

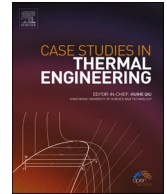


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Experimental study on palmyra oil biodiesel blends in CI engines: Role of injection pressure and EGR in performance enhancement and emission reduction

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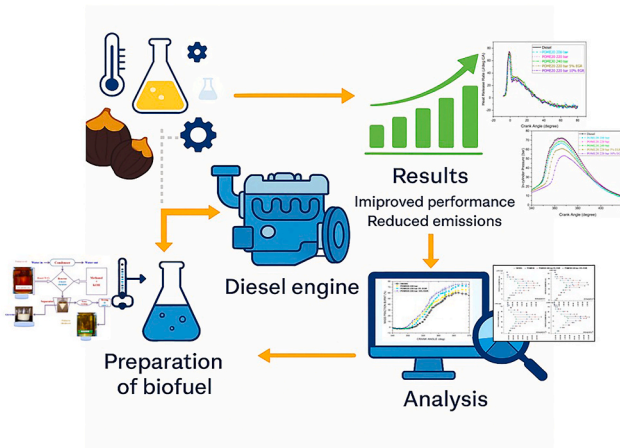
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GRAPHICAL ABSTRACT



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ABSTRACT

The rising global energy demand, particularly in transportation and agriculture, has intensified dependence on petroleum fuels such as diesel, resulting in significant environmental concerns. This study aims to investigate the feasibility of palmyra oil biodiesel as a sustainable alternative fuel for diesel engines by evaluating its performance, combustion, and emission characteristics under different operating conditions. Neat palmyra biodiesel was produced via transesterification and blended with diesel in proportions of POME10, POME20, POME30, and POME40. Experimental evaluation on a conventional diesel engine revealed that POME20 exhibited the best overall performance, achieving the highest brake thermal efficiency (BTE) of 32.48 %, which is about 2.5 % higher than diesel at full load. Furthermore, POME20 reduced CO emissions by 14 %, HC emissions by 19.6 %, and smoke opacity by 9.3 % compared to baseline diesel. To further optimize performance, POME20 was tested in a CRDI diesel engine at varying injection pressures (200 bar, 220 bar, and 240 bar) with a fixed injection timing of 23°bTDC and a compression ratio of 18:1. The results demonstrated that an injection pressure of 220 bar provided superior performance, with a 3.93 % improvement in BTE compared to 200 bar. Additionally, the application of Exhaust Gas Recirculation (EGR) at 5 % and 10 % effectively reduced NOx emissions by 11.88 % and 21.69 %, respectively, without compromising efficiency significantly. Overall, the study establishes POME20 as the most promising blend, capable of enhancing engine performance and reducing harmful emissions. These results underscore the potential of palmyra oil biodiesel as a viable and sustainable alternative to conventional diesel fuel.

Nomenclature:

Diesel Neat diesel
 POME10 10 % POME +90 % Diesel
 POME20 20 % POME +80 % Diesel
 POME30 30 % POME +70 % Diesel
 POME40 40 % POME +60 % Diesel
 POME20 200 bar – POME20 blend tested at injection pressure of 200 bar
 POME20 220 bar – POME20 blend tested at injection pressure of 220 bar
 POME20 240 bar – POME20 blend tested at injection pressure of 240 bar
 POME20 220 bar 5 % EGR – POME20 blend at 220 bar injection pressure with 5 % Exhaust Gas Recirculation
 POME20 220 bar 10 % EGR – POME20 blend at 220 bar injection pressure with 10 % Exhaust Gas Recirculation
 IP – Injection Pressure (bar)

EGR	– Exhaust Gas Recirculation (%)
BTE	– Brake Thermal Efficiency (%)
BSFC	– Brake Specific Fuel Consumption (kg/kWh)
HRR	– Heat Release Rate (J/°CA)
CO	– Carbon Monoxide emission (% vol)
HC	– Hydrocarbon emission (ppm)
NOx	– Oxides of Nitrogen emission (ppm)
SO	– Smoke Opacity (%)
CI Engine	– Compression Ignition Engine
CRDI	– Common Rail Direct Injection

1. Introduction

The IC engines have become a fundamental component of human daily life. In transportation, agriculture, power generation, locomotives, and heavy machinery applications, these internal combustion engines are often employed as petrol engines and diesel engines. Environmental emissions, increased fuel prices, and more importantly, stringent emissions regulations around the world have prompted global researchers to focus on alternative fuels that are precisely achievable, parsimoniously competitive, ecologically satisfied, and readily accessible for diesel engines. Furthermore, the oil should be environmentally friendly and renewable.

Alosius et al. [1] studied the combined effect of injection pressure and EGR on a modified diesel engine fuelled with waste cooking oil. They tested the biodiesel at different injection pressures like 300 bar, 400 bar and 500 bar and two different EGR rates such as 10 % and 20 % at all load conditions. They found that high injection pressure of 500 bar with 10 % EGR has shown high brake thermal efficiency of 34.93 % along with major reduction of exhaust emissions at full load. Sathishkumar and Ibrahim [2] examined the effect of injection pressure and EGR on the premixed charge compression ignition mode. The authors varied the injection pressure from 500 bar to 1000 bar. They reported that the higher BTE and lower tailpipe emissions with increased injection pressure at full load. Karthic et al. [3] performed tests on diesel engine at various injection pressures (200 220 240,260 bar) fuelled with syzygium cumini oil biodiesel blends. Among the tested fuels, 30 % biodiesel blend have shown higher BTE and lower engine emissions at full load. However, the NOx emissions were significantly improved for the biodiesel blends with increased injection pressure. Yoon et al. [4] investigated the palm biodiesel on the diesel engine at different fuel injection pressures like 45 MPa and 65 MPa with different load conditions. They were inferred that increased injection pressure has shown a drastic reduction of CO, HC and smoke emissions at full load. However, there was more NOx emissions at all the loads. Yesilyurt [5] examined the effect of injection pressure on the attributes of diesel engine fuelled with waste cooking biodiesel-diesel blends and the author found optimum injection pressure of 210 bar operated with 20 % waste cooking oil biodiesel have shown improved engine performance and lower emissions at full load.

Rajasekaran et al. [6] studied the combined influence of injection pressure and EGR for the 1-pentanol added low density polyethylene fuel. From their investigation, they reported that injection pressure of 600 bar with 10 % EGR has found best possible engine performance and reduced emissions. Selvaraj and Thangavel [7] used the frying oil methyl ester as biodiesel for diesel engine operation and they performed tests at different injection pressures like 220 bar,240 bar and 260 bar at rated speed of 1500 rpm. They found 16.09 % increase in BTE when the injection pressure was changed from 220 bar to 240 bar. Further, the emissions like CO, HC and Smoke were reduced by 22 %,14 % and 29 % respectively at full load. Mourad et al. [8] used the EGR rates from 0 % to 25 % with 5 % increment in range for the diesel engine powered with preheated biodiesel and they found slight increase in engine performance and 22.2 % reduction of NOx emissions with 20 % EGR at full load. Pavan et al. [9] examined the effect of fuel injection pressure on the CRDI engine characteristics and reported that higher fuel injection pressure with split injection have shown reduced engine exhaust emissions at full load. Minho et al. [10] studied the injection timing, injection pressure and EGR on the attributes of diesel engine operated at different loads. They found retarded injection timing reduced engine exhaust emissions under low combustion temperature conditions as exhibited in Table 1.

Balaji and Cheralathan [15] have inspected the consequence of engines powered with neem biofuel and exposed that an augment of fuel injection pressure consequence in enhanced BTE and decreased BSFC and discharges. Rao, Kumar, and Herbert [16] have proceeded the experimentation with Vateriaindica biofuel for assessing the performance and discharge features and exposed that mixture B25 increases BTE by 33 percent and reduces NO_x discharges by 1047 ppm at 220 bar IP and 75 % applied load conditions. Subbarayan and Kumar [17] performed assessments on an engine using methyl ester of cotton seed oil blended mixtures comprised of both hot and cold exhaust gas recirculation (EGR). Also, detected that applying either hot or cold EGR improved emissions of NO_x, CO, HC, and opacity proportionally with BP for entire bio-fuel mixtures. Also, found that hot EGR was a better performance than cold EGR at decreasing discharges. Rajesh Kumar et al. [18] studied the influence of EGR on an engine using a pentanol/diesel mixture. They noted that while EGR significantly decreased NO_x releases, higher EGR levels consequence to a decrement in BTE because of deficient O₂ in the intake mixture. Moreover, HC and CO discharges augmented because of changes in the correspondence proportion. Ultimately, EGR showed promising outcomes in significantly reducing NO_x discharges.

Parvash Kumar and Naveen Kumar [19] identified that applying EGR to a compressed natural gas-jatropha oil methyl ester blended mixture reduced NO_x discharges substantially at extreme load associated to diesel. Sivakumar, Palanisamy, and Baluchamy [20] noted a 62.5 % reduction in NO_x with excess cooled EGR at 75 % but saw increased hydrocarbon and carbon monoxide emissions. Rajesh, Vineet Kumar, and Sunil Kumar [21] found that EGR diminished NO_x but improved CO, CO₂, and HC discharges at maximum load. Shi et al. [22] discovered that 10 % EGR reduced NO_x and opacity discharges at peak situations. Damodharan et al. [23] found that

progressive injection timing with 10 % EGR reduced NO_x and fume discharges by 38 % and 46 % correspondingly at peak condition for oil made by unused plastic. Verma et al. [24] noted reduced NO_x emissions with EGR at peak load. Reddy et al. [25] saw increased BTE and reduced emissions with advanced IT and 5 % EGR. Mohiuddin et al. [26] noted increased thermal efficiency and decreased pollutants at peak load with CR 16:1, but increased NO_x with higher compression ratios.

Khan et al. [27] presented a comprehensive review on the influence of injection parameters in biodiesel–diesel engines. They concluded that increasing injection pressure improves atomization and combustion, thereby reducing CO, HC, and smoke emissions, but leads to a rise in NO_x at higher pressures. Balaji et al. [28] experimentally investigated the effect of nozzle opening pressure on biodiesel blends. Their study revealed that raising injection pressure up to 250 bar enhanced brake thermal efficiency (BTE) and reduced BSFC, though beyond the optimum, efficiency gains diminished and NO_x emissions increased.

Sarıdemir et al. [29] analyzed corn oil methyl ester blends at different injection pressures. They found that higher IP shortened ignition delay, improved combustion quality, and reduced CO, HC, and smoke levels, but at the cost of increased NO_x.

Galande et al. [30] explored the combined effects of injection pressure and EGR on biodiesel-fuelled CI engines. Results showed that moderate EGR (10–15 %) effectively lowered NO_x, while slightly higher injection pressures helped maintain combustion efficiency and control other emissions. Sethin et al. [31] studied CRDI engines with biodiesel–diesel blends under different EGR rates. They reported that NO_x emissions decreased consistently with increasing EGR, but excessive EGR led to incomplete combustion, causing higher CO, HC, and smoke emissions. Shivashimpi and Yaliwal [32] examined the effect of EGR on palm oil biodiesel. They concluded that EGR up to 15–20 % effectively reduced NO_x but caused higher smoke levels and slightly lower thermal efficiency. Kumar et al. [33] conducted experimental studies using Palmyra oil methyl ester (POME) in a CI engine. Their work demonstrated that POME blends are a technically viable alternative to diesel, with efficiency and emissions highly sensitive to optimized injection pressure and EGR application.

The available literature indicates that limited research has been conducted on the performance, combustion characteristics, and emission parameters of palmyra oil biodiesel, with only a few studies addressing its generic applications. While some investigations have explored the potential of various non-edible oils as biodiesel feedstocks, the specific use of palmyra oil in internal combustion (IC) engines remains underexplored. Existing studies primarily focus on conventional biodiesel sources such as jatropha, neem, and mahua, leaving a significant gap in understanding the feasibility and performance of palmyra oil biodiesel in compression ignition (CI) engines. Palmyra oil, obtained from the palmyra fruit, is an abundant and underutilized resource in many regions of India, with an estimated oil content of 40–45 % reported by Vijay Kumar et al. [34]. Despite its availability and oil-rich composition, there is a lack of systematic research on its conversion into biodiesel and its subsequent application in CI engines. The few studies that do exist on palmyra oil biodiesel fail to provide a comprehensive analysis of critical parameters such as combustion behavior, thermal efficiency, and emissions in real-world engine conditions. Additionally, challenges related to fuel stability, oxidation characteristics, and optimal engine modifications for enhanced performance remain largely unaddressed. The novelty of this study lies in its dual approach: first, it systematically evaluates palmyra oil biodiesel blends in a conventional diesel engine to identify the optimal blend; second, it uniquely investigates the influence of injection pressure variation and the application of Exhaust Gas Recirculation (EGR) in a CRDI engine to optimize performance and mitigate emissions, particularly NO_x. By integrating these advanced engine strategies, this work provides the first comprehensive insight into the feasibility of palmyra oil biodiesel as a sustainable alternative fuel. This research thus addresses critical gaps in the literature while promoting the efficient utilization of indigenous, non-edible oil sources for clean energy applications.

Table 1

Summary of research works related to injection pressure and EGR influence on diesel engine characteristics.

Type of fuels	Type of engine	Test condition	Results	References
Pine -biodiesel-Diesel	Single cylinder, 4-stroke diesel engine	CR-17.5; IT:23° bTDC, IP:200-350 bar, Load:0–100 %	<ul style="list-style-type: none"> ➤ Improved air/fuel mixture during premixed combustion phase results in higher cylinder pressure. ➤ HC, CO and smoke were reduced with biodiesel. However, the NO_x emissions were increased than diesel fuel. 	[11]
Palm oil methyl ester	Single cylinder, 4-stroke diesel engine	SOI _{main} :23° bTDC, SOI _{pilot} :30, 32 and 34° bTDC, IP-400, 520 bar,	<ul style="list-style-type: none"> ➤ Split injections of fuel reduced the CO, HC and Smoke emissions. ➤ Improved combustion characteristics at higher injection pressure 	[9]
Calophyllum Inophyllum Methyl Ester, Diesel	Single cylinder water cooled diesel engine	CR:17.5 IP:600 bar EGR: 0,10,20 %	<ul style="list-style-type: none"> ➤ Significantly reduced NO_x emissions with the use of EGR. ➤ Performance and combustion attributes were reduced due to dilution effect of EGR. 	[12]
Diesel, n-pentanal, Biodiesel	Single cylinder water cooled diesel engine	CR:18 IP:1400 bar EGR:10,20,30,40,50 %	<ul style="list-style-type: none"> ➤ The use of 10 % EGR have shown improved engine performance and reduced exhaust emissions. ➤ Higher EGR rates (more than 20 %) lower engine performance. 	[13]
Palm biodiesel	Single cylinder water cooled diesel engine	CR:17.7 IP:200 and 380 bar EGR:10 %	<ul style="list-style-type: none"> ➤ 10 % EGR rates lower the NO_x emissions significantly with marginal reduction in engine performance. 	[14]

2. Palmyra oil

Palmyra fuel is extracted from dehydrated palmyra kernels (Palmyra oil, obtained from the palmyra fruit trees) either physically or mechanically. The palmyra oil was extracted from the palmyra fruits, which were directly collected from the local areas. These are freely available during the rainy season. The collected fruits were dried to remove the moisture content and then oil was collected by using cold pressing operation. The gathered palmyra kernels are washed with liquid and then dehydrated in an environment to eradicate the humidity in them. The palmyra kernels are then crushed using machinery to extract the oil, and the extracted palmyra oil being more viscous and less evaporative in nature. By utilizing the transesterification process, this issue can be significantly mitigated. The sequence involved in palmyra biodiesel production is shown in Fig. 1.

2.1. Fatty acids (FA) composition of palmyra oil

In order to assess the several fatty acids, gas chromatography is conducted on the unblended oil. In the Gas Chromatogram diagram, abscissa specifies the retention time and ordinate specifies detector signal. Components in the mixture having less boiling point reaches higher peaks, and the percentage of composition is proportionate to the area of the curve. In Fig. 2, maximum peak value indicates highest percentage of composition (Linoleic acid) and minimum peak value indicates lowest percentage of composition (Stearic acid) in the mixture.

2.2. Transesterification

Trans-esterification is the process in which entire glycerol and fatty acids are detached from vegetal extract in the existence of a catalyst (NaOH). This method has been extensively applied to decrease the fluid thickness of vegetable oils, so that improving fuel physical belongings and engine performance. In this method, the heavily split triglyceride molecules of vegetal oils are cracked down into minor, straight-chain particles that resemble diesel particles. The transesterification process consists primarily of three successive chemical processes that transform vegetal oil into biofuel and glycerol. Primarily, triglyceride molecules are transformed into di-glycerides, later di-glycerides as mono-glycerides, and lastly mono-glycerides into glycerol. Trans-esterification method yields one ester molecule from each reaction, resulting in a total of three ester molecules from each glyceride. The transesterification process is primarily influenced by multiple variables like value of free fatty acids (FFA), kind and concentration of catalyst, molar proportion of alcohol to vegetal fuel, temperature, and the mixing concentration. The existence of FAs in oil influences the effectiveness of the conversion process. The key disadvantages of unrefined palmyra oil are its greater viscosity, low volatility, and greater density. Transesterification is the best-known method for lowering biodiesel's viscosity and improving its quality. The palmyra biodiesel extraction through the transesterification process is depicted in Fig. 3.

The features of Diesel and POME bio-fuel blended mixtures such as POME10, POME20, POME30, and POME40 were identified with per ASTM ranges and offered in Table 3.

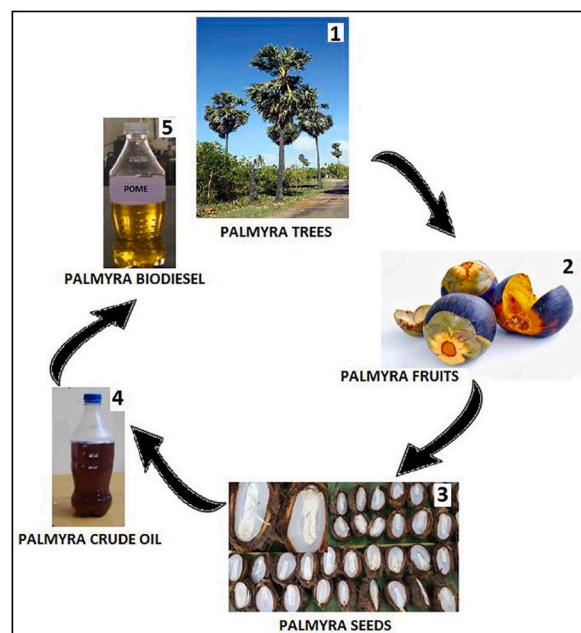
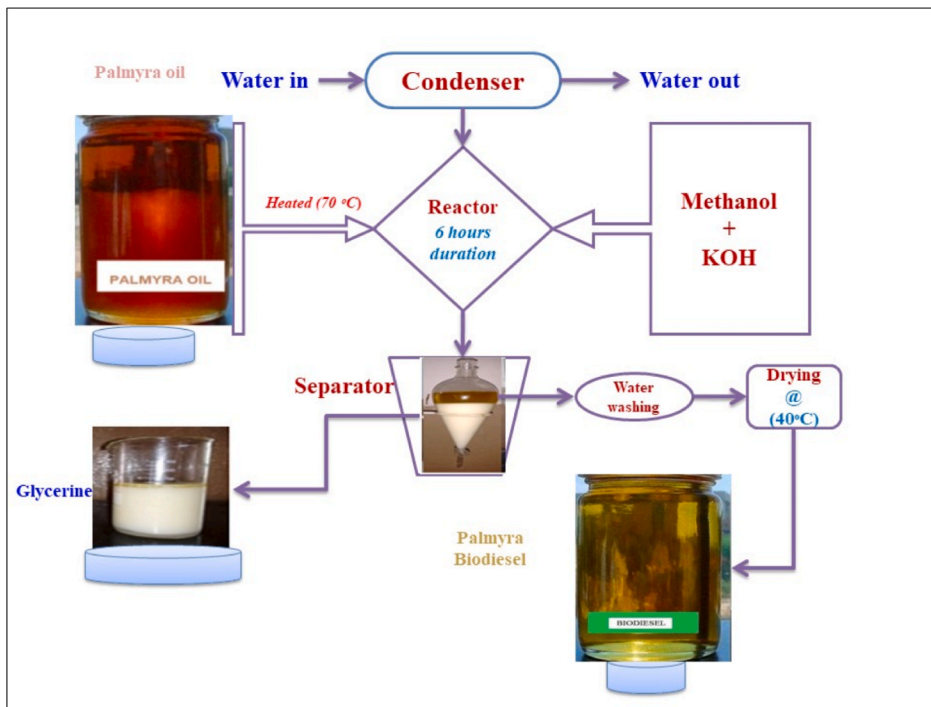


Fig. 1. Palmyra biodiesel extraction sequence [35].

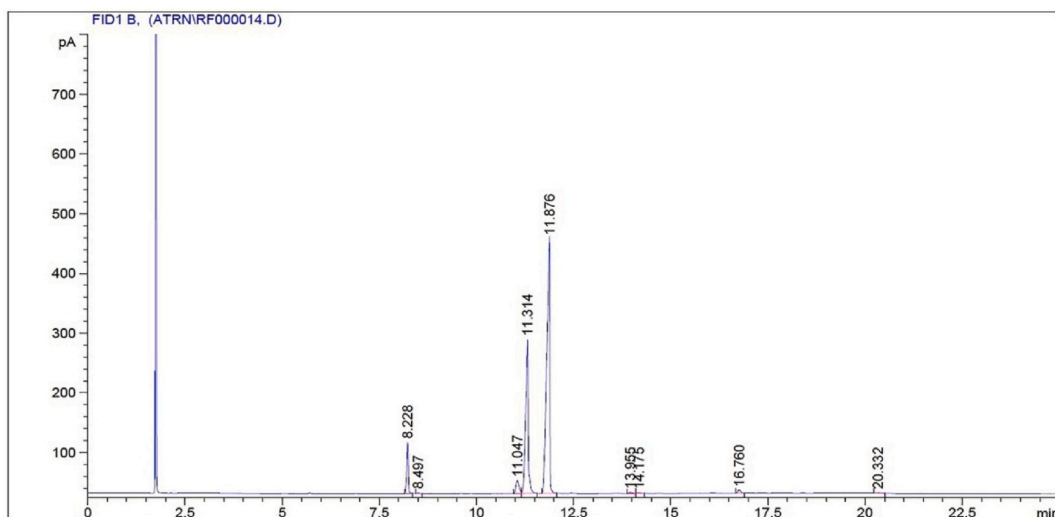
3. Experimental setup

The diesel engine set up used for conducting experiments is provided with a single cylinder, 4-stroke, continual speed, natural aspiration, water cooling, and direct injection.

The arrangement of investigational rig has been exposed in Fig. 3(a), and the photo-graphic image for investigational engine is exposed in Fig. 3 (b). Kirloskar TAF1 engine is applied for examination and has a displacement capacity of 661 cc with a CR of 12:1 to 22:1. The engine progresses 3.5 kW at 1500 rpm speed. The suggested IT was 23° bTDC with a standard IP of 200 bar. The governing



(a)



(b)

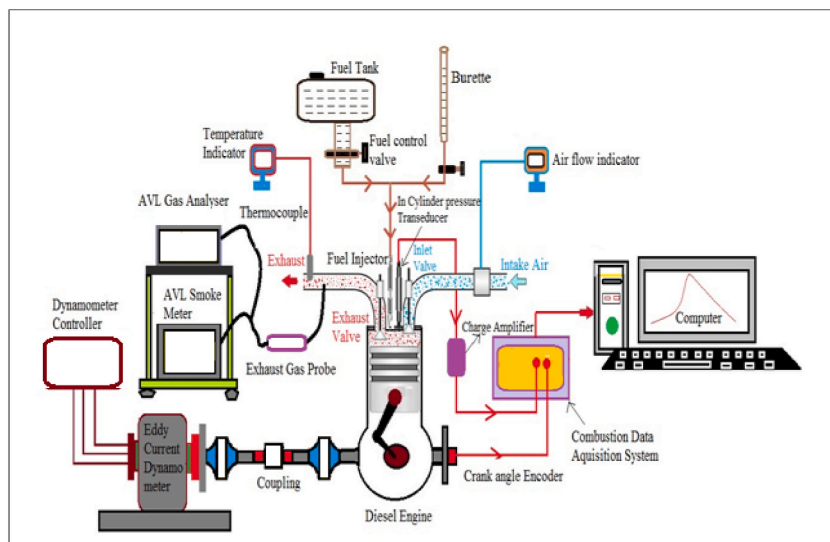
Fig. 2. Palmyra oil methyl ester (POME) (a) Preparation, (b) Gas Chromatography Various fatty acid configurations contained in 100 % biofuel are mentioned in Table 2.

mechanism is utilized to regulate the speed of engine under fluctuating load situations. The yield shaft of the engine is precisely attached to eddy current dynamometer for employed load. The experimental arrangement comprises essential devices for gauging burning pressure against with crank-angle, interfaced with a PC thru an engine indicator for P-V graphs. It also features apparatuses for air-flow, fuel-flow, temperatures, and load measurements. A standalone panel box houses an air box, fuel tank, manometer, fuel gauging unit, transmitters for airflow and fuel flow, process indicator, and engine indicator. Rotameters are used for measuring cooling water and calorimeter water flow. This rig allows for the analysis of engine performance parameters such as BP, IP, FP, BMEP, IMEP, brake thermal efficacy, indicated thermal efficacy, mechanical efficacy, volumetric efficacy, specific fuel consumption, air-fuel proportion, and heat balance. Additionally, an engine performance analysis software package called engine soft, based on LabVIEW, facilitates real-time performance assessment. ICEngineSoft is a LabVIEW-based software package developed by Apex Innovations Pvt. Ltd. for engine performance monitoring, including combustion analysis.

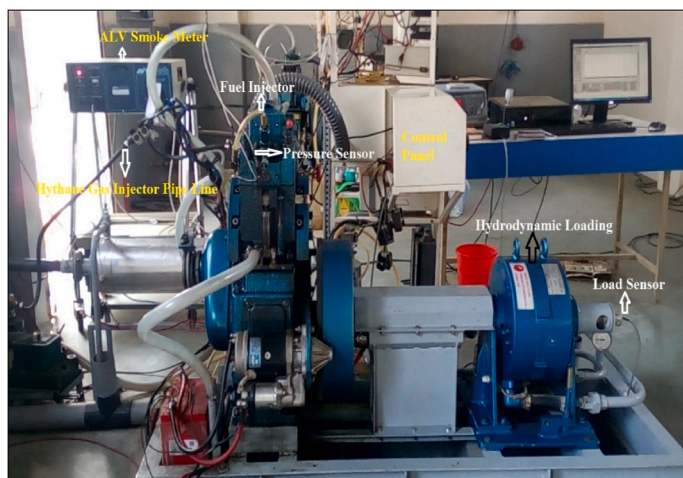
The procedural particulars of the investigational test rig were accumulated in Table 4. After examination and adjustment, essential instruments are provided for measuring engine performance parameters and exhaust discharges under a variety of functioning situations.

3.1. Varying injection pressure

One of the functioning constraints that influences engine performance is injection pressure. Injection pressure may be transformed through the regulating of the spring tension of the pointer in the injector nozzle.



(a)



(b)

Fig. 3. (a) Schematic arrangement of experimental engine set-up [36], (b) Photographic view of experimental test rig [36]

3.2. EGR method for regulating the NO_x discharges

Engines running on biodiesel emit minor levels of HC, CO, and opacity related to conventional diesel, albeit with increased NO_x emissions. To mitigate these NO_x discharges, exhaust gas recirculation (EGR) is a known-established technique. EGR works by regulating and decreasing the O₂ concentration and temperature of the fuel mixture in the burning space. However, higher EGR concentrations result in elevated levels of unburnt HC, CO, and opacity in the exhaust. Nevertheless, EGR remains the best practice for reducing NO_x discharges from engine exhaust. The EGR system involves mixing a part of the exhaust discharges with new air and delivering the same to the engine cylinder in the suction stroke.

The EGR, stated in several of paths. In current research, EGR fraction is founded by the proportion of mass portion of EGR (m_{EGR}) and entire mixture input (m_{INT}).

$$EGR (\%) = \frac{m_{EGR}}{m_{INT}} * 100 \tag{1}$$

m_{int} = Intake mixture.

m_{air} = Mass of newly charged air

m_{EGR} = Exhaust gas circulation mass flow rate.

With the application of EGR, NO_x discharges are found to be reduced drastically. In contrast, improving the rate of EGR results in a higher consequence in BTE since deficient oxygen in the intake mixture. In addition, HC and CO discharges increase because of a shift in the equivalency proportion. Overall, the EGR approach offers the greatest results in words of considerable reduction in NO_x emissions. In this experimental investigation, the POME-20 bio-fuel blend produced major NO_x emissions than diesel. Earlier investigations revealed that diesel engines can be operated with biodiesel s with enhanced performance accompanied by increased NO_x emissions. To comply with the rigorous pollution norms, biodiesel -powered diesel engines must emit less NO_x emissions. This study investigates the effect of EGR at 5 % and 10 % by volume on the performance and discharges of optimum POME biodiesel blend. Initially, experiments are directed on an engine with diesel, POME10, POME20, POME30, and POME40 blends for identifying the optimum blend of POME. Further, engine functioning constraints namely IP, injection timing, and compression ratios are altered to investigate its effect on performance with application of EGR.

3.3. Error and uncertainties

Error nothing but the uncertainty of actual value comparatively the trail value. Errors in any trial happen primarily because of incompatible apparatus or a gauging apparatus, specious standardization, or variations in ambient circumstances or detected evaluations. The error is a consequence replicates its range of uncertainty. The accuracy of a gauged level is refereed with the aid of deviation. Error investigation is crucial for determining the exact restrictions of the gauged and also predictable engine features. The calibration of numerous un-identified uncertainties from well-established constraints is done and is evaluated using (Eq. (2)).

$$\frac{U_y}{y} = \left[\sum_{i=1}^n \left(\frac{1}{y} \frac{\partial y}{\partial x_i} U_{x_i} \right)^2 \right]^{1/2} \tag{2}$$

In the equation, Y is a specific constraint, which is reliant over the further aspect (xi), and the sign U_y signifies the uncertainty in Y. In the current investigational study, 16 observations were recorded at numerous functioning situations of the engine. The deviation for the constraints were BTE, BSFC, EGT, HC, CO, NO_x and SO is measured through successive trials.

The list of apparatuses and their levels, precision, and uncertainties are presented in Table 5.

The proportion of the uncertainties for this experiment is assessed using Eq. (3).

$$\begin{aligned} &= \{(BTE)^2 + (BSFC)^2 + (EGT)^2 + (HRR)^2 + (CP)^2 + (HC)^2 + (CO)^2 + (NO_x)^2 + (SO)^2\}^{1/2} \tag{3} \\ &= \{(0.25 \%)^2 + (0.5 \%)^2 + (0.2 \%)^2 + (1 \%)^2 + (1 \%)^2 + (0.5 \%)^2 + (0.2 \%)^2 + (1 \%)^2 + (1 \%)^2\}^{1/2} \\ &= \{(0.0025)^2 + (0.005)^2 + (0.002)^2 + (0.01)^2 + (0.01)^2 + (0.005)^2 + (0.002)^2 + (0.01)^2 + (0.01)^2\}^{1/2} \\ &= \pm 0.01825 \\ &= \pm 1.825 \% \end{aligned}$$

Table 2
Diverse fatty acids compositions in POME.

S.No.	Kind of fatty acid	Range	Chemical indication	% of weight	Fatty acid manner
1.	Oleic acid	18:1	C ₁₈ H ₃₄ O ₂	31.0	Mono-saturated
2.	Stearic acid	18:0	C ₁₈ H ₃₆ O ₂	3.2	Saturated
3.	Linoleic acid	18:2	C ₁₈ H ₃₂ O ₂	58.4	Poly-saturated
4.	Palmitic acid	16:0	C ₁₆ H ₃₂ O ₂	6.0	Saturated

Table 3
Properties of diesel and POME biodiesel blends.

Properties	ASME Standards	Diesel	POME	POME10	POME20	POME30	POME40
Density (kg/m ³) @ 15 ^o C	ASTMD1298	830	872	836	841	845	849
Viscosity (cSt) @ 40 ^o C	ASTMD 445	3.4	22.2	5.28	7.1	9.0	10.9
Calorific value (kJ/kg)	ASTMD 4809	42500	37889	42039	41577	41116	40655
Flash point (^o C)	ASTMD 93	54	169	66	75	88	98
Fire Point (^o C)	ASTMD 93	58	174	69	79	92	101
Cetane number	ASTMD 613	46	52	47	48	50	51
Pour Point (^o C)	ASTM D97	-10	-11	-8	-6	-4	-2
Freezing Point (^o C)	ASTM D2386	-12	-13	-9	-7	-5	-3
Heat of Vaporization (kJ/kg)	ASTM D2598	250	300	255	262	268	272

Table 4
Technical conditions of the test set up.

Sl. No.	Conditions	Kirloskar TAF1, CI VCR engine
1.	Power and speed	3.5 kW and 1500 rpm
2.	Bore (D)	87.5 mm
3.	Stroke (L)	110 mm
4.	Stroke-volume (V)	661 cm ³
5.	CR	12:1 to 22:1
6.	No. of cylinders	01
7.	Fuel IT before TDC	23 ^o
8.	Fuel IP	200 bar
9.	Number of nozzles	3
10.	Nozzle size	0.3 mm

4. Results and discussion

4.1. Brake thermal efficiency

Brake thermal efficiency (BTE) signifies the effective transformation of heat capacity of oil into beneficial output power. The brake thermal efficiency (BTE) of the tested fuels was found to rise with increasing engine load, which is a typical trend due to improved combustion phasing and reduced relative frictional losses at higher loads. At peak load, diesel exhibited the highest BTE of 32.56 %, while the POME20 blends showed slightly lower efficiencies depending on the injection pressure (IP) and EGR conditions. Among the injection pressures, POME20 operated at 220 bar recorded the best performance, achieving 31.45 % BTE, which is about 2.1 % higher than POME20 at 200 bar (30.85 %) and 3.08 % higher than POME20 at 240 bar (30.51 %). The superior performance at 220 bar can be attributed to improved atomization and better air–fuel mixing, resulting in more efficient combustion, whereas very high pressure at 240 bar likely led to excessive spray penetration and reduced premixed combustion fraction. The application of EGR resulted in a further reduction of BTE, with 5 % and 10 % EGR yielding 28.82 % and 26.58 %, respectively, compared to 31.45 % without EGR at the same IP. This decline is primarily due to oxygen dilution and the higher specific heat of recirculated gases, which slow down combustion and lower peak temperatures, thereby reducing the useful energy conversion. Overall, the results confirm that optimizing injection pressure (220 bar) is beneficial for POME20 operation, while higher EGR fractions, though effective for NO_x control, impose a significant efficiency penalty. These findings are in close agreement with the trends reported by Nayak et al. [37], who also observed improved BTE at an optimal IP and reduced efficiency with increased EGR rates.

Table 5
List of Parameter and their Level, precision & Uncertainty.

S.No.	Apparatus	Parameter	Level	Precision	Uncertainty
1.	AVL DI Gas 444 five gas analyser	CO	0–10 % vol.	±0.03 %	±0.2 %
		1. CO ₂	0–20 % vol.	±0.5 %	±0.15 %
		2. HC	0–20000 ppm	±10 ppm	±0.2 %
		3. O ₂	0–22 % vol	±0.1 %	±0.5 %
2.	AVL 415 smoke-meter	4. NO _x	0–500 ppm	±50 ppm	±1 %
		FSN	0–99.9	±1 %	±1 %
3.	AVLGH14d/AH1 Pressure-transducer	Pressure (P)	0–100 bar	±0.1 bar	±0.15 %
4.	AVL 365C angle-encoder	Crank angle (CA)	0–720 ^o	±1 %	±0.2 %
5.	Temperature indicator	Temperature	0–900 ^o C	± 1 ^o C	±0.2 %

4.2. Brake specific fuel consumption

The amount of charge disbursed per unit BP generation is mentioned as brake specific fuel consumption (BSFC). It is measured in kg/kWhr. Better quality of any fuel indicates lesser BSFC value at all load conditions. The disparity of BSFC for the examined oils with engine load is exposed in Fig. 4(b). From the results, at full load, the brake specific fuel consumption for the examined fuels of diesel and POME20 200 bar, POME20 220 bar, POME20 240 bar, POME20 220 bar 5 % EGR and POME20 220 bar 10 % EGR are 0.23 kg/kWhr, 0.25kg/kWhr, 0.24kg/kWhr, 0.27kg/kWhr, 0.30 kg/kWhr,0.32kg/kWhr respectively at full load. Further, among the different fuel injection pressures of POME20 blend, POME 20 operated at 220 bar shown lower brake specific fuel consumption than other operating conditions. This is due to better mixing of fuel/air mixture results in improved combustion phenomena. Further, the use exhaust gas recirculation of 5 % and 10 % to the POME 20 operated at 220 bar is shown marginal increment in BSFC at maximum load. Also, increment in EGR addition to the POME20 blend is inferred that decrement in BSFC at all load engine operation.

4.3. Mass fraction burnt

The deviation of MFB from the crank angle for all the test blends is shown in Fig. 5 (A). Due to the lack of O₂ component in diesel fuel compared to other fuel blends, the DIESEL fuel blend has a lower MFB range across the full crank angle. Due to increased fuel rich

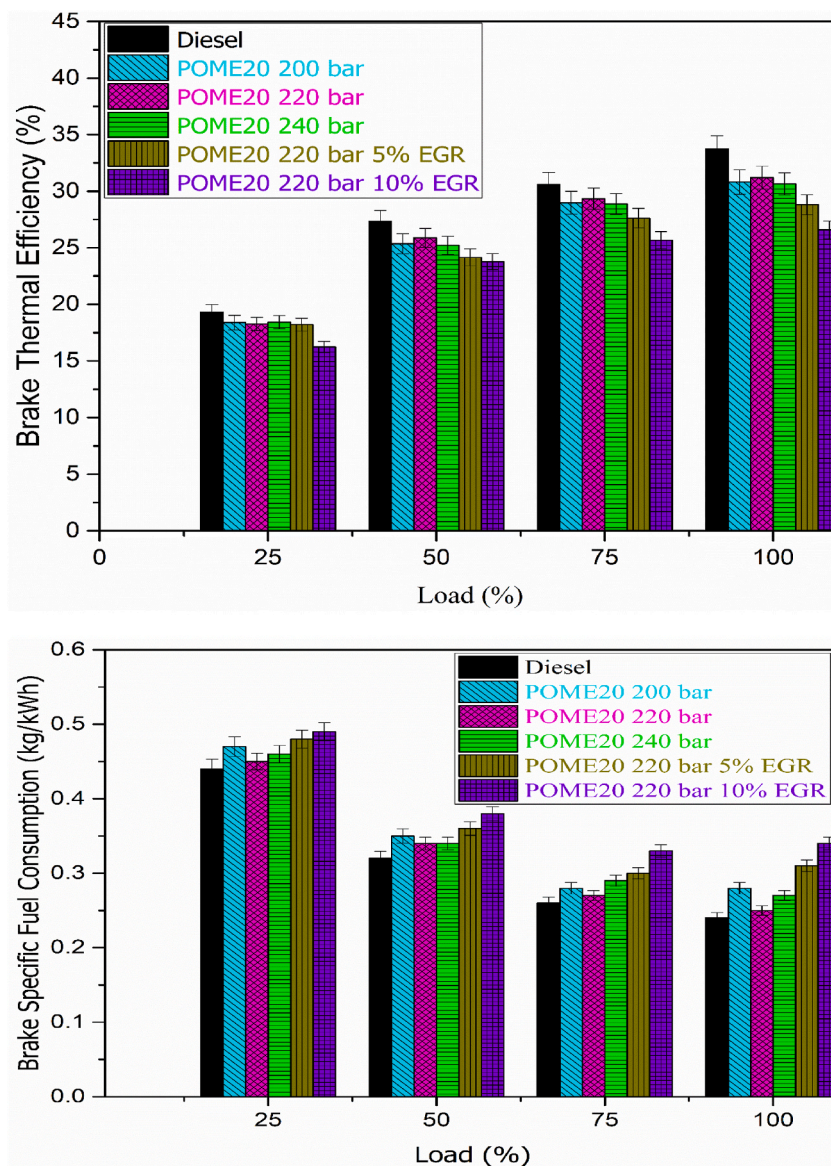
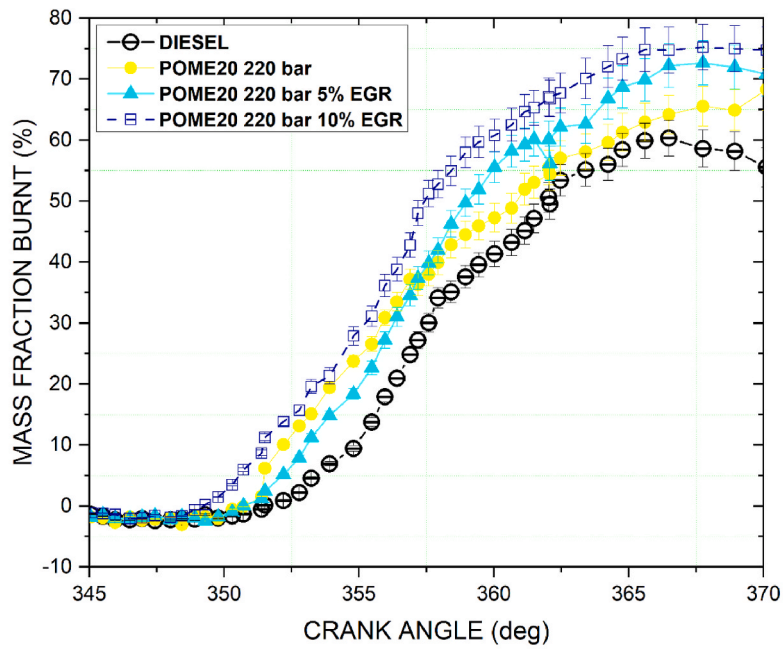
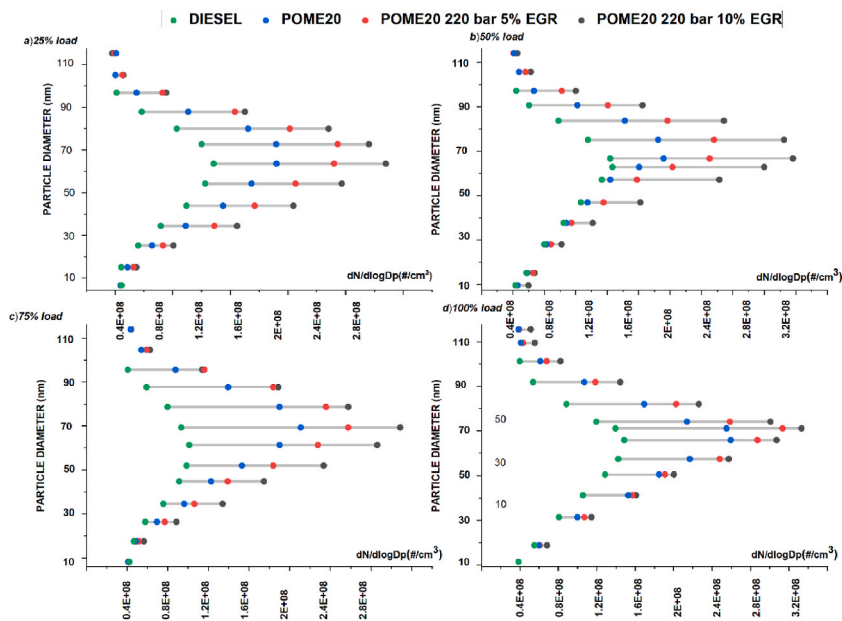


Fig. 4. (a) Variation of BTE (b) BSFC with engine load



(A)



(B)

Fig. 5. (A) Variation of mass fraction burnt with respect to crank angle (B) (a-d) Variation of Particle Size Diameter (PSD) at 25 %–100 % engine load

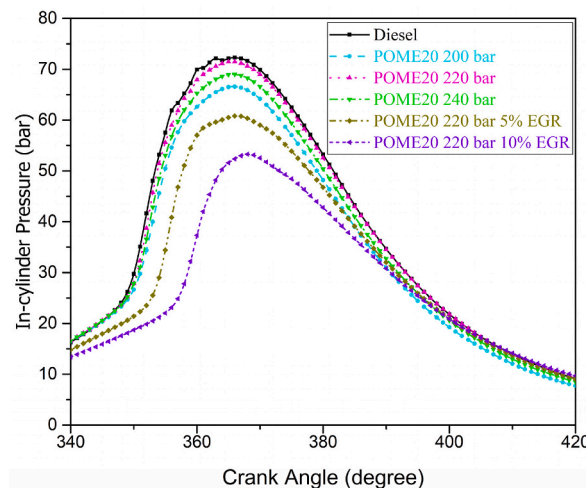
zones and no atomization impact, the blend POME 20 220 bar showed uneven MFB ranges at all crank angles. However, under influence of higher fuel injection pressure and exhaust gas recirculation in the test fuel blends, POME 20 220 bar 5 %EGR and POME 20 220 bar 10 % EGR blends possess typical spectrum of MFB at all crank angles. Biodiesel performance was very closer to the diesel fuel and in the future, biodiesel was partial substitute for the diesel fuel for diesel engine applications reported by Nayak et al. [38].

4.4. Particle size diameter

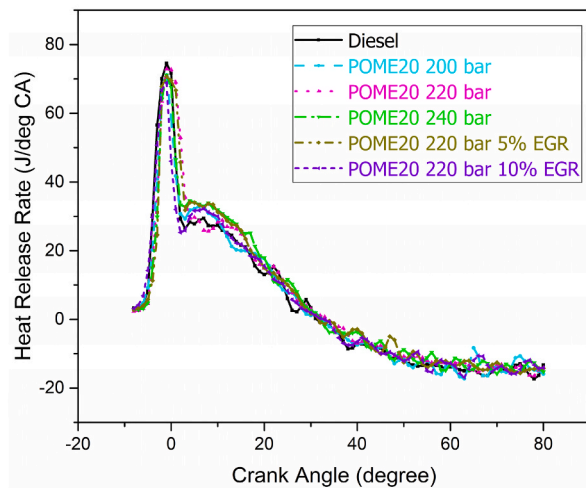
The fluctuation of particle size diameter for the test blends from 25 % to 100 % load condition is shown in Fig. 5 (B) (a-d). It was found that the mineral diesel blend had a greater PSD than the other fuel blends across the whole plot (a-d) whereas the blends POME 20 220 bar 5 %EGR and POME 20 220 bar 20 %EGR had lowered range of PSD with mineral diesel at all the load condition. The POME 20 220 bar blend, on the other hand, exhibited an intermediate trend with mineral diesel because there were enough O₂ molecules present and there were no aromatic hydrocarbons in the fuel.

4.5. In-cylinder pressure

The disparity of in-cylinder pressure for the tested oils at various injection pressures with crank angles are presented in Fig. 6 (a). Cylinder pressure is mostly impacted by the combustion rate process. It is detected that cylinder pressure is supreme for the diesel when related to the POME 20 conducted at dissimilar fuel IPs. The in-cylinder pressure standards of diesel, POME 20 200 bar, POME 20 220 bar, POME 20 240 bar, POME20 220 bar 5 % EGR and POME 20 220 bar 10 % EGR are 73 bar, 66.8 bar, 71.66 bar, 69.85 bar, 61



(a)



(b)

Fig. 6. (a) Variation of in-cylinder pressure and (b) Disparity of heat release rate with crank angle

bar and 54.5 bar correspondingly at full load. Among the different injection pressures, POME 20 operated at 220 bar shown greater cylinder pressure value of 71.66 bar at peak condition. Also, application of exhaust gas recirculation is revealed that slight reduction in cylinder pressure value for all operating conditions. This is because dilution air/fuel mixture because of EGR.

4.6. Heat release rate

The variation of heat release rate (HRR) for the examined fuels with different crank angles are delineated in Fig. 6 (b). HRR indicates the quantity of heat-energy produced while the combustion process. A mathematical equation (4) is developed for the evaluation of the total heat release rate during combustion in sync with the First law of Thermodynamics.

$$\frac{dQ}{d\theta} = \left(\frac{\gamma}{\gamma - 1} \right) P \left(\frac{dV}{d\theta} \right) + \left(\frac{1}{\gamma} - 1 \right) V (dP / d\theta) \tag{4}$$

Where is the heat release rate in J/θ, P indicates the pressure inside the cylinder in Pascal, denotes the adiabatic index, V represents the volume of combustion space in m³

The HRR is mainly rely on the heating value of the oil and the better mixing of air/fuel. HRR outcomes for the diesel, POME 20 200 bar, POME 20 220 bar, POME 20 240 bar, POME20 220 bar 5 % EGR and POME 20 220 bar 10 % EGR are 74.88 J/°CA, 71.2 J/°CA, 72.95 J/°CA, 71.12 J/°CA, 69.88 J/°CA and 67.24 J/°CA correspondingly at peak condition. Extreme HRR is observed for the diesel followed by the POME 20 220 bar when related to the remaining operational situations of the POME 20. The usage of 5 %EGR and 10 % EGR is shown declining trend of HRR since the dilution of fuel/air combination by the exhaust gas recirculation.

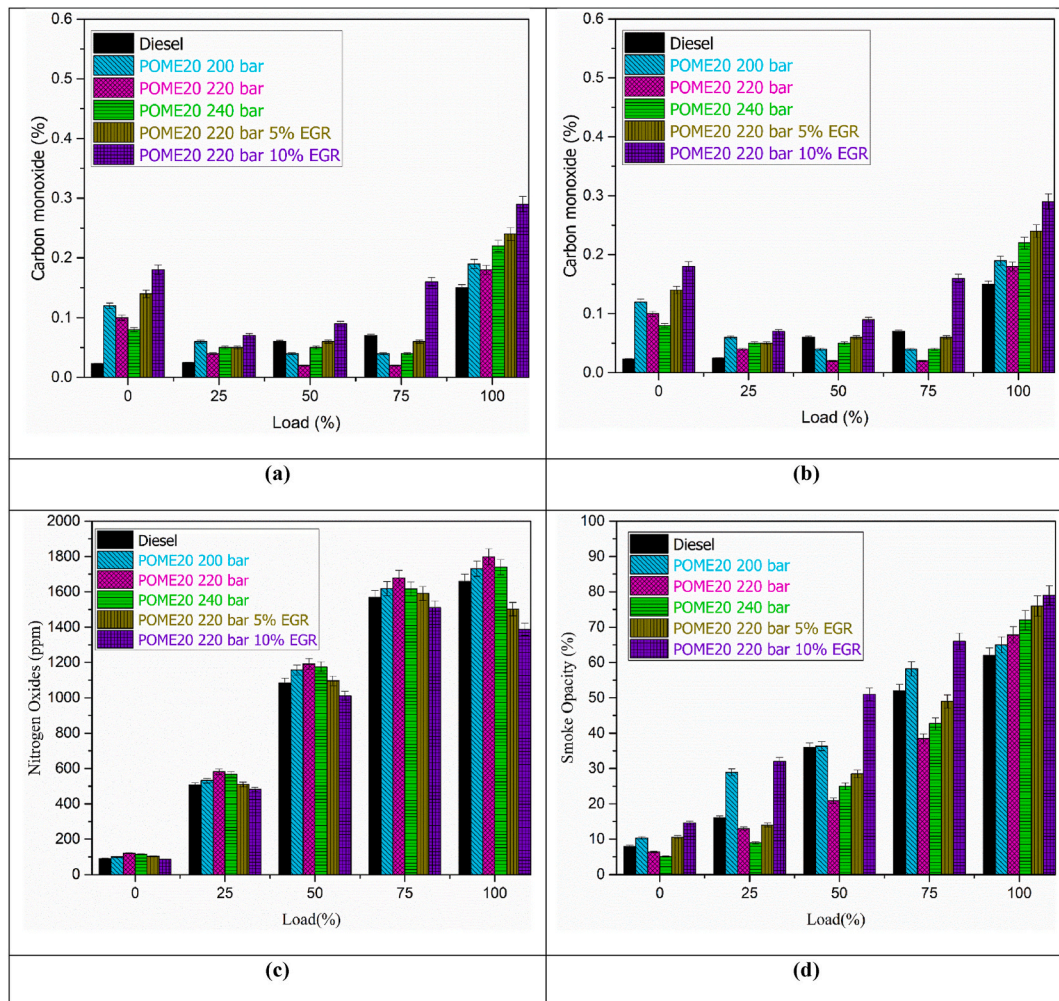


Fig. 7. Variation of (a) carbon monoxide, (b) hydrocarbon emissions, (c) NO_x, (d) Smoke with engine load

4.7. Carbon monoxide (CO)

The disparity of CO emissions with engine load for the oils of diesel and POME 20 operated at diverse IPs such as 200 bar, 220 bar and 240 bar is exposed in Fig. 7 (a). The CO discharges are primarily generated because of incomplete burning. The outcomes of CO emissions at full load related to the diesel, POME 20 200 bar, POME 20 220 bar, POME 20 240 bar, POME20 220 bar 5 % EGR and POME 20 220 bar 10 % EGR are 0.52 %, 0.28 %, 0.21 %, 0.38 %, 0.36 % and 0.81 % correspondingly at peak conditions. The usage of EGR is promoted the formation of CO discharges. Among the operating conditions, IP of 220 bar for the POME 20 blend is found with minor CO emissions than other operating conditions at peak conditions. Because the higher IP of fuel enhances the better mixing due to turbulence created in the burning compartment. Further, it is observed that as the EGR percentage is augmented, the CO discharges are also enhanced at all peak applied loads.

4.8. Hydrocarbons (HC)

The HC exhaust discharges are primarily occurred because of the imperfect burning manner. The HC discharges are affected greatly through the rate of fuel burning in the burning chamber. The HC releases are improved with growth in load for entire the examined fuels throughout the engine operation and these are presented in Fig. 7(b). The values of hydrocarbon emissions of diesel, POME 20 200 bar, POME 20 220 bar, POME 20 240 bar, POME20 220 bar 5 % EGR and POME 20 220 bar 10 % EGR are 74 ppm, 62 ppm, 57 ppm, 60 ppm, 64 ppm, and 82 ppm respectively at peak condition. It is found that the application of POME 20 mixture at different IP is shown decrease in HC discharges when associated to the diesel at peak condition. Nevertheless, the application of 5 % EGR and 10 % EGR to the POME20 functioned at 220 bar is shown increased HC emissions when related to the diesel as well as POME 20 at maximum condition. These results were in line with the results reported by Balaji et al. [28].

4.9. Nitrogen oxides (NO_x)

The NO_x residues are formed in the burning space because of elevated temperature and accessibility of O₂. The use of biodiesel is shown more generation of NO_x emissions when associated to the diesel. The discrepancy of NO_x with engine load for entire tested fuels are show in Fig. 7(c). The higher NO_x emissions are found at peak situations. The NO_x emission value of diesel, POME 20 200 bar, POME 20 220 bar, POME 20 240 bar, POME20 220 bar 5 % EGR and POME 20 220 bar 10 % EGR are 1689 ppm, 1731 ppm, 1798 ppm, 1738 ppm, 1512 ppm and 1388 ppm correspondingly at peak conditions. Significant decrease of oxides of nitrogen discharges for the POME 20 220 bar with 5 % and 10 % EGR application. It is found that 17.83 % and 22.84 % reduction of NO_x emissions for the POME 20 functioned at 220 bar with 10 % EGR when related to the diesel and POME 20 at maximum conditions. The application of EGR to the POME20 have shown lower NO_x emissions reported by Nayak et al. [39]. Similarly, Prasad Rao and Prasad [35] found 10 % EGR with POME20 at a 20:1 compression ratio reduced NO_x by 14.3 % vs. diesel and 23 % vs. POME20 at 18 CR.

4.10. Smoke opacity

The disparity of opacity with respect to engine load for fuels of diesel and POME 20 functioned at 200 bar, 220 bar and 240 bar along with POME 20, 220 bar with 5 % and 10 % EGR is revealed in Fig. 7(d). Opacity resembles the concentration of soot present in exhaust. Soot is also produced due to partial burning manner. The values of soot for the diesel, POME 20 200 bar, POME 20 220 bar, POME 20 240 bar, POME20 220 bar 5 % EGR and POME 20 220 bar 10 % EGR are 68 %, 76 %, 67 %, 72 %, 79 % and 83 % correspondingly at peak conditions. It is found that smoke discharges are lower for the POME 20 functioned at 220 bar. However, the application of EGR to the POME 20 220 bar revealed marginal increased smoke emissions at full load over the POME 20 functioned at 220 bar fuel IP. These results were close conformity with the outcomes inferred by Yilmaz and Donaldson [40].

5. Conclusions

Experimental investigations were carried out on a diesel engine fuelled with different Palmyra oil methyl ester (POME) blends, with particular emphasis on injection pressure (IP) and exhaust gas recirculation (EGR). From the results, the following conclusions can be drawn:

- Optimal Blend Selection: Among the tested blends, POME20 demonstrated the most balanced performance, closely matching diesel in combustion and efficiency while offering improved emission characteristics.
- Injection Pressure Influence: At an optimized injection pressure of 220 bar, POME20 achieved a 3.93 % improvement in BTE and a 4 % reduction in BSFC compared to 200 bar, highlighting the importance of injection optimization.
- Emission Reductions: Application of EGR effectively controlled NO_x emissions, with reductions to 1512 ppm at 5 % EGR and 1388 ppm at 10 % EGR, though higher EGR levels increased BSFC. Additionally, CO, HC, and smoke opacity were significantly lower for POME20 compared to diesel at full load.
- Combustion Behavior: Cylinder pressure and heat release rate (HRR) were highest for diesel, but POME20 at 220 bar exhibited comparable combustion characteristics. Both 5 % and 10 % EGR further reduced combustion intensity, indicating a trade-off between NO_x reduction and combustion performance.

- Overall Feasibility: The combined optimization of blend ratio (POME20), injection pressure (220 bar), and EGR level (5–10 %) establishes palmyra biodiesel as a viable and sustainable substitute for diesel, capable of enhancing efficiency while mitigating harmful emissions.

5.1. Future research work

- To study the effects of the combustion geometry of a diesel engine fuelled with POME20.
- To investigate the impact of various nanoparticle additions to the POME20 blend.
- Optimization of engine parameters using the RSM, TAGUCHI, and artificial neural network techniques
- Furthermore, more scope is available to investigate the tribological characteristics of diesel engine components.

CRedit authorship contribution statement

Jayashri N. Nair: Writing – review & editing, Investigation, Conceptualization. **V. Dhana Raju:** Writing – original draft, Methodology, Investigation. **T. Nagadurga:** Resources, Investigation. **Manzoore Elahi M. Soudagar:** Writing – original draft, Investigation. **Harish Venu:** Methodology, Investigation. **K. Bala Prasad:** Visualization, Investigation. **T.M. Yunus Khan:** Validation, Supervision, Project administration. **Syed Waheedullah Ghori:** Project administration, Methodology. **S. Ramesh:** Writing – review & editing, Supervision, Project administration.

Consent to participate

Not applicable.

Consent to publish

All authors have read and approved this manuscript.

Ethical approval

Not applicable.

Data availability statement

All data generated or analyzed during this study are included within this manuscript.

Declaration of competing 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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References

- [1] M.A. Alosius, P. Thomai, J.J. Thomas, V. Sharma, Impact of combined effects of injection pressure and EGR on modified stationary engine fuelled with biodiesel blend made of waste feedstock oils, *Arabian J. Sci. Eng.* 48 (2023) 12389–12405, <https://doi.org/10.1007/s13369-023-07795-9>.
- [2] S. Sathishkumar, Ibrahim M. Mohamed, An experimental study on the effect of injection pressure on diesel PCCI engine, *Int. J. Ambient Energy* 43 (1) (2022) 5939–5947, <https://doi.org/10.1080/01430750.2021.1997802>.
- [3] S.V. Karthic, M. Senthil Kumar, G. Nataraj, S. Vinoth Kumar, P. Pradeep, R. Pradeep, An assessment on injection pressure and timing to reduce emissions on diesel engine powered by novel biodiesel, *J. Clean. Prod.* 255 (2020) 120186, <https://doi.org/10.1016/j.jclepro.2020.120186>.
- [4] S.K. Yoon, J.C. Ge, N.J. Choi, Influence of fuel injection pressure on the emissions characteristics and engine performance in a CRDI diesel engine fueled with palm biodiesel blends, *Energies* 12 (20) (2019) 3837, <https://doi.org/10.3390/en12203837>.
- [5] M.K. Yesilyurt, The effects of the fuel injection pressure on the performance and emission characteristics of a diesel engine fuelled with waste cooking oil biodiesel-diesel blends, *Renew. Energy* 132 (2019) 649–666, <https://doi.org/10.1016/j.renene.2018.08.024>.
- [6] S. Rajasekaran, D. Damodharan, K. Gopal, B. Rajesh Kumar, M.V. De Pours, Collective influence of 1-decanol addition, injection pressure and EGR on diesel engine characteristics fueled with diesel/LDPE oil blends, *Fuel* 277 (2020) 118166, <https://doi.org/10.1016/j.fuel.2020.118166>.
- [7] K. Selvaraj, M. Thangavel, The effects of fuel injection pressure on combustion and emission characteristics of a diesel engine using frying oil methyl ester, *Energy Sources, Part A Recovery, Util. Environ. Eff.* 45 (3) (2023) 7436–7452, <https://doi.org/10.1080/15567036.2019.1675818>.
- [8] M. Mourad, K.R. Mahmoud, E.S.H. Nour Eldeen, Improving diesel engine performance and emissions characteristics fuelled with biodiesel, *Fuel* 302 (2021) 121097, <https://doi.org/10.1016/j.fuel.2021.121097>.

- [9] P. Pavan, K. Bhaskar, S. Sekar, Effect of split injection and injection pressure on CRDI engine fuelled with POME-diesel blend, *Fuel* 292 (2021) 120242, <https://doi.org/10.1016/j.fuel.2021.120242>.
- [10] M. Choi, K. Mohiuddin, N. Kim, S. Park, Investigation of the effects of EGR rate, injection strategy and nozzle specification on engine performances and emissions of a single cylinder heavy duty diesel engine using the two color method, *Appl. Therm. Eng.* 193 (2021) 117036, <https://doi.org/10.1016/j.applthermaleng.2021.117036>.
- [11] C.G. Saravanan, Kiran K. Raj, M. Vikneswaran, P. Rajakrishnamoorthy, S. Prasanna Raj Yadav, Impact of fuel injection pressure on the engine characteristics of CRDI engine powered by pine oil biodiesel blend, *Fuel* 264 (2020) 116760, <https://doi.org/10.1016/j.fuel.2019.116760>.
- [12] P. Bhowmick, A.K. Jeevanantham, B. Ashok, K. Nanthagopal, D. Arumuga Perumal, V. Karthickeyan, K.C. Vora, A. Jain, Effect of fuel injection strategies and EGR on biodiesel blend in a CRDI engine, *Energy* 181 (2019) 1094–1113, <https://doi.org/10.1016/j.energy.2019.06.014>.
- [13] J. Liang, Q. Zhang, Z. Chen, Z. Zheng, The effects of EGR rates and ternary blends of biodiesel/n-pentanol/diesel on the combustion and emission characteristics of a CRDI diesel engine, *Fuel* 286 (2021) 119297, <https://doi.org/10.1016/j.fuel.2020.119297>.
- [14] H.Y. Kim, J.C. Ge, N.J. Choi, Effects of fuel injection pressure on combustion and emission characteristics under low speed conditions in a diesel engine fuelled with palm oil biodiesel, *Energies* 12 (17) (2019) 3264, <https://doi.org/10.3390/en12173264>.
- [15] G. Balaji, M. Cheralathan, Experimental investigation of varying the fuel injection pressure in a direct injection diesel engine fuelled with methyl ester of neem oil, *Int. J. Ambient Energy* 38 (4) (2017) 356–364, <https://doi.org/10.1080/01430750.2015.1111846>.
- [16] G. Rao, G.N. Kumar, M. Herbert, Effect of Injection Pressure on the performance and emission characteristics of CI engine using Vateriaindica Biodiesel, *Int. J. Ambient Energy* 40 (7) (2019) 758–767, <https://doi.org/10.1080/01430750.2017.1421575>.
- [17] M.R. Subbarayan, J.S.S. Kumar, An experimental investigation of performance and emission characteristics of diesel engine with blends of cottonseed oil methyl ester with cold and hot EGR, *Int. J. Ambient Energy* 38 (1) (2015) 19–28, <https://doi.org/10.1080/01430750.2015.1023844>.
- [18] K.B. Rajesh, S. Saravanan, D. Rana, A. Nagendran, Use of some advanced biofuels for overcoming smoke/NOx trade-off in a light-duty DI diesel engine, *Renew. Energy* 96 (2016) 687–699.
- [19] P. Kumar, N. Kumar, Effect of EGR on performance and emission characteristics of a dual fuel engine fuelled with CNG and JOME, *Biofuels* 7 (6) (2016) 743–751, <https://doi.org/10.1080/17597269.2016.1193838>.
- [20] S. Sivalingam, P. Palanisamy, A. Baluchamy, Experimental investigation on Jatropa oil Methyl Ester fuelled CI engine using high EGR, *Mater. Today Proc.* 39 (2021) 274–278, <https://doi.org/10.1016/j.matpr.2020.07.047>.
- [21] V. Kumar, S.K. Mahla, Influence of EGR on a CI engine running on 20% blend of jatropa biodiesel, *Mater. Today Proc.* 43 (2021) 273–280, <https://doi.org/10.1016/j.matpr.2020.11.659>.
- [22] X. Shi, B. Liu, C. Zhang, J. Hu, Q. Zeng, A study on combined effect of high EGR rate and biodiesel on combustion and emission performance of a diesel engine, *Appl. Therm. Eng.* 125 (2017) 1272–1279, <https://doi.org/10.1016/j.applthermaleng.2017.07.083>.
- [23] D. Damodharan, A.P. Sathiyaganam, D. Rana, B.R. Kumar, S. Saravanan, Combined influence of injection timing and EGR on combustion, performance and emissions of DI diesel engine fuelled with neat waste plastic oil, *Energy Convers. Manag.* 161 (2018), <https://doi.org/10.1016/j.enconman.2018.112355>, 394–305.
- [24] S. Verma, L.M. Das, S.C. Kaushik, S.S. Bhatti, The effect of compression ratio and EGR on the performance and emission characteristics of diesel-biogas dual fuel engine, *Appl. Therm. Eng.* 150 (2019) 1090–1103, <https://doi.org/10.1016/j.applthermaleng.2019.01.080>.
- [25] S.R. Reddy, G. Murali, A.A. Shaik, V.D. Raju, M.S. Reddy, Experimental evaluation of diesel engine powered with waste mango seed biodiesel at different injection timings and EGR rates, *Fuel* 285 (2021) 119047, <https://doi.org/10.1016/j.fuel.2020.119047>.
- [26] K. Mohiuddin, H. Kwon, M. Choi, S. Park, Effect of engine compression ratio, injection timing, and exhaust gas recirculation on gaseous and particulate number emissions in a light duty engine, *Fuel* 294 (2021) 12057, <https://doi.org/10.1016/j.fuel.2021.120547>.
- [27] M.M. Khan, M.A. Wahid, F.Y. Hagos, Review of the effect of injection parameters on the performance and emissions of biodiesel–diesel blends in CI engines, *Fuel Communications* 18 (2024) 100084, <https://doi.org/10.1016/j.fuenco.2023.100084>.
- [28] B. Balaji, R. Venkatesan, A. Kumaravel, L. Subramani, Influence of nozzle opening pressure on the performance and emission characteristics of a diesel engine fuelled with biodiesel blends, *Proc. Inst. Mech. Eng. - Part D J. Automob. Eng.* 238 (3) (2024) 598–609, <https://doi.org/10.1177/09544070231159354>.
- [29] S. Saridemir, H. Aydin, İ. Sezer, Experimental investigation on the effect of injection pressure on combustion, performance, and emission characteristics of a CI engine fuelled with corn oil biodiesel–diesel blends, *Fuel* 267 (2020) 117219, <https://doi.org/10.1016/j.fuel.2020.117219>.
- [30] S.D. Galande, V.K. Kale, P.A. Waghmare, Combined effect of injection pressure and exhaust gas recirculation on performance and emissions of a CI engine using biodiesel blends, *Heat Tran. Asian Res.* 53 (3) (2024) 897–915, <https://doi.org/10.1002/htj.22689>.
- [31] A. Sethin, A.K. Singh, T.N. Verma, Effects of EGR on combustion, performance, and emissions characteristics of a CRDI diesel engine fuelled with biodiesel–diesel blends, *ACS Omega* 9 (2) (2024) 1418–1429, <https://doi.org/10.1021/acsomega.3c07147>.
- [32] M.M. Shivashimpi, V.S. Yaliwal, Effect of EGR on performance and emission characteristics of a diesel engine fuelled with palm oil methyl ester, *Int. J. Veh. Struct. Syst.* 14 (1) (2022) 1–7, <https://doi.org/10.4273/ijvss.14.1.01>.
- [33] P.V. Kumar, T.V.K. Rao, P.K. Reddy, Experimental study of performance, combustion, and emission characteristics of a CI engine fuelled with Palmyra biodiesel blends, *Fuel* 308 (2022) 121985, <https://doi.org/10.1016/j.fuel.2021.121985>.
- [34] Kumar Vijaya, B. Ashok Perumalla, M. Senthil kumar, R. Vignesh, J. Pradeep Bhasker, A. Naresh Kumar, Evaluation of performance, emissions and combustion attributes of CI engine using palmyra biodiesel blend with distinct compression ratios, EGR rates and nano-particles, *Fuel* 320 (2022) 124092, <https://doi.org/10.1016/j.fuel.2022.124092>.
- [35] Prasada Rao Geddam, Prasad Lankapalli Sathya Vara, Combined influence of compression ratio and exhaust gas recirculation on the diverse characteristics of the diesel engine fuelled with novel palmyra biodiesel blend, *Energy Convers. Manag.* X 14 (2022) 100185, <https://doi.org/10.1016/j.ecmx.2022.100185>.
- [36] V. Dhana Raju, P.S. Kishore, K. Nanthagopal, B. Ashok, An experimental study on the effect of nanoparticles with novel tamarind seed methyl ester for diesel engine applications, *Energy Convers. Manag.* 164 (2018) 655–666, <https://doi.org/10.1016/j.enconman.2018.03.032>.
- [37] S.K. Nayak, P.C. Mishra, Emission characteristics of jatropa oil blends using waste wood producer gas, *Energy Sources, Part A Recovery, Util. Environ. Eff.* 38 (14) (2016) 2153–2160, <https://doi.org/10.1080/15567036.2014.989340>.
- [38] S.K. Nayak, P.C. Mishra, G.R. Behera, Characterization of coconut shell imitative producer gas in a diesel engine, *Energy Sources, Part A Recovery, Util. Environ. Eff.* 39 (16) (2017) 1718–1724, <https://doi.org/10.1080/15567036.2016.1141266>.
- [39] S.K. Nayak, G.R. Behera, P.C. Mishra, S.K. Sahu, Biodiesel vs diesel: a race for the future, *Energy Sources, Part A Recovery, Util. Environ. Eff.* 39 (14) (2017) 1453–1460, <https://doi.org/10.1080/15567036.2015.1062827>.
- [40] N. Yilmaz, A. Donaldson, Examination of Causes of Wetstacking in Diesel Engines, *SAE Technical Paper* 2005-01-3138, 2005, <https://doi.org/10.4271/2005-01-3138>.