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Research Article

Effect of lower rate of exhaust gas recirculation on CI engine characteristics fueled with Prosopis juliflora biodiesel: An experimental study

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ABSTRACT

The enormous rise in energy demand with the strict emissions regulations has put together in search of the finest alternative fuel that meets the various emission norms of the vehicles made worldwide. Nowadays, researchers all around the globe aims to reduce the amounts of emissions from the compression ignition (CI) engine. Biofuel resembles the qualities of fossil diesel while it is also proven to be a greener fuel and viable alternative. However, the primary challenge of using biodiesel was higher emissions of Nitrogen oxides (NO_x). Hence to minimize the NO_x, an exhaust gas re-circulation (EGR) system could be utilized which could resolve the challenges associated with this higher NO_x emissions. In this study, juliflora biodiesel was selected and blended with diesel at 20% by volume (B20) and three different EGR percentages 5%, 10%, and 15%, were investigated on the characteristics of CI engine. Based on the test outcomes, a drop in NO_x has been observed with a 15% rate of EGR which is 6.1% lower than conventional diesel. Moreover, brake thermal efficiency increased by 11% as compared to diesel. However, a slight increase in other exhaust emissions was noticed with EGR. The results conclude that, lower rate of EGR (15%) with B20 blend of juliflora biodiesel provides the optimum performance in the engine with least NO_x emission.

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INTRODUCTION

The effects of climate change on human health and ecological quality have made it a global concern. The transportation industry had been the fastest-growing source of greenhouse gas emissions. Biofuels were seen as a viable climate change mitigation strategy and a means to lessen our reliance on petroleum-based energy. Energy is an essential requirement for the advancement of industries and infrastructure, and hence with urbanisation and an increase in population the need for energy is also increasing. Currently the majority of the world's energy utilises fossil fuels which involves coal for power generation, petrol, diesel, natural gas for automobiles etc. [1]. While these resources were limited, i.e., non-replenishable, they also lead to a lot of

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pollution while extracting and utilizing it [2]. The demand for an alternative fuel surge rapidly and biodiesel could be capable to fulfil the demands. It possesses physiochemical properties similar to diesel while it also reduced emissions, thus making it a right fit for direct utilisation in compression ignition (CI) engines [3-5]. The blending of biodiesel attracted researchers in the hope of reducing the dependency on fossil fuels with reduction in a harmful greenhouse gas emissions [6]. The production of biodiesel was achieved via biomass, such as crop grains and seeds etc [7]. However, it must be ensured that for commercial use they should be derived from non-edible biomass, so as to maintain food security [8]. Biodiesels are biodegradable and provide efficient combustion with lower carbon emissions but they tend to be more viscous. Lower blend ratio of biodiesel (B20) had minimal viscous effect, but it led to higher NOx emissions and these problems need to be resolved for their better commercial utilisation [9-11]. The exhaust gas recirculation (EGR) system is often associated in diesel engines to lower NOx emissions [12]. Raja et al. blended the Prosopis juliflora biodiesel (PJB) and isopropanol with diesel fuel while varying the EGR rate between 10% and 30% to study its effects on engine characteristics. At full throttle, the cylinder pressure of the 30ISP mix (30% PJB + 70% diesel fuel) was the greatest, followed by that of the 30ISP-30EGR blend and diesel fuel. With 30% EGR, NOx emissions declined from 1274 to 906 ppm. Increasing the rate of EGR caused a rise in both HC and CO [13,14]. So, the incorporation of lower rate of EGR has to be done to achieve least NOx emission without not much affecting the other emissions trade-off.

Liang. J et. al. carried out experiments to find out how n-pentanol and biodiesel's combined effects would affect a common-rail diesel engine's efficiency and emissions at various rates of EGR. When compared to D100, ternary fuels (n-pentanol with biodiesel diesel blends) caused more HC emissions at low EGR rates. However, with a higher rate of EGR, the ternary fuel's high oxygen availability and cetane number (CN) could substantially decreased the HC emissions. Despite lowering NOx and soot, still higher rate of EGR increased CO and HC. CI engine may benefit more from ternary blends with an EGR at a moderate rate [15]. The key findings of the study by Rao et al. were the impact of compression ratio (CR) with EGR on the CI engine performance. Results of palmyra oil methyl ester 20% (POME 20) blend demonstrated the effects on BTE, BSFC, and emissions with different CR (16:1, 18:1, and 20:1). EGR was used at rates of 5% and 10% when POME20 was operating at a CR of 20:1. The experiment results disclosed that with the employment of 10% EGR to POME20 reduced NOx emissions by 23% comparative to POME20 at normal operating condition [16]. Sakhare et al. [17] examined the same with cottonseed biodiesel B20 with the application of EGR. Cottonseed B20 as an oxygenated fuel with higher CN, had minimal ignition delay as compared to diesel. Cottonseed B20 biodiesel reduced CO and HC emissions because it burns cleanly and contains no aromatic compounds. Generally, NOx increased with Cottonseed B20. While the application of EGR reduced it to the great extent. However, EGR caused a marginal rise in CO and HC. So the compromise has to be made between these emission trade-offs.

Öztürk et al. [18] used 10% canola biodiesel with addition of ethanol on the CI engine and examined the impact of the EGR along with delayed injection timing. The research showed that the best way to improve the combustion was to use a retarded injection timing of 2 CA° with better performance and emission metrics. Harish Venu et al. [19] approached an innovative method of the effect of nanoparticles combined with EGR. This technique could reduce smoke throughout the engine load with a simultaneous drop in all emissions up to part loads. Results from this research with palm biodiesel B30 with a combination of 25% TiO2 nanoparticles and EGR revealed that this approach reduced the BSFC, HC, and CO emissions with a rise in exhaust gas temperature (EGT). Jaliliantabar et al. [12] conducted an experiment to investigate how engine characteristics were affected by various biodiesels when using pilot injection and EGR. The biodiesels made from brassica, cardoon, coffee, used cooking oil, and diesel fuel were examined. The use of EGR (up to 86%) and pilot injection (up to 29.3%) had reduced emissions to great extent. A rise in BSFC with a higher EGR rate caused by a poor combustion quality and a insufficient oxygen for the combustion. Lower rate of 10% EGR was advised to reduce NOx emissions without adversely affecting other emissions or combustion quality [20].

The novel of this paper lies in the selection of juliflora biodiesel and its properties. Some previous biodiesel studies are listed in Table 1. Lower blend ratio of the B20 blend had similar and superior properties than diesel. Hence, this was chosen for the study to analyse the characteristics of the CI engine. This biodiesel could serve as a better alternative to diesel and the findings motivated us to use EGR to overcome the challenges associated with the higher NOx. The main objective of this research is to examine the performance of a juliflora biodiesel blended with diesel at 20% by volume in a VCR diesel engine with lower rate of EGR. Further, to find out the optimum lower rate of EGR with least emission and not much affecting the other parameters. The subsequent sections elaborate on fuel characterization and preparation, experimental configuration, performance and emission parameter testing, and a comparison of the results to those of base diesel.

The previous extensive research showed that several approaches are intended for reducing NO_x emission while using biodiesel blends in CI engine. Fuel reformulation, exhaust gas recirculation, and various additives play major roles. However, some reformulation fuel strategies and the inclusion of additives do not result in improved performance and reduced emissions due to significant variations in combustion characteristics. Juliflora biodiesel and its blends were specially studied with various additives, fuel

Table 1. Comparison of biodiesel properties with various feedstocks

Type of biodiesel	Kinematic Viscosity in CST at 40 °C	Cetane Number	Density in gm/cc	Net Calorific value KJ/kg	Flash point in °C	Author
Juliflora biodiesel	4.14	55	0.88	38247	124	Musthafa et al. (2023)
Soybean Biodiesel	5.249	53.8	0.89	37528	148	Can et al. (2016)
Karanja Biodiesel	4.42	50.8	0.881	37980	172	Agarwal et al. (2015)
Corn oil methyl ester	4.363	48	0.836	39120	167	Nagaraja et al. (2016)
Waste cooking oil	5.87	58	0.844	38200	130	Senthur et al. (2017)
Tamarind seed oil	6.17	50.5	0.881	41900	154	Asokan et al. (2024)
Mahua Biodiesel	5.39	51.2	0.8712	42293	157	Nayak et al. (2014)
Jatropha oil Methyl ester	5.48	51	0.849	38467	172	Javed et al. (2016)
Calophyllum inophyllum biodiesel	5.4	59.5	0.87	37900	170	Nanthagopal et al. (2017)

strategies and dual fuel methods in CI engines. However, only limited work was available on the NO_x reduction process of juliflora biodiesel. The motivation of this study is to improve the emission characteristics and NO_x emission without much affecting the engine performance characteristics. The primary objective of this study is to examine the effect of lower rate of EGR with juliflora biodiesel blend on CI engine performance and emissions. This novel approach with juliflora biodiesel can reduce emission levels, especially NO_x. This research promotes sustainability by working towards a transportation sector that is more environmentally favourable.

MATERIALS AND METHODS

Preparation of Fuel

A transesterification reaction was employed to obtain the biodiesel. The chemical reaction of alcohol with triglycerides i.e., the fats of oils, in the presence of a catalyst is called the transesterification reaction. The endothermic reaction leads to the formation of easter and glycerol. It is process to make the properties of oil similar to diesel. The process of transesterification is depicted in Figure 1. A mixture juliflora and methanol of 16:1 molar ratio was prepared and KOH was used as catalyst. The reaction involved heating the mixture for an hour to 60 °C in a conical flask, the whole being stirred at 700 rpm. Methanol has a boiling point of 64.7 °C and hence the mixture's temperature was maintained to be 60 °C. To prevent the escaping of the volatile components, the top of conical flask was covered with aluminium foil. To settle the broken-down fats, the stir-heated mixture was shifted into a separating funnel and rested for 4 hours. In a conical flask, methoxide was mixed with the fats that settled down, and the mixture was rested for 18 hours to settle. The biodiesel was obtained at the top of the mixture. The moisture removal was attained by continuous heating, while the removal of glycerine was achieved via water washing. Juliflora biodiesel was collected with a higher yield rate of 95%. Processed raw juliflora biodiesel based on the above-mentioned method was procured from local vendor. Further, diesel (JB0), juliflora biodiesel (JB100), and its blend, 20% biodiesel with 80% of diesel (JB20) were prepared and the properties examined as per ASTM standards are illustrated in Table 2.

Engine Experimental Setup

The CI engine's features with a juliflora biodiesel blend were studied in a 4-stroke vertical single cylinder CI engine at various lower percentages of EGR. Eddy current

Table 2. Properties of juliflora biodiesel

Sl. No	Properties	D0	B20	B 100	ASTM	Equipment utilized
1	Kinematic viscosity@40°C (cSt)	3.2	3.57	4.14	D445	Brookfield viscometer
2	Flashpoint (°C)	67	80	124	D93	Pensky Marten Apparatus
3	Fire point (°C)	73	87	130	D92	
3	Density @ 15 °C (kg/m^3)	827	835	886	D1298	Hydrometer
4	Lower heating value (MJ/kg)	42.7	41.6	38.2	D6571	Bomb calorimeter
5	Cetane Number	52	54	55	D613	-

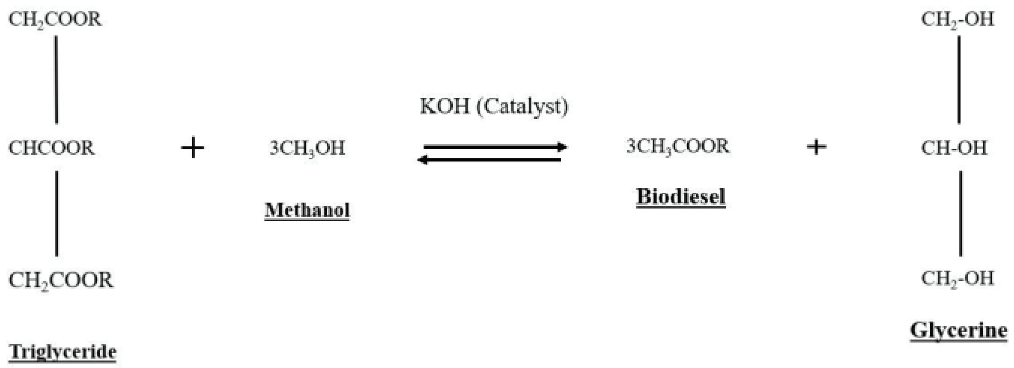

Figure 1. Transesterification process.

dynamometer was utilized to apply load. In this, load varied from 0 to 100%, with an increase of 25% in each step. The engine was designed to function at 1500 rpm for various loads. The time required for 10 cc of fuel consumption was measured with burette and a stopwatch. The levels of fuel and lubricating oil were examined for normalcy with the fuel measurement unit. For the first 30 minutes of the experiment, only pure diesel fuel was used to warm up the engine. Immediately, after the temperature of cooling water approached to 60^{o}C, this process was completed, and rotameters were utilized to detect the flow of cooling water. Moreover, the experimental engine set up was equipped with an EGR valve that regulates the flow of exhaust gas into the intake manifold. The opening and closing of this valve can be controlled mechanically. This study was performed thrice and an average of all values was taken for further study. Figure 2 depicts the experimental setup and the specification were illustrated in Table 3. The emissions from the CI engine which are mainly comprised of NOx, CO, and HCs were detected by using AVL GAS DI 444 N (Five gas analyzer) and smoke were determined by utilizing AVL 437C smoke meter. To obtain better accuracy in measurements, these equipment's were calibrated via reference gases. Engine Soft software was used to evaluate different parameters like fuel consumption, power, efficiency and heat release. Specification of emission analysers were shown in Table 4 and Table 5.

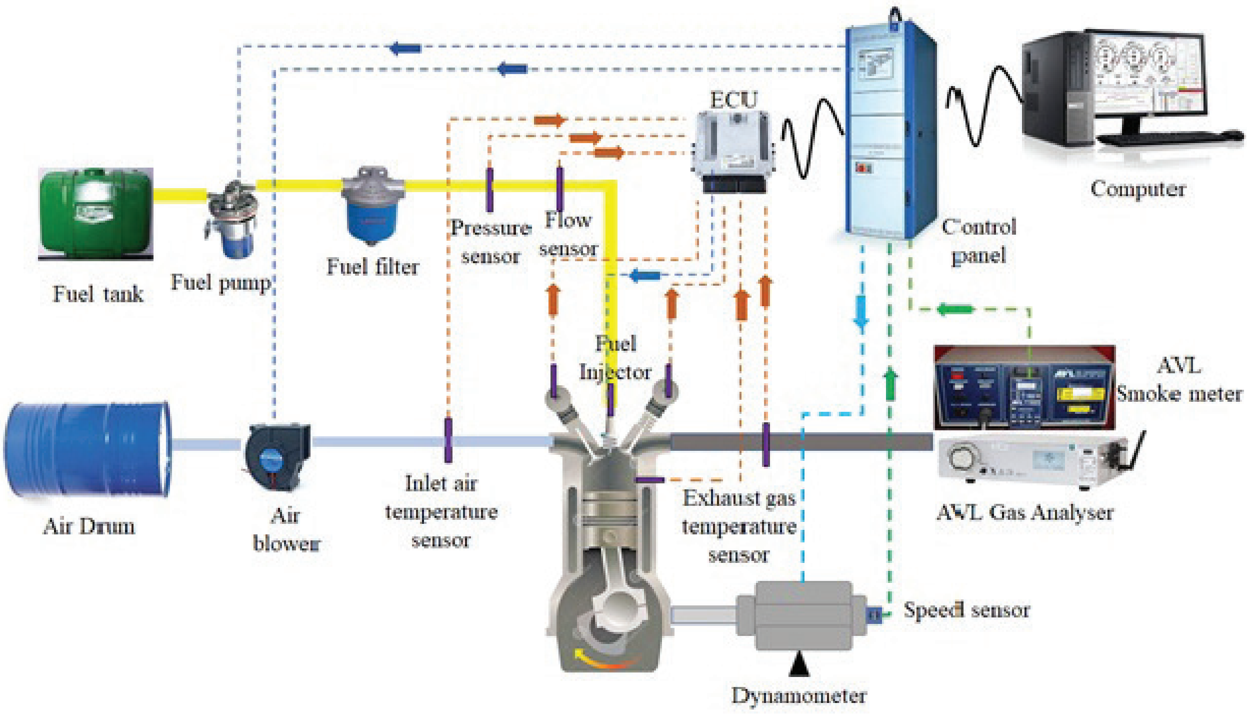

Figure 2. Experimental setup diagram.

Table 3. Engine specifications

Manufacturer	Kirloskar TV1
Power range	3.5 kW with 1500 rpm
Displacement Volume	661 cm^3
Compression Ratio	17.5
Standard Injection timing	23° bTDC
Cooling Type	Water-cooled

Table 4. AVL DI GAS 444N (Five Gas Analyzer)

Measurement Data	Resolution
Manufacturer	AVL India Private Limited, 376e377, Udyog Vihar, Phase IV, Gurgaon, Haryana-122015
Serial No.	3271
Power Supply	19 V DC/ 15 W
CO-0-20% Vol	0.00001% vol
HC 0-2000 ppm vol	1 ppm/10ppm
CO2- 0-20% vol	0.1% vol
O2 – 0-25%vol	0.01% vol
NOx 0-6000 ppm vol	1 ppm vol

Table 5. AVL 437 Smoke Meter

Measurement Data	Resolution
SI No.	2742
Manufacturer	AVL India Private Limited, 376e377, Udyog Vihar, Phase IV, Gurgaon, Haryana – 122015.
Power Supply	190-240 V AC, 50-60 Hz, .5 A or 11.5-36 V DC
Sensor	Selenium Photocell (Size-dia 45 mm)
Operating Temperature	0-50 °C
Light Source	Halogen Lamp, 12 V / 5 W (Colour Temperature: 3000±150 K)
Opacity 0-100%	0.1%
Absorption (K Value)	0-99-99 m-10.01 m-1

Uncertainty Analysis

During the experiments, due to various elements such as environmental operating conditions, instrument selection and calibration, apparatus quality and experiment order, etc., the same results could not be obtained. Therefore, it is crucial to evaluate the reliability of the measured results. The study was performed thrice and the values were averaged for the graphical representation. The uncertainty percentage along with the accuracy of the measuring equipment was employed. The overall uncertainty of ± 2.53% was obtained using the expression derived by Holman as follows:

Total uncertainty
= [(encoder)2 + (pressure sensor)2 + (NOx)2 + (O2)2 + (CO)2 + (CO2)2 + (opacimeter)2 + (HC)2 + (K2 thermocouple)2 + (manometer)2 + (stop watch)2 + (burette)2]½
= [(0.3)2 + (0.01)2 + (0.5)2 + (0.35)2 + (0.02)2 + (0.2)2 + (0.3)2 + (1.1)2 + (1.5)2 + (0.3)2 + (1.5)2]½ = $\sqrt{6.393}$ = ± 2.53 %

RESULTS AND DISCUSSION

Brake Thermal Efficiency (BTE)

Figure 3 portrays the variation in the BTE with an increase in load, for pure diesel and juliflora biodiesel B20 at various rates of EGR. Results indicate that the BTE of B20 was the maximum at 15% EGR. At full load, the values of BTE were noticed as 33.63, 32.23, 33.28, 35.32 and 37.36 for D0, B20, B20 with 5%, 10% and 15% EGR respectively. The engine performance gets better with EGR for all the loads. There was an 11% increment in BTE for B20 with 15% EGR as compared to conventional diesel. This higher BTE could be due the fact that, B20 led to better atomization and thus, better combustion. As atomization improved, the premix combustion increased and ID reduced which resulted in a higher rate of combustion [21]. This increased combustion rate resulted in higher BTE. EGR minimized the heat losses through exhaust gases which boost the BTE [22]. Also, re-combustion of hydrocarbon from EGR enhanced BTE, as it preheats the intake air-fuel mixture [23].

Brake Specific Fuel Consumption (BSFC)

BSFC defines the amount of fuel burnt to generate unit brake power (BP), thus indicating the combustion efficiency. Figure 4 illustrates the BSFC with load and EGR, it could be seen that BSFC at the maximum load for D0, B20, B20 with 5%, 10% and 15% EGR were 0.231, 0.254, 0.238, 0.236, 0.253 kg/kW-h respectively. At peak load, the BSFC was greater for B20 (9.9% higher) and least for pure diesel. This trend in diesel values could be associated with the fact that biodiesel had inferior heating value and high viscous and denser than diesel. The calorific value of the fuel had a directly impact on the BSFC [24]. Due to higher oxygen availability, more fuel must be burned for B20 to supply the power demand at higher loads [25]. The homogeneous air-fuel mixture and areas of spontaneous ignition improved the speed of pre-mixed combustion. As a result, the combustion quality was improved. B20 with 5% and 10% EGR showed least BSFC as similar with diesel whereas higher EGR rate increased the BSFC as like B20. The incorporation of exhaust gas diminishes the power output leads to higher consumption of fuel to produce same unit of BP [26].

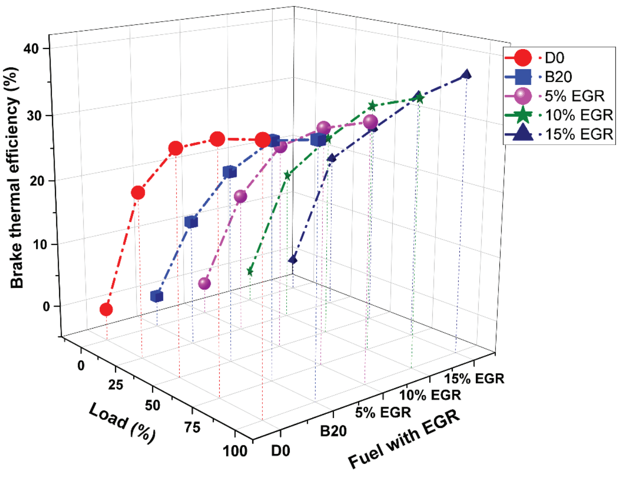

Figure 3. Variations of BTE with respect to the load at different EGR%.

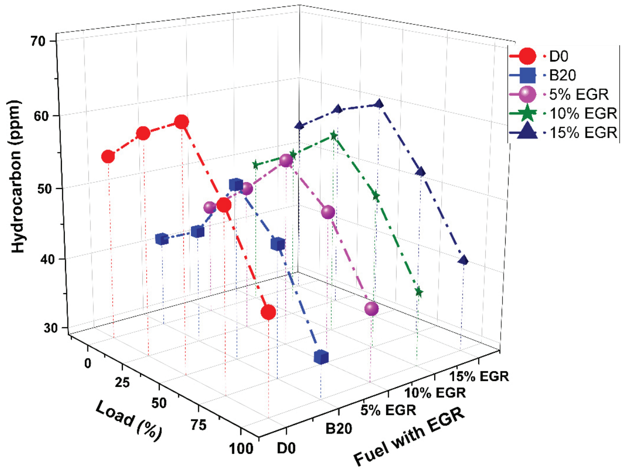

Figure 5. Variations of hydrocarbon emissions with respect to the load at different EGR%.

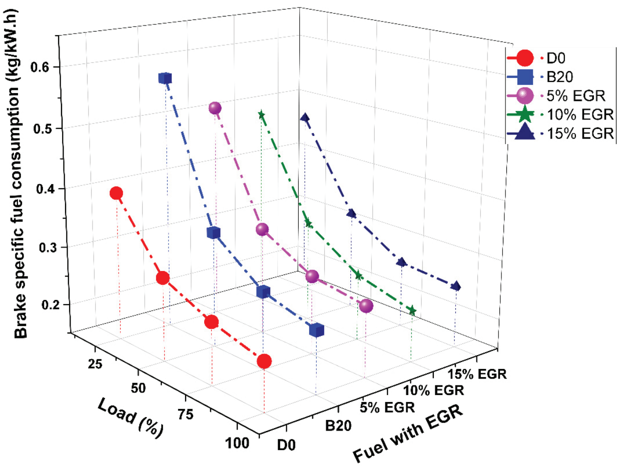

Figure 4. Variations of BSFC with respect to the load at different EGR%.

Hydrocarbon Emissions (HC)

Figure 5 depicts a correlation between HC and load. Lower HC emissions depict better fuel consumption. At low loads, the maximum emissions were noticed with pure diesel, while B20 emits the lowest HC emission. Incomplete combustion was the root cause of HC and it was due to insufficient air/fuel mixing and this observed pattern remains same for greater loads [27]. The values of HC emissions were observed as 42.53, 34.65, 38.95, 39.30 and 41.74 for Diesel, B20, B20 with 5%, 10%, and 15% EGR respectively, at peak load. The HC emissions for B20 were 18.52% lower than diesel because of its higher Cetane number that aids in the fully combustion of the fuel droplets [28, 29]. Lean air-fuel mixture and efficient combustion reduced HC emissions. The HC emission surged with higher EGR percentages due to insufficient oxygen availability for combustion results in a rich fuel mixture with incomplete combustion. Anyhow, the HC emissions were minimal than that of pure diesel.

Carbon Monoxide Emissions (CO)

Figure 6 depicts the CO emission with increasing load. Emissions of CO mostly resulted from incomplete oxidation and low flame temperature caused by an oxygen deficiency in the air-fuel mixture [30]. At low loads, the CO emission was least for B20 with no EGR while the highest emission was observed for 15% EGR; in the case of higher loads, the trend remains the same, while the emissions increase as discussed above. At full load, the values observed on CO emissions were 0.079, 0.072, 0.0786, 0.0796 and 0.0828 for pure diesel, B20, B20 with 5%, 10% and 15% EGR, respectively. Moreover, B20 with no EGR showed 8.86% lesser CO emissions than diesel and B20 with all the levels of EGR. This

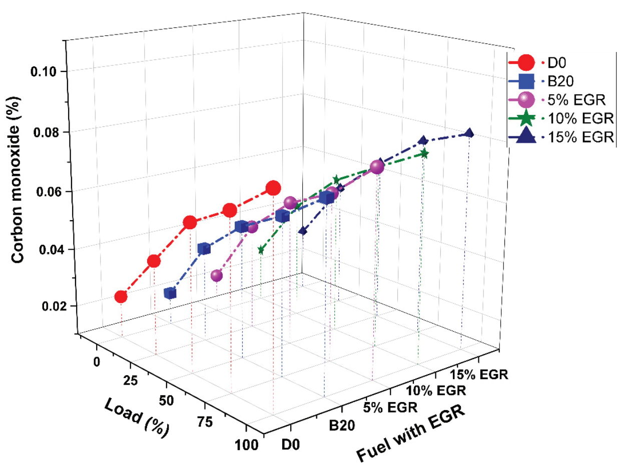

Figure 6. Variations of carbon monoxide emissions with respect to the load at different EGR%.

phenomenon could be due to its higher oxygen availability, but as the rate of EGR increased (above 5%) the amount oxygen available for combustion decreases and hence the above trend was observed [31]. Improved fuel mixing and atomization raised cylinder temperature, which improved carbon oxidation and lowered CO emissions [32].

NO_x Emissions

Figure 7 demonstrates the NOx emissions with respect to the load at various rates of EGR. Many factors contribute to NOx emission, including oxygenated fuel, complete combustion, higher in-cylinder pressure and temperature. NOx emissions increased with load. The NOx emissions were measured as 989.75, 1082.81, 993.59, 984.36, and 928.97 for diesel, B20 (0%), 5%, 10%, and 15% EGR respectively at maximum load. At higher loads, the lowest emission was observed for 15% EGR while the highest NOx for the B20 with no EGR. The main factor for this least NOx emission could be due to the drop in combustion temperature at 15% EGR [33]. The above observations are owing to the fact that, B20 with no EGR corresponding to leaner fuel with greater oxygen availability which would lead to more NOx emission as the higher in cylinder temperature. B20 blend with no EGR emits 9.4% higher NOx than diesel whereas B20 with 15% EGR resulted in 6.1% lower NOx than that of diesel. Also noticed that this higher NOx in the case of biodiesel blend was due to presence of more oxygen [34]. Higher CN also enhanced the NOx forming tendency [35].

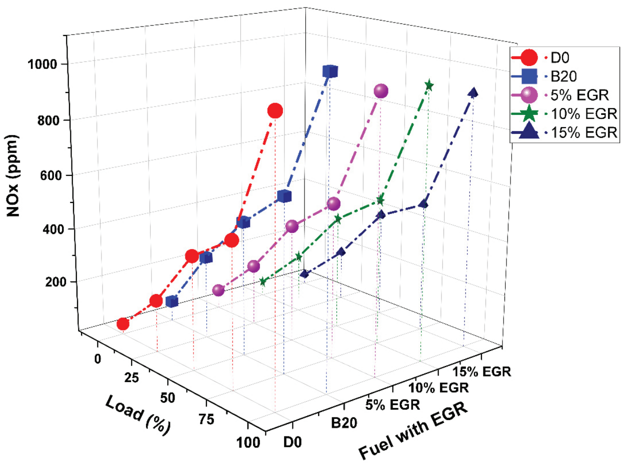

Figure 7. Variations of NO_x emissions with respect to the load at different EGR%.

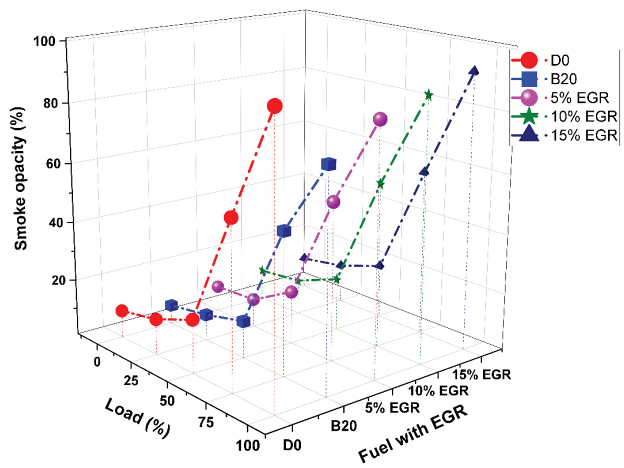

Figure 8. Variations of smoke opacity with respect to the load at different EGR%.

Smoke Opacity

Figure 8 represents the variation in smoke opacity with respect to load. At low load, the smoke was least for diesel and considerably lower for all the other blends except B20 with 15% EGR.

The trend showed that opacity increased with rate of EGR. Physiochemical features of biodiesel, air deficiency, fuel atomization, and air-fuel mixing were the cause of smoke emissions [36]. The values of smoke opacity were 92.94, 73.27, 83.60, 88.27, and 92.16 for diesel, (B20) 0%, 5%, 10% and 15% EGR respectively, at full load. Figure 8 showed that the B20 blend with no EGR resulted in 21.16% lower smoke emissions than diesel fuel. The governing reason behind these observations were the formation of particulate matter due to incomplete combustion, which in turn was an outcome of the insufficient oxygen availability with EGR [37]. It was seen that the smoke opacity was higher in diesel as compared to biofuel with no EGR due to higher oxygen content of biodiesel and hence react with the carbon atoms to form CO or CO2, thus reduced the amount of smoke generated [38].

CONCLUSION

The experimental study mainly concentrated on the impact of EGR on the characteristics of CI engine with juliflora biodiesel. The EGR technique was applied for three different conditions i.e., with 5, 10 and 15 % EGR, and the results were compared with B20 (no EGR) and diesel.

The observations showed a rise in BTE with an increase in EGR percentage i.e., the BTE was lowest for B20 with no EGR, while it increased simultaneously with the rate of EGR. Maximum BTE was noticed for B20 with 15% EGR which was 11% higher than diesel. In the case of SFC, it decreased with the rise in EGR %. However, B20 with no EGR resulted in 9.9% higher SFC than diesel.

Similarly, CO and HC emissions of B20 with no EGR resulted in least emissions which was 8.86% and 18.52% lesser than diesel. Similarly, Smoke opacity of B20 without EGR was 21.16% lower than diesel.

In contrast to the above behaviours the amount of NOx released reduced considerably with an increase in rate of EGR. NOx was highest for B20 without EGR and least for B20 with 15% EGR which was 6.1% lower than diesel. This behaviour of NOx reduction was the major reason for the incorporation of the EGR technique.

NOMENCLATURE

ASTM	American society of testing and materials
B20	Juliflora biodiesel 20% + 80% diesel
BSFC	Brake specific fuel consumption
BTE	Brake thermal efficiency
CO	Carbon Monoxide
CO_2	Carbon dioxide
EGR	Exhaust Gas Recirculation
HC	Hydrocarbons
NO_x	Nitrogen oxides
POME	Palmyra oil methyl ester
VCR	Variable Compression Ratio

AUTHORSHIP CONTRIBUTIONS

Authors equally contributed to this work.

DATA AVAILABILITY STATEMENT

The authors confirm that the data that supports the findings of this study are available within the article. Raw data that support the finding of this study are available from the corresponding author, upon reasonable request.

CONFLICT OF INTEREST

The author declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

ETHICS

There are no ethical issues with the publication of this manuscript.

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