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NUMERICAL AND EXPERIMENTAL EVALUATION ON THE POOLED EFFECT OF WASTE COOKING OIL BIODIESEL/DIESEL BLENDS AND EXHAUST GAS RECIRCULATION IN A TWIN-CYLINDER DIESEL ENGINE

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Abstract

Nowadays, worldwide, many countries are engaged in reducing the vehicular exhaust emissions from diesel engines as diesel engines are the main source of power in various transport applications. Biofuels obtained from various feedstocks serve as a better alternative fuel in CI engines because of its emission reducing capabilities. The major drawback in the usage of biofuels in CI engine is the rise in the formation of nitrogen oxides which would be harmful to human health. WCO biofuel was processed using trans-esterification technique and the contents available were analyzed using gas chromatography mass .spectroscopy (GCMS). Four different blends, namly B100, B60, B40, and B20 were made. The physio-chemical properties of the prepared test fuels were identified using ASTM standards. The investigation on the characterisation of performance, combustion, sound and emission of the test engine was done. Fuel combustion modeling was done using ANSYS Fluent for diesel, WCO biofuel and best suited blend obtained from experimental results. From both the simulated and the experimental results, it was found that B20 blend fuel would be best suited to the test engine with a maximum reduction of 17% in unburned hydrocarbon (HC), 30% in carbonmonooxide (CO), 14.08% in smoke, 7.35% in carbondioxide (CO_2) and 16.46% increase in NOx emission respectively. With an intention to reduce NOx emission in the selected B20 blend fuel, EGR at three rates, namely (5%, 10%, and 15%) were utilized. Again, the experiments were conducted with varying EGR rates for B20 blend fuel. A good percentage of reduction in NOx was obtained with increase in EGR rates. But other emissions like CO, HC, smoke, and CO_2 emissions were found to increase with rise in EGR rates. Thus, a comparison was made with three rates of EGR emission values with all types of test fuels to optimize the EGR rate leading into the inlet charge. 10% EGR rate gave a maximum reduction of 16.34% in NOx emission without affecting much in the emissions like HC, CO, Smoke, and CO_2 along with a small drop in performance.

Keywords: WCO biofuel, Diesel, Exhaust gas recirculation, Performance, Combustion, Emission.

1. Introduction

In recent days compression ignition (CI) engines have been more popular than gasoline engines because of their low cost in maintenance, high power, fuel economy and high range of torque. In the last century, it became a predominant power application in transport industry and also in powering the farm equipment. Though the emissions from diesel are named to be carcinogenic, it is still better than gasoline engines as far as the amount of emission emitted to the atmosphere is concerned. The emissions from the diesel engines serve as a source of global warming that has deteriorated the health of human beings more in recent times. So, this prompted many researchers to concentrate on bio-derived fuels as an alternative to the diesel fuel. Also increasing demand for the alternative fuel due to the fast depleting petroleum diesel has led to biofuel production from vegetable oils. Due to higher cost of edible vegetable oils, production of biofuels from non-edible vegetable oils is preferred [1]. Nowadays, there is very less research on utilizing the non-edible vegetable oils commercially to substitute for petroleum diesel. In this research, esterified waste cooking oil possessing fuel properties on a par with diesel is used as an alternative for diesel [2]. Due to chemical structure and dense molar mass, viscosity of WCO is greater in comparison with diesel. This is the major factor which restricts the usage of WCO directly diesel engines [3]. Because of increased WCO viscosity, atomization of fuel and characteristics of spray are greatly affected by the increase in the size of the fuel droplets, thereby lowering the performance and increasing the toxic gas emissions [4]. Viscosity of the WCO oil can be reduced by using various chemical pretreatment methods in which transesterification is one of the most common methods used worldwide [5].

Mohamed Al-Dawody obtained biofuel from rapeseed oil and blended it with diesel. He found 93.36%, 82.56 %, 81.06%, and 47.27% reduction in smoke emission obtained with B100, B50, B20, and B10 respectively in comparison with diesel. B10 blend emitted less CO and HC with increased NOx [6]. Because of its higher viscosity, there is a decrease in brake thermal efficiency (BTE) with an increase in brake specific fuel consumption (BSFC). Most of the WCO blends emitted higher NOx and lesser CO and HC emissions [7]. Karavalakis et al., [8] studied the effects of WCO biofuel, olive oil, soybean oil and animal fat oil blended with diesel. They concluded that WCO usage increased polyaromatic hydro carbon emissions in the engine due to the presence of cyclic acids and polymerization reaction. Cheung et al., [9] made a detailed study on the WCO biofuel and methanol blends and reported that the increase in aldehyde emissions with lesser alkene emissions. Many researchers [10-12] have used various WCO biofuel-diesel blends in diesel engines and selected B20 as the optimal fuel blend. This made the researchers raise the usage of B20 in CI engines. But, due to the increase in NOx emissions, many researchers [13-15] promoted the usage of alcohols in CI engines because of its lower viscosity and density in comparison with diesel. We could see the usage of various alternative fuels like animal fat oil, soybean oil, rape seed oil, olive oil and WCO in CI engine which reduced various emissions like CO, HC, and smoke with respect to drastic rise in NOx emission. Wei et al., [16] reported HC, CO, NOx, and smoke characterisation of a CI engine using WCO biofuel / diesel blends. The outcomes of their research depicted that xylene and toluene were reduced and a decrease in mass concentration of particles was observed. Araujo et al., [17] showed that 45% of production cost could be saved by the usage of WCO biofuel. Due to this usage of WCO biofuel has been increasingly investigated with respect to diesel engines. Di et al., [18] reported various emissions on 4 cylinder CI engine using WCO biofuel with various blends such as 100%, 80%, 60%, 40%, and 20% vol respectively at various engine loads. There was a reduction in aldehyde emissions while there was an increase in the formation of benzene and acetaldehyde respectively. Also, similar results were found by Cheung et al., [19] who made investigation using a neat WCO biofuel on 4 cylinder CI engine at different load conditions. The researchers here have discussed the various unregulated emissions from CI engine along with the most needed regulated emissions.

From the literature, we could find that the major amount of emission from diesel engine is NOx which is composed of NO_2 and NO (Nitrogen dioxide and nitric oxide). The former is considered as more toxic than the latter. Formation of NO is one of the main reasons for the depletion of ozone layer and also the formation of smog in the environment which affect the human health. NO is formed inside the cylinder at high temperature zone during diffusion combustion phase. The basic reactions in zeldovich mechanism which determines the decomposition of NOx inside the cylinder are as follows:

$$N + O_2 \rightarrow NO + O \quad (1)$$

$$N + OH \rightarrow NO + H \quad (2)$$

$$O + N_2 \rightarrow NO + N \quad (3)$$

NOx formation is mainly attributed to oxygen availability and formation of peak temperature inside the combustion chamber. There are various NOx controlling strategies like addition of cetane enhancers, retardation of fuel injection, water injection and exhaust gas recirculation. Cetane enhancers are more expensive while it reports only less amount of NOx reduction. Fuel retardation results in less power with increased SFC, smoke, and HC emissions. Injection of water becomes failure during colder climates and water storage tank is necessary to store the water which would add more weight to the existing engine.

EGR is a post treatment method in which exhaust gases are sent to the inlet to replace the fresh air entering into the cylinder. Due to the replacement, oxygen concentration in the fresh air would be reduced. The specific heat of the inlet mixture is increased by the mixing of exhaust gas affecting the fuel-air mixture and ultimately reducing the combustion temperature. Because of this reason, formation of NOx would be greatly reduced. The percentage of EGR can be calculated using the measurement of the concentration of CO_2 at the inlet and the outlet represented as $[CO_2]_{int}$ & $[CO_2]_{out}$ respectively [44].

$$EGR\% = \frac{[CO_2]_{\text{int}} - [CO_2]_{atm}}{[CO_2]_{out} - [CO_2]_{atm}} \quad (4)$$

The percentage of EGR can also be found using the ratio of recirculated exhaust gas mass (M_{EGR}) to the mass of inlet charge (M_i).

$$EGR\% = \frac{M_{EGR}}{M_i} * 100 \quad (5)$$

Rajesh Kumar et al., [20] reported that because of oxygen availability in biofuels, there was reduction in UBHC, CO, and smoke emissions. But NOx emissions were high because of high temperature of flame. Usage of EGR reduced NOx emissions. Increasing the percentage of EGR in the inlet air reduced the duration of combustion in the premixed stage and increased the diffusion combustion stage. It also resulted in ignition delay to be longer [21]. Oxygen concentration at the inlet was reduced due to the addition of exhaust gas which resulted in the reduction of peak temperature of combustion. The main reason behind this was the slower reaction rate of combustion [22]. Though EGR reduced NOx emissions, it increased HC, CO, and smoke emissions. The rise in HC and CO emissions would be slighter while the increase in smoke emission was noticeable [23]. Increase in EGR lowered the air-fuel ratio, thereby decreasing the oxygen availability. This variation in air-fuel ratio increased the various exhaust gas emissions. EGR also reduced the flame temperature [24]. Das et al., [25] reported on the usage of EGR in a multi cylinder SI engine along with hydrogen as a pilot fuel and found reduced BSFC and also reduction in NOx emissions. Because of usage of EGR, the volume of exhaust gases emitted was reduced. Kusaka et al., [26] also showed that there would be an increase in BTE with reduction in HC emissions when the inlet air was heated along with EGR at lower load conditions. Increase in UBHC emissions reported around 20-30% was on a par with CI engine with no EGR. Agarwal D et al., also reported on the increase in HC and reduction in soot emissions in the case of CI engines [27].

Table 1 EGR effects on characterisation of diesel and biofuels

Fuel used	EGR Concentration	Engine Specification	Performance	Combustion	Emission	Optimum Fuel and % EGR	Reference
Pentanol / diesel blends, PEN10, PEN20, PEN30, PEN45	10% 20% 30%	Kirloskar TAFE make, DI, 4S, RO - 4.7 kW @ 1500 rpm, IP - 20-21 MPa, IT - 23° bTDC	BTE ▼ BSFC ▲	-	NOx▼ Smoke▼ HC▲ CO▲	PEN45 20% EGR	[20]
Diesel	10% 15% 20%	Indec PH2, DI, 4S, RO - 9 kW @ 1500 rpm, IP - 210 bar, CR 16.5:1	BTE ▲ BSFC▼	-	NOx▼ Smoke▲ HC ▲ CO▲	Diesel 15% EGR	[27]
Diesel	2.5% 5% 7.5% 10%	MWM D229-4, DI, 4S, RO - 40 kW @ 1800 rpm, CR - 17:1	BTE▼ BSFC▲	HRR ▼ CP▼	CO2 ▲ CO ▲ HC ▲ NOx▼	Diesel 7.5 % EGR	[37]

PET - Pentanol fuel, IT - Injection timing, RO - Rated Output, CR - Compression ratio, 4S - Four Stroke, IP - Injection Pressure.

Most fluid flow problems can be solved using Computational Fluid Dynamics (CFD) software. By defining the boundary conditions, various CFD software like ANSYS Fluent could perform simulations of the fluid interactions. Furthermore, to make a good research, before conducting the experiments, it is better to get solutions by simulation. Rajesh Govindam et al. [28] prepared different models to analyse various blends of biofuel in the diesel engine using ANSYS Fluent. High peak temperature and in-cylinder pressure were obtained as results while validating the models. Norrizam Jaat et al., [29] predicted the characteristics of combustion with high peak pressure and temperature with ambient conditions for Jatropha biofuel in diesel engine using Ansys Fluent. The usage of simulation software has improved the confidence in conducting the experiments and would easily make the comparison in the obtained results.

M.S.Gad et al [45] conducted experiments on the diesel engine with WCO biodiesel and gasoline additives to compare the performance, emission and combustion characteristics with neat diesel fuel. Three fuel blends namely BG8, BG4, and BG2 consisting of 8%, 4%, and 2% gasoline and 92%, 96%, and 98% WCO respectively were used. The emissions such as smoke, NOx, HC and CO were reduced by 30%, 20%, 30%, and 25% respectively along with improved cylinder pressure and heat release rate due to the usage of WCO and gasoline additives. Mohamed Nour et al [46] investigated the aluminium oxide nano particle addition over the ethanol blended jojoba biodiesel in a diesel engine and found that 75 mg/L addition of nano particle enhanced the overall chaarcteristics of the engine. Ahmed I. El-Seesy et al [47] conducted an experimental investigation in the diesel engine to optimize the aluminium oxide nanoparticle addition over jojoba biodiesel blends. They found that 20 mg/L of nanoparticle addition reduced the emissions such as smoke, HC, CO and NOx by 35%, 60%, 80%, and 70% respectively. While 40 mg/L addition showed remarkable improvement in performance and combustion characteristics of the engine.

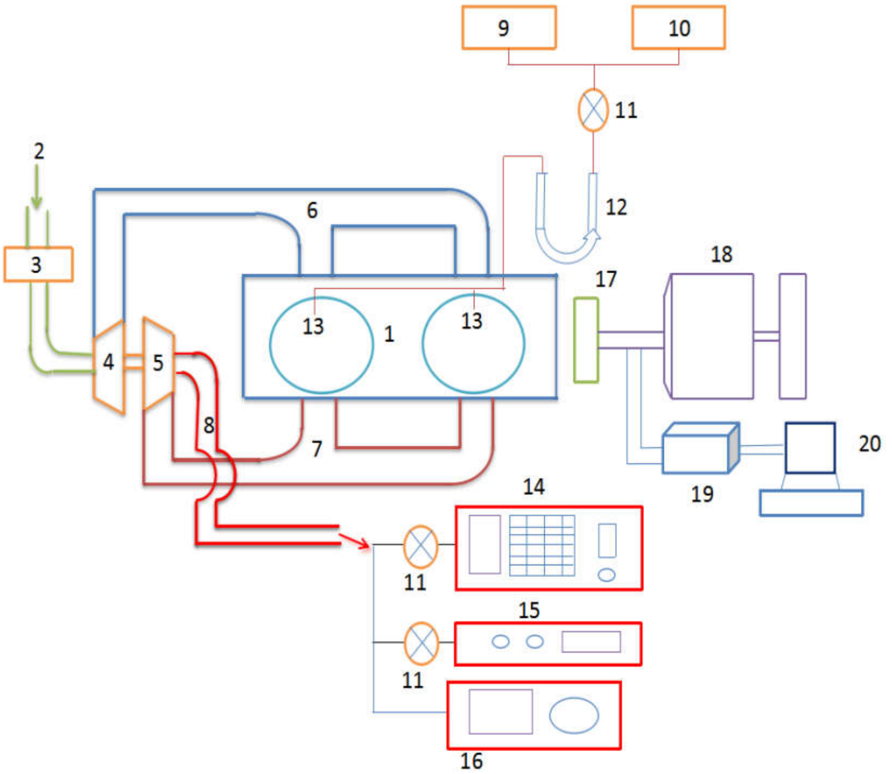
From the literature, it is clear that WCO biofuel can be used as an alternative fuel in CI engines along with reduction in various emissions like CO, HC, and smoke along with increased NOx. To control NOx emission, EGR was found to be an effective method. Many researchers made efforts to optimize the WCO fuel blend which ended in increasing NOx. Only very less number of research works was found in the area of optimizing the WCO fuel blend along with reduction in NOx and without compensating the performance and other emissions. Thus, in this research work, WCO biofuel is prepared using transesterification method and it is analyzed using gas chromatography-mass spectroscopy (GCMS) method. It is then mixed with diesel in vol proportions such as 100%, 60%, 40%, and 20% respectively. The fuel properties of the prepared blends were studied. The combustion modeling has been done for the prepared blends of biofuel, B100, and diesel which are compared by using ANSYS Fluent software. Also characterisation on combustion, performance, noise and emission of various test fuels has been studied in a two cylinder CI engine. Depending upon experimental characterisation and simulated results of combustion, a suitable blend ratio is selected for the WCO biofuel. Further to reduce NOx emissions in the selected blend ratio, EGR is introduced into the inlet at varying ratio of 5%, 10%, and 15% respectively. Thus optimization has been done in terms of percentage of EGR introduced in the optimized WCO blend.

2. Materials and Methods

2.1 Test Engine Set-up

A twin cylinder, water cooled, 4 stroke, D.I diesel engine was used for the current investigation. The complete schematic representation of the test engine setup with EGR used is in fig. 1. Fig. 2 shows the actual engine set-up. This type of engine is used in the case of tractors falling under

Bharat Stage-III norms. The major engine specifications are listed in Table 2. The various instruments used for the characterisation of the test engine and uncertainties and errors predicted using a separate method in the experimental calculations [30] are detailed in Table 3.



1. Twin Cylinder Diesel Engine
2. Air inlet
3. Air Filter
4. Air Compressor
5. Exhaust gas Turbine
6. Inlet Manifold
7. Exhaust Manifold
8. Exhaust gas Outlet
9. Diesel Tank
10. biofuel Tank
11. Control valve
12. U-tube Manometer
13. Fuel injector
14. Smoke meter
15. AVL Di-gas analyzer
16. Thermocouple
17. Crank angle encoder
18. Electrical dynamometer
19. Indi-meter

Fig. 1 Schematic diagram of engine setup using EGR

Fig. 2 Engine Setup

Table 2 Engine Specifications

Parameter	**Specification**
Model and make	Simpons S217 Tractor Engine
Maximum Rating	21 kW @ 2000 rpm
Cubic Capacity	1670 cc
Configuration type	Vertical In-Line Diesel Engine
Injection system	Direct Injection
Bore	91.44 mm
Stroke	127 mm

Compression Ratio	18:5:1
Connecting rod length	223.81 mm
No of Cylinders	Two
Aspiration	Natural
Cycle	4 Stroke
Cooling System	Water cooled
Governing	Mechanical
Fuel Pump	Mico Bosch In-line Pump
Injection Timing	24° bTDC
Lubricating Oil	SAE 1 or SAE 3
No. of nozzle holes	5
Injector nozzle size	0.262 mm @ 148°
Injection Pressure	250 bar

Table 3 Measuring Instruments used

Instruments used with model	Measuring parameter	Measuring range	Accuracy	Errors
E50 Eddy Current	Torque	234 Nm @ 1500 to 3000 rpm	± 0.25	± 0.2

Dynamometer				
FMGDN80G100 Air flow meter	Amount of flow of air	160 m^3/hr	± 1	± 1
6613CQ09-01 KISTLER Pressure Sensor	Pressure	0 - 200 bar	± 0.75	± 0.1
AVL DI GAS 444N analyser	CO	0 – 15 % vol	± 0.013	± 0.9
	HC	0 – 20,000 ppm	± 3	± 1.1
	O_2	0 – 25 % vol	± 0.025	± 0.8
	CO_2	0 – 20 % vol	± 0.1	± 1.05
	NOx	0 – 2,000 ppm	± 5	± 1.15
AVL 437 smoke-meter	Smoke	0 - 100% capacity	± 1	± 1

2.2 Biofuel preparation

In this research work, Waste Cooking Oil (WCO) was collected from the hostel mess of Mepco Engineering College, Sivakasi. The oil was used to fry papads served during lunch. A one step transesterification process shown in fig. 3 was done to convert the raw WCO into biofuel. In this process, solid filtration was done by using a strainer of 4µm in which the filtered oil was then heated to about 100°C for around 15 minutes. The heating was done to eliminate water particles present in the WCO oil. Using a mechanical stirrer, constant stirring at 1000 rpm for 10 minutes is done by adding 1% weight of potassium hydroxide and methanol to the heated oil. The ultrasonicator bath was kept constant at 65°C. The mixture obtained was allowed to settle down for

2 hours in a separation vessel. Three different blends, namely B20, B40 and B60 were prepared respectively. Analysis was made on all the three prepared blends & WCO and compared with respect to diesel. The physio-chemical properties of the fuel estimated using different methods of standard are listed in Table 4.

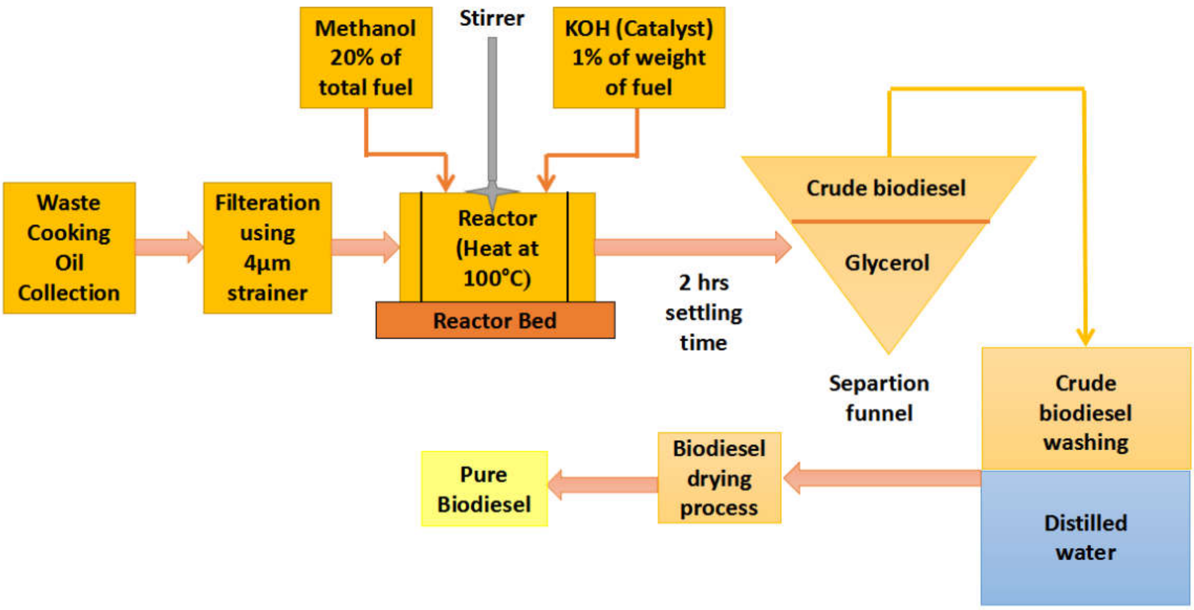


Fig. 3 Biofuel Production

Table 4 Determination of test fuel properties

S.No	Fuel properties	Diesel	B20	B40	B60	B100	ASTM Test standard
1	Kinematic Viscosity @	2.31	2.04	2.77	3.23	4.07	D445

	40°C (cSt)						
2	Density (kg/m^3)	832	820	837	853	875	D4052
3	Calorific Value (kJ/kg)	42485	41448	40091	38452	36123	D240
4	Flash point (°C)	71	88	127	163	186	D93

2.3 GCMS results of waste cooking oil and biofuel

The GCMS technique was employed to find out the chemical constituents that were present in the fuel. This is a type of analytical method to differentiate substances in a test fuel using gas chromatography and mass spectrometer. Fig. 4(a) represents the fatty acid contents of WCO and fig. 4(b) shows the methyl ester compounds that are present in WCO biofuel.

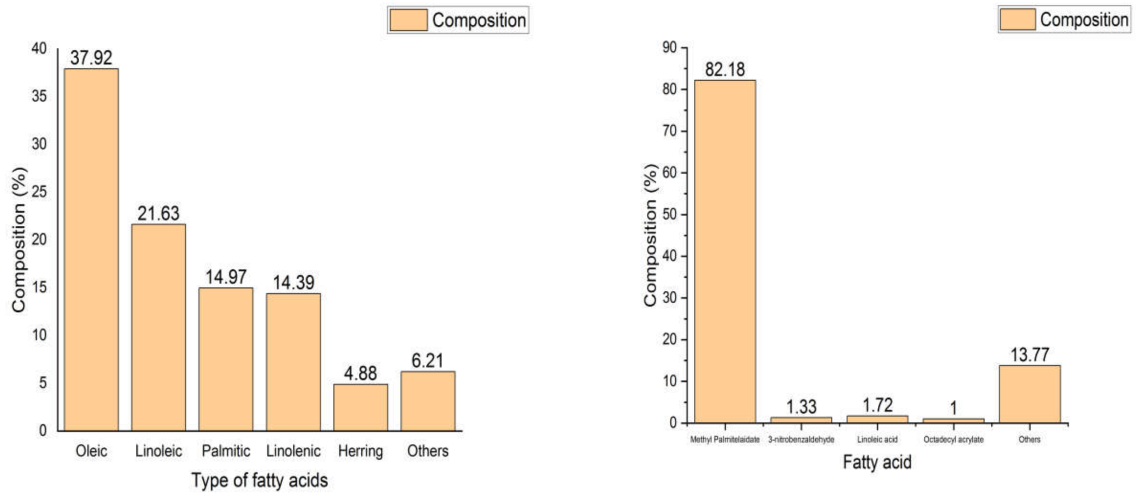


Fig. 4 Bar chart of (a) % Fatty acid present in WCO and (b) % methyl ester compounds present in the WCO biofuel

The GCMS results obtained for WCO are presented in Table 5. The major constituent chemicals which are present in WCO consist of 37.92% of fatty acid type of oleic acid. The second major constituent of around 21.63% of fatty acid type is linoleic acid. The third and the fourth fatty acid contents present are 14.97% of palmitic acid and 14.39% of linolenic acid respectively. WCO had 264 g/mol as average molecular weight. The GCMS results of WCO biofuel are presented in Table 6. About 82.18% of the WCO biofuel obtained had methyl ester palmitate. 1% of octadecyl acrylate, 1.72% of linoleic acid and 1.33% of 3-notrobenzaldehyde are the other minor chemical constituents that are present in the WCO biofuel. The author has given a more detailed description in his previous study [41] about the GCMS of WCO and WCO biofuel and so it is not explained now in a detailed manner.

Table 5 Fatty acid composition of waste cooking oil

S.No	Peak no	Identified compounds	Molecular Weight	Molecular formula	Area

1.	14	Cyclopentadecanone, 2-hydroxy-	240.3816	$C_{15}H_{28}O_2$	15.79
2.	5	13-octadecadienol, Z-3, 2-Methyl-Z	280.548	$C_{19}H_{36}O$	12.17
3.	1	n-hexadecanoic acid	256.43	$C_{16}H_{32}O_2$	9.04
4.	4	trans-13-Octadecenoic acid	282.468	$C_{18}H_{34}O_2$	7.37
5.	16	Oleic Acid	282.468	$C_{18}H_{34}O_2$	7.23
6.	12	2-Oxecanone, 10-methyl-,	170.2487	$C_{10}H_{18}O_2$	4.6
7.	22	2-Trifluoromethylbenzoic acid, 1-cyclopentylethyl ester	190.121	$C_8H_5F_3O_2$	4.46
8.	20	2-Trifluoromethylbenzoic acid, 1-cyclopentylethyl ester	190.121	$C_8H_5F_3O_2$	4.19
9.	11	Oleic Acid	282.468	$C_{18}H_{34}O_2$	3.46
10.	2	Octasiloxane, 1,1,3,3,5,5,7,7,9	577.233	$C_{18}H_{54}O_7Si_8$	3.07
11.		Octasiloxane, 1,1,3,3,5,5,7,7,10		$C_{16}H_{48}O_7Si_8$	
12.	15	Oleic Acid	282.468	$C_{18}H_{34}O_2$	2.92
13.	19	2-[(tert-butyl dimethyl silyl)oxy]-1-isopropyl-4-methyl-, Benzene	264.484	$C_{16}H_{28}OSi$	2.18
14.	6	Octadec-9-enoic acid	283.46	$C_{18}H_{34}O_2$	1.92
15.	18	N-(1-methylethyl)-N,3-diphenyl-, 2-Propenamide	252.358	$C_{14}H_{24}N_2O_2$	1.84
16.	17	6-Octadecenoic acid	282.468	$C_{18}H_{34}O_2$	1.63
17.	21	[4-(1,1-dimethylethyl)phenoxy]-, Acetic acid, methyl ester	222.284	$C_{13}H_{18}O_3$	1.62
18.	8	2-p-Nitrophenyl-5-ethoxy-oxadiazole-1,3,4	70.051	$C_2H_2N_2O$	1.43
19.	9	2,4-dimethyl, Benzo[h]quinoline	207.276	$C_{15}H_{13}N$	1.26

20.	7	2-Ethylacridine	207.276	$C_{15}H_{13}N$	1.19
21.	10	n-Decanoic acid	172.268	$C_{10}H_{20}O_2$	1.11
22.	13	6-Octadecenoic acid, (Z)	282.468	$C_{18}H_{34}O_2$	1.08
23.	3	(E,E)-2,4-Decadienal,	152.237	$C_{10}H_{16}O$	0.27

Table 6 FAMEs composition of WCO biofuel

S.No	Peak	Identified compounds	Molecular formula	Molecular Weight	Area
1.	3	Methyl ester, 10,13-Octadecadienoic acid	$C_{19}H_{34}O_2$	294.479	53.99
2.	1	Methyl ester, 9-Octadecenoic acid	$C_{19}H_{36}O_2$	296.495	22.49
3.	2	Methyl ester stearic acid	$C_{19}H_{38}O_2$	298.511	4.71
4.	12	Methyl ester, cis-13-Eicosenoic acid	$C_{21}H_{40}O_2$	324.549	0.97
5.	8	cis-13-Octadecenoic acid	$C_{18}H_{34}O_2$	282.468	0.97
6.	11	4-Hydroxybenzoxazolone	$C_7H_5NO_3$	151.121	0.92
7.	4	13.trans.-octadecatrienoate, Methyl 9.cis.,11.trans.t	$C_{19}H_{32}O_2$	292.463	0.89
8.	5	methyl ester, 9-Octadecenoic acid, (E)-	$C_{19}H_{36}O_2$	296.495	0.55
9.	7	9,12-Octadecadienoic acid (Z,Z)-	$C_{18}H_{32}O_2$	280.452	0.55
10.	6	Methyl ester, eicosanoic acid	$C_{21}H_{42}O_2$	326.565	0.4
11.	9	9,12-Octadecadienoic acid (Z,Z)-	$C_{18}H_{32}O_2$	280.452	0.4
12.	10	9-Dicarboxylic acid, Tricyclo[5.2.1.0(2,6)]dec-8-ene-8, 4-methylene-, dimethyl ester, endo	$C_6H_{12}FNO$	133.166	0.31

2.4 Test Procedure

The experiments were carried out at 100%, 75%, 50%, 25% load conditions of the engine with respect to the indicated mean effective pressure of 5.29, 2.73, 1.64, and 1.16 bar respectively. The lubricating oil was maintained at temperatures between 68 and 88°C. The test engine had 24° Crank Angle bTDC and the pressure of injection was maintained at 250 bar. Throughout the experiments, the room temperature was maintained at ambient conditions to increase the reliability in the readings [49-50]. To start the trial for each run, the engine was allowed to run for 5-10 mins with the respective fuel before the recording of the readings [53-55]. Every test done was repeated thrice, and the average values were taken for the plotting of the graph, and so repeatability was ensured [51-52]. Table 7 represents the design matrix of test fuels used along with their blending percentage and EGR conditions.

Table 7 Summary of test fuels, blends & conditions

Fuel No.	Test Fuel								EGR condition			Short form of fuel
	Diesel, vol%				WCO							
	100 %	80 %	60 %	40 %	20 %	40 %	60 %	100 %	5 %	10 %	15 %	
1	√											D100
2		√			√							B20
3			√			√						B40
4				√			√					B60
5								√				B100
6		√			√				√			B20 5%EGR
7		√			√					√		B20 10%EGR
8		√			√						√	B20 15%EGR

3. CFD analysis of fuel combustion using Ansys Fluent

3.1 Problem Modeling

A cylindrical combustion geometry of dimensions 1800 mm * 225 mm was created by using Ansys Modeller. The geometry was meshed using Ansys represented in fig 5 and the edges were named as per the requirements for applying boundary conditions.

The properties of the fuel were taken from table 5 for combustion analysis. Turbulence Chemistry Interaction-Eddy Dissipation model was used in the analysis of combustion of biofuel to assume it as a complete combustion. The combustion modeling for three different fuels namely, diesel, B20, and B100 was carried out. The type of analysis used was 2D axisymmetric. K-epsilon type of turbulence model was implemented. The simulation was made to run initially on the created mesh and ensured the predicted results of tempearture, NOx and CO_2 were steady and also the imbalances accuring below 1% along with 10^{-4} residual error. Again the simulation was made to run with another mesh which was finer about 1.5 times the size of the intial element mesh. Now the imbalances were below 1%, residual error dropped below 10^{-4} and the predicted results of temperature, NOx and CO_2 were steady. The difference in the points which was monitored between the two simulations were within the acceptable limits. Again the mesh element size was reduced and the points mointored were found steady. The number of iterations were around 6 with different element sizes varying from 13 mm - 0.7 mm respectively. As finer the mesh resolution, the results were accurate. While 12000 number of elements with element size of about 1 mm has been found better with respect to the accuracy in results and also with the simulation runtime. Thus the solution predicted was found independent of the mesh that has been created [48]. The basic combustion equations for various elements are:

Diesel: $C_{10}H_{22} + 15.5O_2 \Rightarrow 10CO_2 + 11H_2O + Heat$ (6)

B20: $C_{10}H_{22}\,(80\%) + C_{17}H_{34}O_2\,(20\%) + 40O_2 \Rightarrow 27CO_2 + 28H_2O + Heat$ (7)

B100: $C_{17}H_{34}O_2 + 24.5O_2 \Rightarrow 17CO_2 + 17H_2O + Heat$ (8)

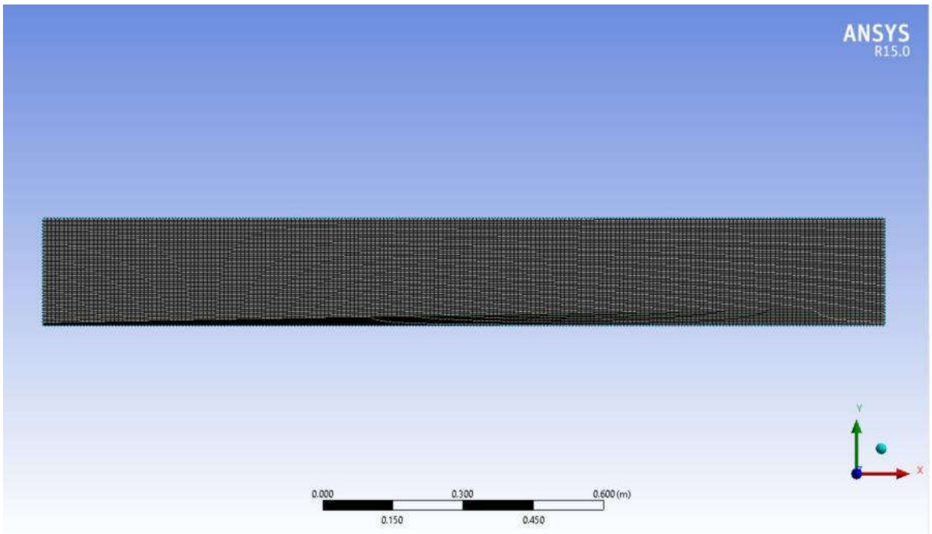


Fig. 5 Meshed cylindrical combustor

3.2 Predicted Results:

The mass fraction of O_2 was 0.76 at 0.5m/s,300K at the air inlet and the mass fraction of diesel/biofuel at the fuel inlet was 1 at 50m/s,300K. The major properties of diesel considered were viscosity as 2.76 cSt, calorific value as 44000 kJ/kg, density as 825kg/m^3, and specific heat constant as 1750 J/kg-K. The temperature profile of diesel-air mixture shown in fig 6(a) was predicted with a peak temperature of about 2.12e^{+03} K. The high temperature was because of high heating value and low viscosity of diesel. The major properties of B20 considered were viscosity as 2.93 cSt, calorific value as 41417.42 kJ/kg, density as 820kg/m^3, and specific heat constant as 2050 J/kg-K. The temperature profile of biofuel (B20) - air mixture shown in fig 6(b) was predicted with a peak temperature of about 1.652e^{+03} K. The low temperature in comparison with diesel was because of low heating value and increased viscosity of B20 blend. The major properties of biofuel (B100) considered were viscosity as 4.07 cSt, calorific value as 36099.34 kJ/kg, density as 875kg/m^3, and specific heat constant as 2050 J/kg-K. The temperature profile of biofuel (B100) - air mixture shown in fig 9(c) was predicted with a peak temperature of about 1.52e+03 K which was lesser than the conventional diesel-air mixture. The reason would be the same as mentioned for B20 blend.

The contours of mass fraction of pollutant NOx emission of diesel are depicted in fig 7(a) ranging between 0.12 and 0.39 mass fraction. The contours of mass fraction of pollutant NOx emission of B100 fuel are shown in fig 7(c) ranging between 0.1 and 0.5 mass fraction. The contours of mass fraction of pollutant NOx emission of B20 fuel are shown in fig 7(b) ranging between 0.12 and 0.8 mass fraction. The mass fraction of NOx produced was higher in B20 than in B100 and diesel fuel during combustion. This increase in mass fraction of NOx could be reduced by the application of EGR introduced into the inlet air.

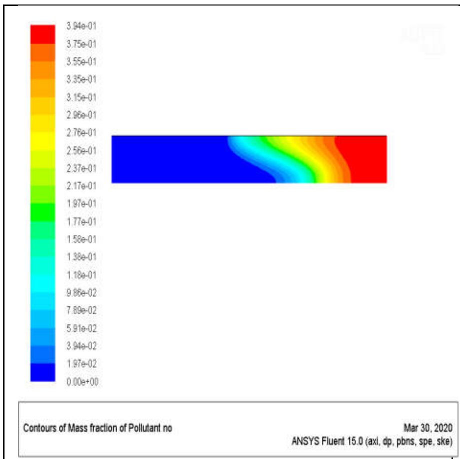


Fig. 6(a) Temperature profile - Diesel

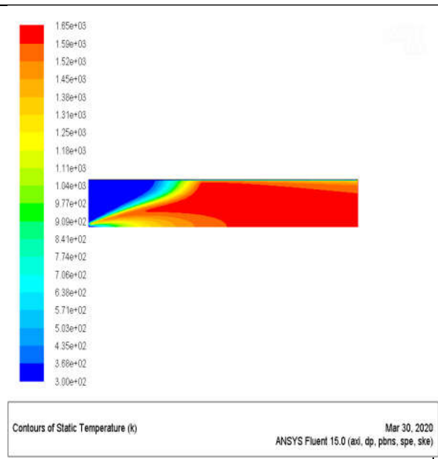


Fig. 6(b) Temperature profile - B20

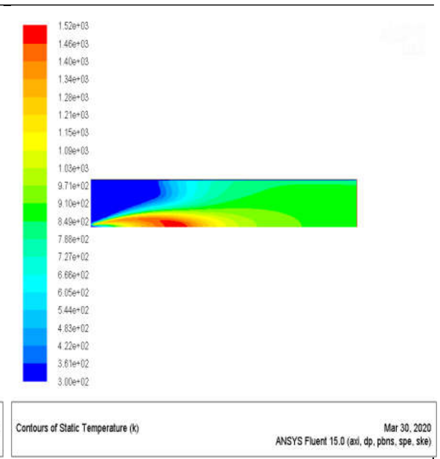


Fig. 6(c) Temperature profile - biofuel (B100)

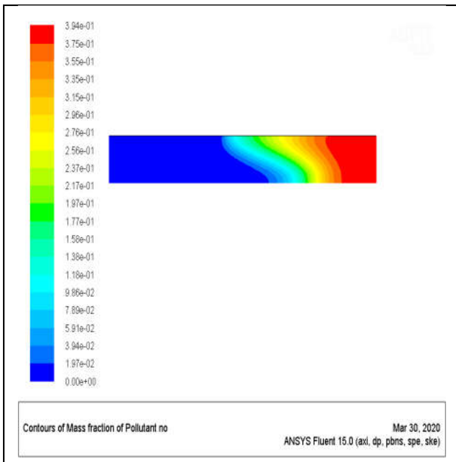


Fig. 7(a) Mass fraction of NOx - Diesel

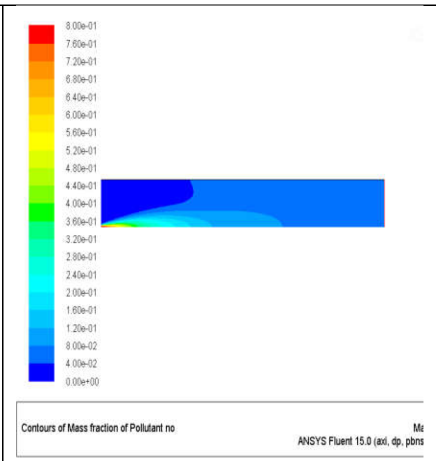


Fig. 7(b) Mass fraction of NOx - B20

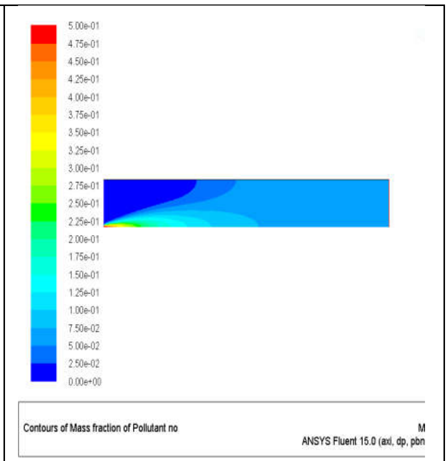


Fig. 7(c) Mass fraction of NOx - biofuel (B100)

The contour of mass fraction of CO_2 emission of diesel is shown in fig 8(a) ranging between 0.1 and 0.19 mass fraction. The contour of mass fraction of CO_2 emission of biofuel (B100) are shown in fig 8(c) ranging between 0.1 and 0.2 mass fraction. The contour of mass fraction of CO_2 emission of biofuel (B20) are shown in fig 8(b) ranging between 0.1 and 0.16 mass fraction. In comparison with all the three CO2 emission mass fractions, B20 fuel seems to perform better with which there are no differences in the case of B100 and diesel fuel.

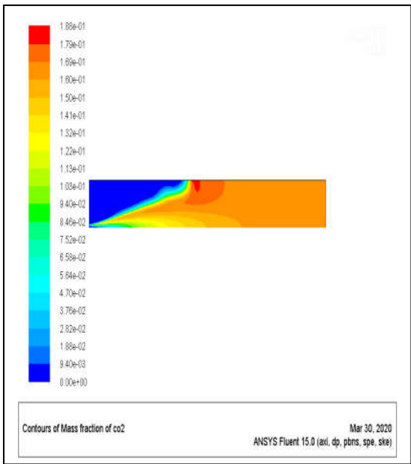


Fig. 8(a) Mass fraction of CO2 - Diesel

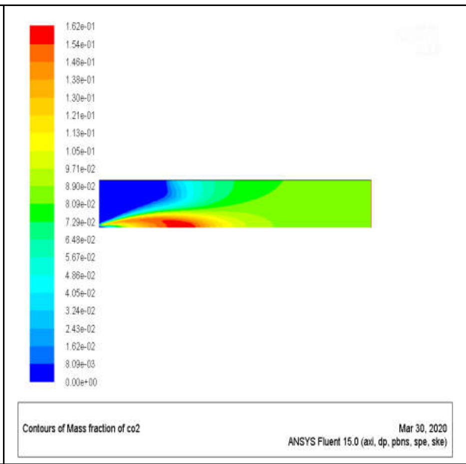


Fig. 8(b) Mass fraction of CO2 - B20

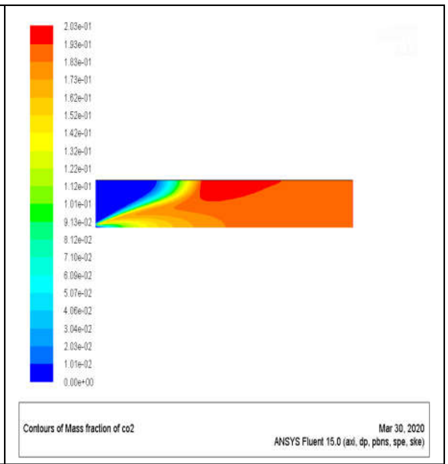


Fig. 8(c) Mass fraction of CO2 - biofuel (B100)

4. Results and Discussions

4.1 Characteristics of Performance

4.1.1 Variation in BTE

Fig. 9 represents comparison of BTE of diesel, WCO biofuel and prepared blends with increase in load. The graph explains clearly about the conversion of heat into work. BTE was calculated using engine torque, speed, and rate of fuel consumption. The graph shows a general trend done by various researchers [35, 36] in which BTE increases with rise in load for all types of test fuels. The upper limits of BTE obtained at 100% load condition are 33.12, 30.92, 31.06, 31.26, and 32.52

percentage for diesel, B100, B60, B40, and B20 respectively. Increasing blend percentage of WCO biofuel in diesel decreased BTE. The main reason behind this trend was increasing viscosity and decreasing calorific value with respect to the increase in blending percentage of biofuel. B20 blend fuel behaved very much like pure diesel and better than other blends of WCO biofuel [34].

In the view of controlling NOx in the B20 blend fuel, exhaust gases were introduced into the air inlet at 5, 10, and 15 % respectively. From fig. 9, percentage increase in EGR would slightly decrease BTE. The main reason was reduction in the rate of burning impinging the normal combustion process of B20 fuel blend. The combustion losses were increasing due to increase in EGR rates.

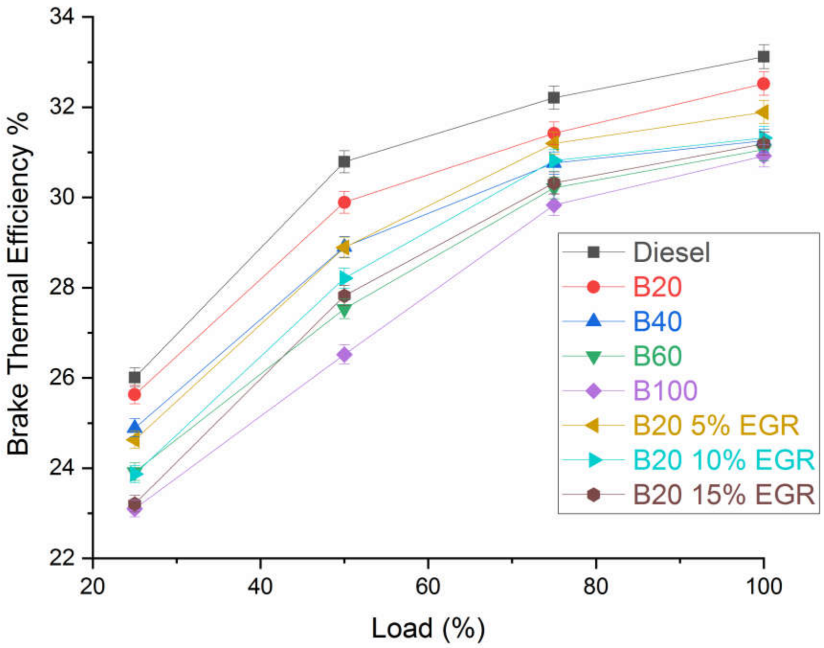


Fig. 9 Load Vs Brake Thermal Efficiency

4.1.2 Variation in SFC

Fig. 10 represents comparison of SFC of diesel, WCO biofuel and its blends with increase in load. The graph shows a general trend observed by various researchers [33, 35] in which SFC fell with rise in load for all types of test fuels. The SFC measured at 25% load condition were 0.311, 0.389, 0.378, 0.359, and 0.339 kg/kWhr for diesel, B100, B60, B40, and B20 respectively. Comparison shows the increase in SFC at all load conditions with the increasing percentage of biofuel blends. Biofuel has extracted the same power output with more consumption of fuel in comparison with diesel due to high density and lower calorific value. The difference between SFC at lower loads was high while at higher load conditions it was found to be low. Since at higher loads, the air fuel mixture inducted into the cylinder became lean which consumed lesser amount of fuel. From fig. 10, increasing rates of EGR would slightly increase SFC at lower loads, while at higher loads no much difference was found [20]. The reason at high loads was that the mixture was becoming lean, while at lower loads in-cylinder temperature decreased causing incomplete combustion due to increase in EGR application.

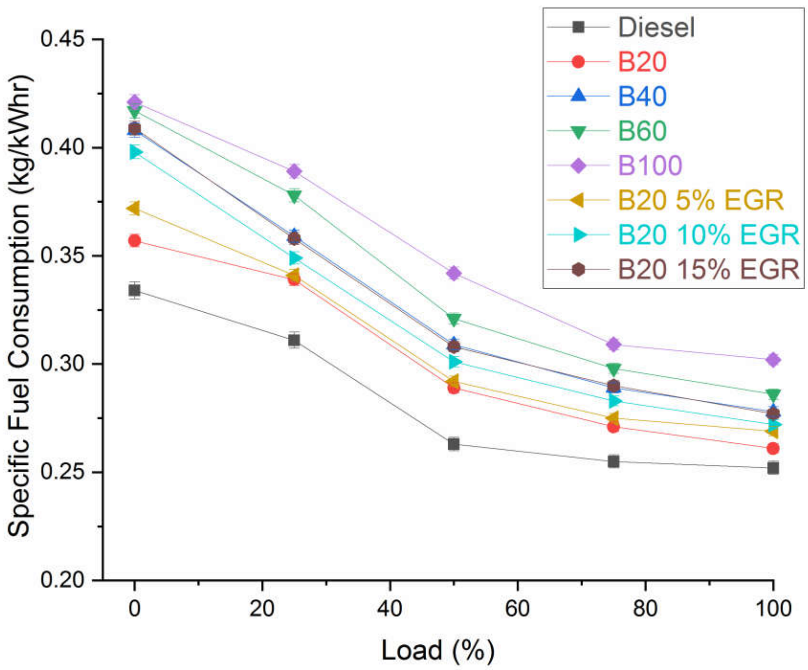


Fig. 10 Load Vs Specific Fuel Consumption

4.2 Characteristics of Various Emissions

4.2.1 Variation in CO emission

Fig. 11 depicts the comparison of CO emission values of diesel, WCO biofuel and prepared blends along with increase in load. The graph shows a general trend seen by a researcher [33] in which CO emission increases sharply for higher load for all types of blends and fuels including both diesel and WCO biofuel. This rise is because of increased fuel injection inside the combustion chamber and very less time for the combustion to take place. At lower and medium load conditions, only slight differences are observed in CO emissions for the blends. But still, with the increase in the blending percentage of WCO, CO emission decreases. This is due to plenty of oxygen available in WCO biofuel resulting in CO_2 conversion at lower and medium loads [35]. At 100% load condition, CO emissions obtained are 0.1, 0.09, 0.09, 0.08, and 0.07 % vol for diesel, B100, B60, B40, and B20 respectively. B20 blend serves better in comparison with other higher blends. This is due to less time for combustion into which increased availability of oxygen in increasing WCO blends quenches the flame and reduces the flame temperature. Increase in variation of EGR rates in B20 fuel increases CO emission since EGR introduction reduces the oxidation reaction of CO to CO_2 by decreasing the available oxygen level and replacing it by CO_2 at the inlet.

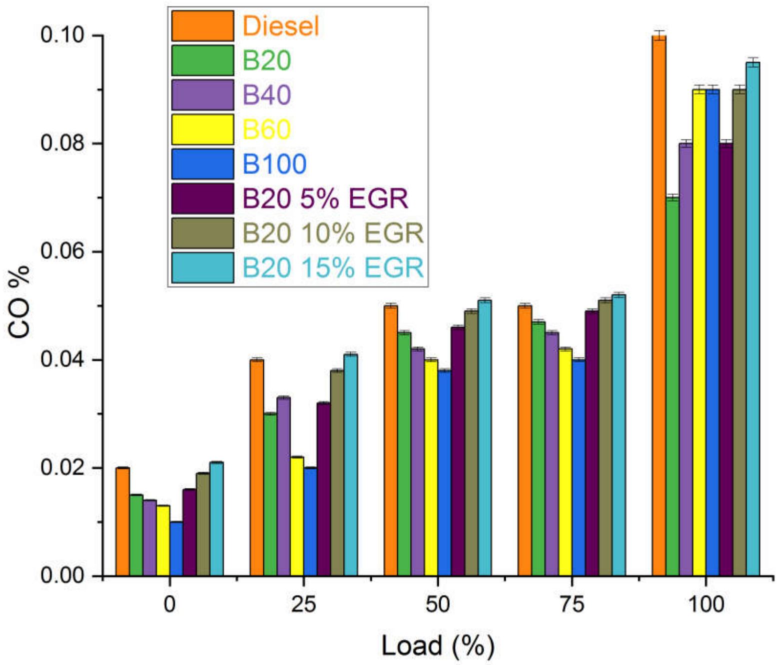


Fig. 11 Load Vs CO Emission

4.2.2 Variation in HC Emission

Fig. 12 represents the comparison of HC emission values of diesel, WCO biofuel and its prepared blends with respect to change in load. The graph shows a trend in which HC emission decreases for lower and medium loads for all types of blends and fuels including both diesel and WCO biofuel. At 100% load condition, HC emissions obtained are 8.2, 7.9, 7.5, 7.2, and 6.8 for diesel, B100, B60, B40, and B20 respectively and they are increasing for all types of fuels [33]. Increased mass of fuel inducted to produce engine power leading to incomplete combustion would be a major reason. Increasing the blend percentage of WCO at lower and medium load conditions does not have a major effect in HC emission between the blends but still less than diesel fuel. The reason could be that increased oxygen level in WCO biofuel facilitates complete burning inside the combustion chamber. At higher loads, B20 has performed better than all other blends. Here the reason could be the presence of lean air fuel mixture getting quenched due to excess oxygen available in WCO biofuel guiding to incomplete combustion. Increasing percentage of EGR in B20 blend increases HC emission [27] since the rise in EGR rates produces larger zones of flame quenching at the diffusion stage of combustion.

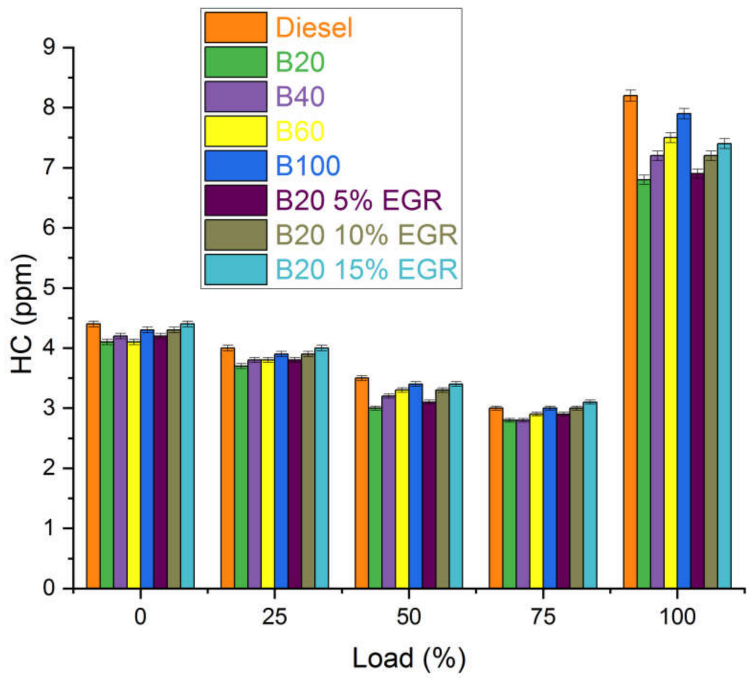


Fig. 12 Load Vs HC Emission

4.2.3 Variation in NOx Emission

Fig. 13 shows the trade-off between NOx emission values of diesel, WCO biofuel and its prepared blends with respect to change in load. The graph shows a general trend noted by various researchers [6, 7, 16] in which NOx emission increases with respect to rise in load for all types of test fuels. The reason is rise in flame temperature due to quick reaction rate with increase in load [34]. Increased oxygen level in biofuel enables complete burning thus increasing in-cylinder temperature and also due to high heat release rate NOx emission increases. The trends between the blends are the same at all load conditions. At 100% load condition, NOx emissions obtained are 870, 873, 901, 952, and 992 ppm for diesel, B100, B60, B40, and B20 respectively. From the above values, all WCO blends and biofuel have higher NOx than diesel. This would be ascribable to better burning at diffusion phase and biofuel accumulation at the premixed phase of combustion. B20 shows higher NOx emission compared with other blends and biofuel. The reason is higher cumulative heat release rate rendered by oxygen content to the diesel to burn effectively and produce higher flame temperature. To reduce NOx emission in B20 blend fuel, EGR is introduced into the inlet. With the increase in percentage of EGR, NOx emission decreases. Exhaust gases reduce the oxygen level in the combustion by replacing it with CO_2. The reduction in NOx is higher at full load while it is lower at part loads. The reason is that oxygen availability for combustion decreases as the load increases, thus reducing the cylinder flame temperature.

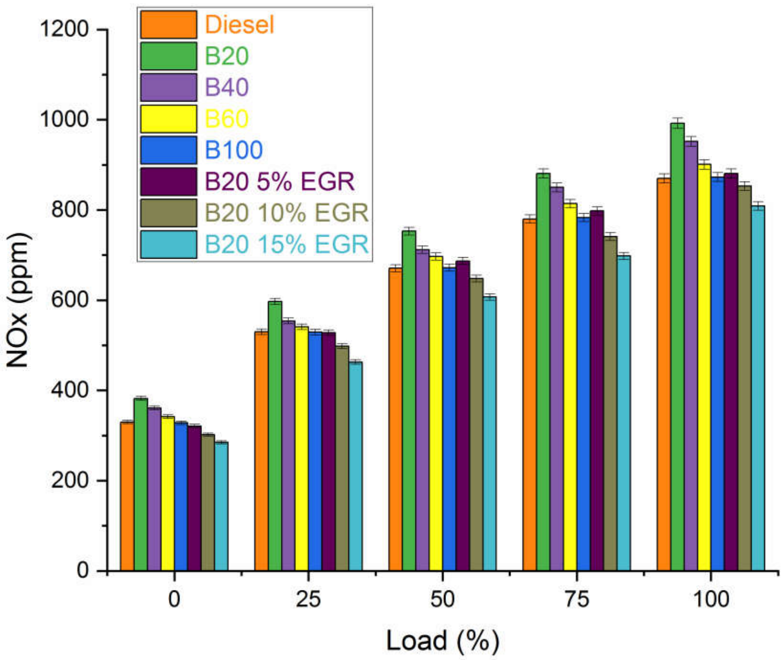


Fig. 13 Load Vs NOx Emission

4.2.4 Variation in Smoke Emission

Fig. 14 depicts the trade-off between smoke opacity values of diesel, WCO biofuel, and its prepared blends with respect to increase in load. The graph shows a trend observed by various researchers [6, 7, 16] in which it shows an increase in smoke opacity with respect to rise in load for all types of test fuels. This is due to the consumption of increased quantity of fuel and lesser air fuel equivalence ratio at higher loads. At 100% load condition, smoke opacities are 94.2, 85.4, 86.4, 87.5, and 89.5% and at 50% load, smoke opacities are 42.5, 56.1, 52.4, 49.5, and 48.2% for diesel, B100, B60, B40, and B20 respectively. This trend between the blends shows that at lower and part loads, smoke opacity increases with the rise in blends of WCO biofuel. The reason is air fuel mixture being rich, increases the viscosity of WCO biofuel and atomization of fuel being poor. While at higher load conditions, though B100 has high viscosity, air-fuel mixture is lean and so high oxygen content available in biofuel combusts the mixture at a better rate than diesel and other WCO blends. B20 fuel has shown a better result for smoke opacity at higher loads and at lower and part loads, there is no much difference from diesel fuel. Increase in percentage of EGR raises smoke opacity with respect to change in load [27]. The reason behind is that the mixing of exhaust gas reduces the oxygen availability leading to incomplete combustion. In general, soot bump occurs with the increase in EGR rates thus making it difficult to control the combustion inside the cylinder.

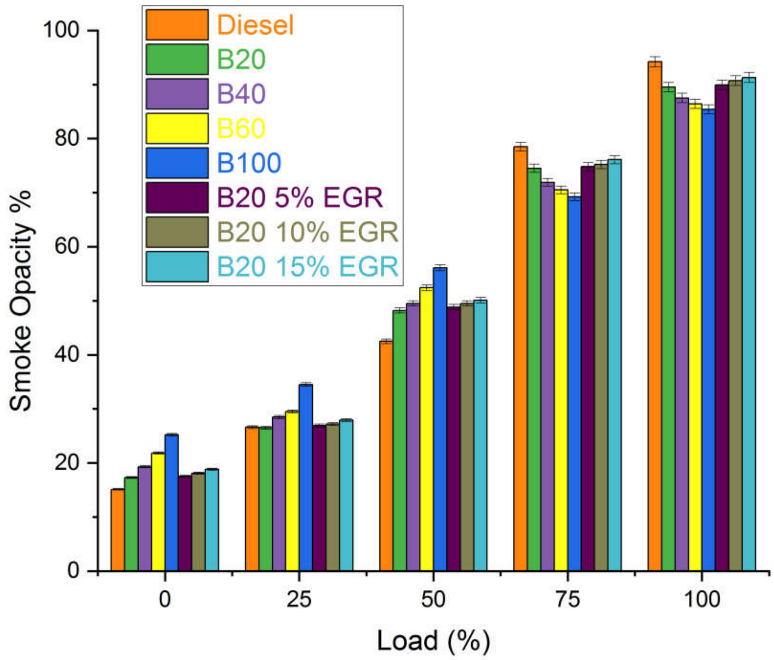


Fig. 14 Load Vs Smoke Emission

4.2.5 Variation in CO_2 Emission

Fig. 15 represents the comparison of CO_2 emission values of diesel, WCO biofuel, and prepared blends along with increase in load. The graph shows a similar trend noticed by researcher [32] in which CO_2 emission increases gradually at all load conditions for all types of blends and fuels including both diesel and WCO biofuel. This rise is due to the increased mass of fuel injection inside the combustion chamber. With increase in blending percentage of WCO, CO_2 increases. The reason is plenty of O_2 available in WCO biofuel resulting in CO to CO_2 conversion. At 100% load condition, CO_2 emission obtained are 5.1, 5.7, 5.5, 5.4, and 5.2 % vol for diesel, B100, B60, B40, and B20 respectively. B20 blend serves better in comparison with the other higher blends only at lower and part load conditions. The reason is that rich air fuel mixture burning needs more oxygen content which is less in B20 in comparison with its higher blends. At higher loads, B20 fuel has higher CO_2 emissions than the other blends since less oxygen content in comparison with its higher blends prevents the flame quenching thus increasing the conversion of CO to CO_2. Increase in the percentage of EGR in B20 blend increases CO_2 emission with the increase in load since EGR introduction has substantial amount of CO_2 in the exhaust gas which is sent into the fresh air inlet which contains some negligible amount of CO_2 thus increasing the emission at the outlet [37].

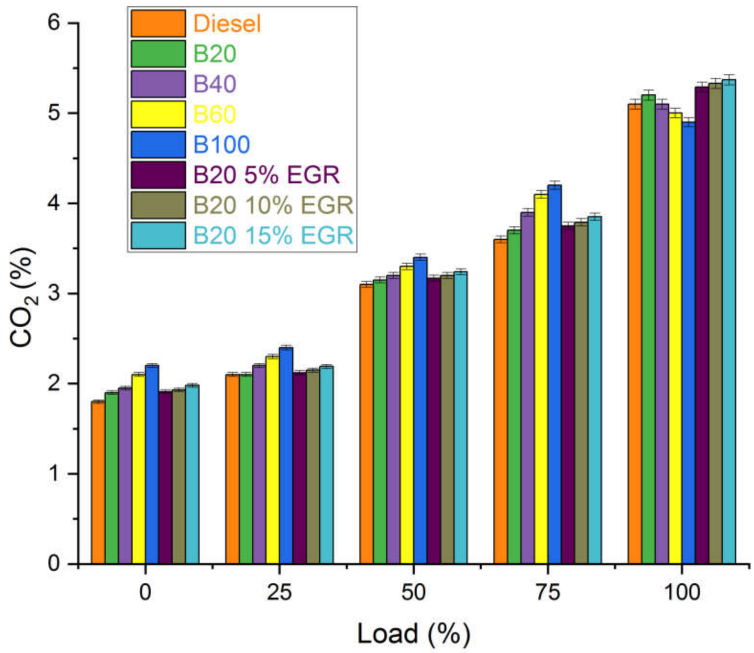


Fig. 15 Load Vs CO_2 Emission

4.2.6 Variation in Exhaust gas temperature

Fig. 16 depicts the trade-off between EGT values of diesel, WCO biofuel, and its blends with the increase in load. The graph shows a similar trend observed by various researchers [32, 35] in which EGT increases along with increase in load conditions for all types of test fuels. The reason behind this was burning of more amount of fuel at higher load and higher engine in-cylinder temperature. On comparing the fuels, WCO blends performed better than diesel. At 100% load condition, EGT values are 426, 427, 451, 483, and 513 °C for diesel, B100, B60, B40, and B20 respectively since blends had high release rate which helped them in complete combustion increasing EGT. But increase in percentage of WCO blend has led to a decrease in EGT. This is because of high oxygen availability and the consequent flame quenching taking place at the diffusion combustion phase. Increase in the percentage of EGR increases EGT for B20 fuel. The reason might be higher specific heat of air at inlet [36] and also less oxygen availability at the inlet as discussed in the earlier sections.

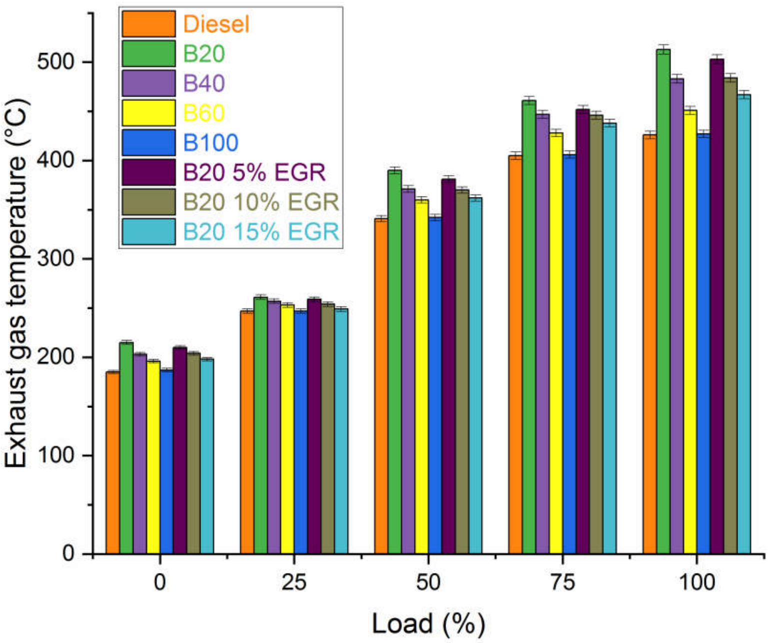


Fig. 16 Load Vs Exhaust Gas Temperature

4.2.7 Emission variation

The table 8 represents the comparison of various emissions parameters as a summary. The main aim of this research is to compare various blends of WCO and select the most suitable fuel for the diesel engine. Here, B20 blend and EGR variation in B20 fuels have been taken as base fuels and compared with diesel, B40, B60, and B100. A color code varying from red, yellow, and green in fig. 16 depicts the percentage variation in emission values. The negative values in fig. 16 represents the increase in emission values while the positive values depict the decrease in emissions. Sharp increase in emission is coded as red while sharp decrease as green and yellow means moderate in variation. The analysis is done only for no load, part load, and full load conditions since 25% load values did not vary much with no load and similarly part load with 75 % load condition. From the previous sections, B20 blend fuel performed well in reducing various emissions like HC, CO, Smoke, and CO_2. Now, the first column has been considered for comparison to comment on B20 blend fuel. More negative values are seen at NOx emission while a few for CO_2 at full load, smoke at full load and CO at no load which has minor variations less than 7% except for CO showing -50% in comparison with B100 (reason quoted in CO emission section). Since the fuel is burnt completely producing high combustion temperature, B20 produces more NOx emission in comparison with all the other fuels. To prevent this NOx emission, EGR has been introduced at 5, 10, and 15% variation. EGR reduces NOx while it raises emissions like CO, HC, Smoke, and CO_2. So, optimizing EGR percentage is essential. Now, the other three columns except the first one have been considered for further analysis. With 5% EGR rate, reduction in NOx has occured from B20 but still in comparison with the other fuels there are many negative values in the figure. With 10% EGR rate, the conversion has only positive values in the figure with a maximum reduction of 16.34%, while the other emissions at this column (3rd column), have many positive values with a few negative values of minor variations except in the case of CO at low and part loads. With 15% EGR rate, reduction in NOx is better than 10% rate with a maximum reduction of 21.05%, while the other emissions at this column (4th column), have many negative values with a few positive values of minor variations. Finally, considering all the columns B20 fuel with 10% EGR rate is found to be better suited to the test engine.

Table 8 Emission variation summary

Emission	Load	Fuel	B20	B20 5% EGR	B20 10%	B20 15% EGR
CO	No load	Diesel	25.00	20.00	5.00	-5.00
		B40	-7.14	-14.29	-35.71	-50.00
		B60	-15.38	-23.08	-46.15	-61.54
		B100	-50.00	-60.00	-90.00	-110.00
	Part load	Diesel	10.00	8.00	2.00	-2.00
		B40	-7.14	-9.52	-16.67	-21.43
		B60	-12.50	-15.00	-22.50	-27.50
		B100	-18.42	-21.05	-28.95	-34.21
	Full load	Diesel	30.00	20.00	10.00	5.00
		B40	12.50	0.00	-12.50	-18.75
		B60	22.22	11.11	0.00	-5.56
		B100	22.22	11.11	0.00	-5.56
HC	No load	Diesel	6.82	4.55	2.27	0.00
		B40	2.38	0.00	-2.38	-4.76
		B60	0.00	-2.44	-4.88	-7.32
		B100	4.65	2.33	0.00	-2.33
	Part load	Diesel	14.29	11.43	5.71	2.86
		B40	6.25	3.13	-3.12	-6.25
		B60	9.09	6.06	0.00	-3.03
		B100	11.76	8.82	2.94	0.00
	Full load	Diesel	17.07	15.85	12.20	9.76
		B40	5.56	4.17	0.00	-2.78
		B60	9.33	8.00	4.00	1.33
		B100	13.92	12.66	8.86	6.33
NOx	No load	Diesel	-15.76	2.73	8.48	13.64
		B40	-5.82	11.08	16.34	21.05
		B60	-11.70	6.14	11.70	16.67
		B100	-16.46	2.13	7.93	13.11
	Part load	Diesel	-12.22	-2.38	3.43	9.54
		B40	-5.76	3.51	8.99	14.75
		B60	-8.03	1.43	7.03	12.91
		B100	-12.05	-2.23	3.57	9.67
	Full load	Diesel	-14.02	-1.26	1.95	7.01
		B40	-4.20	7.46	10.40	15.02
		B60	-10.10	2.22	5.33	10.21
		B100	-13.63	-0.92	2.29	7.33
Smoke	No load	Diesel	-14.57	-15.89	-19.87	-24.50
		B40	10.36	9.33	6.22	2.59
		B60	20.64	19.72	16.97	13.76
		B100	31.35	30.56	28.17	25.40
	Part load	Diesel	-13.41	-14.82	-16.47	-17.88
		B40	2.63	1.41	0.00	-1.21
		B60	8.02	6.87	5.53	4.39
		B100	14.08	13.01	11.76	10.70

	Full load	Diesel	4.99	4.56	3.72	3.08
		B40	-2.29	-2.74	-3.66	-4.34
		B60	-3.59	-4.05	-4.98	-5.67
		B100	-4.80	-5.27	-6.21	-6.91
CO2	No load	Diesel	-5.56	-6.11	-7.22	-10.00
		B40	2.56	2.05	1.03	-1.54
		B60	9.52	9.05	8.10	5.71
		B100	13.64	13.18	12.27	10.00
	Part load	Diesel	-1.61	-2.26	-3.23	-4.52
		B40	1.56	0.94	0.00	-1.25
		B60	4.55	3.94	3.03	1.82
		B100	7.35	6.76	5.88	4.71
	Full load	Diesel	-1.96	-3.73	-4.51	-5.29
		B40	-1.96	-3.73	-4.51	-5.29
		B60	-4.00	-5.80	-6.60	-7.40
		B100	-6.12	-7.96	-8.78	-9.59

4.2.8 Numerical and Experimental Comparison

The simulation was carried out by using Ansys Fluent software and the results were predicted for the mass fraction of NOx and CO_2 emissions. The predicted results of NOx emission for the blend B20 showed an increase of 16.9% and 17.6% in comparison with diesel and B100 fuel respectively. The experimental results of NOx emission for the blend B20 showed a highest increase of 15.76% and 16.46% in comparison with diesel and B100 fuel respectively. The simulated results showed higher percentage variation than the experimental results and it is represented in the fig 17. The error occured was around +6.7% between the numerical and experimental comparison for NOx emission. The predicted results of CO_2 emission for the blend B20 showed an increase of 5.8% with diesel and a decrease of 12.52% in comparison with B100 fuel. The experimental results of CO_2 emission for the blend B20 showed an increase of 5.5% with diesel and a decrease of 13.46% in comparison with B100 fuel. The error occured was around ±6.9% between the numerical and experimental comparison for CO_2 emission. The fig. 18 depcits the numerical and experimental values of CO_2 emission at various load conditions. Thus the error occured was within the acceptable limits.

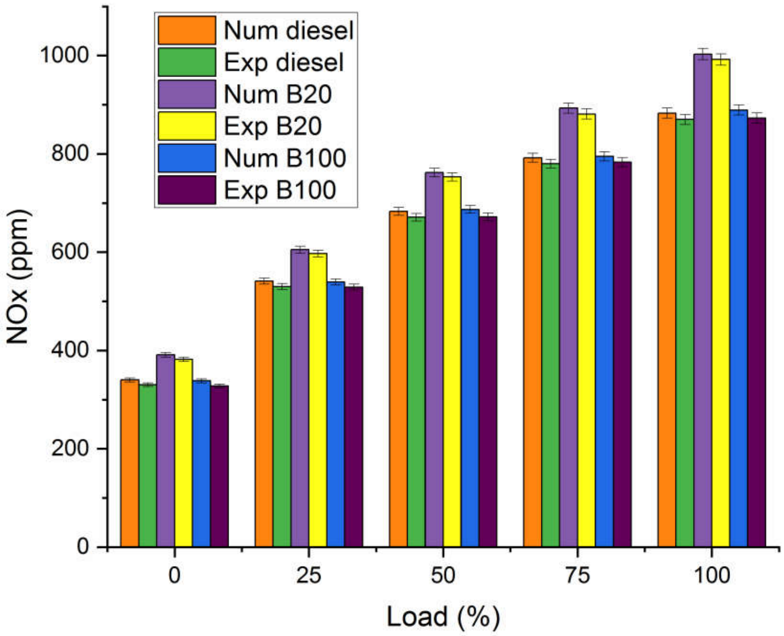


Fig. 17 Numerical vs Experimental NOx emissions

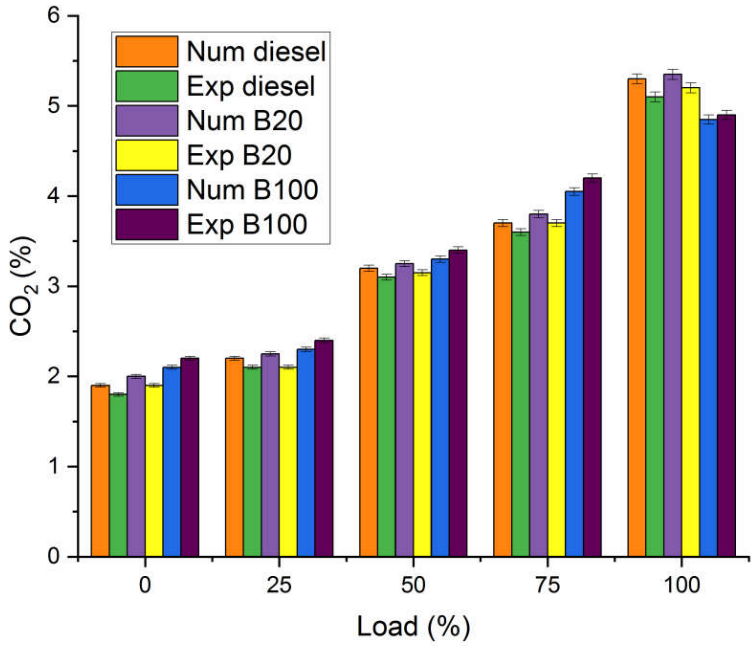


Fig. 18 Numerical vs Experimental CO_2 emissions

4.3 Combustion Characteristics

4.3.1 In-Cylinder Pressure

Fig. 19 represents the variation in in-cylinder pressure with crank angle for all WCO blends, diesel, and WCO biofuel at fuller load condition. The burning capability of fuel along with the mixing of air characterizes cylinder pressure. The obtained peak cylinder pressure values are 89.2, 86.5, 90.2, 91.3, and 92.5 bar for diesel, B100, B60, B40, and B20 respectively. This trend shows that B20 blend has high peak pressure when compared with all the blends thus increasing the in-cylinder pressure as discussed in the previous sections. All blends and WCO diesel follow similar trend of diesel in the cylinder pressure which indicates that WCO fuel is suitable for this engine. Introduction of EGR has decreased the cylinder pressure in the B20 blend fuel. The reason is increase in heat capacity of inlet mixture and reduction in availability of oxygen [37], thus affecting the burning rate and reducing pressure inside the cylinder. This results in the reduction in CO_2 and H_2O because of an endothermic reaction leading to reduced NOx.

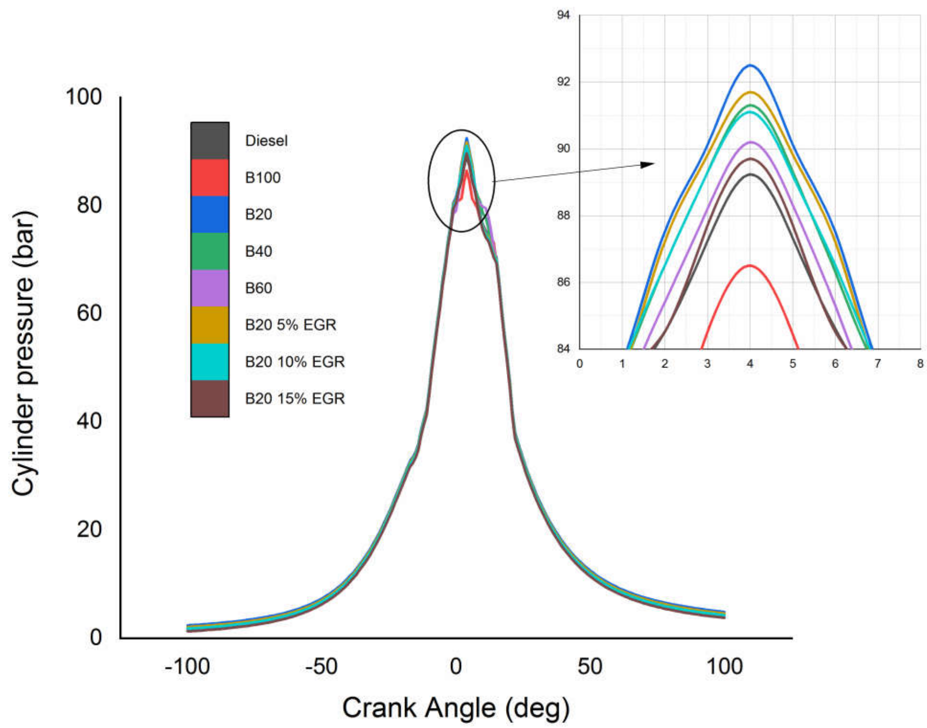


Fig. 19 Crank angle Vs In-cylinder pressure

4.3.2 Heat Release Rate

Fig. 20 depicts HRR variation with crank angle for all WCO blends, diesel, and WCO biofuel at fuller load condition. This graph defines the various combustion related parameters like ignition delay period, start of combustion, start of ignition and fuel quantity getting ignited at premixed stage of combustion. There are two stages in combustion, namely premixed stage and diffusion stage. The two stages of combustion have been separately shown in fig 18. Two different peaks in the curve with initial one representing the premixed stage and the consecutive peak representing the diffusion stage of combustion [38]. The negative values in the curve depict the fuel evaporation. At full load, the obtained peak HRRs are 39.06, 36.83, 42.85, 44.42, and 47.32 kJ/m^3deg for diesel, B100, B60, B40, and B20 respectively. All types of blends have exhibited similar trend with respect to diesel HRR curve. WCO biofuel and diesel show lower HRR when compared with WCO blends, while in diesel ignition occurs soon due to higher calorific value of diesel and in the case of WCO biofuel, beyond higher oxygen content in the fuel, it has released lesser HRR due to shorter ignition delay period. B20 blend fuel has exhibited high HRR when compared with all the other types of blends. The reason behind could be longer delay period. The sufficient oxygen content in the fuel helped the diesel to burn effectively inside the cylinder to produce high combustion chamber temperature. Also the duration of diffusion stage is higher thus facilitating better burning of mixture of fuel and air. Rise in EGR in B20 blend decreases HRR. The reason behind this is reduced temperature of combustion caused by poor atomization and reduced rate of air-fuel mixing with B20 blend [37].

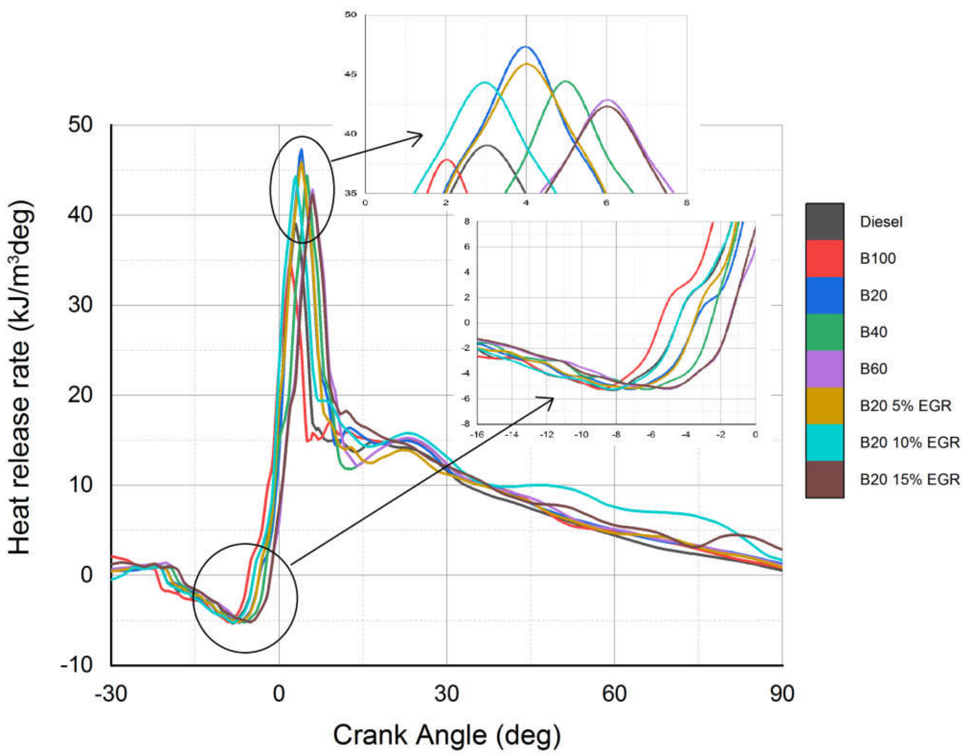


Fig. 20 Crank angle vs Heat release rate

4.3.3 Combustion noise

Fig. 21 represents the sound level variation along with the increase in engine load for all types of test fuels. The major amount of noise arising from CI engines is noise during combustion which occurs because of combustion of fuel taking place inside the combustion chamber. The noise could be sensed because of the pressure variation inside the cylinder [39]. At part load condition, the noise levels obtained are 88, 86, 83, 80, and 78 dB[A] for diesel, B100, B60, B40, and B20 respectively. The trend shows that B20 blend has lower noise level when it is compared with all the other blends since increasing in-cylinder pressure causes complete combustion while other blends show more pressure fluctuations because of incomplete combustion leading to more noise and at 100% load condition, the obtained noise levels are 97, 98, 95, 90, and 87 dB[A] for diesel, B100, B60, B40, and B20 respectively. Similar trend is followed by B20 but while comparing B100 with diesel, there is a slight increase in the noise level for B100. It is due to high oxygen content quenching the flame causing incomplete combustion and pressure variation inside the cylinder. Introduction of EGR increases the noise level in B20 blend fuel. It is because of increase in the heat capacity of the inlet mixture and reduction in oxygen availability [37]. Thus affecting the combustion rate and fluctuating the in-cylinder pressure.

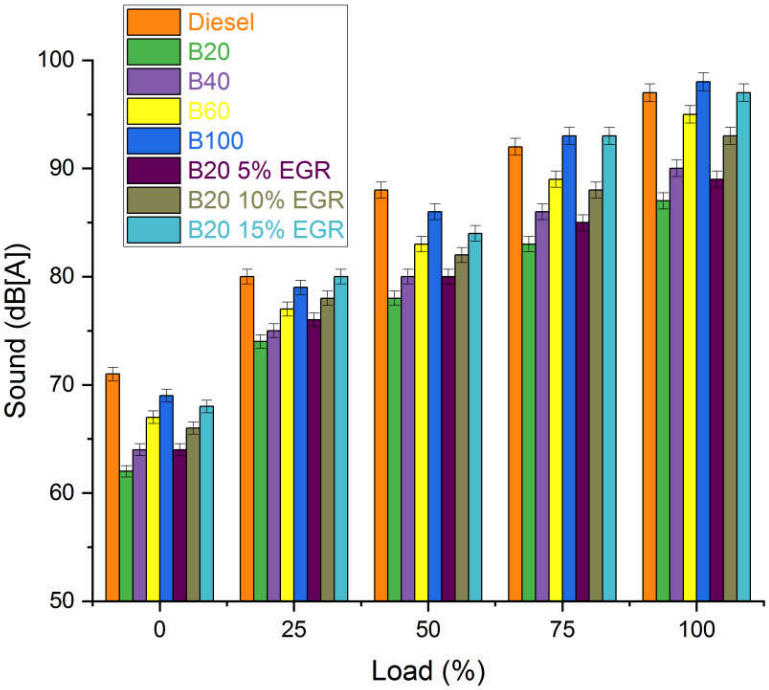


Fig. 21 Load Vs Sound

5. Conclusion

In this current research, WCO biofuel was obtained using trans-esterification method and its chemical constituents were determined using GCMS method. WCO biofuel was then blended with diesel in varying quantities like 20%, 40%, and 60%. The fuel properties were determined by using ASTM standards. With all the test fuels, performance, emission, combustion, and noise characteristics were determined by using 4-stroke, two cylinder, D.I. diesel engine fitted along with electrical dynamometer. B20 blend was found to be the best suitable fuel with respect to various characteristics of the test engine. Fuel combustion modeling was also carried out using ANSYS Fluent software for diesel, B20, and B100 fuels to predict temperature profile and mass fraction of NOx and CO_2. The predicted results are well in accordance with the experimental results. To control NOx, EGR was used in the selected blend fuel at varying rates of 5%, 10%, and 15%. The following conclusions were drawn from the current research work:

- At all load conditions, B20 blend showed reduced BTE with a maximum of 1.85% at full load with respect to diesel while an increase in BTE with a maximum of 4.92, 4.49, and 3.87% at full load for B100, B60, and B40 respectively. The reason was due to high calorific value, low viscosity in comparison with the other WCO blends. EGR addition decreased BTE because of reduced flame temperature. Both 5% and 10% EGR rates showed better performance in comparison with B40, B60, and B100 while 15% EGR rate showed reduced BTE at all load conditions.
- At all load conditions, B20 blend showed increased SFC with a maximum of 6.89% with respect to diesel while reduced SFC with a maximum of 12.5, 14.4, and 15.2% at no load with respect to B40, B60, and B100. EGR addition increased SFC because of excess fuel need to maintain the power. Both 5% and 10% EGR rates showed reduced SFC in comparison with B40, B60, and B100 while 15% EGR rate showed increased SFC at all load conditions.
- B20 blend fuel showed high HRR and in-cylinder pressure when compared with all the other test fuels. This might be due to the availability of sufficient O_2 to burn diesel which simultaneously increased the combustion flame temperature. With the addition of EGR, cylinder pressure and HRR decreased. This was attributable to the reduction in oxygen availability and reduced rate of air-fuel mixture.

- B20 blend showed reduced noise level at all load conditions in comparison with all the other types of test fuels. This could be attributed to reduced pressure fluctuations inside the engine. With EGR addition, noise level increased due to the presence of pressure variations.
- With respect to the emission parameters like HC, CO, Smoke, NOx, and CO_2, a separate table was provided in the previous section which explained that B20 with 10% EGR rate was selected as most suitable fuel with a good reduction in NOx emissions without affecting HC, CO, Smoke, and CO_2 emissions.

From the current research work, it can be stated that B20 blend fuel would be an optimum fuel to enhance combustion, performance, sound and emission parameters (except NOx) of test engine. Further to reduce NOx emission, B20 with 10% EGR rate would be selected as optimum rate without affecting much combustion and performance parameters of the test engine.

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Conflicts of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Nomenclature

BTE - Brake Thermal Efficiency (%)

SFC - Specific Fuel Consumption (kg/kWhr)

WCO - Waste Cooking Oil

EGR - Exhaust Gas Recirculation

CI - Compression Ignition

ASTM - American Standards for Testing and Materials

DI - Direct Injection

HC - Hydrocarbon (ppm)

CO - Carbon monooxide (% vol)

NOx - Oxides of nitrogen (ppm)

CO_2 - Carbon dioxide (% vol)

GCMS - Gas Chromatography Mass Spectroscopy method

HRR - Heat Release Rate (kJ/m^3deg)

CP - Cylinder Pressure (bar)

B20 - 20% WCO biofuel and 80% diesel

B40 - 40% WCO biofuel and 60% diesel

B60 - 60% WCO biofuel and 40% diesel

B100 - 100% WCO biofuel

Annexure

GCMS results obtained for WCO and WCO biofuel are represented in fig.22