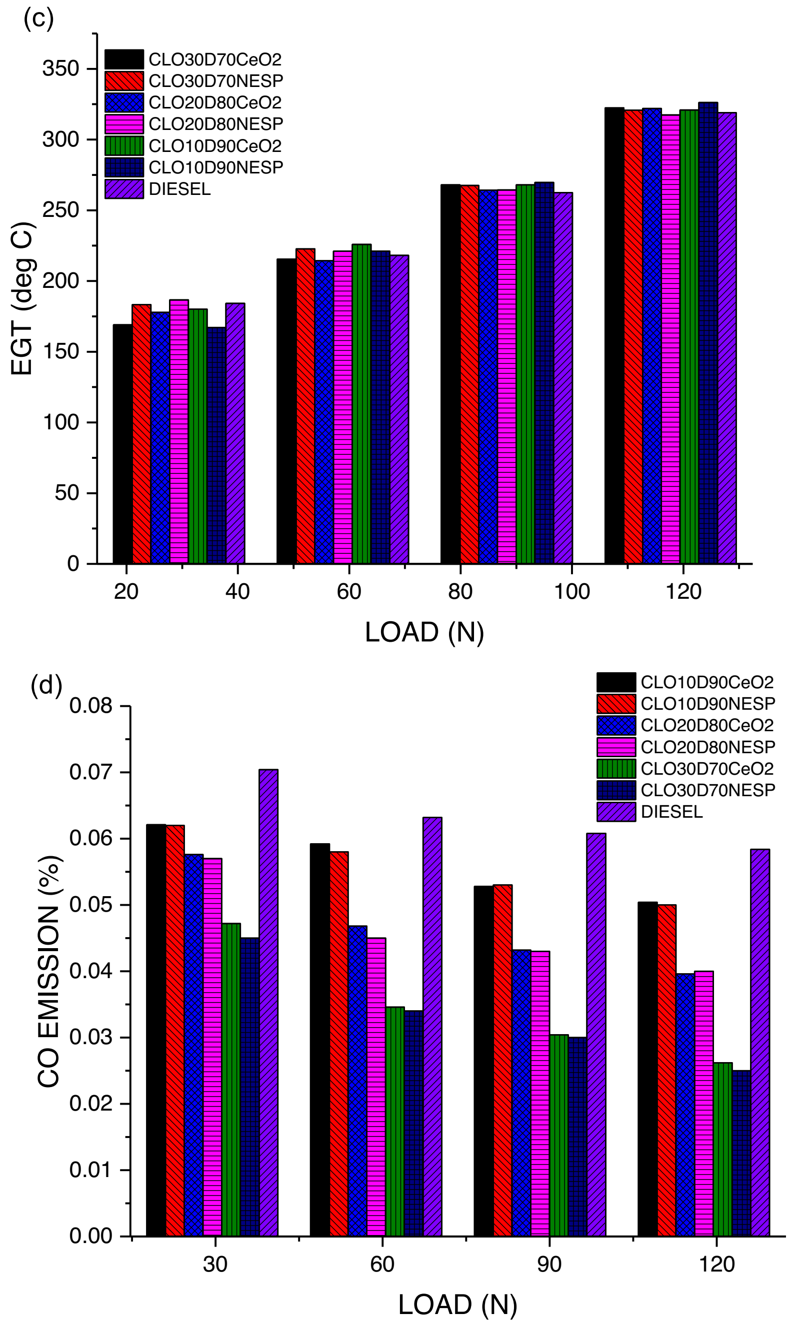
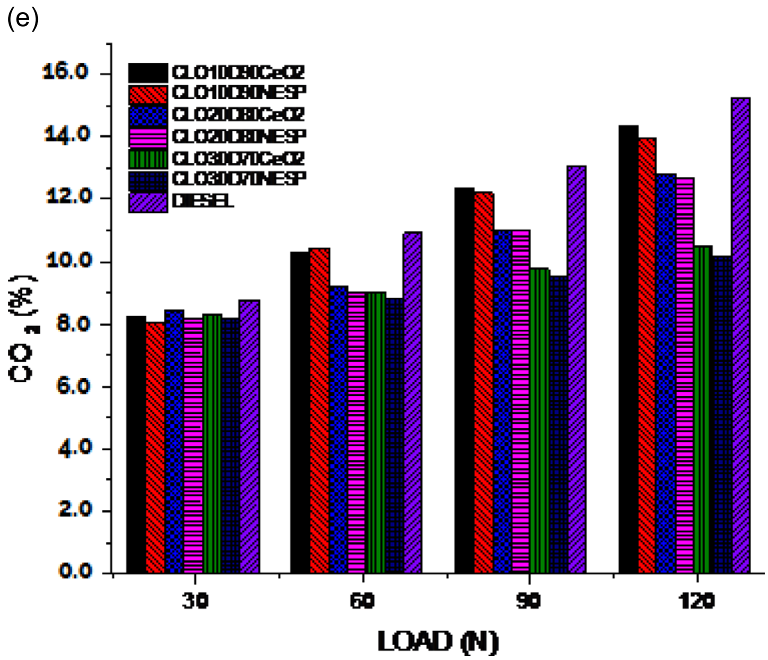


Fig. 3. Continued

molecules volatility, more in cylinder temperature and loads. At maximum loading condition, the BTE values for the various *Curcuma longa* waste oil – diesel blends compared with diesel fuel are as follows: CLO10D90CeO$_2$ (4% higher), CLO10D90NESP (4% higher), CLO20D80CeO$_2$ (6% lower), CLO20D80NESP (1% lower), CLO30D70CeO$_2$ (5% lower), CLO30D70NESP (5% lower). The test results revealed that BTE increased with increasing the load. The high BTE achieved was due to high calorific value and less heat loss; and the lower BTE achieved was due to low calorific value of fuel [15]. The fuel viscosity may also a factor that leads to atomization, vaporization and combustion rate [16]. At full loading condition, BTE of bio-fuel blends was equal to BTE of diesel fuel due to improved atomization and better mixing. Also the presence of nano metal oxides improved the BTE by enhancing the combustion process [17].

3.1.2 Brake Specific Fuel Consumption

BSFC is the quantity of fuel to produce the energy of 1 kWh on crankshaft. Brake power is the measure of actual



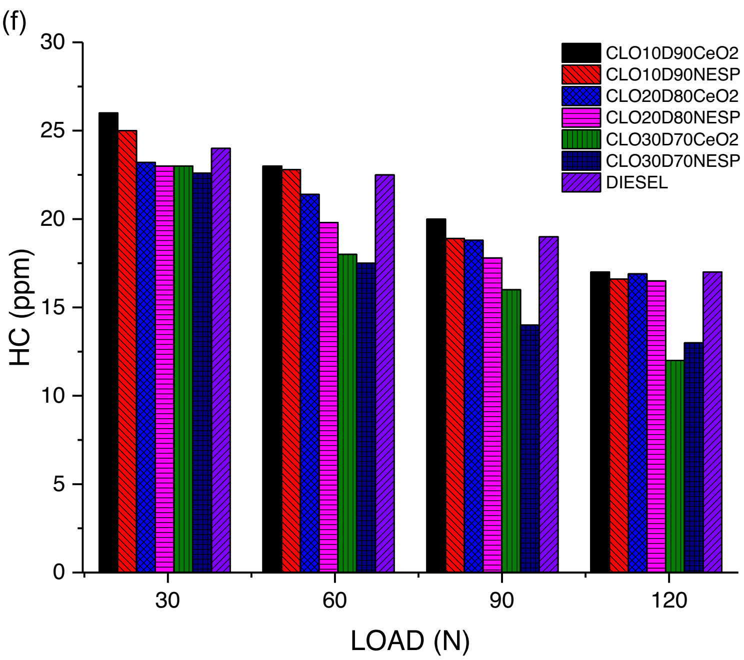


Fig. 3. Continued

power output obtained in the crankshaft. Figure 3b shows the variation of BSFC (BSFC in kg/kW-h) against the variation of load. Initially the BSFC was higher due to inadequate combustion at low load due to very low amount of combustion temperature. BSFC decreased with increase in load [17]. The application of nano additives like cerium oxide and heterogenous bio nano additive (NESP) enhanced the combustion by supplying adequate amount of oxygen. The specific fuel consumption may decrease due to the higher calorific value of fuel and nano metal oxides in *Curcuma longa* waste oil – diesel blends. At 30 N loading condition, the CLO10D90CeO_2, CLO10D90NESP, CLO20D80CeO_2, CLO20D80NESP, CLO30D70CeO_2 and CLO30D70NESP had 1.7%, 1.7%, 6.8%, 5.1%, 10.2%, and 8.5% more BSFC than diesel fuel respectively. At load value of 60 N, the CLO10D90CeO_2, CLO10D90NESP, CLO20D80CeO_2, CLO20D80NESP, CLO30D70CeO_2 and CLO30D70NESP had 5.4%, 5.4%, 16.2%, 16.2%, 18.9%, and 18.9% more BSFC than diesel fuel respectively. At load value 90 N, the CLO10D90CeO_2, CLO10D90NESP, CLO20D80CeO_2,

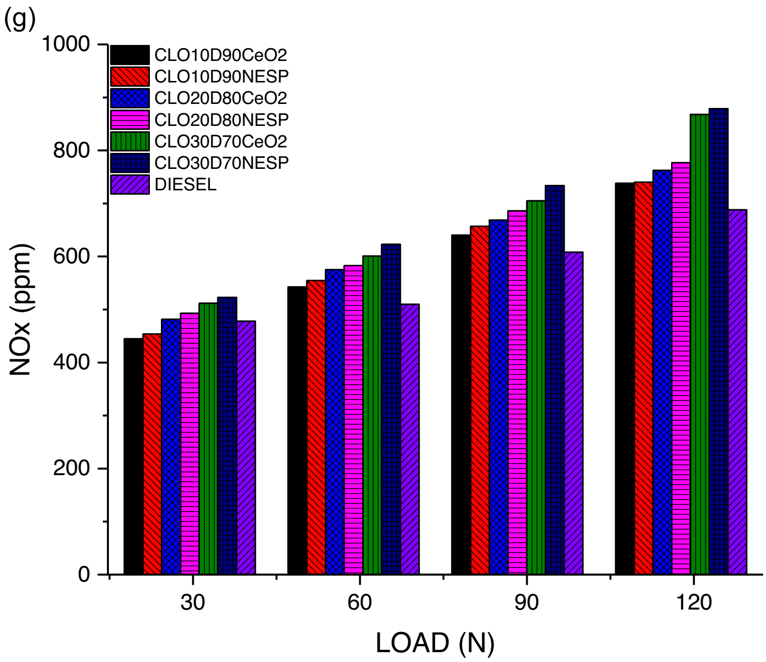


Fig. 3. Continued

CLO20D80NESP, CLO30D70CeO$_2$ and CLO30D70NESP had 0.0%, 0.0%, 6.3%, 6.3%, 7.8%, and 9.4% more BSFC than diesel fuel respectively. At load value 120 N, the CLO10D90CeO$_2$, CLO10D90NESP, CLO20D80CeO$_2$, CLO20D80NESP, CLO30D70CeO$_2$ and CLO30D70NESP had 0.0%, 0.0%, 10.3%, 3.4%, 10.3%, and 10.3% more BSFC than diesel fuel respectively. Higher BSFC was observed with lower percentage *Curcuma longa* – diesel blends having nano cerium oxide particles at minor loads.

3.1.3 Exhaust Gas Temperature

EGT is an indication of quality of burning/combustion within the IC engine. Better the burning/combustion of fuel, the EGT will be low; and many research results showed that EGT will increase with increase of load [18]. Figure 3c presents the variation plot for the EGT with respect to the loading condition. At low load of 30 N, the Exhaust Gas Temperature (EGT) for the proposed fuel blends CLO10D90CeO$_2$, CLO10D90NESP, CLO20D80-CeO$_2$, CLO20D80NESP, CLO30D70CeO$_2$ and CLO30D70-NESP was noted to be lower than that of the diesel except CLO20D80NESP. It pointed out that at initial condition, only minimum energy was lost in the form of exhaust gas than diesel for all *Curcuma longa*-diesel fuel blends, except in CLO20D80NESP. With further increase in load also, only less difference was noted and recorded between the EGT while using *Curcuma longa* fuel blends and diesel. At higher loading conditions, there will be highest combustion efficiency; and the EGT values for all the diesel blends were also found to be higher, but there is only very less deviation in the results with that of the diesel blend. At higher loading condition, CLO20D80NESP was noted to have lesser EGT value comparatively [16].

3.2 Emission characteristics

An AVL DICOM4000 gas analyzer was used to measure carbon monoxide (CO), carbon dioxide (CO_2), NO_X and hydrocarbon (HC) emissions.

3.2.1 CO emission

CO emission depends upon how much the air–fuel ratio moves towards stoichiometric. CO emission may decrease with increase of oxygen content in the fuel, less water content in the fuel and better combustion results [16]. The fuel spray and atomization characteristics have significant influence in the combustion. The low kinematic viscosity and more volatility of the fuel will improve the spray characteristics and produce highly homogenous air – fuel mixture results in increase of delay in combustion speed and reduces the reaction time [4]. From the literatures study, it was noted that the CO emission may increase due to (i) low temperature prevailing conditions at lower compression ratio, (ii) poor fuel air mixing and high residual gases dilution, (iii) at low compression ratio, insufficient compression heat, ignition delay, and (iv) worsening of fuel atomization due to high in-cylinder pressure at higher compression ratio. The variation in the CO emission with respect to the varying loading condition is as represented in Figure 3d. The decrease of CO emission upto 30% was observed with more amount of *Curcuma longa* oil in fuel blends while comparing with diesel fuel; and this may be due to the excess amount of oxygen present in the fuel as well by using nano additives having metal oxides. The heterogeneous bio nano additive NESP acted as a catalyst, so it contributed more in CO emission reduction than cerium oxide nano catalyst.

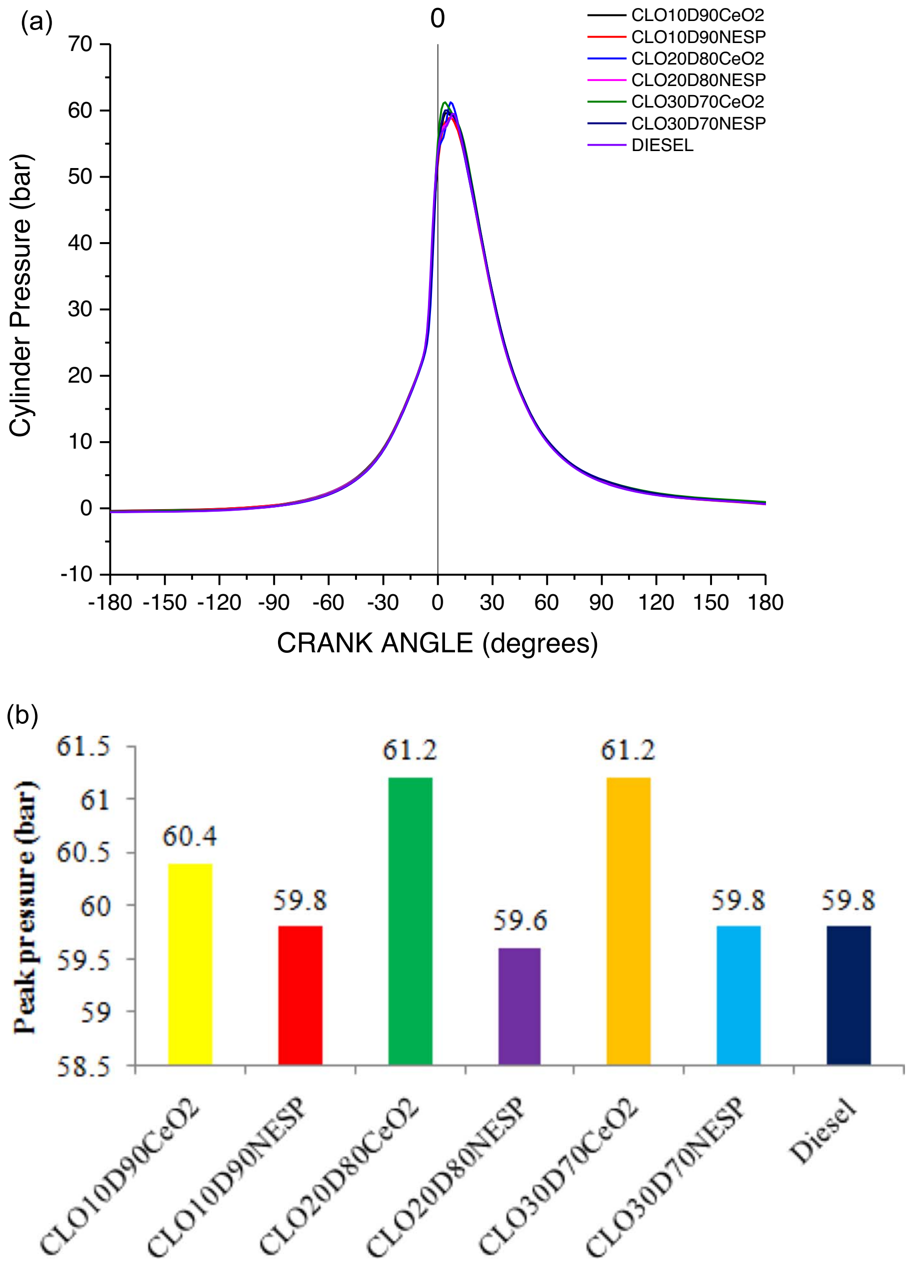


Fig. 4. (a) Cylinder pressure *versus* CA plot. (b) Maximum cylinder pressure for the diesel blends. (c) HRR *versus* CA plot.

3.2.2 CO_2 emission

Carbon dioxide emission may rise due to complete combustion facilitated by higher pressure and temperature at the end of the compression stroke. Incomplete combustion may cause the reduction in carbon dioxide emission. Figure 3e shows the percentage of CO_2 emission while using the proposed oil blends for various loading conditions. At lower loading conditions, all *Curcuma longa* diesel fuel blends had CO_2 emission lesser than the diesel fuel. After increasing the load, the CO_2 emission percentage increased correspondingly due to the facilitation of complete combustion. However, the fuel blends having more amount of *Curcuma longa* oil emitted lesser amount of carbon dioxide by the combined effect of more oxygen content in the blend as well the inclusion of metal oxide nano catalyst.

3.2.3 Hydrocarbon emissions

HC emission depends upon the lean combustion and quenching of fuel at low load condition. The hydrocarbon emission may get reduced due to temperature rise at the end of the compression. Relevant literature studies revealed that hydrocarbon emission will be low in bio-fuels due to the higher existence of oxygen which will readily react with

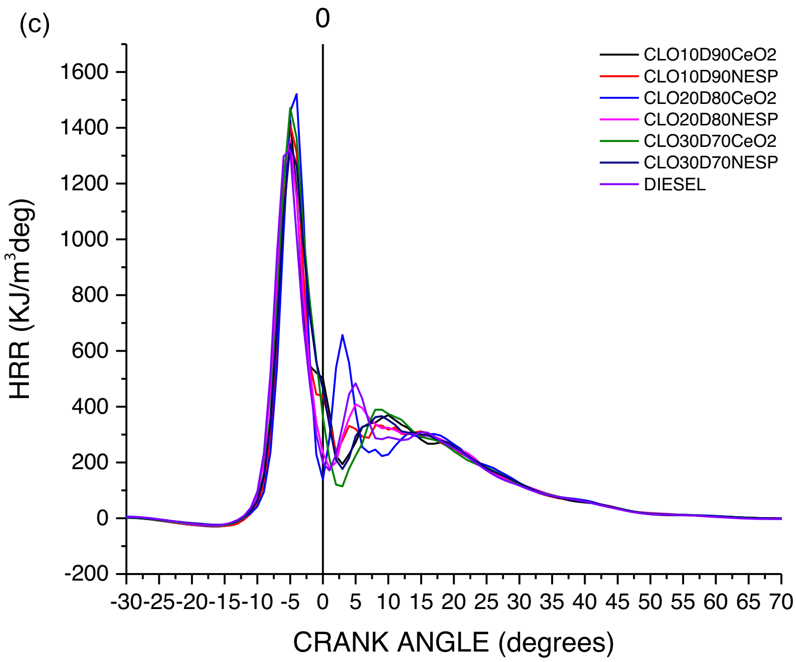


Fig. 4. Continued

Table 3. Plan of experimentation for the optimization study and the results of output variables.

S. No.	Load (N)	% of *Curcuma longa* in the blend	Nano additive	SFC (kg/kW-h)	vol/vol. % of CO emission	vol/vol. % of CO_2 emission	NO_X emission in ppm	HC emission in ppm	EGT in deg °C	BTE (%)
1.	30	10	NCOP	0.650	0.0621	0.412	444.8	26.0	180.03	12.93
2.	30	10	NESP	0.640	0.0620	0.403	454.0	25.0	167.17	13.01
3.	30	20	NCOP	0.630	0.0576	0.420	481.6	23.2	177.81	13.10
4.	30	20	NESP	0.620	0.0570	0.410	493.0	23.0	186.70	13.46
5.	30	30	NCOP	0.600	0.0472	0.416	512.0	23.0	169.03	13.92
6.	30	30	NESP	0.580	0.0450	0.410	523.0	22.6	183.21	14.49
7.	60	10	NCOP	0.440	0.0592	0.514	542.6	23.0	225.89	19.91
8.	60	10	NESP	0.440	0.0580	0.521	555.0	22.8	221.07	18.66
9.	60	20	NCOP	0.430	0.0468	0.460	575.2	21.4	214.38	19.25
10.	60	20	NESP	0.430	0.0450	0.452	583.0	19.8	221.14	19.47
11.	60	30	NCOP	0.390	0.0346	0.452	601.0	18.0	215.50	21.25
12.	60	30	NESP	0.390	0.0340	0.440	623.0	17.5	222.66	21.29
13.	90	10	NCOP	0.345	0.0528	0.616	640.4	20.0	268.04	24.38
14.	90	10	NESP	0.350	0.0530	0.611	657.0	18.9	269.71	23.48
15.	90	20	NCOP	0.340	0.0432	0.550	668.8	18.8	264.27	23.32
16.	90	20	NESP	0.340	0.0430	0.550	686.0	17.8	264.40	23.19
17.	90	30	NCOP	0.320	0.0304	0.488	705.0	16.0	268.01	25.84
18.	90	30	NESP	0.320	0.0300	0.477	734.0	14.0	267.52	25.74
19.	120	10	NCOP	0.320	0.0504	0.718	738.2	17.0	320.93	26.46
20.	120	10	NESP	0.320	0.0500	0.699	740.0	16.6	326.22	26.20
21.	120	20	NCOP	0.320	0.0396	0.640	762.4	16.9	321.95	26.09
22.	120	20	NESP	0.300	0.0400	0.633	777.0	16.5	317.44	27.37
23.	120	30	NCOP	0.290	0.0262	0.524	868.0	12.0	322.42	28.93
24.	120	30	NESP	0.290	0.0250	0.509	879.0	13.0	320.77	28.84

Table 4. Normalized values of the various performance characteristics of the oil blends.

S. No.	Normalized values						
	SFC	CO	CO_2	NO_X	HC	EGT	BTE
1.	0.0000	0.0000	0.9714	1.0000	0.0000	0.9191	0.0000
2.	0.0278	0.0027	1.0000	0.9788	0.0714	1.0000	0.0050
3.	0.0556	0.1213	0.9460	0.9153	0.2000	0.9331	0.0106
4.	0.0833	0.1375	0.9778	0.8890	0.2143	0.8772	0.0331
5.	0.1389	0.4016	0.9587	0.8452	0.2143	0.9883	0.0619
6.	0.1944	0.4609	0.9778	0.8199	0.2429	0.8992	0.0975
7.	0.5833	0.07817	0.6476	0.7748	0.2143	0.6308	0.4363
8.	0.5833	0.1105	0.6254	0.7462	0.2286	0.6611	0.3581
9.	0.6111	0.4124	0.8191	0.6998	0.3286	0.7032	0.3950
10.	0.6111	0.4609	0.8444	0.6817	0.4429	0.6607	0.4088
11.	0.7222	0.7412	0.8444	0.6403	0.5714	0.6961	0.5200
12.	0.7222	0.7574	0.8825	0.5896	0.6071	0.6511	0.5225
13.	0.8472	0.2507	0.3238	0.5495	0.4286	0.3658	0.7156
14.	0.8333	0.2453	0.3397	0.5113	0.5071	0.3553	0.6594
15.	0.8611	0.5094	0.5333	0.4841	0.5143	0.3895	0.6494
16.	0.8611	0.5148	0.5333	0.4445	0.5857	0.3887	0.6413
17.	0.9167	0.8545	0.7302	0.4007	0.7143	0.3660	0.8069
18.	0.9167	0.8652	0.7651	0.3340	0.8571	0.3691	0.8006
19.	0.9167	0.3154	0.0000	0.3243	0.6429	0.0333	0.8456
20.	0.9167	0.3262	0.0603	0.3201	0.6714	0.0000	0.8294
21.	0.9167	0.6065	0.2476	0.2685	0.6500	0.0269	0.8225
22.	0.9722	0.5957	0.2698	0.2349	0.6786	0.0552	0.9025
23.	1.0000	0.9677	0.6159	0.0253	1.0000	0.0239	1.0000
24.	1.0000	1.0000	0.6635	0.0000	0.9286	0.0343	0.9944

the hydrocarbons present in the fuel. The hydrocarbon emission of the oil blends at various loading conditions is presented as a plot which is shown in Figure 3f. In the case of hydrocarbon emission, the oil blends which had higher volume percentage of *Curcuma longa* oil showed better results than the diesel fuel due to the presence of excess oxygen. The included nano additives acted as a catalyst which speeded up the combustion. The hydrocarbon emission got reduced significantly (about more than 5%) with increase in load due to the higher fuel requirement for producing the brake power.

3.2.4 NO_X emissions

Figure 3g shows the plot for NO_X emission *versus* load. From the results, it was observed that the NO_X emission got increased with the increase in load. The higher concentration of *Curcuma longa* oil in the fuel blends had shown more increasing trend of oxides of nitrogen. The main cause of the higher NO_X emissions was the availability of higher amount of oxygen present in the vegetable oil and in the added nano particles. The NO_X emission for the proposed oil blends was observed to be about 3 times higher than that of the diesel fuel at the higher loading conditions.

3.3 Combustion characteristics

3.3.1 Cylinder pressure

The cylinder pressure at 60 N loading condition was measured with the help of a pressure gauge attached with it. Figure 4a shows the plot drawn for the cylinder pressure *versus* Crank Angle (CA). The combustion peak pressure of 61.2 bar was observed with CLO20D80CeO_2 and CLO30D70CeO_2. For clarity, the peak pressure obtained for the proposed diesel blends have been separately presented in Figure 4b. The maximum peak cylinder pressure was observed in fuel blends having CeO_2 nano additive.

3.3.2 Crank Angle versus Heat Release Rate

The HRR value was calculated using the formula presented in equation ((1)) [19]. In the proposed study, the HRR values were calculated per unit cylinder volume, therefore its unit has been expressed as (kJ/m^{3}deg.):

$$\mathrm{HRR} = \frac{\gamma}{\gamma-1}p\frac{\mathrm{d}V}{\mathrm{d}\theta} + \frac{\gamma}{\gamma-1}V\frac{\mathrm{d}p}{\mathrm{d}\theta}, \tag{1}$$

where, "γ" is the specific heat ratio. "V" and "p" are the cylinder volume and cylinder gas pressure respectively.

Table 5. GRC and GRG values for the trials.

S. No.	GRC							GRG	Rank
	SFC	CO	CO_2	NO_X	HC	EGT	BTE		
1.	0.3333	0.3333	0.9460	1.0000	0.3333	0.8608	0.3333	0.5914	10
2.	0.3396	0.3339	1.0000	0.9594	0.3500	1.0000	0.3345	0.6168	6
3.	0.3462	0.3627	0.9026	0.8551	0.3846	0.8820	0.3357	0.5813	12
4.	0.3529	0.3670	0.9575	0.8183	0.3889	0.8028	0.3409	0.5755	13
5.	0.3674	0.4552	0.9238	0.7636	0.3889	0.9772	0.3477	0.6034	8
6.	0.3830	0.4812	0.9575	0.7352	0.3977	0.8322	0.3565	0.5919	9
7.	0.5455	0.3517	0.5866	0.6894	0.3889	0.5753	0.4700	0.5153	23
8.	0.5455	0.3598	0.5717	0.6633	0.3933	0.5960	0.4379	0.5096	24
9.	0.5625	0.4597	0.7343	0.6248	0.4268	0.6275	0.4525	0.5554	15
10.	0.5625	0.4812	0.7627	0.6110	0.4730	0.5957	0.4582	0.5635	14
11.	0.6429	0.6590	0.7627	0.5816	0.5385	0.6220	0.5102	0.6167	7
12.	0.6429	0.6733	0.8098	0.5492	0.5600	0.5890	0.5115	0.6194	5
13.	0.7660	0.4002	0.4251	0.5261	0.4667	0.4408	0.6375	0.5232	21
14.	0.7500	0.3985	0.4309	0.5057	0.5036	0.4368	0.5948	0.5172	22
15.	0.7826	0.5048	0.5172	0.4922	0.5073	0.4503	0.5878	0.5489	18
16.	0.7826	0.5075	0.5172	0.4737	0.5469	0.4499	0.5822	0.5515	17
17.	0.8571	0.7745	0.6495	0.4549	0.6364	0.4409	0.7214	0.6478	4
18.	0.8571	0.7877	0.6804	0.4288	0.7778	0.4421	0.7149	0.6698	3
19.	0.8571	0.4221	0.3333	0.4253	0.5833	0.3409	0.7641	0.5323	20
20.	0.8571	0.4260	0.3473	0.4238	0.6035	0.3333	0.7456	0.5338	19
21.	0.8571	0.5596	0.3992	0.4060	0.5882	0.3394	0.7380	0.5554	16
22.	0.9474	0.5529	0.4065	0.3952	0.6087	0.3461	0.8368	0.5848	11
23.	1.0000	0.9392	0.5655	0.3391	1.0000	0.3387	1.0000	0.7404	1
24.	1.0000	1.0000	0.5977	0.3333	0.8750	0.3411	0.9889	0.7337	2

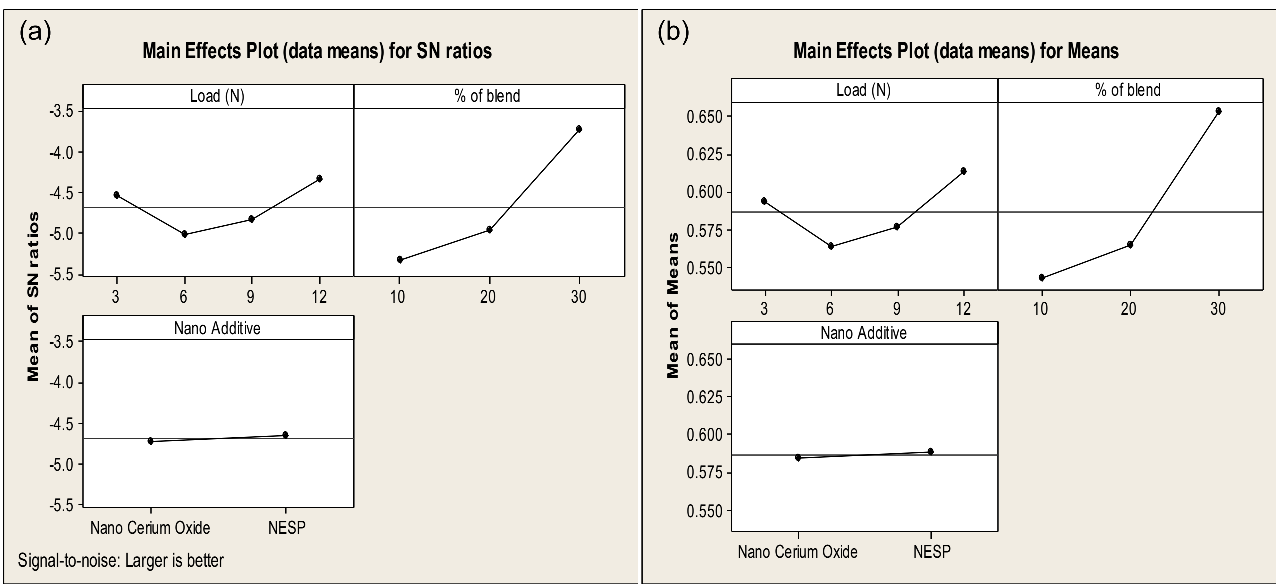


Fig. 5. (a) Main effect plot for the S/N ratio values of predicted GRG. (b) Main effect plot for the mean values of predicted GRG.

Table 6. ANOVA results.

Source	DF	Adj SS	Adj MS	*F*-value	*P*-value	Contribution
Load	3	0.00846	0.00282	1.79	0.188	9.40%
% of *Curcuma longa* in the blend	2	0.05464	0.02732	17.31	0	60.67%
Nano additive	1	0.00013	0.00013	0.08	0.777	0.49%

Here, HRR has been calculated along the CAs during the interval from inlet valve closing to exhaust valve opening. Figure 4c shows the inference between the CA and Heat Release Rate (HRR) for various *Curcuma longa* oil – diesel fuel blends. The maximum HRR was obtained with the nano cerium oxide mixed fuel blends. The HRR in kJ/m^3-deg obtained for the various *Curcuma longa* oil – diesel blends CLO10D90CeO$_2$, CLO10D90NESP, CLO20D80CeO$_2$, CLO20D80NESP, CLO30D70CeO$_2$ and CLO30D70NESP were 8%, 7%, 15%, 3%, 11% and 2% higher than the diesel fuel respectively.

From the results of experimental analysis, it was proven that the proposed *Curcuma longa* diesel blends can be used as an alternative to diesel. In the literatures also it can be observed to arrive at the similar conclusions such as with waste cooking sunflower oil – diesel blends [11], and CSO – diesel blends [12].

3.4 Grey Relational Analysis

While an oil blend is proposed, it is expected to possess desirable properties for all the performance characteristics. Therefore in the present study, the experimental results were subjected to a multi response optimization analysis – Grey Relational Analysis (GRA) [20]. For which, the dependent variables such as specific fuel consumption, the emission rates of carbon monoxide, carbon dioxide, HC, NO_X, and emission gas temperature were considered under lower-the-better criterion; and the factor – break thermal efficiency was considered under larger-the-better criterion [21]. For identifying the optimal output performance characteristics, significant process variables were selected as load, the percentage of *Curcuma longa* in the oil blends and the type of nano additive. Loading condition was considered at four different levels *viz.* 30, 60, 90 and 120 N. The percentage of *Curcuma longa* oil in the proposed oil blends was considered at three different levels such as 10%, 20% and 30%. Nano additives such as NCOP and NESP were added, which were also considered as a input variable. Twenty four combinations of trials were planned for the optimization study, and the experimental plan is represented in Table 3 along with the obtained results. For each applied load, the measurements were taken after five minutes of time for getting stabilized results.

As each output performance characteristic is measured in different units, all the performance characteristics were normalized between "0" and "1" by considering "lower the better criteria" and "larger the better criteria" suitably. The normalized values of the performance characteristics are presented in Table 4.

In the second step of GRA, deviation sequence values were calculated by considering the variation of each normalized value from their corresponding maximum value [22, 23].

In the next step of GRA, Grey Relational Coefficient (GRC) values and Grey Relational Grade (GRG) values were predicted which are provided in Table 5. The maximum value of GRG obtained out of the analysis was given rank 1 which was selected as the optimal combination [24]. In the same way, ranking was provided for the remaining combinations [25].

From the results of GRA, the 23rd combination (120 N load – 30% *Curcuma longa* oil in the blend – NCOP inclusion) was identified as the optimal combination which yielded the optimal performance characteristics as follows: 0.29 kg/kW-h, 0.0262% CO emission, 0.524% CO_2 emission, 868 ppm NO_X emission, 12 ppm HC emission, 322.42 °C emission gas temperature and 28.93% BTE. However, there were certainly few uncontrollable factors during the observation and measurement of experimentation. Hence, signal to noise ratio values for each output response characteristic were analyzed with the aid of main effect plots [26, 27] which are shown in Figures 5a and 5b.

The main effect plots revealed that the 24th combination was the best combination for providing the optimal results on the performance characteristics of the mixed oil blends, which was actually ranked as 2 in the GRA (without considering the noise factors into the analysis). By comparing the results of the 24th combination with that of the 23rd combination, all the performance characteristics were seemed to have improved over the 23rd combination except the NO_X emission rate.

3.5 ANOVA analysis

ANOVA technique was employed with the aid of Minitab software of version 14.0 to check the mostly influencing input variable in achieving the optimal oil blend exhibiting better characteristics [25]. The obtained ANOVA results are presented in Table 6. The ANOVA results revealed that the percentage of *Curcuma longa* waste oil added in preparing the proposed oil blends was the most influencing significant input variable in achieving better characteristics (60.67%). Further, it was noted that the nano additives added into the oil blends seemed to have comparatively lesser significance in achieving the optimal results in the desirable characteristics of the proposed oil blends.

4 Conclusion

A new bio-based oil was introduced in the proposed work namely *Curcuma longa* waste oil. The proposed oil was mixed with different proportions with diesel and tested for various performance characteristics, emission and combustion characteristics in order to test its suitability to be used as an alternative to diesel fuel. NCOP and NESP were added into the prepared oil blends with the view of improving the characteristics of the oil blends. The significant results of the proposed investigation are detailed below.

(i) The prepared oil blends produced more or less same and better results than the diesel fuel. Therefore, it can be suggested to use the proposed oil blends as a better alternative to diesel which will reduce the utilization of diesel fuel in a significant range.
(ii) The inclusion of nano additives such as nano cerium oxide and bio additive NESP helped to reduce the carbon monoxide emission upto 30% for all the proposed oil blends than diesel fuel.
(iii) Higher BSFC was observed with lower percentage of *Curcuma longa* – diesel blends having nano cerium oxide particles at minor loads.
(iv) The combustion characteristics got improved while using the *Curcuma longa* oil – diesel fuel blends with nano additives.
(v) GRA results revealed that the performance characteristics of the proposed oil blends were superior at higher loading condition (120 N), higher concentration of *Curcuma longa* oil in the blend (30 vol.%) and with the inclusion of NESP additive.
(vi) From the ANOVA results, the majorly influencing input variable affecting the performance characteristics of the proposed oil blends was identified as the percentage of *Curcuma longa* oil in the blend.

In overall, it is concluded that the utilization of *Curcuma longa* oil will highly reduce the usage of diesel in the future, which would be helpful to face the energy demand significantly.

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