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SCIENTIFIC PAPER

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COMBUSTION, EMISSION, AND PERFORMANCE CHARACTERISTICS OF HYBRID BIOFUEL AT DIFFERENT COMPRESSION RATIOS

Article Highlights

- Future automobile energy utilities
- Hybrid biofuel was prepared by transesterification and pyrolysis methods
- Brake thermal efficiencies of hybrid biofuel fuels were higher than those of conventional fuel

Abstract

The primary aim of this study is to alternate between conventional fossil fuels and reduce the emissions of greenhouse gases and smoke from diesel engines. The current study aimed to improve the performance and emission characteristics of a variable compression ratio (VCR) diesel engine operated with hybrid biodiesel. Experiments were done with the best hybrid biodiesel, which was made by mixing 20% rubber seed oil (RSO) with 80% waste plastic oil (WPO). The tests were done at four compression ratios (CRs): 16:1, 17:1, 18:1, and 20:1. Under a CR of 20:1 and at full load, the engine's brake thermal efficiency went up by 30.5%, its brake-specific fuel consumption went down by 0.347 kg/kWh, and notably diminished emissions of carbon monoxide (0.43% volume), hydrocarbons (79 ppm), and smoke (22%). However, with increasing CRs, NOx emissions rose unfavourably (1092 ppm) compared to diesel (820 ppm). Also, diesel and clean (WPO) were compared to see how the CR values affected combustion, performance, and emissions. Compared to diesel, under maximum load and the CR of 20:1, hybrid biodiesel demonstrated approximately 3.7% higher brake thermal efficiency. The findings suggest potential applications for this hybrid biodiesel in the automobile sector, the power generation industry, and marine applications.

Keywords: rubber seed oil, waste plastic oil, performance, emission, variable compression ratio.

The emissions from the CI engine create major air pollution, which can affect human health. Therefore, many researchers explored different alternate fuels that minimized air pollution. They combined two biofuels that can be utilised in CI engines as an alternative fuel. Liu *et al.* [1] produced rubber seed oil (RSO) using an ultra-stable Y (USY) zeolite catalyst. This catalyst is suitable for producing liquid fuels from RSO. Wuttichai *et al.* [2] studied the composition and properties of the extracted RSO and high-free fatty acid oil after transesterification using different catalysts like CaO, sodium metasilicate-based egg shells, and CaO with waste coral fragments. Christine *et al.* [3] studied the synthesis of WPO by catalytic pyrolysis using

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nitrogen as a carrier gas. The WPO is extracted from polythene bags. The catalysts used are silica, alumina, barium carbonate, Y zeolite, and zeolite.

Recent studies have been performed by many researchers on the combustion and performance parameters of a CI engine operated with alternate fuels such as waste palm oil [4], apple seed oil [5], biodiesel derived from chicken waste [6], rice bran oil [7], tamanu oil [8], and marula seed oil [9]. A variable compression ratio (VCR) engine's combustion efficacy and exhalation smoke properties were studied by Nagaraja *et al.* [4]. Their CR values varied from 16:1 to 20:1 with 90 °C pre-heated palm oil, and their blends ranged from 5% to 20%. The outcome shows that the output smoke temperature is diminished for all experiments and that CO and HC emissions drop as blend percentages and CR values increase.

Using Eagle Marmelo oil, Krishnamoorthi and Malayalamurthi [10] investigated the effect of varying CR and nozzle holes. The findings show that a higher CR value improves combustion characteristics. Elevation in the CR is also associated with decreased BSFC, HC, CO, and smoke emissions and improved thermal efficiency. Singh and Shukla [11] investigated the combustion characteristics of the VCR engine by varying CR from 15:1 to 18:1 using castor biodiesel blends varying from B00 to B50. The results indicated that cylinder pressure reached its maximum at the CR of 18:1 and B50 blend, and the net heat release rate decreased for B00 at CR 15:1.

Mohit *et al.* [7] conducted tests on a VCR diesel engine using rice bran oil blends ranging from 10% to 40% at CR values ranging from 15:1 to 18:1. The study focused on analysing the performance and exhaust emission parameters of these tested blends. Mohammed *et al.* [12] explored the impact of different waste cooking oil blends ranging from 10% to 50% at CR values of 14:1, 16:1, and 18:1 on a CI engine. The study delved into assessing performance, emission, and combustion parameters in this context. The findings suggest that brake-specific fuel consumption decreases as the compression ratio (CR) increases for all blends.

Tamanu oil blends were experimentally examined on VCR engines (16:1, 18:1, 20:1, and 22:1) by Antony and Bose [8]. In contemplation of an increase in performance and lower emissions, the test findings showed that this alternative fuel could be mixed with diesel up to 40% at an ideal CR value of 20:1. Moreover, according to researcher suggestions, as the CR values rise, the BTHE values rise as well. By employing esterified tamanu oil, Raj and Kandasamy [13] experimented to ascertain the operating conditions of the VCR engine. The outcome demonstrates that emissions are decreased, and engine performance is increased. Gandure and Ketlogetswe [9] compared the performance of marula seed oil and diesel on a VCR engine. According to the findings, the engine performance with marula oil is very close to that with diesel at CR 16:1. The operation behaviour of the engine, exhalation smoke properties, and flame efficiency of a VCR engine employed on waste cooking and sunflower oil methyl esters and their mixes of 20%, 40%, 60%, and 80% were studied by Muralidharan and Vasudevan [14].

The findings show that increased CR values are associated with a greater ignition interval and a slower heat dissipation rate. Amarnath *et al.* [15] assess the engine operation behaviour and exhalation qualities of smoke in a VCR engine using the methyl esters of Karanja and Jatropha. According to the findings, both biodiesels function better at superior CR values. In comparison to diesel pollutants, biodiesel produces fewer emissions. Ashok Kumar *et al.* [16] researched a VCR engine fuelled with Pinnai oil blends at CR ranging from 15:1 to 18:1 and investigated the performance parameters. They also examined the engine's operations, combustion efficiency, and emission behaviour. The findings showed that the mixes' BSFC values were extremely close to those of diesel.

The CI engine operations, flame efficiency of the engine, combustion efficiency, and exhalation qualities of smoke were examined by Ravi *et al.* [17]. As the CR rises, the engine’s performance improves. They provided a detailed analysis of NOx reduction methods like EGR. Rinaldini *et al.* [18] assessed the performance of a CI engine running on WPO and the behaviour of its emissions. The findings indicated that WPO causes an increase in NOx emissions. According to Mani *et al.* [19], the WPO was used as fuel in a CI engine, and though CO and HC exhalations were relatively excessive, the BTHE of the WPO was equal to that of diesel. Devaraj *et al.* [20] investigated WPPO blended with 5% and 10% diethyl ether in a CI engine and looked at the engine parameters, emission characteristics, and combustion efficiency. The findings showed that although smoke pollution has decreased, BTE with WPPO has improved. In their study, Ibrahim *et al.* [21] examined a compression-ignition engine's emissions and combustion efficacy utilizing a 50:50 volume percentage blend of crude RSO and palm oil. According to reports, higher blend ratios result in higher NOx emissions and exit smoke temperatures while decreasing CO emissions.

Coir-pith gas and RSO blends are analysed in a diesel engine by Ramadhas *et al.* [22]. Higher specific energy consumption and increased exhaust emissions are obtained with blends at all load conditions. Senthilkumar and Sankaranarayanan [23] investigated the diesel engine characteristics at WPO. The findings demonstrate that WPO increases carbon monoxide, NOx, and HC pollution more rapidly than diesel. In their research, Kasiraman *et al.* [24] investigated the operational parameters of a compression-ignition (CI) engine using neat cashew nut shell oil (CSNO) and camphor oil (CMPRO) as fuel. It is reported that the CMPRO 30 blend showed good performance compared with diesel in terms of BTE and heat energy dissipation at full load. Hifjur *et al.* [25] evaluated the diesel engine using Mahua and Simarouba oil blends B10 and B20 in 50:50 volumes. It is reported that the B10 blend can be used for long-term use based on assessing fewer soot deposits after 100 hours of engine operation than diesel.

HCCI-DI engines powered by acetone-butanol-ethanol were studied by Ibham *et al.* [27]. As a result of the addition of acetone, butanol, and ethanol, NOx emissions were successfully reduced, and brake thermal efficiency and fuel consumption were also improved. Christopher *et al.* [28] evaluated the performance parameters of biodiesel produced from local South African canola and sunflower oil feedstocks. According to their report, the smoke emissions from biodiesel and its diesel blends were lesser than those from pure diesel, but there was an increase in nitrogen oxide emissions. Garavand *et al.* [29] utilized a combination of diesel, waste fish oil biodiesel, and 2%, 4%, 6%, and 8% ethanol to fuel diesel engines while incorporating graphene quantum dots to enhance their properties. Their findings revealed that the mixture containing 45 ppm GQD, 6% ethanol, 10% biodiesel, and 90% diesel exhibited the highest braking force and engine torque and lower unburnt hydrocarbon and NOx emissions.

Samuel *et al.* [30] researched a hydrodynamic cavitation reactor for producing biodiesel from low-free-fat acid RSO. They studied the impacts of transesterification variables, including 3%–5% wt. KOH, 30–50 minutes of reaction time, and a 3.5/7.0 ethanol/RSO molar ratio. The study found that at a 6/1 ethanol/oil molar ratio, a 4.5 wt. % KOH concentration, and a 40-minute reaction period, RSO production reached 92.5% of the maximum. Singh *et al.* [31] focused on utilising microalga Spirulina blends with diesel in a VCR engine with various loads, CRs, and blend concentrations. At a 16:1 CR and 20% blend concentration, the engine had a 31.357% BTE and a 0.274 kg/kWh BSFC. It also had lower nitrogen oxide levels of 1804.9 ppm, CO_2 levels of 869.075 g/kWh, and PM levels of 0.2807 g/kWh. Hananto *et al.* [32] examined how the emissions from the CI engine create major air pollution, which can affect human health. Their findings indicated that the introduction of butanol into diesel engines led to lower exhaust gas temperatures and CO emissions while simultaneously increasing HC emissions and smoke opacity. Therefore, many researchers, including Samuel *et al.* [33], explored alternate fuels that minimise air pollution.

The literature review highlights that the VCR engine exhibits optimal performance, achieving maximum power output while maintaining low emissions when fuelled with unmixed pure biodiesel and hybrid alternative fuels. However, no prior research has been conducted on the utilization of a specific hybrid alternative biodiesel comprising a blend of 20% RSO and 80% waste plastic oil (WPO), particularly at varying CR values ranging from 16:1 to 20:1. The primary objective of this research is to analyse and compare the effects of different CR values on several performance and combustion characteristics, including BTHE, BSFC, cylinder peak pressure, ignition delay, and HRR. Additionally, the study aims to evaluate emissions, such as EGT, NOx, HC, CO, and smoke opacity, when using the aforementioned hybrid alternative biodiesel. Comparisons will be made with the performance and emissions characteristics of conventional diesel and neat WPO. This analysis is valuable for engine manufacturers who produce high CR engines in large volumes, as it assists in selecting an optimum CR. Allowing these manufacturers to enhance engine performance and emissions control will also lead to the development of more environmentally friendly and efficient engines.

MATERIALS AND METHODS

Production of RSO methyl esters

RSO is a non-edible oil made from rubber seeds. It is usable as biodiesel. Biodiesel is created when RSO is transformed into methyl, ethyl, or butyl esters. Due to its low volatile property and excessive viscous behaviour compared to diesel, biodiesel in IC engines causes issues such as pumping, atomization, injector choking, piston wear, etc. The raw RSO contains saturated and unsaturated fatty acid compositions. The unrefined RSO contains 22% free fatty acids (FFA). Methanol is a reactant in the biodiesel synthesis process because it is more reactive and readily available on the market. The RSO consists of three esters and around 20% glycerine. The glycerine can be replaced with alcohol to make a less viscous biodiesel by transesterification.

Non-edible RSO has been considered a potential feedstock in India. Therefore, it has been selected as fuel in the present investigation. Eq. (1) describes the chemical process that transforms unprocessed RSO into a methyl ester of RSO. R1, R2, and R3 represent long hydrocarbon or fatty acid chains. The transesterification process requires two stages because the RSO contains 22% free fatty acids. The first stage is acid esterification, in which the reactant methanol and sulfuric acid catalyst react with the FFA present in raw RSO to produce methyl ester and water. It is given by Eq. (2). This process reduces the free fatty acid level. After that, using potassium hydroxide as an additive, the low FFA prior-processed oil can undergo second-stage alkaline esterification processing to transform the triglycerides into methyl esters and the fatty acids into soap and water. It is given in Eq. (3):

$$\begin{array}{l} H_2C - O - \overset{\overset{O}{\|}}{C} - R_1 \\ \quad | \\ HC - O - \overset{\overset{O}{\|}}{C} - R_2 \\ \quad | \\ H_2C - O - \overset{\overset{O}{\|}}{C} - R_3 \end{array} + 3CH_3OH \underset{KOH}{\overset{Catalyst}{\longrightarrow}} \begin{array}{l} H_3C - COOR_1 \\ H_3C - COOR_2 \\ H_3C - COOR_3 \end{array} + \begin{array}{c} H_2C - OH \\ | \\ HC - OH \\ | \\ H_2C - OH \end{array} \quad (1)$$

$$HO - \overset{\overset{O}{\|}}{C} - R + CH_3OH \overset{H_2SO_4}{\longrightarrow} H_3C - O - \overset{\overset{O}{\|}}{C} - R + H_2O \quad (2)$$

$$HO - \overset{\overset{O}{\|}}{C} - R + KOH \longrightarrow KO - \overset{\overset{O}{\|}}{C} - R + H_2O \quad (3)$$

Using methanol as the reactant and sulfuric acid as the catalyst, 22% of the FFA is reduced to less than 2% within the initial stage of acid esterification. The second phase of transesterification is finished when potassium hydroxide, a catalyst, is applied to the previously processed oil for alkaline esterification to produce the methyl ester of RSO. The transesterification conditions leading to the production of RSO methyl ester encompassed a 4/10 methanol/RSO molar ratio, 6 ml of H_2SO_4 acid catalyst, 6 g of KOH alkaline catalyst, a reaction time of 60 minutes, a magnetic stirrer speed set at 1000 rpm, and a reaction temperature of 60 °C. These conditions resulted in a yield of 76% relative to the maximum possible output.

Production of the WPO

The thermochemical pyrolysis process breaks waste plastics down into valuable yields at elevated temperatures, also without oxygen. Pyrolysis produces volatile fractions and impurities such as carbonised char or solid residues. Saturated and fragrant hydrocarbons and non-condensable gas with a significant calorific value comprise the volatile fractions. The distillation process converts volatile fractions into WPO [19].

Figure 1a depicts the distillation plant's conceptual layout. A thin cylindrical vessel encloses the stainless steel reactor. The silicone oil fills the gap between the reactor and the cylindrical vessel, and an electrical heating coil is submerged in the oil. A metallic sheet surrounds and insulates the outer layer with glass wool. The distillation plant consists of a pressure gauge, a pressure relief valve, a feed hopper with a control valve, a thermocouple sensor, an oil level indicator, a control panel, and a slag drain.

The slag drain removes the residual oil after distillation. The outlet of the plant is connected to the water-cooled condenser. The condensed liquid from the pyrolysis plant is poured into the distillation plant through a feed hopper with a control valve. The valve is fully closed after pouring the oil. The heat is transferred from the coil to the silicone oil and then to the plastic oil. The reactor temperature increases from 200 °C to 350 °C, evaporating the plastic vapours. The plastic vapour from the plant is passed through the condenser. The condensate liquids are gathered at the fractioned oil collector, creating WPO.

The pyrolysis conditions in this study involved (i) maintaining the pyrolysis plant reactor temperature between 500 °C and 700 °C and (ii) maintaining the inside temperature of the distillation plant reactor between 200 °C and 350 °C, based on equivalent petro-diesel fractional properties. The optimum yield of WPO was calculated as follows: Initially, 10 kg of waste plastic was used. After degradation, WPO yielded 75% to 80%, leaving 20% to 25% of waste. The fractionated plastic oil obtained after distillation accounted for 60 to 65% of the conversion. The liquid fuel was delivered approximately 3.5 hours after the initiation of the pyrolysis process.

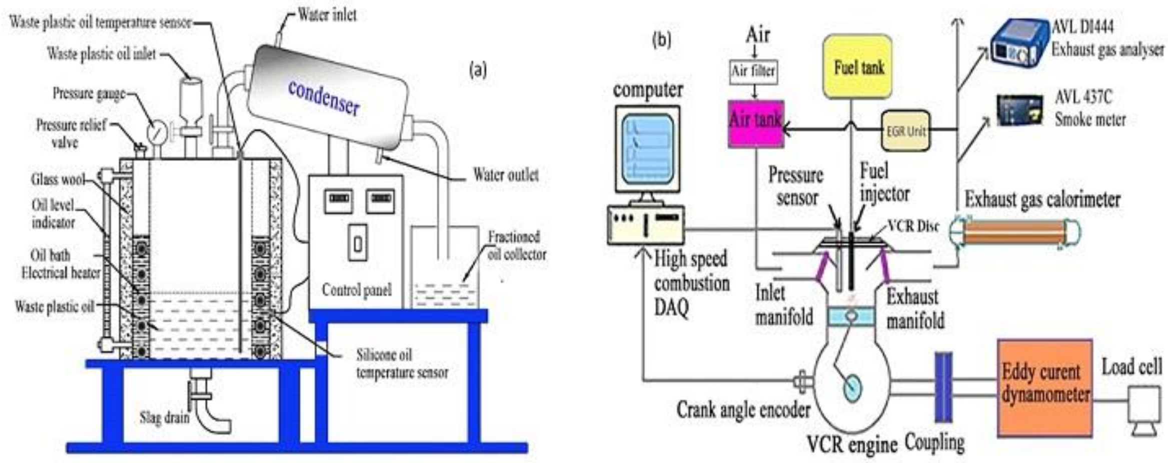

Figure 1. Schematic diagram of (a) Distillation plant (b) Experimental setup.

Gas chromatography and mass spectrometry (GC-MS) analysis of WPO

The main feature of GC-MS is that it combines the features of gas-liquid chromatography and mass spectrometry. The WPO is characterised using a GC instrument. The working principle of a mass spectrometer is followed by the separation of gas-phase ions according to mass/charge ratio and their sequential detection. The mass spectrometry (MS) instrument is operated at a temperature of 220 °C, with the ion source temperature set at 200 °C, covering mass-to-charge numbers from 20 to 1200 m/z. Figure 2a illustrates the schematic diagram of the GC-MS instrument. The GC-MS chromatogram of WPO is depicted in Figure 2b.

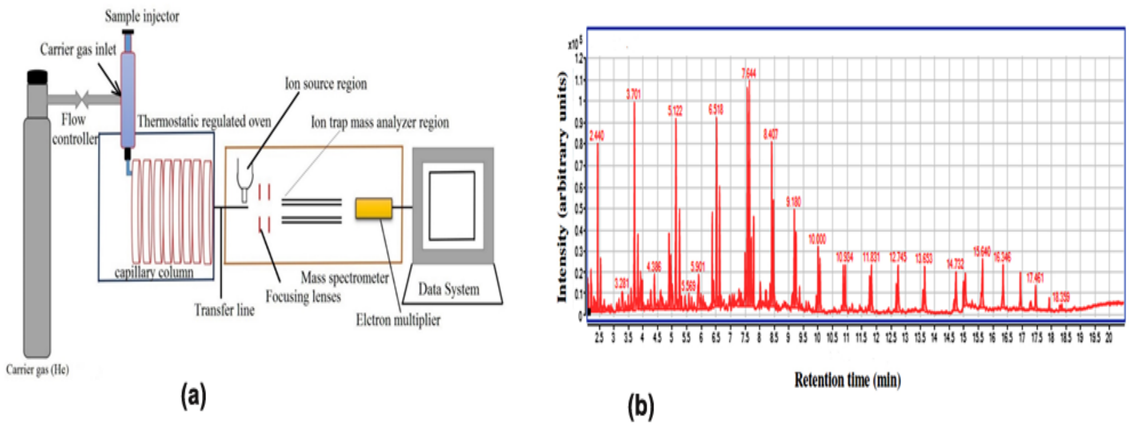

Figure 2. Diagram of (a) GC-MS instrument (b) GC-MS chromatogram of WPO.

The foremost constituents of WPO obtained from GC-MS analysis are given in Table 1. It can be seen that the WPO consists of 20 compounds. From Table 1, the compounds are in the range from C_7 to C_{22} approximately. It shows that WPO has similarities to diesel. In addition, the oil properties of $C_{12}H_{25}$ are closest to diesel. From the area percentage, the average chemical formula of the WPO is calculated as $C_{11.55}H_{21.8}$, but the average chemical formula of common diesel is $C_{12}H_{24}$.

Physio-chemical properties of RSO, WPO and diesel

Table 2 summarises the essential physical and chemical characteristics of RSO, WPO, and diesel in accordance with ASTM standards.

Experimental setup

Figure 1b illustrates the experimental arrangement. The engine used for this research is the Kirloskar (AV1) engine, a vertical, direct-injection, water-cooled, naturally aspirated engine with a rated

Table 1. Main components of WPO obtained from GC-MS analysis.

Peak	Reaction Time (min)	Area %	Chemical formula	Chemical compounds
1	2.440	60.54	$C_9H_{16}O$	Cyclopentanone, 2-(1-methylpropyl)-
2	3.281	16.71	$C_{10}H_8N_2O_2S_2$	N-(4-Oxo-2-thioxo-thiazolidin-3-yl)-benzamide
3	3.701	100	$C_7H_{14}O_2S$	trans-2, 4-Dimethylthiane, S, S-dioxide
4	4.386	18.59	C_9H_8	Benzene, 1-ethynyl-4-methyl-
5	5.122	93.42	$C_{11}H_{24}O$	1-Undecanol
6	5.901	33.63	$C_{12}H_{22}O_3$	1, 3-Dioxan-4-one, 2-heptyl-6-methyl
7	6.518	80.52	$C_7H_{14}O_2S$	trans-2, 4-Dimethylthiane, S, S-dioxide
8	7.644	89.56	$C_{12}H_{25}F$	Dodecane, 1-fluoro-
9	8.407	62.9	$C_{18}H_{36}$	5-Octadecene, (E)-
10	9.18	43.05	$C_7H_{14}O_2S$	trans-2,4-Dimethylthiane, S, S-dioxide
11	10.000	32.67	$C_7H_{14}O_2S$	trans-2, 4-Dimethylthiane, S, S-dioxide
12	10.934	26.48	$C_{12}H_{25}F$	Dodecane, 1-fluoro-
13	11.831	27.87	$C_{12}H_{25}F$	Dodecane, 1-fluoro-
14	12.745	32.86	$C_{12}H_{25}F$	Dodecane, 1-fluoro-
15	13.653	33.85	$C_{14}H_{30}O$	Heptane, 1, 1'-oxybis-
16	14.732	32.79	$C_{14}H_{30}O$	Heptane, 1, 1'-oxybis-
17	15.64	39.08	$C_{12}H_{25}F$	Dodecane, 1-fluoro-
18	16.346	31.8	$C_{12}H_{25}F$	Dodecane, 1-fluoro-
19	17.461	16.77	$C_{22}H_{46}$	2, 2-Dimethyleicosane
20	18.359	4.77	$C_{12}H_{10}O_4S$	2-Hydroxy-3-(thiophen-2-yl)methyl-5-methoxy-1, 4-benzoquinone

Table 2. Physio-chemical properties of diesel, RSO and WPO.

Properties	ASTM Method	Biofuel ASTM D6751 limits	Diesel	RSOME	WPO	R 20 P 80
Specific gravity at 15 °C	D 4052	0.87 to 0.89	0.82	0.8102	0.9155	0.893
Net calorific value, kJ/kg	D 4809	-	44800	38650	43340	41362.4
Flashpoint, °C	D 93	Min. 130	50	66	54	56
Fire point, °C	D 93	-	57	68	56	58
Kinematic viscosity at 40 °C, cSt	D 445	1.9 to 6.0	2	12.75	3.18	3.704
Cetane index	D 613	48 to 70	50	56	51	38.4
Water content, wt. %	D 2709	Max. 0.050	0.025	0.3	0.01	0.065
Oxygen by difference, %	E 385	-	Nil	22	1.5	5.6

power of 3.7 kW at 1500 rpm. The CR of the engine is modified from 16:1 to 20:1. Legion Brothers of Bangalore is responsible for the modification work. Table 3 contains all of the test engine's specifications.

VCR arrangement

A manual change of CR is possible by using a specially designed CR graduation disc attached to the cylinder head. The graduation disc will not affect the combustion chamber geometry. In the current study, the cylinder head disc plate is rotated and moved up and down to alter the clearance volume of the cylinder, which in turn alters the CR.

Figure 3 depicts a photograph of a CR graduation disc and tightening lever. The calculation for the CR values is found in Eq. (4):

$$\textit{Compression ratio} = \frac{\textit{Total cylinder volume}\,(V_s + V_c)}{\textit{Clearence volume}\,(V_c)} \tag{4}$$

where V_s=πd^{2}l/4 is the swept volume of the cylinder (m^3), V_c is the clearance volume of the cylinder (m^3), *d* is the bore diameter (80 mm), and *l* is the stroke length (110 mm).

Combustion parameters measurement

Combustion pressure sensor with charge amplifier

It is necessary to obtain the values of cylinder gas pressure and crank angle to acquire essential combustion characteristics like peak pressure, peak pressure occurrence, maximum rate of pressure rise, HRR, combustion duration, ignition delay, mass percentage burned, etc. The in-cylinder gas pressure was measured using a piezoelectric pressure transducer manufactured by Cityzen (model CY-CP-

Table 3. Technical specifications of the experimental setup.

Particulars	Specifications
Make and Model	VCR multi-fuel, vertical, water-cooled, direct injection, naturally aspirated engine. Legion Brothers, Bangalore, modified the engine to change the compression ratio arrangement. The Kirloskar AV1 engine makes the base crankcase.
Compression ratio range	6:1 to 20:1
Rated brake power	3.7 kW
Rated speed	1500 rpm
No. of cylinders / No. of strokes	01 / 04
Bore x Stroke	80 x 110 mm
Displacement volume	552.64 cc
Nozzle opening pressure	200 bar
Maximum load	10 kg
Software	"Engine Test Express v14" Engine performance analysis software

200B), integrated with a Cityzen charge amplifier. Through the action of a diaphragm on the quartz components, the cylinder gas pressure detected by the sensor becomes an electrostatic charge. The experiment involves measuring the crank angle and in-cylinder gas pressure for 50 consecutive cycles. A data acquisition system (DAS) with a resolution of 0.5 °CA is employed to eliminate the impact of cycle-to-cycle changes. The DAS uses a high-impedance connection to capture the charge amplifier's output and save it in an Excel file on the PC. The low-level charge is converted into a proportional voltage by the amplifier.

Figure 3. Photographic image of CR graduation disc and pointer.

Experimental errors and uncertainties

The tests utilized standardized measuring instruments, and the error rates for each instrument were computed to minimize the measurement error rate to the lowest possible percentage. The first reading of the independent variables like load, speed, and others were computed using the percentage uncertainty of the corresponding instruments provided in Appendix 1. The total percentage of uncertainty was ± 2.28 %.

RESULTS AND DISCUSSION

In this segment, we examine the effects of the CR values on CI engine operations, combustion, and emission parameters for the VCR engine when it is run on hybrid alternative fuel (R-20/P-80 blend) at various CR values of 16:1, 17:1, 18, and 20:1. Furthermore, diesel and neat WPO are also compared.

Pressure-crank angle graph

In terms of crank angle, the pressure computation is a crucial instrument. It also provides enough data to perform a combustion analysis and calculate the heat release rate from the fuel. An engine's maximum pressure rises as more fuel is consumed during the pre-mixed combustion stages. Figure 4a represents the fluctuation in engine pressure at maximum load conditions for hybrid alternative fuel (R-20/P-80 blend), neat WPO, and diesel. Typically, raising the CR values enhances engine pressure and engine operations. According to Figure 4a, diesel has a peak pressure of 62 bar, and hybrid alternative fuel has a peak pressure of 66 bar at a 16:1 CR. The hybrid alternative fuel with a 17:1 CR has a peak pressure of 66.5 bar. When fully loaded, the peak pressures at the 18:1 and 20:1 CRs are 68.5 bar and 70 bar, respectively. WPO maximum pressure was also attained at 67 bar at a 16:1 CR. The elevated pressure at 20:1 CR is higher for hybrid alternative fuel than the peak pressure at 16:1 CR. As a result of the higher viscous property, lower volatile behaviour, and higher oxygen content of biofuels, this increase in cylinder pressure is made possible by enhancing the CR, which is more advantageous for biofuels than diesel. Higher CRs seem to improve the performance of biodiesel [5–8].

Heat Release Rate (HRR)

In C.I. engines, the HRR value is measured as the sum of the work done and the change in internal or chemical energy of the fuel released during the combustion process. Figure 4b compares the heat release rates of WPO and diesel at full load with different CRs for hybrid alternative fuel. The HRR values of hybrid alternative fuel (R-20/P-80 blend) are 80, 82.5, 83.8, and 85.38 J/°CA, with CR values of 16:1, 17:1, 18:1, and 20:1. At a 16:1 CR, the diesel and WPO have maximum heat release rates of 73.8 and 83 J/°CA, respectively. The HRR value increased with an enhancement of the CR value because of the excellent spray developed in the combustion chamber, the enrichment air entrainment phenomenon, enhanced biofuel volatility properties, faster prior mixing of blends, and greater diffusive combustion stages [5–8].

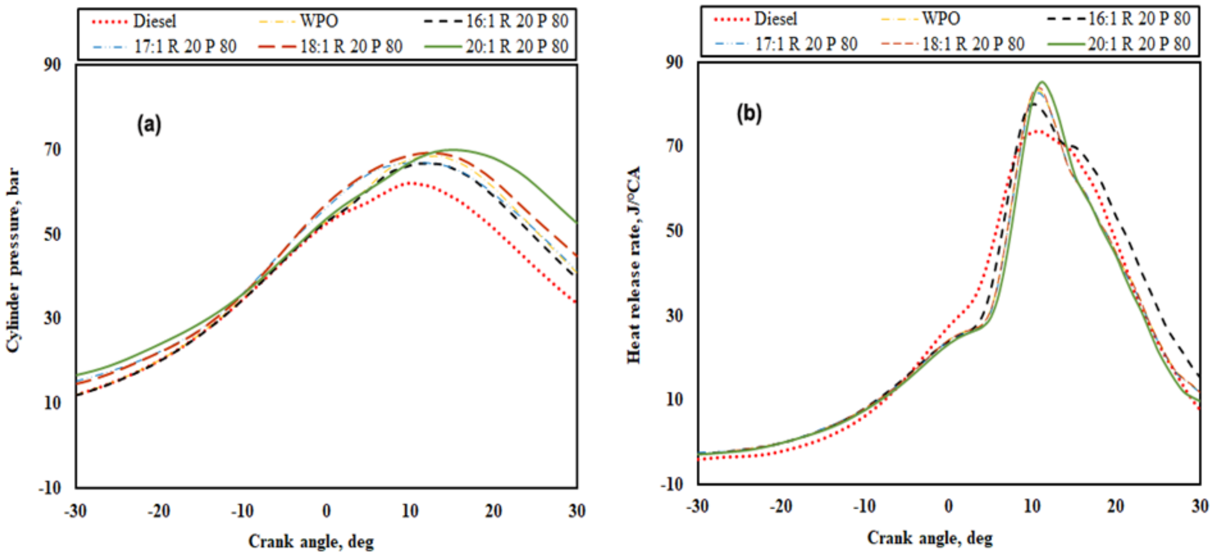

Figure 4. Variation of Engine parameters at full load conditions: (a) Pressure versus crank angle; (b) HRR versus crank angle.

Ignition delay

Figure 5 (a) illustrates the relationship between the load and the ignition delay for the tested fuels at varying CRs. The hybrid alternative fuel has ignition delays at full load of 11.6 °CA, 11.5 °CA, 10.6 °CA, and 10.5 °CA, respectively, with CR values of 16:1, 17:1, 18:1, and 20:1. Similarly, the diesel and WPO ignition delays were observed at 10.8 °CA and 11.8 °CA, respectively, at a CR value of 16:1 with maximum load settings.

In this study, the fuel-air mixture's pre-ignition creates a rise in cylinder heat, which causes the ignition delays to reduce with increasing loads at different CRs. Moreover, the ignition delay gets shorter as CRs rise. The air and gas temperature inside the cylinder rises due to higher CR values, aiding in the charge's early burning. Thus, the ignition delay is decreased. Compared to 17:1, 18:1, and 20:1 CRs, the 16:1 CR results in a longer ignition delay for hybrid alternative fuel because there are more premixed combustion phases and less diffusion combustion, respectively [6–9].

Cylinder peak pressure/ Engine maximum pressure

The degree of engine maximum pressure mainly depends on the volume of diesel or alternative fuel evaporated during the ignition gap interval. However, the evaporation of liquid fuel is significantly influenced by viscosity. The change in engine maximum pressure with full load for the tested fuels at various CRs is shown in Figure 5b. The maximum engine pressure for hybrid alternative fuel is 58, 59, 61, and 62.1 bar, respectively, at the no-load state for CRs of 16:1, 17:1,

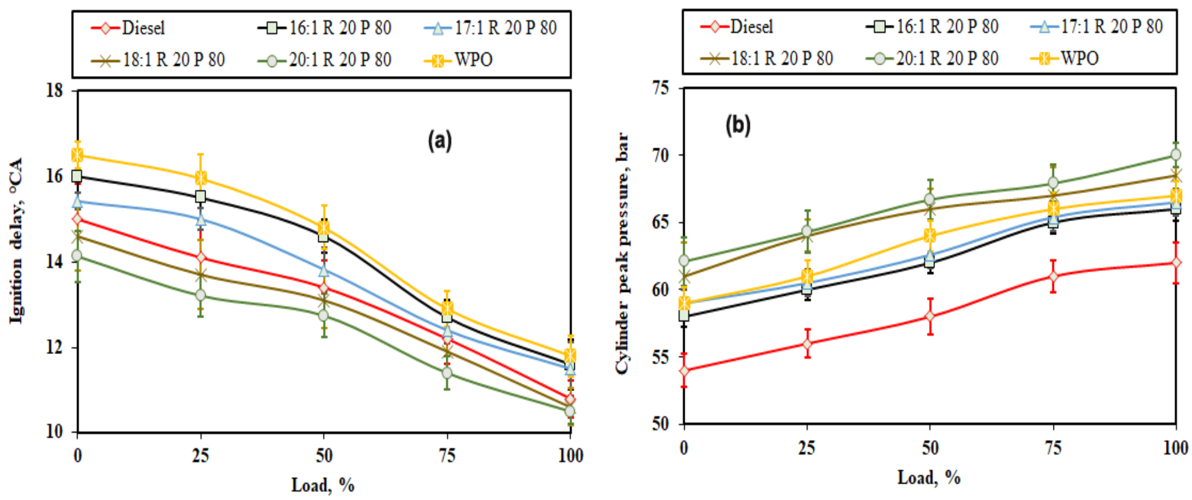

Figure 5. Variation of engine parameters at different load conditions: (a) Ignition delay versus load; (b) Cylinder peak pressure versus load.

18, and 20:1. The engine maximum pressure of hybrid alternative fuel at CRs of 16:1, 17:1, 18:1, and 20:1 is 66, 66.5, 68.5, and 70 bar, respectively, at maximum loaded condition. The engine maximum pressure of diesel and alternative biofuel WPO at a CR of 16:1 is 62 bar and 67 bar, respectively. Because of a greater combustion temperature in the quicker prior mixing of air-fuel combustion stages and a decrease in CV values, which raises the density of the blends in the course of combustion [7–11]. In addition, the cylinder peak pressure of hybrid alternative fuel (R-20/P-80 blend) is higher at a higher CR of 20:1.

Brake thermal efficiency (BTHE)

Figure 6a depicts the impact of the CR values on the BTHE of the tested fuels. According to the experimental results, the BTHE values increased with increasing load under all test conditions. At maximum load conditions, the BTHE for diesel, WPO, and hybrid alternative fuel at a 16:1 CR are 26.8%, 23.4%, and 25.8%, respectively. The BTHE of an R-20/P-80 blend at CRs of 16:1, 17:1, 18, and 20:1 is 12%, 12.8%, 14.2%, and 15%, respectively, at 25% load. At full load, the BTHE for hybrid alternative fuel at CRs of 17:1, 18:1, and 20:1 is 26.8%, 28.74%, and 30.5%, respectively. The BTHE values of hybrid alternative fuels are higher than diesel and WPO. At full load, the CR of 17:1 offers almost similar efficiency, but the BTHE values increased when the CRs of 18:1 and 20:1 for the R-20 / P-80 blends were increased because the fuels burn more efficiently at higher temperatures and pressures and have reduced volatility at higher CRs, which are supported by the intake air's higher temperature and pressure [8–14]. According to the results of the experimental research, the threshold CR for hybrid alternative fuel is 17.1, and higher brake thermal efficiency is attained when the pressure is maintained above the threshold limit. Additionally, when the CR is lowered to 16:1 or 17:1, it is discovered that the BTHE values of the hybrid alternative fuel are worse than diesel. The hybrid alternative fuel's extended ignition delay at low CRs (16:1 or 17:1) is responsible for the inadequate combustion characteristics.

Brake specific fuel consumption (BSFC)

Figure 6b depicts the change in BSFC for the different blends under varied loads and CR values. Figure 6b clearly shows that the BSFC falls as the CR rises, and the BSFC of the WPO and its RSO blends also reflects a similar trend compared to diesel. The BSFC values of WPO and diesel at a 16:1 CR are 0.465 kg/kWh and 0.375 kg/kWh, respectively, at maximum load. For CRs of 16:1, 17:1, 18, and 20:1, the BSFC values for the hybrid alternative fuel under 25% load circumstances are 0.75, 0.721, 0.68, and 0.66 kg/kWh, respectively. The BSFC values for the hybrid alternative fuel at maximum load conditions are 0.41, 0.39, 0.362, and 0.347 kg/kWh for CRs of 16:1, 17:1, 18, and 20:1. By comparing the BSFC values of diesel and WPO at CRs of 18:1 and 20:1. It is found that the hybrid alternative fuel has lower BSFC values due to a lower clearance volume, better combustion, and lower heat losses. The above factors produce more heat energy to obtain the desired brake thermal efficiency. Higher CRs also result in higher maximum engine pressure, significantly boosting engine power production while lowering fuel consumption per unit of output [10–15]. Additionally, the more considerable clearance volume, the least amount of heat generated, and the lower cylinder gas temperature are the causes of the rise in the BSFC values of the hybrid alternative

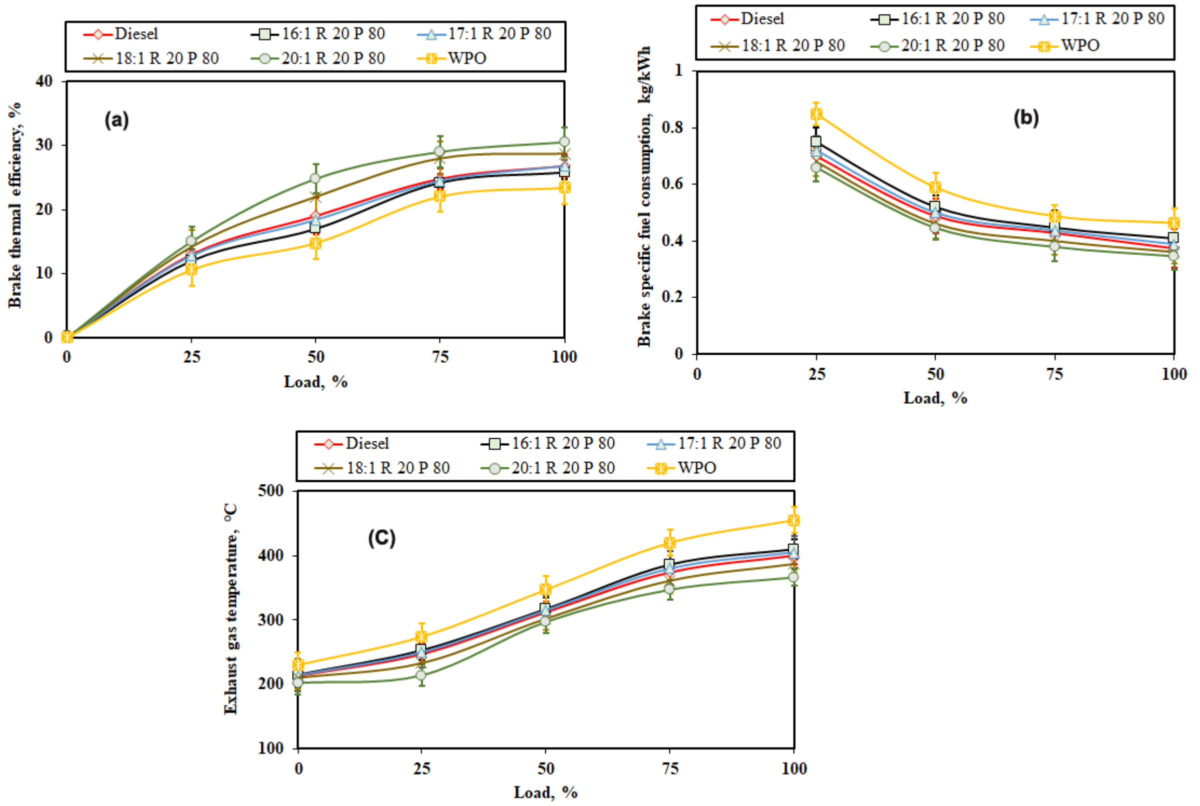

Figure 6. Variation of engine parameters at different load conditions: (a) Brake thermal efficiency; (b) Brake specific fuel consumption; (c) Exhaust gas temperature.

fuel at CRs of 16:1 and 17:1. The combustion chamber must consume more blends to accomplish it.

Exhaust gas temperature (EGT)

Figure 6c depicts the temperature fluctuations of the exhaust gases for the operated fuels as a function of different load and CR conditions. According to experimental findings, the EGT values of hybrid alternative fuel rise with increasing load and fall with increasing CRs, as shown in Figure 6c. Furthermore, the minimum EGT contributes to the maximum BTHE. Due to its higher viscosity and density than diesel, the EGT values of the hybrid alternative fuel at 16:1 and 17:1 CRs are higher than diesel during the operational period.

EGT values for the hybrid alternative fuel for CRs of 16:1, 17:1, 18:1, and 20:1 are 215 °C, 214 °C, 210 °C, and 202 °C, respectively, with no load. The EGT values of the exhaust gas temperature of the hybrid alternative fuel at CRs of 16:1, 17:1, 18:1, and 20:1, are 410 °C, 405 °C, 387 °C and 366 °C respectively, at maximum load. Similarly, the EGT values of the WPO and diesel for the 16:1 CR are 455 °C and 400 °C, respectively, at maximum load conditions. The increase in blend temperature inside the cylinder, which reduces the ignition period and results in more efficient and thorough fuel burning, is one of the potential causes of the decrease in EGT at higher CRs of 18:1 and 20:1 [14–19]. This fuel blend burns more efficiently than diesel and converts more energy per unit of fuel.

Oxides of nitrogen emissions

Nitric oxide (NO) and nitrogen dioxide (NO_2) are often referred to as "oxides of nitrogen emission"–the interaction of oxygen and nitrogen gases during burning fresh air and fuel results in NOx emissions. The crucial factors for generating NOx pollution are the extreme burnt gas temperature, the degree of oxygen content, and the residence time for the reactions. A tiny quantity of N_2 in gasoline derived from vegetable oils helps create NOx emissions in addition. Figure 7a illustrates the variance in nitrogen oxide emanations from diesel, WPO, and hybrid alternative fuel exhaust at various CR values and loads. For CRs of 16:1, 17:1, 18:1, and 20:1, the hybrid alternative fuel emits 205 ppm, 250 ppm, 300 ppm, and 330 ppm of NOx, respectively. When the engine is operating at maximum load, and a standard CR value of 16:1, diesel and the hybrid alternative fuel emit 820 ppm and 920 ppm of NOx, respectively; meanwhile, the NOx emission values for CRs of 17:1, 18:1, and 20:1 are 960 ppm, 1050 ppm, and 1095 ppm, respectively. Similar to this, WPO emits 1010 ppm of NOx at full load and a standard CR value of 16:1. According to experimental results, the maximum cylinder temperature causes the NOx emission for the hybrid alternative fuel to rise at the higher CRs of 18:1 and 20:1, in comparison to diesel and WPO. As a result, as the CR values rise, the fuel-burning temperature rises, releasing more NOx into the atmosphere [15–21].

Low NOx emissions are caused by insufficient oxygen supply at lower CRs of 16:1 and 17:1, which causes incomplete fuel combustion and lower in-cylinder temperatures. However, higher CRs produce more NOx pollution because more oxygen is available, resulting in complete combustion and proper breakdown of the fuel particles when the fuel is injected. When the cetane number is reduced, it prolongs the ignition delay period, increasing fuel accumulation and leading to higher NOx emissions.

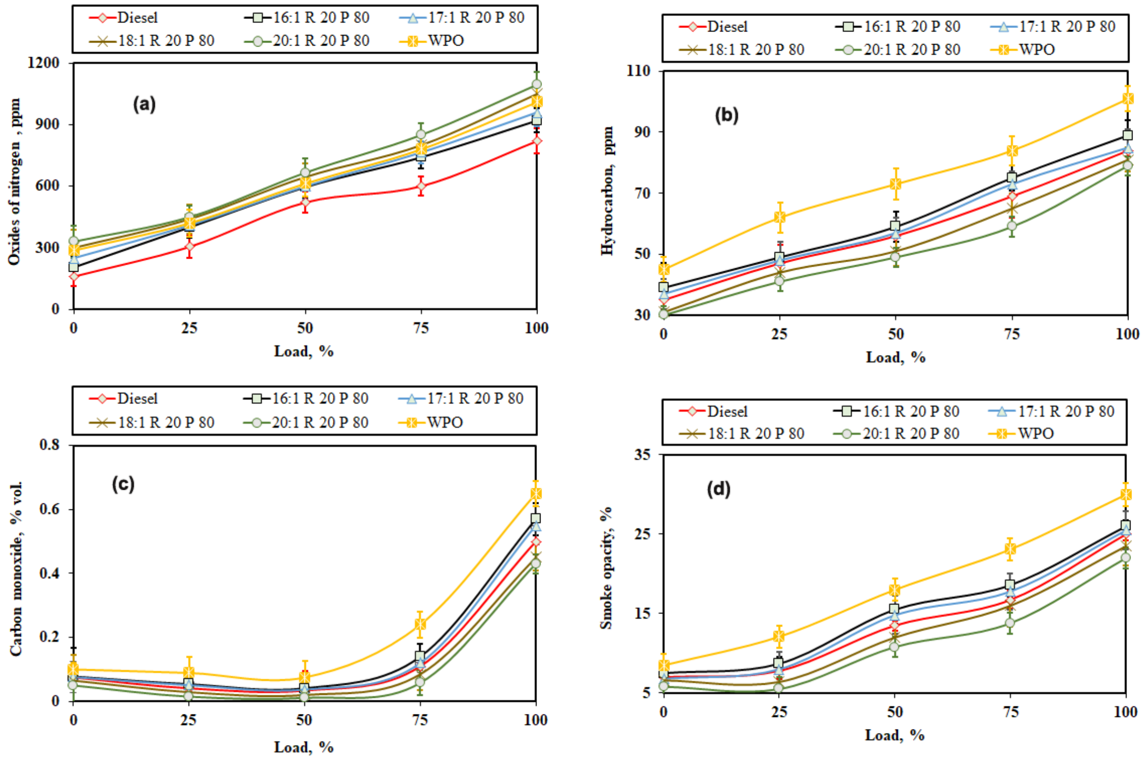

Figure 7. Variation of emissions with different load conditions: (a) Oxides of nitrogen; (b) Hydro carbon; (c) Carbon monoxide; (d) Smoke opacity.

Hydrocarbon (HC) emissions

The amount of HC released by engines in their exhaust smoke is a sign of inefficient fuel burned while the engine is running and an indicator of combustion efficiency. The fuel characteristics and engine operating circumstances majorly impact the HC emissions into the atmosphere, which are made up of partially burned fuel. The change in HC emission levels for the samples with various CR values and loads is shown in Figure 7b. At CRs of 16:1, 17:1, 18, and 20:1, the HC emission from hybrid alternative fuel is 39 ppm, 37 ppm, 31 ppm, and 30 ppm, respectively, with no load. For a full load, the HC emission from hybrid alternative fuel is 89 ppm, 85 ppm, 81 ppm, and 79 ppm, respectively, at CRs of 16:1, 17:1, 18, and 20:1. While the HC emissions from diesel and WPO are delivered at 84 ppm and 101 ppm at conditions of maximum load and 16:1 CR, respectively.

Increased CR reduces the ignition period, effectively reducing the over-mixing of the A/F values and emitting a low quantity of HC particles into the atmosphere. Because of the increased temperature and pressure during combustion in the engine cylinder and the oxidation of unburned hydrocarbons, HC emissions are decreased at greater CRs [18–22]. The increased combustion temperature might negatively impact NOx emissions. More gasoline is gathered in the delay period for CRs of 16:1 and 17:1. Additionally, there will be insufficient compression heat and ignition delays. Due to this, HC emissions are higher than those of diesel.

Carbon monoxide (CO) emissions

In many nations, CO pollution is the most prevalent harmful air and a toxic gas. Additionally, it has no flavour, colour, or odour. The A/F relation to the stoichiometric proportions significantly impacts CO emissions caused by inadequate blend combustion. Figure 7c depicts the variation of carbon monoxide emissions for tested fuels with loads and CRs. The CO emissions for diesel and R 20 P 80 blend at a standard CR of 16:1 are found to be 0.5% volume and 0.57% volume, respectively, at full load.

At no load, hybrid alternative fuel emits 0.078% volume, 0.076% volume, 0.065% volume, and 0.05% volume of CO pollution at CRs of 16:1, 17:1, 18, and 20:1. The CO pollution emitted by hybrid alternative fuel at full load for CRs of 17:1, 18:1, and 20:1 is 0.55% volume, 0.45% volume, and 0.43% volume, respectively. Similarly, the CO pollution emitted by WPO at full load for CRs of 16:1 is 0.65% volume. The factors influencing the CO emissions for hybrid alternative fuel are lower CRs of 16:1 and 17:1, higher spray coverage, bigger fuel droplets, improper swirling, and a lower cylinder temperature. The improved air-fuel mixing, greater air temperature within the combustion chamber, and shorter ignition lag may contribute to lower CO emissions at higher CRs [20–24]. The fuel burns quicker and more thoroughly as a result.

Smoke opacity emissions

The most noticeable byproduct of a diesel engine is the emitted gas flow, which contains trapped solid soot molecules and is known as smoke opacity emission. The formation of smoke opacity emissions occurs due to the extreme air deficiency in the CI engine, and the smoke opacity output rises as the A/F values fall. Figure 7d presents the fluctuations of smoke opacity emission with various CR values and loads for tested fuels. At full load conditions, the smoke opacity emissions for diesel, WPO, and hybrid alternative fuel at a 16:1 CR are 25%, 30%, and 26%, respectively. At no load, the hybrid alternative fuel's smoke opacity emission at CRs of 16:1, 17:1, 18, and 20:1 is 7.5%, 6.8%, 6.6%, and 5.8%, respectively. At maximum load, the smoke opacity emission for hybrid alternative fuel at CRs of 17:1, 18:1, and 20:1 is 25.5%, 23.5%, and 22%, respectively.

According to experimental results, the smoke opacity emission rises when the engine load levels are increased, while the emission declines with an increase in CRs from 16:1 to 20:1. When a blend's CR is increased, it improves fuel combustion and raises combustion temperature, both of which reduce smoke opacity. Higher CR values result in greater brake thermal efficiency, which claims to support the preceding fact, whereas at a lower CR of 16:1 and 17:1, incomplete combustion of fuel takes place. Hence, more smoke opacity emission is produced [22–26]. Table 4 gives the percentage increase or decrease of combustion, performance, and emission parameters at different CRs for hybrid alternative fuel at full load.

Table 4. A comparison of hybrid biodiesel with different compression ratios to diesel at full load.

Sl. No.	Parameter	16:1 CR	17:1 CR	18:1 CR	20:1 CR
	Combustion Parameters				
1	Ignition delay (°CA)	+7.41	+6.48	-1.85	-2.78
2	Maximum heat release (J/°CA)	+9.59	+13.01	+14.79	+16.96
3	Maximum cylinder pressure (bar)	+6.45	+7.26	+10.48	+12.9
	Performance parameters				
1	Brake thermal efficiency (%)	-3.73	0	+7.24	+13.81
2	Brake-specific fuel consumption (kg/kWh)	+9.33	+4	-3.47	-7.47
3	Exhaust gas temperature (°C)	+2.5	+1.25	-3.25	-8.5
	Emission parameters				
1	Oxides of nitrogen emission (ppm)	+12.19	+17.07	+28.05	+33.54
2	Hydrocarbon emission (ppm)	+5.95	+1.19	-3.57	-5.95
3	Carbon monoxide emission (% volume)	+14	+10	-10	-14
4	Smoke opacity emission (%)	+4	+2	-6	-12

"+" indicates percentage increase; "-" indicates percentage decrease.

CONCLUSION

An experiment was carried out using RSO blended with WPO (R-20/P-80) on a single-cylinder, water-cooled VCR engine. The combustion, performance, and emission properties of the hybrid alternative biofuels were compared to diesel and neat WPO. To achieve a robust study soon, (i) conducting extended durability tests to assess the engine's long-term performance and reliability when running on hybrid biodiesel at different CRs, (ii) developing computational models to simulate and analyse the combustion process in the engine when using hybrid biodiesel, aiding in design improvements, (iii) evaluating the engine's performance during cold starts and warm-up phases when operating on hybrid biodiesel at different CRs, (iv) assessing the compatibility of the engine's fuel system components with the hybrid biodiesel to ensure reliable and consistent fuel delivery, (v) examining the engine's components and systems for any potential wear and tear caused by the use of hybrid biodiesel at varying CRs and (vi) conducting on-road or real-world testing of the engine with hybrid biodiesel to evaluate its performance, fuel economy, and emissions in real-world driving conditions can be additional examined. The results of this investigation lead to the following deductions:

At 20:1 CR, the cylinder peak pressure of the hybrid biofuels (70 bar) is higher due to the higher combustion temperature, and the ignition lag is less than that of diesel (62 bar). As the CR values increase, the rate at which heat is released increases due to proper fuel spraying and optimal coverage of the blends in the cylinder. Compared to diesel, at maximum load and a 20:1 CR value condition, the BTHE value of the hybrid biofuel is around 3.7% higher, and the BSFC value is 7.45% lower. In addition, the EGT at full load and a CR of 20:1 are 8.5% lower than diesel. The hydrocarbon and carbon monoxide emissions for the hybrid alternative biofuel at full load and 20:1 CR are 5.9% and 14% less than diesel, respectively. When compared to diesel, NOx emissions are significantly greater for all CRs. The smoke opacity emission of the hybrid alternative biofuel at full load and 20:1 CR is 12% less than that of diesel.

The findings mentioned above underscore the diverse potential advantages and applications of hybrid fuel across various sectors, including automotive, power generation, and maritime applications.

LIST OF SYMBOLS AND ABBREVIATIONS

A/F	-	Air fuel ratio
ARAI	-	Automotive Research Association of India
BP	-	Brake power, kW
BSFC	-	Brake-specific fuel consumption, kg/kWh
BSO	-	Babassu oil
BTDC	-	Before the top dead centre, °CA
BTHE	-	Brake thermal efficiency, %
CO	-	Carbon monoxide, % volume
cSt	-	Centi Stoke
CR	-	Compression ratio
CV	-	Clearance volume, m^3
DAS	-	Data acquisition system
EGT	-	Exhaust gas temperature, °C
H_2SO_4	-	Sulphuric acid
HC	-	Hydrocarbon, ppm
HRR	-	Heat release rate, J/^{0}CA
JME	-	Methyl ester of *Jatropha curcas*
KME	-	Methyl ester of karanja oil
KOH	-	Potassium hydroxide
MSW	-	Municipal solid waste
NO	-	Nitric oxide
NO_2	-	Nitrogen dioxide
NOx	-	Oxides of nitrogen, ppm
R-20/P- 80	-	20% RSO blended with 80% WPO
SFC	-	Specific fuel consumption, kg/kWh
VCR	-	Variable compression ratio
WPO	-	Waste plastic oil
WPPO	-	Waste plastic pyrolysis oil
wt.	-	Weight, kg

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NAUČNI RAD

KARAKTERISTIKE SAGOREVANJA, EMISIJE I PERFORMANSI HIBRIDNOG BIOGORIVA PRI RAZLIČITIM ODNOSIMA KOMPRESIJE

Primarni ciljevi ove studije su naizmenično korišćenje konvencionalnih fosilnih goriva, smanjenje emisija gasova sa efektom staklene bašte i dima iz dizel motora, kao i poboljšanje karakteristika performansi i emisija štetnih gasova dizel motora sa promenljivim kompresijom koji radi sa hibridnim biodizelom. Eksperimenti su rađeni sa najboljim hibridnim biodizelom, koji je napravljen namešavanjem 20% kaučukovog ulja sa 80% ulja od otpadne plastike . Ispitivanja su obavljena pri četiri stepena kompresije: 16:1, 17:1, 18:1 i 20:1. Pri stepenu kompresije od 20:1 i pri punom opterećenju, termička efikasnost motora porasla je za 30,5%, specifična potrošnju goriva pala je za 0,347 kg/kWh, a značajno je smanjena emisija ugljen-monoksida (0,43% v/v), ugljovodonike (79 ppm) i dima (22%). Međutim, sa povećanjem stepena kompresije, emisije azotovih oksida su porasle nepovoljno (1092 ppm) u poređenju sa dizelom (820 ppm). Takođe, upoređeni su dizel i čist biodizel of ulja otpadne plastije da bi se videlo kako vrednosti stepena kompresije utiču na sagorevanje, performanse i emisije. U poređenju sa dizelom, pod maksimalnim opterećenjem i stepenom kompresije od 20:1, hibridni biodizel je pokazao približno motora. Nalazi ukazuju na potencijalnu primenu ovog hibridnog biodizela u automobilskom sektoru, industriji proizvodnje energije i pomorskim aplikacijama.

Ključne reči: kaučukovo ulje, ulje otpadne plastike, performance, emisije, promenljivi stepen kompresije.