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Research Article

A Comprehensive Study on the Effect of Dimethyl Carbonate Oxygenate and EGR on Emission Reduction, Combustion Analysis, and Performance Enhancement of a CRDI Diesel Engine Using a Blend of Diesel and *Prosopis juliflora* Biodiesel

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This paper examines the combined effects of ignition improvers (DMC) and EGR on the CRDI small single-cylinder diesel engine's performance, combustion, and emissions. In this experimentation, 20% (B20) optimal mix of Prosopis juliflora oil biodiesel (PJOB) and 5 ml dimethyl carbonate (DMC) additive was used as test fuel. The fuel handling CRDI system factors such as injection pressure set at 600 bar and injection timing set to 21 (bTDC) with a compression ratio of 16 were considered for the study. For the EGR trial, 20% of the exhaust gas was recirculated under various BMEP circumstances. The test was performed with and without EGR and DMC additive conditions like (i) diesel @ 0% EGR, (ii) diesel + 5 ml DMC @ 20% EGR, (iii) B20 @ 0% EGR, and (iv) B20 + 5 ml DMC @ 20% EGR at the engine power output. The amalgamation of dimethyl carbonate (DMC) additives and EGR reduces NOx and smoke while increasing CO and HC emissions. In addition, the DMC additive and EGR improve thermal efficiency slightly. The overall clubbing of DMC additive and EGR rate indicates better performance for the selected factors than a CRDI engine with a six-hole conventional mechanical fuel injection system. The outcome of the work clearly demonstrates that both the 5 ml DMC additive and the 20% EGR rate of the B20 blend show optimum values of BTE, BSFC, and EGT of 32.93%, 0.27 kg/kw·hr, and 310.89°C, which is closer to diesel. Factors of combustion like cylinder peak pressure (CPP) and heat release rate (HRR) are 70.93 bar and 58.13 J/deg. The tailpipe exhaust of NOx and smoke is 1681 ppm and 31.30 (% vol), which is less than diesel. The HC and CO levels are 93 ppm and 0.38 (% vol), respectively, which are significantly higher than diesel fuel.

1. Introduction

Consumption of nonrenewable energy sources has real and long-term negative repercussions for human health, neighborhood circles, and ecosystems, as well as the global environment. The growing demand and use of diesel engines in a wide range of industries cause exhaust gases like NOx and CO to be released into the air, which can cause climate change, respiratory ailments, and other problems. This has led to a reduction in the use of diesel and the addition of biodiesel that is compatible with the engine [1]. Biodiesel is a renewable fuel that can be used instead of gasoline. Good-burning biodiesel has many advantages over gasoline, including lower idle noise and better cold starting [2]. Renewable and sustainable feedstocks can be used to produce biodiesel, which does not include aromatics or sulphur and can be blended with other energy sources to improve its chemical qualities. The high viscosity and density of biodiesel

(B100 percent) cause atomization issues, which results in greater emissions of smoke, HC, and CO [3]. According to all published research, biodiesel's economic viability is threatened by its high viscosity, density, poor cold flow characteristics, and high NOx emissions [4]. Asha et al. reported that different additives mixed with alternative fuels such as synthetic oils such as coal, natural gas, biomass fuel, and waste plastic oils, gaseous fuels like H_2 gas, methane gas, coal, natural gas, and LPG, and oxygenated fuels like esters, ethers, and alcohol [5]. Research was done on methanol, ethanol, and butanol, three of the many alcohols that are available. These alcohols were found to be useful in lowering exhaust emissions. In terms of good knock resistance, good understanding, and fewer HC and CO emissions, butanol and pentanol are better than ethanol and methanol. In recent years, alcohols like isomers of propanol and butanol have become more popular because of their good physical and chemical properties. They are easy to make and can be recycled [6]. This study showed that, in recent days, growing pollution levels on a global scale have driven authorities to look for new ways to minimize pollution or to improve existing techniques. A few techniques have been widely used to cut down on NOx emissions. These include delayed injection timing, a shorter ignition delay, EGR, split injection, exhaust catalysts, and changes to the combustion chamber modification [7]. They experimented with biodiesel mixes to see how different fuel injection pressures, injection timings, and compression ratios affected diesel engine performance. With an ideal compression ratio of 20, injection timing of 25° bTDC, and injection pressure of 200 bar, it was discovered that a 20% biodiesel blend performs better. Other studies evaluated biodiesel and its blends for similar performance, emission, and combustion tendencies [8]. These investigations using bioethanol (30%), diesel (30%), and castor oil (40%) mixtures found that the BTE performed similarly to diesel while emitting more smoke [9]. Extensive research was carried out on the maximum pressure rise rates seen in diesel (70%), gasoline (15%), and *n*-butanol (15%) blends, as well as decreased ignition delay and combustion duration. When compared to diesel, the BSFC and CO emissions increased, while the NOx levels decreased [10]. The analysis indicated that using these mixes culminated in enhanced brake thermal efficiency and decreased brake-specific fuel consumption. Performance, combustion, and emission characteristics of bael oil-diesel-diethyl ether mixes on a VCR engine were investigated [11]. Experiment results demonstrate that 20% dimethyl ether reduces the CO, HC, NOx, and smoke emissions of neat cashew nut shell biodiesel by 3.4%, 4.2%, 8.8%, and 8.4%, respectively [12]. The excellent features of using dimethyl carbonate oxygenate are as follows: (1) first and foremost, DMC being a safe and environmentally friendly product that is nontoxic to humans and the environment as well as noncorrosive, (2) low soot precursor concentrations in fuel-rich combustion zones due to the high oxygen content of 53.28 percent by weight [13], (3) fossil fuels being completely miscible (diesel and gasoline), (4) a rather high H/C ratio, (5) the lack of carbon-carbon links in its molecular structure, (6) the low boiling point that is critical for spray mixing as well as atomization, (7) the decomposition into the methoxy formyl radical ($CH_3OC=O$), and (8) the low carbon-to-oxygen (C/O) ratio, all of which contribute to its ability to reduce soot formation [14]. As a result, DMC improved the performance of engines without markedly raising the level of NOx emissions. DMC could be an important additive for diesel fuel because it has a high amount of oxygen, does not have carbon-carbon nuclear bonds, has a good boiling point, and is easy to dissolve in diesel [15]. According to a number of studies, using ignition improvers can help cut down on exhaust emissions. When compared to diesel at full load, RSME25 (rubber seed methyl ester-diesel mix) with 30% DMC fumigation reduced NOx emissions and smoke opacity by 28% and 36%, respectively [16]. They showed that BD80DMC20 had a 1.9% growth in BTE, which meant that the clean biodiesel would use 4% less fuel than the clean biodiesel at its highest setting. According to the study, when BD100 was mixed with 20% DMC, it reduced 7.51% of CO, 5.40% of HC, 4.75% of NOx, and 3.240% of smoke opacity. It also lowers the extreme pressure at 10% DMC vol, which increases the total HRR values and the crank angle that goes with them, which makes the engine run better [17]. According to this investigation, it is shown that B20 with 5% DMC is better than the other samples in terms of combustion characteristics. This is based on graphs that show how crank angle, cylinder pressure, and heat release rate show that B20 with 5% DEE is better than B20 with 5% DEE [18]. It was observed that NOx emissions rose by 3.20% and 2.9% for mixtures of 20% *t* and 30%. From 25.30% to 51.7%, CO emissions dropped, and HC emissions rose from 34.3% to 89% when DMC was mixed with gasoline [19]. They investigated whether the use of DMC blends cut down on smoke intensity, particulate matter, and NOx exhaust. In this case, there was a rise in CO and HC emissions [20]. This research showed that the DMC in biodiesel CO and HC emissions had gone down compared to diesel. When diesel is used, nitrogen oxide (NOx) is less likely to be released. When B100 and DMC were added, the NOx level went down a little bit [21]. A few studies have shown that DMC is a great addition to diesel or biodiesel, and it can make the fuel even better. DMC is a good flammable liquid because it is nonhygroscopic and easy to mix with diesel [22]. Dimethyl carbonate and pentanol are oxygenated additions that have been researched for their influence on Neem biodiesel and fuel. The results of the investigation show that the performance has improved. Blending dimethyl carbonate and pentanol to Neem biodiesel and diesel resulted in a significant reduction in emissions. Approximately 50% Neem biodiesel and 50% diesel combination, 90% base fuel, and 10% dimethyl carbonate and pentanol combination were employed to achieve the necessary characteristics and performance parameters. The outcome of the experimentation demonstrated that there is a considerable reduction in the emissions excluding NOx. Pentanol and dimethyl carbonate can lower CO by 4.9% and 7.4% from no load to full load, respectively, with a 10% addition of the two. Blending pentanol and dimethyl carbonate with base gasoline reduces HC emissions by 3.1% and 4.7%, respectively [23]. They evaluated the use of *Calophyllum inophyllum* biodiesel and diesel in a CRDI diesel engine. This analysis found that, by increasing the pilot injection rate from 5% to 15%, it was possible to get a BTE of about 36.85%. The 15% pilot injection cut HC and CO emissions by about 53.60% and 44.70% compared to diesel fuel. As a result, NOx emissions were cut by about 10.5% by adding the EGR 10% rate with a 15% pilot injection. It would be best to use 15% pilot injection and 10% EGR to get an optimum engine outcome [24]. It is established that waste fatty substances can yield high-quality fuel. Modern common rail direct injection (CRDI) engines prefer 75% bioconstituent blends, while diesel engines may experience slight efficiency degradation. For biodiesel blends made from animal fat, the average brake-specific fuel consumption increased by 13% compared to the baseline. BSFC for rapeseed oil and diesel mixtures increased. This has been linked to a 2% decrease in brake fuel conversion efficiency for all examined biodiesels. Biodiesel with diesel cuts emissions significantly. The rapeseed oil biodiesel/diesel blends reduced HC emissions by 12%, CO emissions by 19%, and CO_2 emissions by 5.3% [25]. The results show that using 30% waste high-density polyethylene oil compositions with minor modifications like delayed injection timing and low EGR rates can significantly reduce NOx emissions while maintaining performance and combustion variables [26]. This research is reported to use EGR to study 1-pentanol/diesel hybrid engine emissions. The results showed that increasing the EGR rate reduces the BTE of the engine. Using 20% EGR reduced NOx emissions by nearly 47%, whereas boosting the EGR rate led to producing high CO and HC emissions [27]. Researcher investigated the impacts of different EGR rates up to 30% on emissions and performance and spray characteristics of diesel/biodiesel/n-pentanol combinations on a diesel engine. It discovered that increasing the EGR rate lowered CO emissions of ternary mixes to levels comparable to D100, reduced THC pollutants, and increased the trade-off relationship between soot and NOx compared to diesel [28]. The inclusion of EGR also delays the combustion beyond the top dead centre (TDC), resulting in heat loss to the engine parts and an increase in fuel consumption to achieve the same power output as with the greater alcohol content's low CN [29]. These determined the effects of hydrogen and 1-hexanol on a 2-cylinder, 4-stroke CRDI CI engine's combustion, performance, and emissions. When operating at 80% load, hydraulic cylinder pressure increased by 5.87%, while heat release rate decreased by 1.58% when compared to pure diesel. Thermal efficiency rose while NOx and HC emissions were reduced when compared to pure diesel with hydrogen enrichment [30]. Increased EGR rates lead to an increase in CO emissions, primarily due to a decrease in the oxidation process and an increase in CO emissions. As a result, CO oxidation is hampered by the presence of inert gases in the exhaust [31].

The *Prosopis juliflora* plant is widely distributed around the world and has 46 species, of which 40 are reported to be endemic to North America. This plant is abundant in India's desert regions, and it is also present in a number of other nations. Its seed oil is nonedible in the natural world, as is the plant. Earlier investigations have also claimed that some nonedible oils may be suitable for use in a diesel engine if they are blended with diesel [32]. From the aforementioned literature survey, it has been established that numerous edible and nonedible oils have the potential to be used as biofuels in diesel engines with little or no engine modifications. This is due to the greater cetane and oxygen percentages found in these fuels, which can result in the most efficient combustion and heat release rates by altering the combustion efficiency. So far, there has been no reported research using PJOB and dimethyl carbonate combined with biodiesel for EGR. As a primary goal, this study shows a novel approach to recirculating exhaust gas from neat diesel, diesel with 5 ml DMC, B20 (20 percent PJOB + 80 percent diesel), and B20 with 5 ml DMC at an optimal EGR rate of 0% and 20%, respectively.

1.1. Scope and Motivation of the Present Research Work. A notable issue in CI engines employing biodiesels is higher NOx and smoke emissions, in addition to increased brake-specific fuel consumption, from the substantial literature review of biodiesel, oxygenated fuels, and engine modifications [7]. The price of fuel is another important factor influencing the use of biodiesel. As a result, cost-effective fuels and NOx control solutions must be investigated. The present study is based on the fact that no previous studies have been conducted on the usage of ternary mixes (PJOB-diesel-DMC) in a CRDI diesel engine at high fuel injection pressure and EGR rate. This research concentrated on the combined influence of PJOB-diesel-DMC mixes, as well as cold EGR, and on the characteristics of a CRDI diesel engine.

2. Equipment and Methodology

2.1. Preparation of Test Fuel. Table 1 illustrates the primary characteristics of dimethyl carbonate enhancer, baseline diesel, and biodiesel derived from *Prosopis juliflora* oil and the test blends. The *Prosopis juliflora* species belongs to the Fabaceae family and is usually encountered in extremely slightly hot locations; it is capable of surviving in the absence of a water source in these conditions. It is a mesquite from the Caribbean and Asia. Regarding ecological management of wood and forage, in the heartwood of the plant, there is an unusual flavanol mesquitol. These are even more reasons why biodiesel plants should be grown and used to make fuel. It has been proven that two-step transesterification is the best way to make biodiesel out of *Prosopis juliflora* oil and make it a perfect substitute for diesel. For this study, the analytical grades of dimethyl carbonate (purity: 99.9%) were procured from Merck Millipore, India. The four test fuels used in engine trials, which included two binary and one ternary blends, were labeled as follows: (1) pure diesel, (2) diesel + 5 ml DMC, (3) B20 (80% of diesel + 20% of PJOB), and (4) B20 + 5 ml DMC. The fuels were blended using the splash blending method. They were steady and homogenous even after an isolation time of about 7-8 days. Moreover, prior to completing the trials, the homogeneity of the test samples was accomplished with the aid of a mixer.

2.2. Test Engine and Its Description. As illustrated in Figure 1, the test fuels are evaluated in a CRDI-equipped engine. Table 2 lists the engine specs. A Kirloskar-made diesel engine

Table 1: Physical properties of blending stocks.

Properties	ASTM standard	Diesel	PJOB	Diesel + 5 ml DMC	B20	B20 + 5 ml DMC
Kinematic viscosity (at 40°C) (cst)	D 445	2.42	4.64	2.63	2.91	2.70
Density (at 15°C) (kg/m^3)	D 4052	813	885	828	839	831
LHV (MJ/kg)	D 240	42.5	39.13	42.23	41.95	42.17
CCI	D 4737	47	41.76	49.4	55.31	53.65
Flash point (°C)	D 92	58	118	59.4	74	69

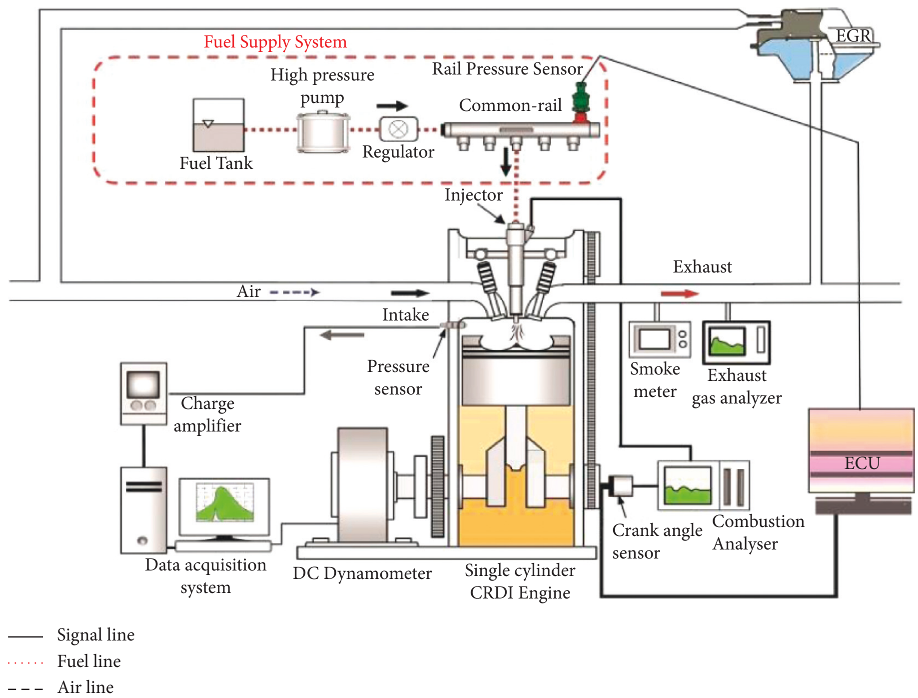

Figure 1: Schematic layout of the experimental setup.

Table 2: Engine specifications.

Make and model	Kirloskar, TV1
Number of cylinders	One
Stroke	Four
Bore * stroke length	87.5 mm * 110 mm
Swept volume	661 cc
Compression ratio	12–22
Rated output	3.5 kW at 1500 rpm
Rated speed	1500 rpm
Cooling system	Water cooled
Injection timing, CA bTDC	23°
Injection pressure	600 bar

Table 3: Range, accuracy, and resolution of the instruments.

Measured quantity	Range	Accuracy	Resolution
HC	0–30000 ppm	±10 ppm	1 ppm vol
CO	0–15%	±0.02%	0.01% vol
CO_2	0–20%	±0.3%	0.01% vol
NOx	0–5000 ppm	±5 ppm	1 ppm vol
Smoke	0–100%	±1%	0.1%

rated at 3.5 kW at 1500 rpm was employed in the experiment. The engine configuration was a single-cylinder, four-stroke, variable compression ratio (VCR) water-cooled diesel engine coupled to a dynamometer. It was fitted with the necessary sensors and actuators, as well as an open ECU that complied with Nira i7r specs, in order to convert the engine to electronic injection. A common rail direct injection (CRDI) system was required to achieve the injection pressures required for the test. A high-pressure pump was added to the fuel filter after the fuel supply line was reworked to meet the CRDI arrangement on the engine. Finally, a fuel reservoir and pressure regulator are coupled to the common rail and used to maintain fuel pressure. A rail pressure sensor is attached to the rail and then connected to the Nira i7r ECU to maintain fuel pressure. A high-speed digital data acquisition device was used to collect the pressure and TDC signals, which were then electronically stored in the computer to calculate the engine's combustion parameters. The AVL Digas 444 analyzer measured NOx, HC, CO, and CO_2. The AVL 437C smoke metre monitored the smoke opacity. Table 3 shows the instruments' range, accuracy, and resolution.

2.3. Error Analysis. The atmosphere, test preparation, and reading all have an impact on the results of equipment calibration and measurement. It is essential to do an uncertainty analysis to verify the accuracy of the experiment [33]. This section evaluates the errors in various measurements. Moffat RJ28's mathematical correlation is used to determine the maximum errors in calculations. The maximum potential errors in temperature, pressure, exhaust gas emissions, time, and speed are calculated from the minimum values of output and accuracy of the instruments. This approach is based on a detailed characterization of the various experimental measurements' uncertainties. How much uncertainty there is in the value of "S" is determined by the predictor factors (X_1, X_2, and $X_3 \ldots\ldots X_n$) that are used to evaluate it.

$$\frac{\partial S}{S} = \left\{ \left(\frac{\partial X_1}{X_1}\right)^2 \left(\frac{\partial X_2}{X_2}\right)^2 + \cdots + \left(\frac{\partial X_n}{X_n}\right)^2 \right\}^{(1/2)}, \quad (1)$$

where ($\partial X_1/X_1$), ($\partial X_2/X_2$), and so on are the errors in the predictor factors. ∂X_1 is the system accuracy, and X_1 is the smallest output value. As stated in equation (1), there is a maximum of 0.403% inaccuracy in the estimation of BTE [34]. Furthermore, the errors correlating with the in-cylinder pressure measurement and the CA were calculated to be 0.34 and 1.98 percent, respectively. According to the analyzer specifications, NOx emission and smoke opacity can be measured with a maximum error of 4%.

2.4. EGR Setup. In this work, the EGR strategy's efforts to diminish the higher in-cylinder temperatures and charge temperatures thereby reduce the formation of NOx emissions. Additionally, it raises EGR's density, which in turn raises its volume. The EGR chiller receives a portion of the exhaust gas before it is fed into the air intake port. Since the cooling water in the EGR cooler is kept at a consistent temperature, it acts as a heat exchanger, allowing the heat from the detained exhaust gas to be absorbed. In this experiment, the castoff gas was cooled to 35°C. The EGR rate is managed by the EGR valve. The orifice is used to measure exhaust gas flow. Recirculated exhaust gas was better when it was delivered to the inlet port early in the process. The amount of EGR was determined using the following equation:

$$\text{EGR\%} = \left[\frac{(CO_2)_{\text{intake}}}{(CO_2)_{\text{exhaust}}}\right] \times 100. \quad (2)$$

The AVL 444 N gas analyzer was used to calculate the amount of CO_2 emitted by varying the flow rate of the exhaust until the intake amount of CO_2 met the required value [26].

2.5. Test Procedure. At first, the investigation was carried out with diesel fuel and *Prosopis juliflora* oil biodiesel (B20) without any engine modification and at ambient circumstances. The engine was run for 5 minutes before each observation to ensure a steady state. Further, the experiments were conducted by adding 5 ml by volume of dimethyl carbonate enhancer to the diesel fuel and an optimal blend of B20% at a compression ratio of 16 and injection timing of 21° bTDC with from the lowest to the highest load, which corresponded to brake mean effective pressures (BMEP) of 1.06 bar, 2.07 bar, 3.11 bar, and 4.16 bar, respectively, and exhaust gas recirculation (EGR) rates of 0% and 20% at a pressure of 600 bar. The four named test fuels are used to carry out engine trials such as (1) diesel fuel, (2) B20 blend, (3) diesel + 5 ml DMC additive, and (4) B20 + 5 ml DMC additive. Experiments were carried out on a VCR-CI engine outfitted with a CRDI system under constant operating conditions and EGR rates (0% and 20%) at rated power output, and the studies were carried out on the same day and in remarkably similar ecological conditions. The main objective of this research is to enhance the engine's efficiency and diminish NOx and smoke emissions with marginal engine factors changes, as the author's earlier research using the same ternary blend with no engine changes yielded lower efficiency and higher smoke emissions than diesel fuel.

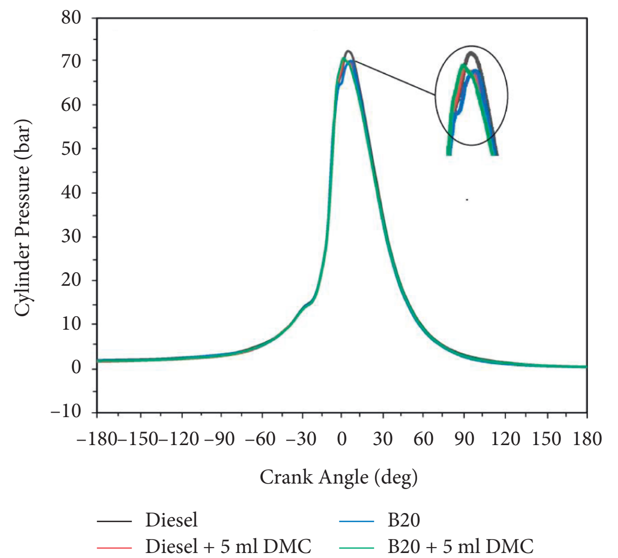

Figure 2: CP versus crank angle at maximum BMEP.

3. Engine Characteristics

3.1. Combustion and Performance Analysis

3.1.1. Cylinder Pressure versus Crank Angle. Figure 2 shows the fluctuation in in-cylinder pressure for biodiesel blends with and without DMC enhancer with various EGR rates at BMEP = 4.14 bar. In this experiment, 5 ml of DMC enhancer is mixed with the diesel and B20 blend. According to the results, both samples without and with DMC enhancer added have greater peak cylinder pressures, with 72.45 bar, 70.07 bar, 69.67 bar, and 70.93 bar for diesel, diesel + 5 ml DMC, B20, and B20 + 5 ml DMC being the highest in each case, respectively. The combination of B20 + 5 ml DMC @ 20% EGR gives high cylinder pressure range closer to diesel compared to B20 and diesel + 5 ml DMC mix. When comparing the B20 and diesel + 5 ml DMC mixtures, the combination of B20 + 5 ml DMC @ 20% EGR produces a high cylinder pressure range that is closer to that of diesel.

The cause of peak pressure has increased as a result of the addition of DMC, an oxygenated ingredient that improves the calorific value of PJOB mixes while they are blended together. A higher heating value leads to more heat being generated during burning. A greater heating value will result in a maximum cylinder pressure, as cylinder pressure is a function of the fuel's combustion phase [17].

3.1.2. Heat Release Rate versus Crank Angle. The heat release profiles provide some numerical data on the progress of combustion. The HRR increases the rate at which chemical energy is released from the fuel during combustion. Figure 3 shows the predicted heat release rates for various DMC enhancer and EGR rates corresponding to BMEP = 4.14 bar. The graph indicates that the peak HRR found at B20 mixes produces 10.38% higher than diesel. With respect to the EGR rate of 20%, at the concentration of the DMC enhancer, the maximum heat release rates are 59.67 J/deg for diesel + 5 ml DMC and 58.13 J/deg for B20 + 5 ml DMC, respectively. This is due to the fact that DMC is an oxygenated additive. As a result, the calorific value of biodiesel will be increased [16]. Heat release rates were reduced by increasing the EGR rate from 0% to 20%. These results may be explained by the dilution, thermal, and chemical effects of EGR gases, which lead to a decrease in the burning zone's temperature and, thus, a decrease in HRR peak temperatures [35]. As discovered, EGR had a comparable effect on decreasing HRR peaks.

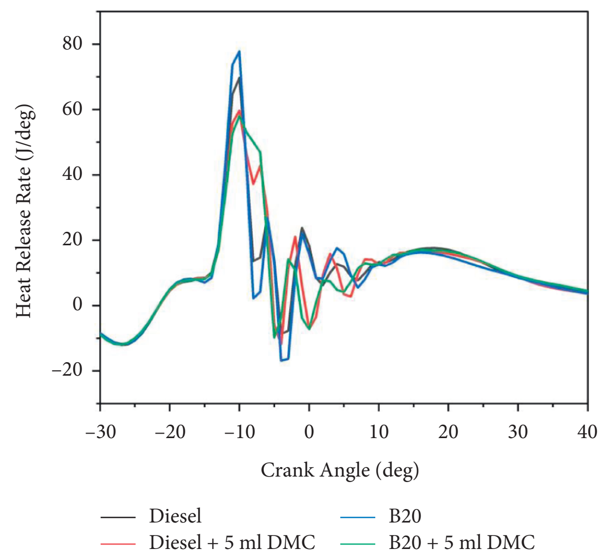

Figure 3: HRR versus crank angle at maximum BMEP.

3.1.3. Brake Thermal Efficiency. Figure 4 illustrates the impact of DMC and EGR on BTE of the four test fuels at altered BMEP of the engine. The test samples of diesel, diesel + 5 ml DMC, B20, and B20 + 5 ml DMC fuels have BTE ranges of 16.83% to 34.9%, 15.19% to 31.27%, 15.21% to 29.71%, and 16.85% to 32.93%, respectively. At the test fuel, the BTE falls initially and subsequently upsurges as the EGR concentration rises and the high-low BTE of blended fuels was set up for all EGR rates.

The following is the order of the reactions: diesel > B20 + 5 ml DMC > diesel + 5 ml DMC > B20. On the basis of the graph, it can be seen that raising the DMC fractions at full load results in a minor improvement in the BTE value. Due to the presence of oxygen atoms of DMC, the issue of a high air-to-fuel ratio in the energy zone is overcome when the phase of interfacial burning occurs, leading to a decline in incomplete burning [16]. The minor increase in BTE with greater DMC fractions may be due to an increase in ignition delay, leading to a rapid release of energy, which reduces heat loss from the engine and leads to an increase in brake thermal efficiency [20]. It was noticed that the diesel had more BTE than other mixes due to its higher heating value. Additionally, it is also found that the BTE of the engine degrades as the PJOB ratio in the mix is raised. In contrast, the BTE of the B20 + 5 ml DMC @ 20% EGR fuel blend is 5% and 9.77% greater at the engine's

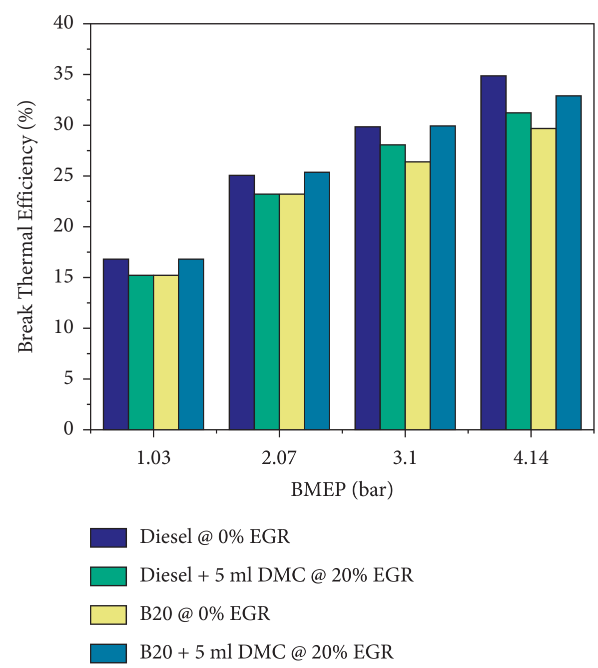

Figure 4: Brake thermal efficiency for the test fuels at different BMEP.

maximum BMEP, respectively, for diesel + 5 ml DMC @ 20% EGR and B20 mixes. Fuel consumption (kg/h) and power output (kW) were used to determine BSFC (P). Engine rpm and torque were used to compute power output. BSFC (kg/kWh) = Fuel consumption rate (kg/h)/P (1) & BTE (%) = (360 × P)/(Calorific value of fuel (MJ/kg) × Fuel consumption rate (kg/h)) (2).

3.1.4. Brake-Specific Fuel Consumption. Figure 5 shows how DMC and EGR influence the BSFC of the four test samples in this study. The main factors that affect the BSFC

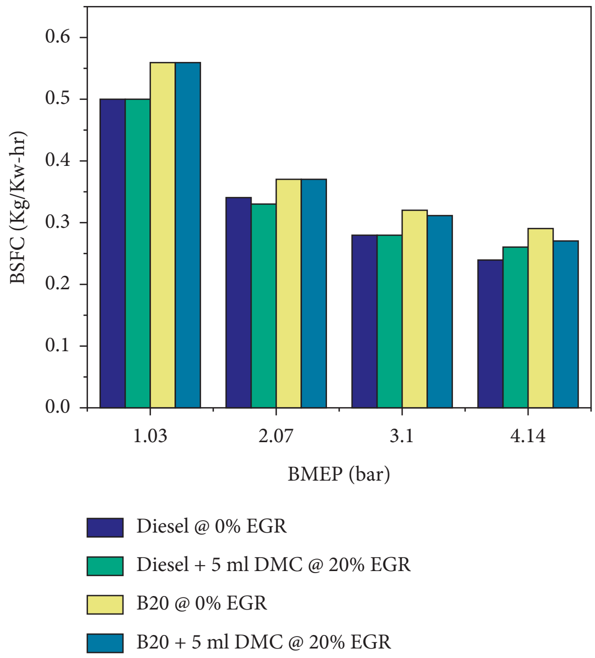

Figure 5: Brake-specific fuel consumption for the test fuels at different BMEP.

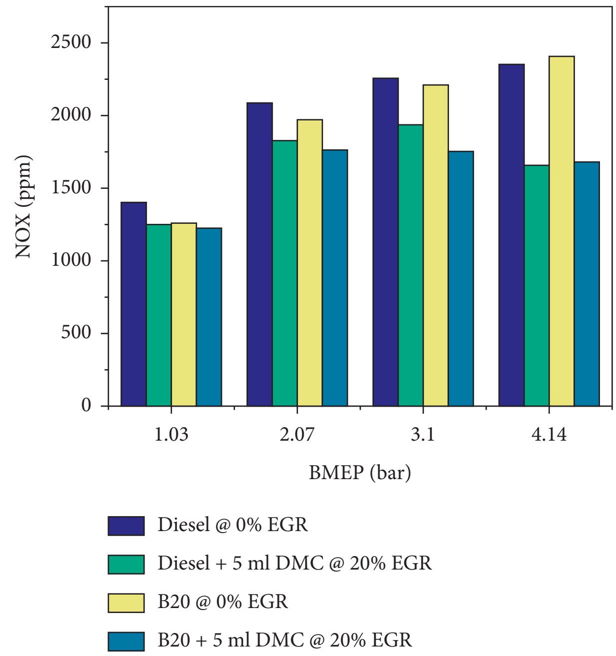

Figure 6: NOx for the test fuels at different BMEP.

correlation are the volumetric fuel injection system, the fuel density, the viscosity, and the heating value [36]. According to the findings, higher biodiesel percentage fuels had higher BSFC values (B20 > B20 + 5 ml DMC > diesel + 5 ml DMC > diesel). The plot indicates that BSFC drops with a higher engine load. The EGR levels range from 0% to 20%, the biodiesel mixes have a lower BSFC than diesel in terms of engine load, BSFC values range from 0.51 kg/kW·hr to 0.24 kg/kW·hr for diesel, 0.5 kg/kW·hr to 0.26 kg/kW·hr for diesel + 5 ml DMC, 0.56 kg/kW·hr to 0.29 kg/kW·hr for B20, and 0.56 kg/kW·hr to 0.27 kg/kW·hr for B20 + 5 ml DMC. The BSFC was reduced when DMC enhancer was added to diesel and biodiesel mixes compared to biodiesel without DMC. When comparing B20 + 5 ml DMC to B20 blends, the average drop in BSFC was 6.94%, while the average rise in BSFC was 11.11% and 3.75%, respectively, when compared to diesel and diesel + 5 ml DMC. It has been shown that the addition of DMC to biodiesel blends increases the calorific value while simultaneously decreasing the BSFC [37]. Because of its volatile nature, the mixing of air into the fuel mixture improved the quality of the addition of DMC to biodiesel blends, which resulted in enhanced atomization of the fuel mixtures.

3.2. Tailpipe Emission Analysis

3.2.1. Oxide of Nitrogen (NOx). Figure 6 depicts the impact of various EGR rates and fuels on NOx emissions. NOx levels in diesel ranged from 1408 ppm to 2353 ppm, diesel + 5 ml DMC from 1252 ppm to 1659 ppm, B20 from 1255 ppm to 2406 ppm, and B20 + 5 ml DMC from 1221 ppm to 1681 ppm. In all test samples, the load increases, the NOx first rises up to 75% of its maximum, but at full load, the NOx is slightly lowered. The key determinants of NOx generation are the oxygen content and temperature inside the cylinder. In general, NOx generation increases exponentially with in-cylinder combustion temperature, and a prolonged ignition delay also leads to increased NOx emissions [30]. The plot demonstrates that the diesel + 5 ml DMC and the B20 + 5 ml DMC fuels' 20% EGR rates are reduced by NOx emissions of 31.2% and 29.4%, respectively, compared to the diesel and B20 fuels' 0% EGR rate. For the same fuel, the NOx slowly diminishes as the EGR level rises. This change in NOx drops around 32.3% than adding DMC to test samples and has a 20% EGR rate. This is due to EGR's ability to reduce in-cylinder temperature and dilute oxygen concentration in the fuel mixture, causing combustion to depart from circumstances that favour NOx formation [12]. The B20 + 5 ml DMC at 20% EGR condition gave optimal NOx reduction than other mixes.

3.2.2. Smoke. Figure 7 shows the smoke opacity at the effect of DMC and EGR rates proportional to the engine BMEP. It ranges from 28.6% to 37.2% for diesel, 21.3% to 32.6% for diesel + 5 ml DMC, 22.5% to 33.3% for B20, and 39.4% to 58.6% for B20 + 5 ml DMC fuels. The EGR rates of 0% to 20% and addiction of DMC represent the proportionate amount of smoke drops with the rise in engine BMEP. According to the graph, the smoke values are diesel > B20 > diesel + 5 ml DMC > B20 + 5 ml DMC. This is because, with maximum engine loads, more fuel is fed into the combustion chamber to achieve the desired output power, which creates more fuel-rich zones and results in increased tailpipe emission of smoke opacity [11]. The explanation for this is the additional oxygen supply in the DMC, which has resulted in the efficient combustion of mixes, and the hybrid of DMC and biodiesel has a lower viscosity. Additionally, it improves fuel

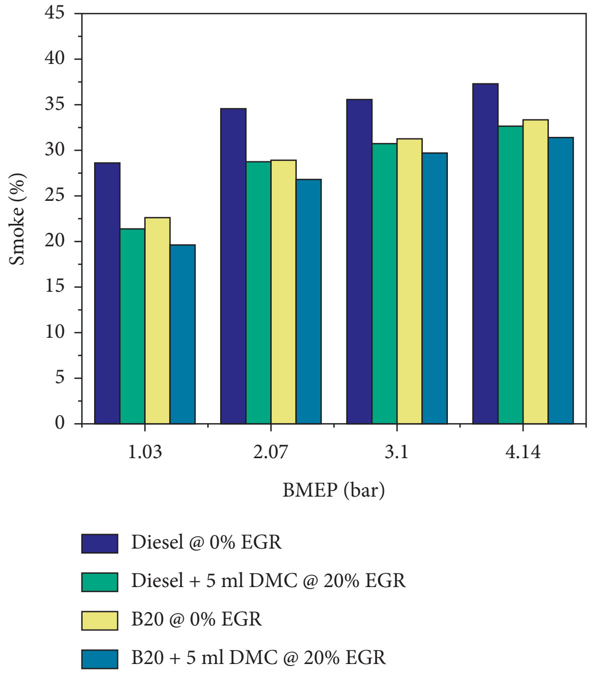

Figure 7: Smoke for the test fuels at different BMEP.

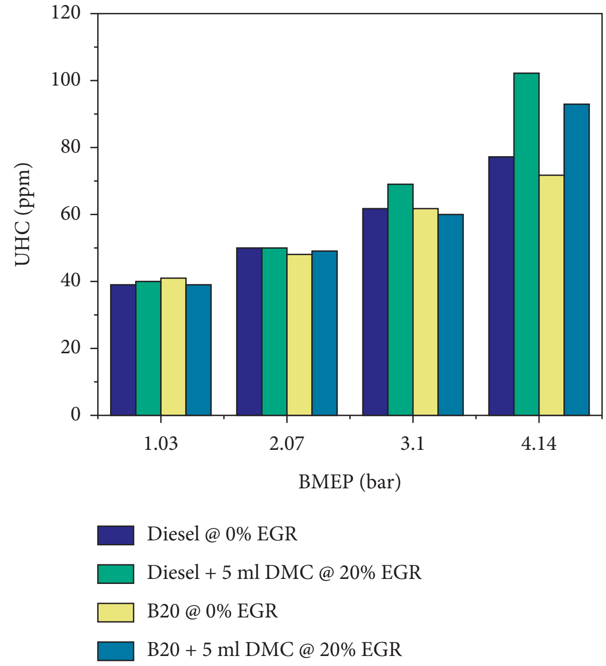

Figure 8: HC for the test fuels at different BMEP.

spraying for a better combustion process, and smoke opacity is reduced [22]. It was noted that the B20 + 5 ml DMC mix @ 20% EGR level emits less smoke compared to all other mixes. This could be because the B20% + 5 ml DMC blend burns at a higher mass fraction around the TDC position, resulting in high-temperature zones that promote soot oxidation with the help of the higher oxygen content of DMC, resulting in lower smoke emissions.

3.2.3. Unburned Hydrocarbon (UHC). Figure 8 represents the variants of hydrocarbon emissions under the influence of DMC and EGR with varying BMEP of the test engine. From plot shows an increase in HC emissions with increasing engine BMEP and EGR in test mixes. The values of HC emissions for diesel, diesel + 5 ml DMC, B20, and B20 + 5 ml DMC fuels vary from 39 ppm to 77 ppm, 40 ppm to 102 ppm, 41 ppm to 72 ppm, and 39 ppm to 93 ppm, respectively. Emissions of hydrocarbons are influenced by a variety of factors, including fuel properties, engine settings, and fuel atomization [36]. The observation of all mixes showed that HC emissions rose as EGR rates increased. Exhaust gas ignition results in incomplete combustion and an increase in the amount of HC emitted. Additionally, it may result in less oxygen being consumed during the combustion process [27]. But the DMC enhancer slightly overcomes this issue. The HC emits the value of DMC addiction of the B20 mix at a 20% EGR level closer to diesel fuel. The primary reasons for this significant reduction in HC emissions are the high oxygen content of biodiesel and oxygenated alcohol, which provide some excellent effects throughout the combustion process, including postflame oxidative and increased heating rate, which further optimizes the oxidation of unburned HC [22].

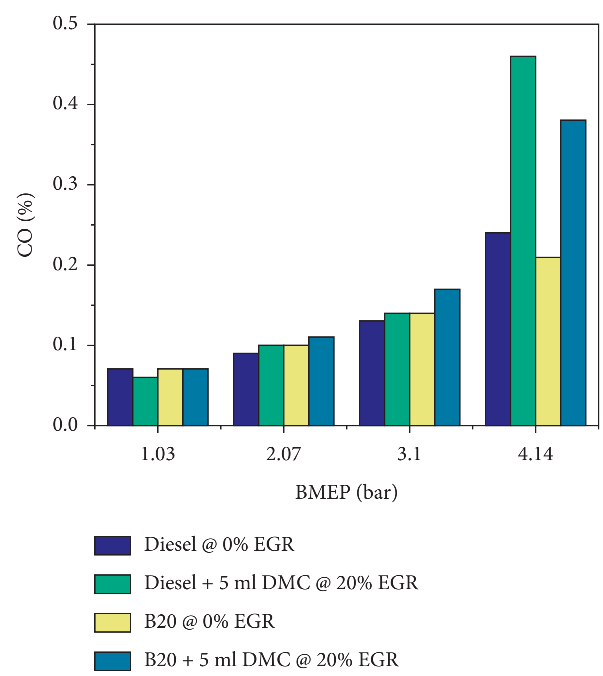

Figure 9: CO for the test fuels at different BMEP.

3.2.4. Carbon Monoxide (CO). In Figure.9, the carbon monoxide (CO) emission rate is shown at the addiction of DMC and EGR rates, at various BMEP = 4.14 bar. Carbon monoxide (CO) emissions were governed by one phase at the stage of hydrocarbon fuel ignition. CO emissions are primarily caused by poor fuel ignition and a lack of oxygen accessibility during combustion [7].

Table 4: Comparison of results of the present study with the other investigations that utilized *Prosopis juliflora* biodiesel and dimethyl carbonate as oxygenates in diesel engines.

Reference	Diesel engine specifications	Fuel	Test conditions	Reference fuel	Blend designation	Performance	NOx	Smoke	HC	CO
Present study	Kirloskar 1 cylinder, 4S, RP: 3.5 KW@ 1500 rpm, and CR: 16 : 1	B D + B + DMC	Constant speed	Diesel	D @ 0% EGR D + DMC @ 20% EGR B20 @ 0% EGR B20 + 5 ml DMC @ 20% EGR	▲ ▼ ▼ ▲	▲ ▲ ▲ ▼	▲ ▼ ▼ ▼	▼ ▲ ▼ ▲	▼ ▲ ▼ ▲
[11]	Kirloskar 1 cylinder, 4S, RP: 3.5 KW@ 1500 rpm, and CR: 12 : 1–18 : 1	B D + B + DEE	Constant speed	Diesel	D70-BD20-DEE10 D60-BD30-DEE10	▼ ▲	▼ ▲▼	▼ ▼	n/a n/a	▼ ▼
[29]	Kirloskar 1 cylinder, 4S, RP: 4.4 KW@ 1500 rpm, and CR: 17.5 : 1	LDPE	Constant speed	Diesel	D70L30 D70L20DEC10	▼ ▼	▼ ▼	▼ ▼	▲ ▲	▲ ▲
[1]	Onan DJC 4 cylinders, 4S, RP: 12 KW@ 1800 rpm, and CR: 19 : 1	B D + B D + B + Pr D + B + nB D + B + Pn	Constant speed	Diesel	B100 D50-B50 D40-B40-PR20 D40-B40-nB20 D40-B40-Pn20	▲ ▼ ▲ ▲ ▲	▲▼ ▼ ▼ ▼	n/a n/a n/a n/a n/a	▼ ▲ ▲ ▼ ▼	▼ ▼ ▼ ▼ ▼
[7]	Kirloskar 1 cylinder, 4S, RP: 5.2 KW@ 1500 rpm, and CR: 17.5 : 1	D + WPO D + WPO + *n*-oct	Constant speed	Diesel	D80-WPO20 D70-WPO20-oct10	▲ ▲	▲ ▼	▲ ▼	▼ ▼	▼ ▼
[15]	Kirloskar 2 cylinders, 4S, RP: 8.4 KW@ 2400 rpm, and CR: 18.5 : 1	BD + DMC	Constant speed	Diesel	BD90-Dmc10 BD80-Dmc20	▲ ▲	▲ ▲	▼ ▼	▲ ▲	▼ ▼
[20]	Kirloskar 1 cylinder, 4S, RP: 5.2 KW@ 1500 rpm, and CR: 17.5 : 1	CIME D + CIME D + CIME + HX	Constant speed	Diesel	B100 D50-B50 D50-B40-HX10 D50-B35-HX15 D50-B30-HX20 D50-B20-HX30 D50-B10-HX40	▼ ▼ ▼ ▼ ▼ ▼ ▼	▲▲ ▲▲ ▲ ▲ ▲	▼ ▼ ▼ ▼ ▼ ▼ ▼	▼ ▼ ▼ ▼ ▼ ▼ ▼	▼ ▼ ▼ ▼ ▼ ▼ ▼
[22]	Kirloskar 1 cylinder, 4S, RP: 3.5 KW@ 1500 rpm, and CR: 17.5 : 1	WPO D + WPO + HX	Constant speed	Diesel	WPO D50-WPO40-HX10 D50-WPO30-HX20 D50-WPO20-HX30	▼ ▼ ▼ ▼	▲ ▲ ▲ ▼	▲ ▼ ▼ ▼	▲ ▲ ▲ ▲	▲ ▲ ▲ ▲

From experiments, the CO value increased at rising DMC proportion and EGR levels with various BMEP. Based on results, it displays the following sequence: diesel + 5 ml DMC @ 20% EGR > B20 + 5 ml DMC @ 20% EGR > diesel @ 0% EGR > B20 @ 0% EGR. The B20 mix had a lower value of CO compared to all other test mixes because it had a higher quantity of oxygen level [10]. The addition of DMC oxygenate reduces CO emissions. CO emissions are reduced by the use of several oxygenated alcohols as fuel additives. The presence of too much oxygen in biodiesel mixes and fuel additives causes CO to be oxidized inside the combustion chamber, lowering CO emissions [22]. But the EGR rates produce a higher value of CO emissions due to interference by EGR with CO oxidation by creating an oxygen-depleted environment. CO emissions rise as the rate of EGR increases [26]. Comparison of the results of the present study with the other investigations that utilized *Prosopis juliflora* biodiesel and dimethyl carbonate as oxygenates in diesel engines is shown in Table 4.

4. Conclusion

The study's findings are summarized and given in the following. The further phase of this research focused on the impact of EGR on the performance and emissions of CRDI diesel engines with the diesel/PJOB/dimethyl carbonate mixed ternary fuel used in the current inquiry.

(i) The maximum in-cylinder pressure was noticed with the B20 + 5 ml DMC @ 20% EGR level, 2.38% and 3.88% more than the diesel + 5 ml DMC and B20 mixes, but 2.13% lower than diesel fuel. The peak heat release rate (HRR) was ascertained with the B20, about 10.38% higher than diesel.

(ii) The BTE was somewhat increased by lowering the EGR rate and increasing the DMC concentration in all blends. At 20% EGR rates, the brake thermal efficiency (BTE) for B20 + 5 ml DMC is higher than that for other test samples, but it is still 5.64% lower than for pure diesel, and the B20 blends show better results in BSFC. The average decline in BSFC was 6.94% compared to other test samples.

(iii) The NOx exhaust of the optimal mix of B20 + 5 ml DMC @ 20% EGR level is an average of 32.13% lower than that of other test samples. But the clear introduction of EGR reduces the in-cylinder combustion temperature and can, therefore, reduce NOX emissions considerably.

(iv) Smoke emission dropped when the use of 5 ml DMC proportion was 20% EGR level. Smoke emission was suppressed by 15.86%, 3.98%, and 6.1%, respectively, as compared to the other three test samples.

(v) Both UHC and CO emissions were reduced in the presence of a DMC enhancer but increased by the inclusion of the EGR concept.

Finally, it is concluded that the ternary mix (B20 + 5 ml DMC) operated at standard engine condition and 20% EGR rates can be efficiently utilized in a CRDI-equipped diesel engine.

5. Future Study

When compared to other blends, the D80B20 + 5 ml DMC blend performed exceptionally well in this testing. Higher PJOB content in diesel/PJOB blends has been linked to increased smoke emissions and decreased engine efficiency, according to the study. Future studies on increasing the quantity of PJOB in diesel engine applications should take into account the following points:

(1) Modifying compression ratio, fuel injection pressure, and exhaust gas recirculation rates can all be used in optimization studies.

(2) Finally, engine durability tests are necessary to support the use of PJOB as a diesel fuel alternative.

Abbreviations

ASTM:	American society of testing and materials
Diesel + 5 ml DMC:	97.5% by vol diesel + 2.5% by vol dimethyl carbonate additive
B20%:	80% by vol diesel + 20% by vol biodiesel
B20% + 5 ml DMC:	80% by vol diesel + 17.5% by vol biodiesel + 2.5% by vol dimethyl carbonate additive
bTDC:	Before top dead centre
BMEP:	Brake mean effective pressure
BSFC:	Brake-specific fuel consumption
BTE:	Brake thermal efficiency
CO:	Carbon monoxide
CO_2:	Carbon dioxide
CRDI:	Common rail direct injection
CA:	Crank angle
ECU:	Electronic control unit
EGR:	Exhaust gas recirculation
HRR:	Heat release rate
HC:	Hydrocarbons
NOx:	Oxides of nitrogen
ppm:	Parts per million.

Data Availability

The data used to support the findings of this study are included within the article. Should further data or information be required, these are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

Authors' Contributions

T. Ramesh participated was responsible for writing the original draft and reviewing and editing the paper and contributed to conceptualization. A.P. Sathiyagnanam contributed to investigation and supervision. Melvin Victor De Poures contributed to project administration, and P. Murugan was responsible for resources.

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