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Optimizing Emission Reduction and Performance Stability in Diesel Engines: A Study on the Effects of Exhaust Gas Recirculation with Biodiesel/Diesel Fuel Blends

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Abstract- This study aims to evaluate the effects of Exhaust Gas Recirculation (EGR) on the performance and emission characteristics of a single-cylinder, four-stroke diesel engine fueled with a blend of 70% diesel and 30% biodiesel (B30). The engine was operated at a constant speed of 1500 rpm under varying load conditions, using three fuel configurations: pure diesel (B0), B30 without EGR, and B30 with EGR rates ranging from 0% to 40% in 10% increments. The impact of these fuel EGR combinations on engine performance metrics such as brake thermal efficiency (BTE), exhaust temperature, and emissions including nitrogen oxides (NOx), soot, carbon monoxide (CO), and carbon dioxide (CO_2) was systematically analyzed. The experimental results indicate that B30 combined with EGR can be used effectively under the same operational conditions as diesel. Specifically, BTE decreased by 6% with B30 at 10% EGR, but increased by 7% under the same conditions in a different trial, suggesting sensitivity to combustion parameters. Exhaust gas temperature decreased by 16% at 40% EGR. Notably, NOx and soot emissions were significantly reduced by 68% and 37%, respectively, with B30 at 40% EGR. However, this was accompanied by an increase in CO and CO_2 emissions by 33% and 25%, respectively. These findings confirm that integrating EGR with biodiesel–diesel blends can substantially lower NOx emissions and exhaust temperatures, supporting its potential as a viable strategy for cleaner combustion in diesel engines. However, optimization is necessary to balance emission reductions with efficiency and carbon-related emissions.

Keyword: Biodiesel fuel additives; exhaust gas recirculation EGR; engine emissions; biodiesel/diesel blends; NOx emissions; Soot opacity

I. INTRODUCTION

The growing concerns over fossil fuel depletion, environmental degradation, and the pressing need to mitigate climate change have accelerated the global shift toward sustainable energy systems. Among the sectors contributing significantly to greenhouse gas (GHG) emissions, the transportation and power generation sectors, predominantly powered by diesel engines are primary targets for cleaner, more sustainable alternatives [1-6]. The pursuit of sustainability in diesel engine operations thus centers on reducing dependence on petroleum-based fuels and minimizing the harmful emissions associated with conventional combustion processes [7-14].

Biodiesel, a renewable and biodegradable fuel derived from organic sources such as waste cooking oil (WCO), presents a promising alternative to conventional diesel [15-22]. It offers several environmental advantages, including lower emissions of carbon monoxide (CO), unburned hydrocarbons (HC), and particulate matter (PM) due to its oxygen-rich molecular structure [23-31]. However, the use of biodiesel in compression ignition engines often results in elevated nitrogen oxides (NOx) emissions, one of the most challenging pollutants to control due to its significant role in ozone formation and respiratory health risks [32-42].

To address this, Exhaust Gas Recirculation (EGR) has emerged as an effective in-cylinder strategy to reduce NOx emissions by recirculating a portion of the exhaust gases back into the intake air. This dilutes the oxygen concentration and lowers peak combustion temperatures, thereby suppressing NOx formation [43-49]. When integrated with biodiesel/diesel blends, EGR offers a synergistic pathway to reducing overall emissions while maintaining acceptable engine performance [50-56]. The challenge, however, lies in balancing the trade-offs. While EGR reduces NOx emissions, it can potentially compromise combustion efficiency and increase emissions of CO and CO_2, especially at high EGR rates. Similarly, biodiesel blends can alter combustion characteristics, influencing parameters such as brake thermal efficiency (BTE), specific fuel consumption, and exhaust temperature [57-64].

The enormous volume of petroleum fuel burnt has a direct correlation to both hazardous exhaust emissions for human health and global warming. At first, biodiesel fuels were suggested as a workable substitute fuel to deal with these problems [53-56]. This viewpoint is supported by the many published studies in the field that study looks at how Exhaust gas recirculation (EGR) is one of the effective methods to control the combustion and emissions of a diesel engine[50-52]. To reduce climate change and the dependency on fossil fuels, the global community is turning rapidly to energy sources that are more renewable and sustainable. In particular, biodiesel has received much interest as a sustainable energy source and an alternative to fossil fuels. In terms of the world's energy demands, biodiesel provides a cleaner and more sustainable alternative to fossil fuels while having significantly lower environmental effects [65-70]. Currently, global fossil fuel prices are increasing primarily because of the ongoing conflict between Russia and Ukraine, illustrating the importance of this issue. By May 2022, the average wholesale price of tallow methyl ester had reached 111. USD per metric ton of oil equivalent, representing a remarkable increase of over 133% compared to the levels seen in 2018−2019.3 Also, the conflict between Russia and Ukraine slowed the global economy's recovery from the COVID-19 pandemic, and this conflict related economic limitation increased commodity prices, with disruptions to supply connections causing inflation in many regions worldwide [71-74].

Despite these challenges, the biodiesel market is predicted to increase at a 6.1% compound annual growth rate (CAGR) to 49[3].4 billion USD by 2027, and this growth indicates the biodiesel industry's global demand. The global biodiesel market is expected to expand from 36.55 billion USD in 2022 to 38.93 billion USD in 2023, reflecting a 6.5% CAGR [4]. Furthermore, the world is making enormous strides toward carbon neutrality to minimize carbon emissions, and adopting alternative fuels such as biodiesel is an important part of this change [5]. Indonesia, Malaysia, and Thailand are prominent biodiesel producers in Southeast Asia, and they mostly use crude palm oil (CPO) as the primary feedstock for biodiesel production because of its high oil content. Therefore, CPO has become a significant agricultural commodity, especially in Indonesia and Malaysia, which have become key players in the regional production of CPO to date. The International Energy Agency reported that approximately 47.87 billion liters of biodiesel were produced globally in 2022[6]. In 2022, the Food and Agriculture Organization of the United Nations reported that these two nations are global palm oil giants, accounting for more than 20.6% of total world production [38, 75-77]. In order to meet the present emissions standards, exhaust gas recirculation (EGR) is one of the most effective means of reducing NOx emissions from the CI engine by reducing the availability of extra oxygen and the temperature during the combustion because of high specific heat of exhaust gas [78-81].

Cooled exhaust gas recirculation (EGR) to increase the fuel-air ratio and found that hot EGR at light loads improved thermal efficiency due to the increase in charge temperature with corresponding reduction in NOx and smoke formation. Cooled EGR has been reported to give slightly lower thermal efficiency with greater NOx reduction, when compared to hot EGR [82-85].

II. EXPERIMENTAL METHODOLOGY AND PROCEDURE:

A. *TEST RIG SETUP:*

A-1. Engine and Test Rig Installation.

The engine is mounted on a test rig designed to allow the operator to adjust, measure, and modify various parameters while the engine is running. A direct injection diesel engine model (ZS1125NM) is connected to a hydraulic dynamometer (model ATE-160 LC), enabling load variation during operation. The test rig is also equipped to facilitate fuel type switching while the engine is running. This is achieved using flow control valves that allow the operator to open, close, and regulate the fuel flow to the engine. Fuel consumption is measured using a calibrated fuel measurement bench, which includes graduated markings for precise volume readings. Emissions are monitored using a gas analyzer device (GASBOARD-5020), which continuously analyzes exhaust gases during engine operation. For soot measurement, the GASBOARD-

6010 analyzer is used; it provides printed outputs indicating the soot concentration in the exhaust gases. The test rig also includes an RPM indicator to display engine speed, and thermocouples are employed to measure both intake and exhaust gas temperatures. The schematic and actual views of the test rig are presented in Figures 1 and 2.

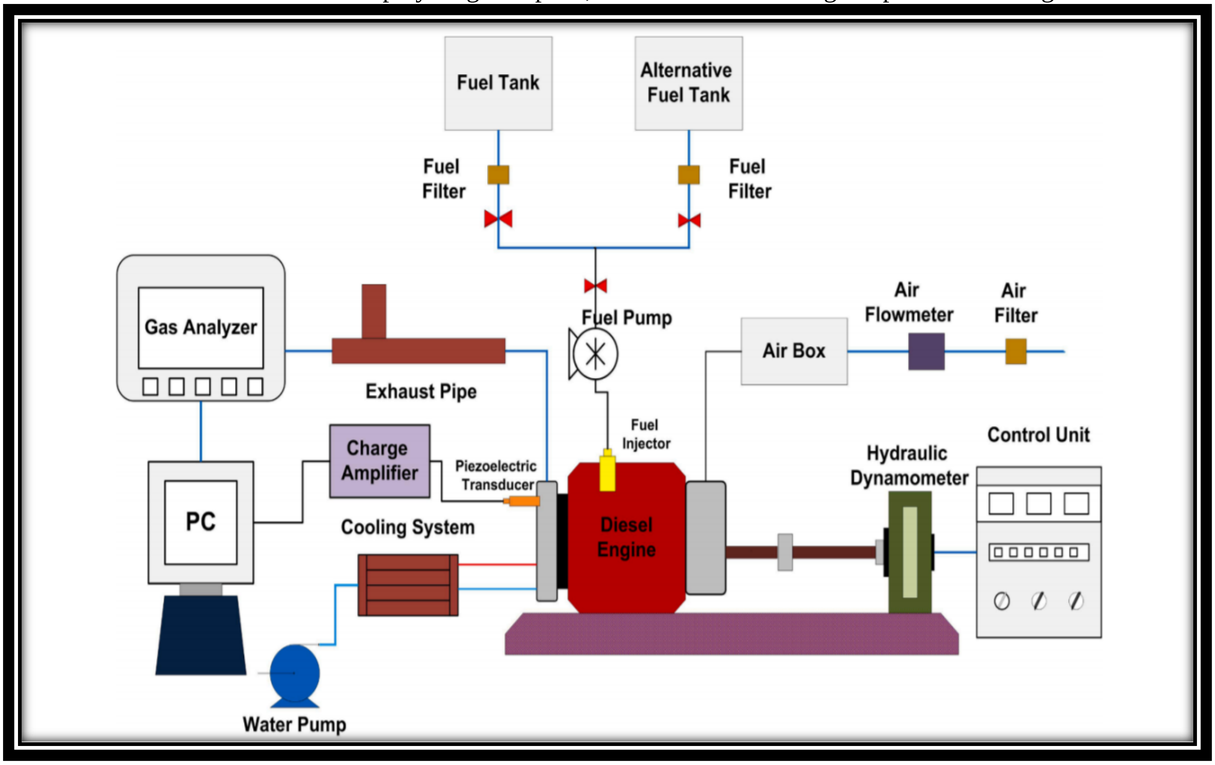

Figure 1. Schematic diagram of test rig

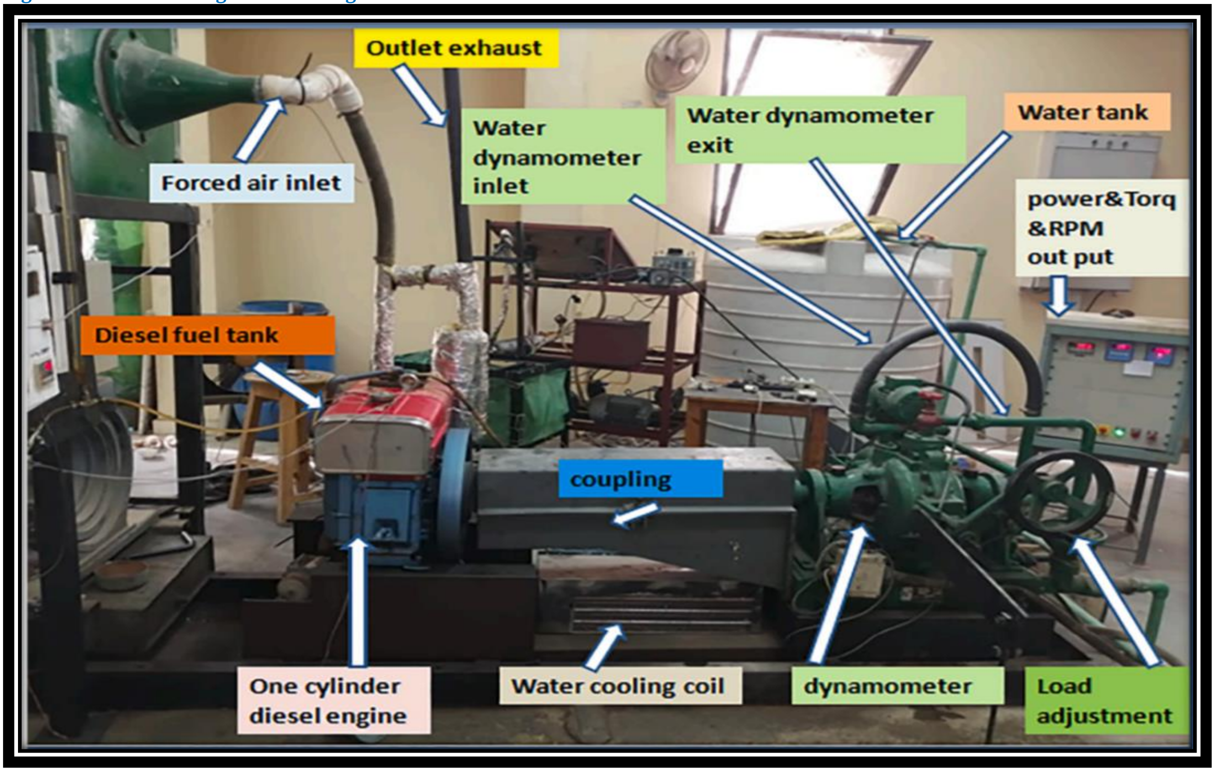

Figure 2. Actual photo of the test rig

A.2. Diesel Engine Specifications.

The used direct injection engine has the following characteristics in the **Table1**.

Table 1. Specifications of direct injection engine.

Parameters	Specifications
Type of engine	Engine model "ZS1125NM" Single cylinder, four strokes, horizontal, water cooling
Bore* stroke* displacement	125 mm * 120 mm* 1.473 L
Power of the engine	30 HP /2200 rpm
Cooling system	condenser
Lubrication system	Pressure /splash

A.3 Hydraulic dynamometer characteristics.

The dynamometer attached to the engine has the following characteristics in **Table 2.**

Table 2. Characteristics of Dynamometer.

Parameters	Specifications
Model	ATE-160LC
Type of Weighing Mechanism	Digital Torque indicator Load Cell
Load Cell Capacity	0 - 350 Kg. (0 - 1050 N-m)
Calibration Lever Arm Length	0.7645 m
Speed Sensing	60 Teeth Wheel with Sensor
Drive Attachment	Shaft Attached to Half Coupling
Absorption Type	Water/Hydraulic

B. *PRODUCTION METHODS OF BIODIESEL:*

B.1 Production Stage

During the production stage, a catalytic transesterification reaction is used to convert waste cooking oil (WCO) into biodiesel [53-58]. The main reactants in this process are waste cooking oil, methanol, and a catalyst (sodium hydroxide, NaOH). The chemical reaction occurs at a controlled temperature of 65 °C under continuous mixing for one hour [59-64]. It is critical to maintain this temperature, as exceeding 65 °C may lead to thermal degradation or burning of the oil. To ensure this, an electric heater is used and regulated to turn off once the temperature reaches to be 65 °C. The temperature was adjusted automatically by turns back on if the temperature drops below this threshold [86, 87].

The highest biodiesel yield achieved in this study was 93%, which occurred at a methanol-to-oil volumetric ratio of 0.2035:1 and a catalyst concentration of 0.65% by weight. The transesterification reaction takes approximately one hour and produces biodiesel, glycerol, and other impurities such as fats and dirt. Following the reaction, the mixture requires a separation phase, where glycerol is allowed to settle and separate from the biodiesel [88-92]. This separation typically takes about 12 hours to ensure a clean product. The experimental setup and the schematic diagram of the biodiesel production rig are shown in Figures 3 and 4.

B.2 Washing Stage

The next step in the production process is the **washing stage**, which aims to purify the produced biodiesel by removing residual dirt, unresolved fats, and other impurities using water under controlled temperature and mixing conditions. In this stage, hot water at 100 °C is used in a 1:1 volumetric ratio with biodiesel [93-98]. The mixture is agitated for one minute using a controlled mixing cycle turning the electric mixer on for 8 seconds and off for 3 seconds to prevent foam formation. After each cycle, the mixture is allowed to settle to enable separation of water and impurities from the biodiesel. This washing process is repeated approximately 3 to 5 times until the water appears clean, indicating effective purification [99-105].

Care must be taken to maintain the appropriate water-to-oil ratio and washing duration, as deviations can result in unwanted soap formation due to excessive emulsification. During the washing stage, some physical properties of the biodiesel are altered [106-110]. For instance, the color becomes visibly clearer, and the density decreases from 885.6 kg/m^3 to 851.6 kg/m^3. This reduction in density is favorable, as it narrows the density gap between diesel and biodiesel, making the biodiesel more compatible with fuel systems originally designed for conventional diesel. After the washing stage, the purified biodiesel is ready for use in engine combustion. However, long-term storage presents challenges due to the risk of oxidation, which can alter the thermal and physical properties of the biodiesel [111-114]. To minimize these effects, it is crucial to store biodiesel in sealed containers that protect it from exposure to air. Images illustrating the biodiesel washing process and the final purified product are shown in Figures 5, 6, 7, and 8.

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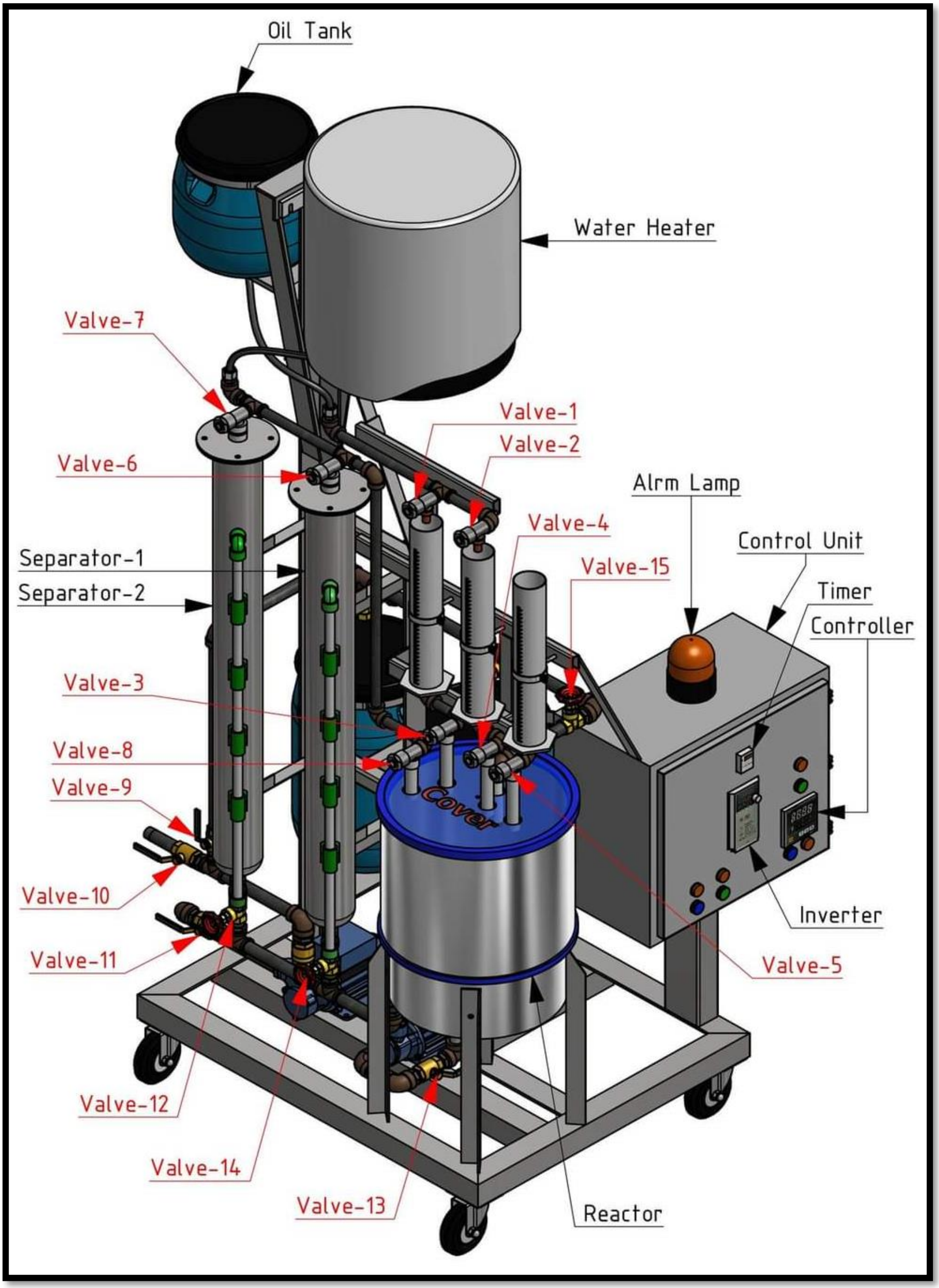

Figure 3. schematic diagram of production rig.

Figure 4. production test rig.

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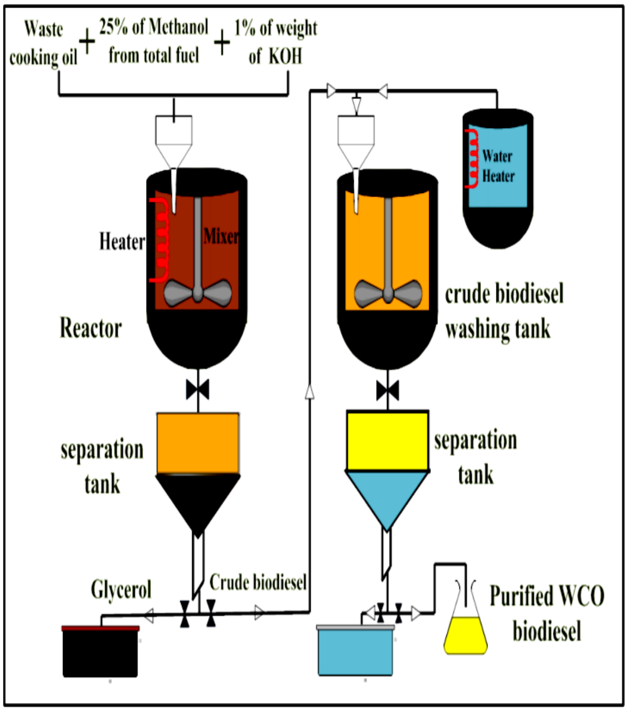

Figure 5. Schematic diagram of washing rig.

Figure 6. Washing test rig.

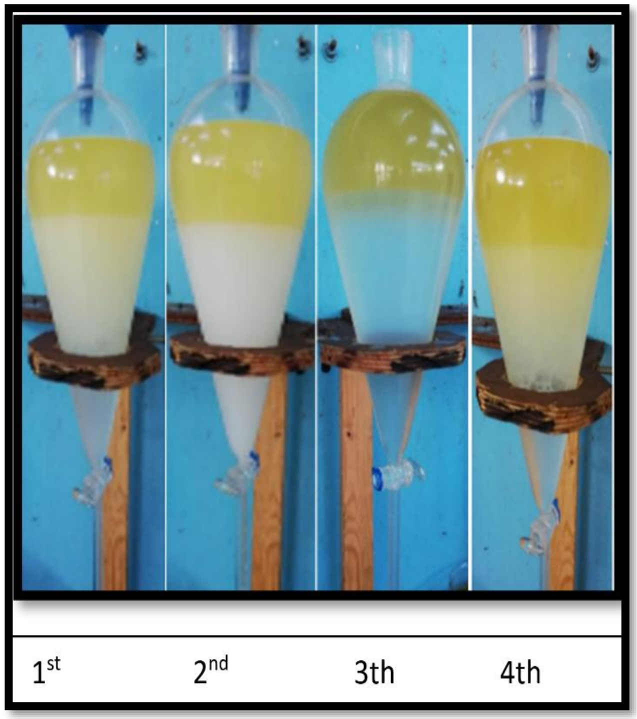

Figure 7. Stage of washing biodiesel.

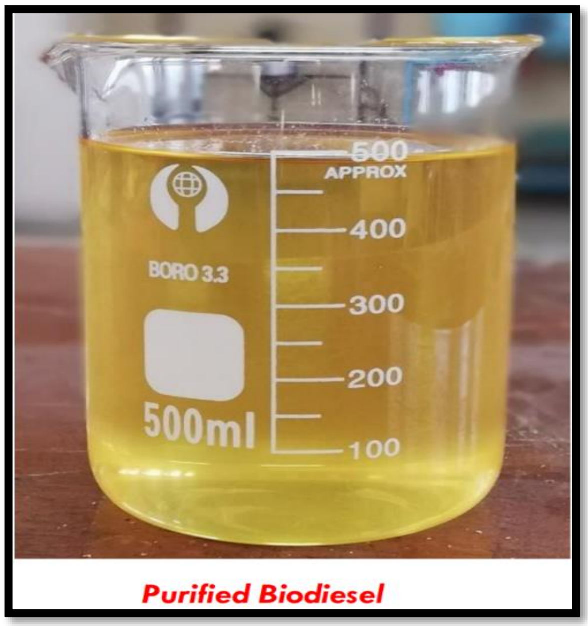

Figure 8. Purified biodiesel.

C. *EGR System and Fuel Preparation:*

The EGR (Exhaust Gas Recirculation) system is a key part of a vehicle’s emissions control system, used primarily in diesel and gasoline engines to reduce NOx (nitrogen oxide) emissions , it consist of the following: EGR Valve to Controls the amount of exhaust gas recirculated back into the intake manifold, their types is Vacuum-controlled (older systems) and Electronic (modern systems) [115-118]. In addition, EGR Cooler to Cools down the hot exhaust gases before they enter the intake manifold to reduce combustion temperature and NOx formation. In addition, EGR Pipe / Tubing to Channels exhaust gases from the exhaust manifold to the intake manifold. EGR Temperature Sensor is used to Monitors the temperature of recirculated gases. DPFE Sensor (Differential Pressure Feedback) to Measures pressure drop across a restriction in the EGR line to estimate flow. And, the Intake and Exhaust Connections to Ports or flanges on the exhaust and intake manifolds to connect EGR tubing [119-126]. Control Electronics (in ECU) to Monitors engine load, temperature, throttle position, and determines when and how much EGR is needed.

The diesel was mix with Biodiesel 30% with volumetric proportions. The mixtures were thoroughly mixed with manual stirring device for five consecutive minutes at a mixing speed of nearly 100 rpm @ room temperature before being placed within the fuel tank. Five blends were created by combining diesel and in the following portions: (70%Diesel + 30% Biodiesel fuel) @ (0%EGR to 40%EGR) by increasing 10% every experiment [127-131]. Figure 9 show EGR system and attached on the engine.

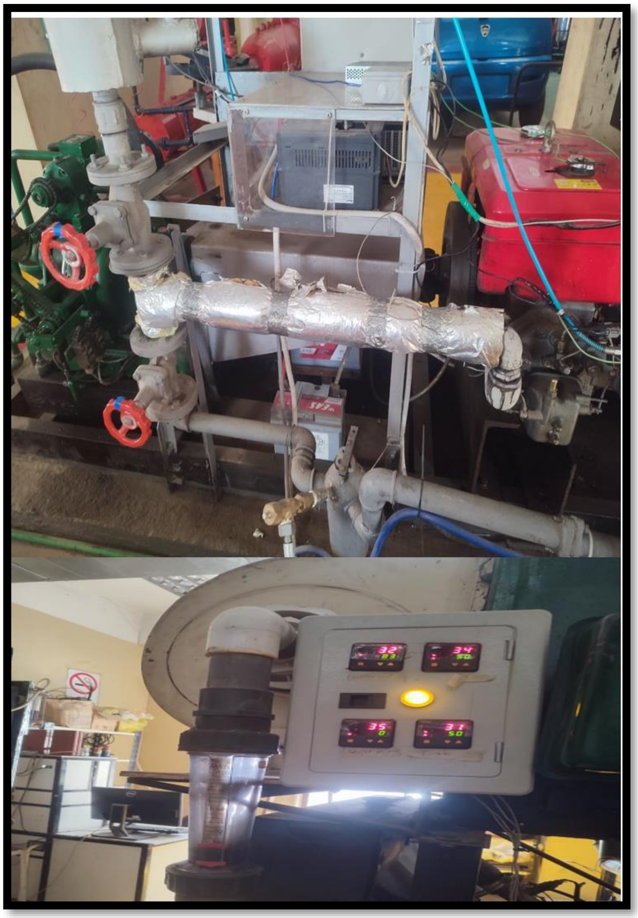

Figure 9. EGR system and attached on the engine.

D. *MEASUREMENT AND UNCERTAINTY (ERROR ANALYSIS):*

The Following Table shows the Emission Analyzer and Sensors Used in the test Table 3. In Figure 10 we find actual pictures of the measuring devices used to measure polluting emissions and soot resulting from the engine [132-135].

Table 3. Devices and sensors utilization

Device/sensor	Utilization
1st thermocouple	To measure air temperature
2nd thermocouple	To measure exhaust temperature
Speed sensor	To measure engine speed, attach to the engine's crankshaft.
DASHBOARD-	Measure the values of [CO, O2, and CO2] in (% vol) and [HC, NOx] in (ppm).
Orifice system	Measure the volume of air flowing into the engine
GASBOARD-6010 opacity meter	Used to measure soot opacity

Figure 10. Emission gas and opacity analyzers.

Because of the use of many devices, equipment, and optical measurement methods, each of them has an error rate that makes the results of the studied research need to be reviewed. Therefore, the total error rate resulting from the research must be studied by using Equation 1.

$$\frac{\Delta w}{w}=\sqrt{\sum_{x=1}^{\infty}\left(\frac{\Delta x_n}{x_n}\right)^2}--------eq.1$$

Where; $\frac{\Delta w}{w}$ is a total uncertainty rate of the experimental results, Δx_n is an error of the equipment, $\frac{\Delta x_n}{x_n}$ is an Uncertainty of each device used. Measuring fuel consumption is one of the methods used to measure specific fuel consumption (SFC) in which the measurement is done using a stopwatch and looking to determine the scale on the burette for its range. Where 10 cubic milliliters are measured during the time measured on the stopwatch, and we find the percentage of error in the measured volume Δx = ± 0.1cm, x =10 cm the uncertainty value (accuracy) will be Δ x/x= ±0.01=±1%. Table 4 shows the devices used, their range, and the measurement accuracy of each device.

Table 4. Device characteristics and accuracy.

Instrument	Parameters	Range	Accuracy
GASBOARD-6010 opacity meters	Soot opacity	0-100%	+2%, -2%
Shaft encoder	Speed	0-7200CA	+0.2%, -0.2%
Thermocouple	Exhaust gas temp.	0-800 0C	+1%, -1%
GASBOARD-5020 emission gas analyzers	CO	0-20%	+0.06%, -0.06%
	HC	0-9999ppm	+0.12%, -0.12%
	CO2	0-20%	+0.4%, -0.4%
	NO	0-5000ppm	+0.5%, -0.5%
	O2	0-25%	+0.1%, -0.1%
Graduated cylinder/stop watch	Fuel flow meter	1-30 cm3	+1%, -1%

From the above, the total uncertainty includes many factors in the experiment, as appeared in the accuracy of the devices used and the accuracy of the methods used. Thus, by applying Equation 1 to the coefficients, it becomes clear that the accuracy of the results in the experiment is as follows:

$$\frac{\Delta w}{w}=\sqrt{(1)^2+(2)^2+(0.2)^2+(1)^2+(0.06)^2+(0.12)^2+(0.4)^2+(0.5)^2+(0.1)^2+(1)^2}*\%$$

Δ W / w =2.735 %

The total error value will be Δ w = ± 0.02735

E. EXPERIMENTAL METHODOLOGY:

In this study, the experiment was conducted on a single-cylinder, four-stroke diesel engine operating at a constant speed of 1500 rpm under different load conditions. The experiments begin at no load and partial load and reach full load. The experiments were carried out using a mixture of diesel with biodiesel at different percentage of EGR. The effect of the combustion of the mixture with EGR on the combustion characteristics, engine performance, and the value of the resulting emissions was studied. This EGR percentage 10%, 20%, 30%, 40% respectively, and compares it with its values for pure diesel.

III. RESULTS AND DISCUSSION:

A. BRAKE THERMAL EFFICIENCY-BTE:

The Brake thermal efficiency is defined as the percentage of chemical energy produced by the fuel that is converted into usable work. We can evaluate its value from Equation 2, 3.

$$BTE=\frac{power}{m^{\bullet}*Cv}*100\%------(eq.2)\qquad [122].$$

$$m^{\bullet}=\rho*V^{\bullet}_{ol}----(eq.3)$$

where; $m^{\bullet}$ is defined as mass flow rate, Cv is defined as the calorific value of each fuel, ρ is defined as the density of each fuel, $V^{\bullet}_{ol}$ is defined as volume flow rate.

Figure 11 illustrates the variation in brake thermal efficiency (BTE) for pure diesel (100%) and a blend of 70% diesel and 30% biodiesel (B30) at EGR rates of 0%, 10%, 20%, 30%, and 40%, under different engine loads at a constant speed of 1500 rpm. As shown in the figure, thermal efficiency increases with increasing engine load across all operating conditions due to reduced relative heat loss. The results indicate that blending 30% biodiesel with diesel improves the average thermal efficiency by approximately 4% under EGR rates of 0% and 40%. However, a decrease in average thermal efficiency was observed at intermediate EGR rates: 6% at 10% EGR, 3% at 20% EGR, and 2% at 30% EGR. This decline is primarily attributed to the dilution of the intake air with inert exhaust gases primarily carbon dioxide (CO_2) which reduces the availability of oxygen required for complete combustion. Since biodiesel, inherently has lower energy content compared to petroleum diesel, the combined effect of EGR and reduced oxygen concentration further compromises combustion efficiency, leading to a reduction in both power output and overall thermal efficiency.

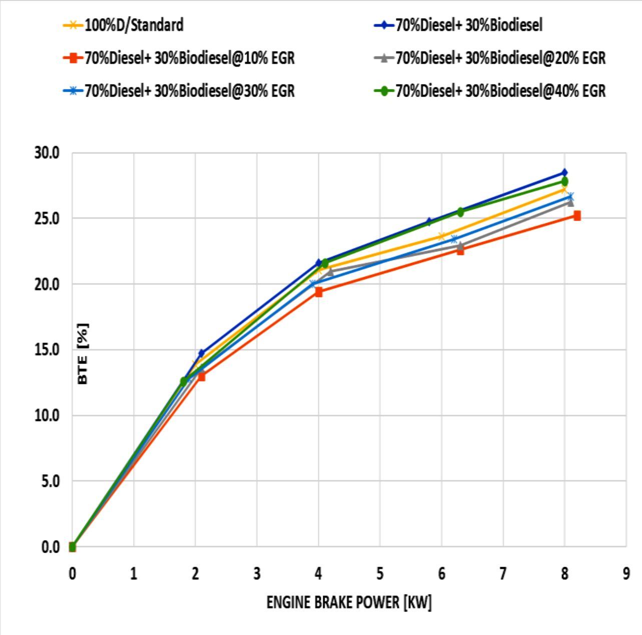

Figure 11. Brake Thermal Efficiency- BTE under Various Loads Conditions.

B. BRAKE SPECIFIC FUEL CONSUMPTION-BSFC:

Brake-specific fuel consumption, or BSFC, is the amount of fuel required to produce one unit of braking power and is determined by the calorific value of the fuel. Brake-specific energy consumption (BSEC) should be used as the benchmark when using a variety of fuels with different calorific values. By dividing the overall energy used by the braking force produced, the BSEC is determined. To get the BSEC value in MJ/kWh,

Use equation 4.

$$BSEC = \frac{[(m^{\circ} * LHV)_{diesel} + (m^{\circ} * LHV)_{NH4OH} + (m^{\circ} * LHV)_{WCO}] * 3600}{power} --- eq.4$$

Where, BSEC in (MJ/kW.hr), m˚ in (kg/sec), LHV in (MJ/kg), and Power in (kW).

Figure 12 illustrates the variation in Brake Specific Energy Consumption (BSEC) for pure diesel (100%) and a blend of 70% diesel and 30% biodiesel (B30) at EGR rates of 0%, 10%, 20%, 30%, and 40%. From the figure, it is evident that adding 30% biodiesel to diesel fuel results in a 4% decrease in average BSEC at EGR levels of 0% and 40%, indicating improved fuel energy utilization under these conditions. However, at intermediate EGR rates 10%, 20%, and 30% the average BSEC increases by 7%, 3%, and 3%, respectively. This increase is primarily attributed to lower combustion temperatures and incomplete combustion resulting from reduced oxygen availability due to the recirculation of inert exhaust gases (mainly CO_2). The lower energy density of biodiesel compared to conventional diesel further contributes to the increased energy requirement per unit of power output at these EGR rates.

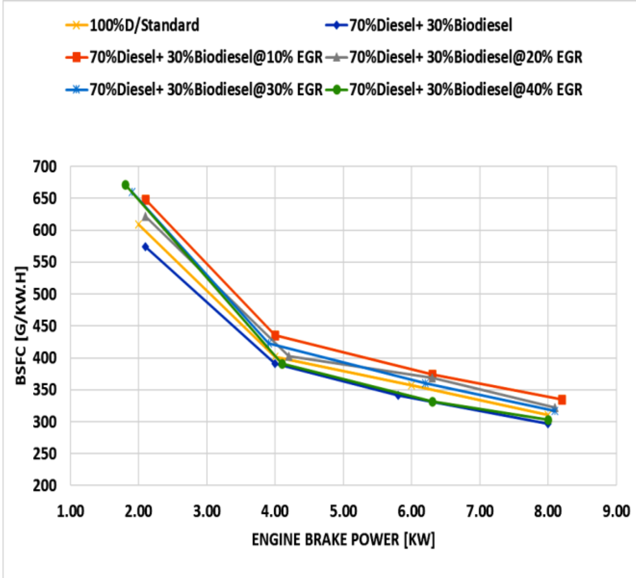

Figure 12. Brake-Specific Fuel Consumption Under Variation of Load Conditions.

C. EXHAUST GAS TEMPERATURE-EGT:

Since the temperature of the exhaust gases and the heat loss from them are directly related to the thermal efficiency of the engine, measuring the temperature of the exhaust gases is essential. Figure 13 shows an example of how exhaust temperatures fluctuate under different loads. It is clear from the figure that average exhaust gases temperatures decreasing by 4%, 5%,8%,12% and 16% for (Diesel 70%& Biodiesel 30%) @ EGR percentage 0%,10%, 20%,30%,40% ,respectively.

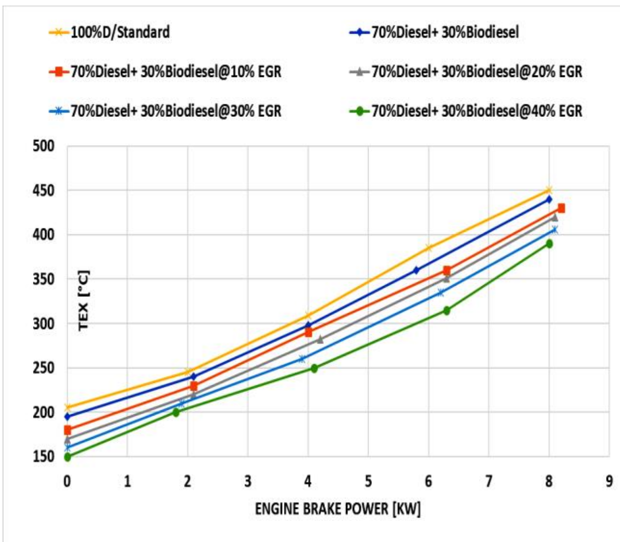

Figure 13. Exhaust gas temperature under variation of load conditions.

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D. OXIDES OF NITROGEN –NOX:

One of the primary motivations for employing Exhaust Gas Recirculation (EGR) is the reduction of nitrogen oxide (NO_x) emissions, which is especially significant for biodiesel, as it typically generates higher NO_x levels compared to conventional diesel. EGR helps address this drawback by lowering combustion temperatures and reducing oxygen concentration in the intake mixture. Figure 14 illustrates the variation in NO_x emissions for pure diesel (100%) and a 70% diesel-30% biodiesel blend (B30) under EGR rates of 0%, 10%, 20%, 30%, and 40%, at various engine loads and a constant engine speed of 1500 rpm. The figure clearly shows that average exhaust gas temperatures decreased by 15%, 48%, 59%, 63%, and 68% for the B30 blend at 0%, 10%, 20%, 30%, and 40% EGR, respectively. This trend reflects the effectiveness of EGR in lowering NO_x emissions, as both oxygen concentration and flame temperature are reduced, which suppresses the formation of thermal NO_x during combustion.

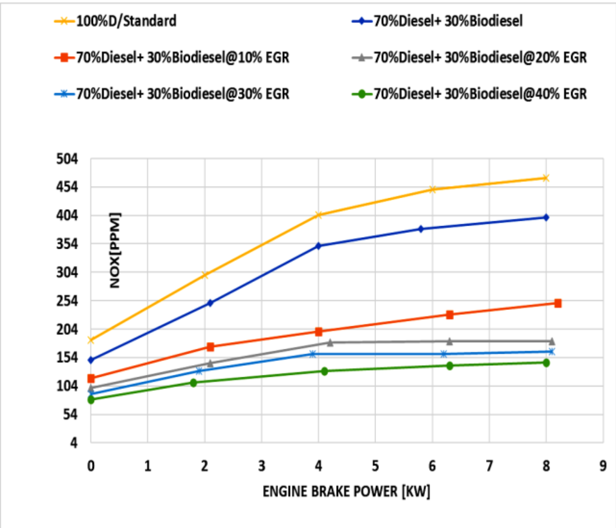

Figure 14. Oxides of Nitrogen under Variation of Loads Conditions

E. CARBON MONOXIDE-CO:

Biodiesel typically produces lower carbon monoxide (CO) emissions compared to conventional diesel, primarily due to its higher oxygen content, which promotes combustion that is more complete. However, the application of Exhaust Gas Recirculation (EGR) can lead to a rise in CO emissions, as it introduces inert gases into the intake charge, reducing oxygen availability and combustion efficiency. When biodiesel and EGR are used together, CO emissions may increase slightly, but they generally remain within acceptable limits. Overall, the net effect is a modest increase in CO emissions, which still often remains lower than that of pure diesel under certain conditions.

Figure 15 presents the variation in CO emissions for Diesel 100% and a 70% diesel- 30% biodiesel blend (B30) with EGR rates of 0%, 10%, 20%, 30%, and 40%, across various engine loads at a constant speed of 1500 rpm. The results indicate that average CO emissions for the B30 blend increased by 8%, 16%, 23%, and 33% at EGR levels of 10%, 20%, 30%, and 40%, respectively, compared to the baseline. Notably, CO emissions decreased by 8% when using the B30 blend with 0% EGR, highlighting the cleaner combustion characteristics of biodiesel in the absence of exhaust gas dilution.

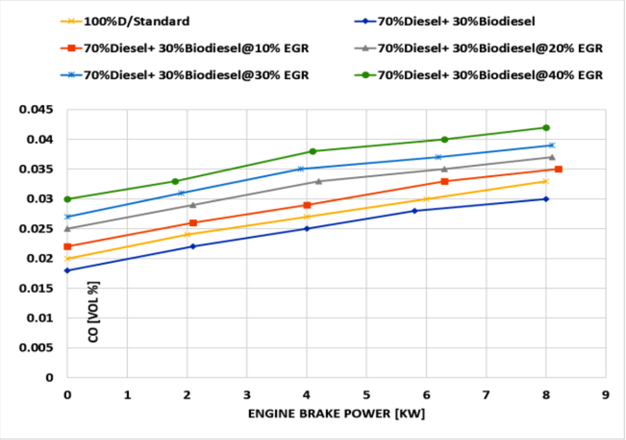

Figure 15. The variation of the Carbon monoxide under various load conditions.

F. CARBON DIOXIDE-CO_2:

Carbon dioxide (CO_2) emissions may be slightly higher when using biodiesel, primarily due to increased fuel consumption and lower energy content compared to diesel. However, biodiesel is generally considered carbon-neutral over its lifecycle, as the CO_2 released during combustion is offset by the CO_2 absorbed during the growth of the feedstock plants. As a result, the net lifecycle CO_2 emissions remain lower than those of fossil diesel, even if tailpipe CO_2 appears slightly elevated.

Figure 16 illustrates the variation in CO_2 emissions for Diesel 100% and the 70% diesel–30% biodiesel blend (B30) at EGR rates of 0%, 10%, 20%, 30%, and 40%, across various engine loads at a constant speed of 1500 rpm. The results show that average CO_2 emissions for the B30 blend increased by 6%, 11%, 18%, and 25% at EGR levels of 10%, 20%, 30%, and 40%, respectively. In contrast, a 6% decrease in CO_2 emissions was observed with 0% EGR, indicating the cleaner combustion of biodiesel in the absence of recirculated exhaust gases. Despite these increases, when viewed from a full lifecycle perspective, biodiesel still contributes to lower net CO_2 emissions, reinforcing its value as a more sustainable alternative to conventional diesel.

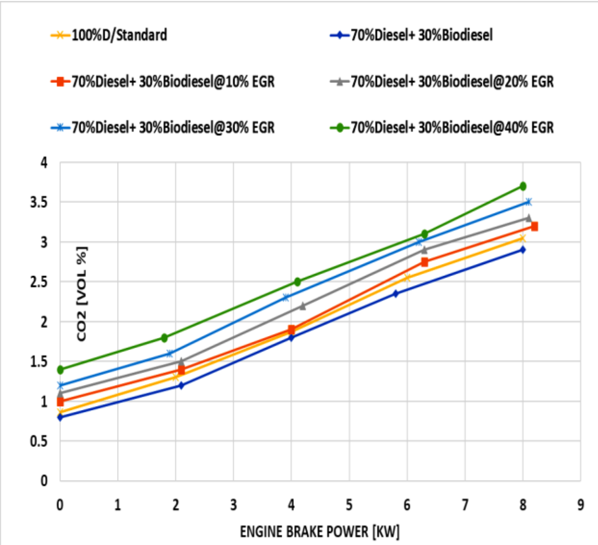

Figure 16. The variation of the Carbon dioxide under various load conditions.

G. OXYGEN- O2:

The oxygen (O_2) concentration in exhaust gases provides insight into the air–fuel mixture and combustion completeness. When using biodiesel alone, O_2 levels in the exhaust are typically slightly higher than those of conventional diesel, due to the inherent oxygen content in biodiesel and often leaner combustion. When Exhaust Gas Recirculation (EGR) is introduced, it reduces the intake oxygen concentration by replacing some of the fresh air with inert exhaust gases. This dilution results in lower combustion temperatures and less oxygen available for complete combustion. Despite this, some unburned oxygen may still appear in the exhaust if combustion efficiency is compromised. When combining biodiesel with EGR, the exhaust O_2 levels tend to decrease compared to biodiesel without EGR, as less air is admitted into the cylinder. However, these levels may still be slightly higher than diesel with EGR, due to biodiesel's inherent oxygen content and differences in combustion characteristics.

Figure 17 illustrates the variation in exhaust oxygen levels for Diesel 100% and a 70% diesel–30% biodiesel blend (B30) with EGR rates of 0%, 10%, 20%, 30%, and 40%, across various engine loads at a constant engine speed of 1500 rpm. The results indicate that, for the B30 blend, average oxygen concentration in the exhaust decreased by 4%, 6%, 9%, and 12% at EGR levels of 10%, 20%, 30%, and 40%, respectively, while a 3% increase was observed at 0% EGR. These findings confirm that EGR effectively reduces residual oxygen in the exhaust, particularly when used with biodiesel blends.

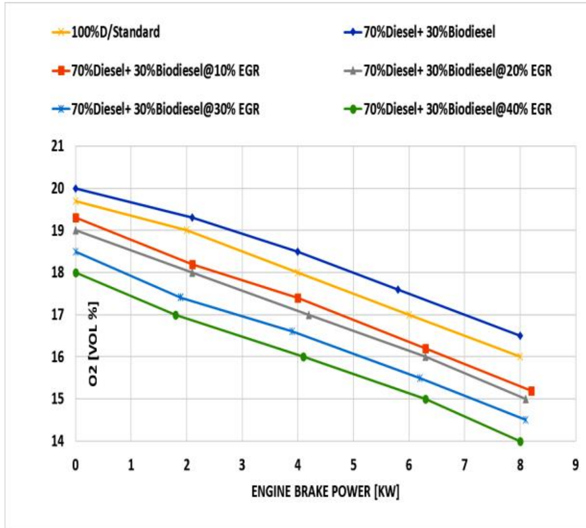

Figure 17. The variation of the oxygen under various load conditions.

H. SOOT LEVEL:

Soot, or smoke opacity, represents the concentration of visible particulate matter in exhaust gases and is a direct indicator of combustion completeness and fuel-air mixing quality. High soot levels generally suggest incomplete combustion and poor air–fuel mixing.

Using biodiesel alone significantly reduces smoke opacity compared to pure diesel. This is largely due to biodiesel's inherent oxygen content, which promotes a more complete and cleaner combustion process, resulting in lower soot formation. Using EGR alone typically increases smoke opacity, as it reduces the available oxygen in the intake charge, thereby hindering complete combustion and promoting soot formation. When biodiesel and EGR are combined, the smoke opacity remains lower than with diesel and EGR alone, as the oxygen-rich nature of biodiesel partially compensates for the oxygen dilution caused by EGR. Thus, the combination strikes a balance, maintaining acceptable soot levels while reaping the NO_x reduction benefits of EGR.

Figure 18 illustrates the variation in soot (smoke) levels for Diesel 100% and the 70% diesel–30% biodiesel blend (B30) with EGR rates of 0%, 10%, 20%, 30%, and 40%, across different engine loads at a constant speed of 1500 rpm. The results clearly show that, for the B30 blend, average soot levels decreased by 17%, 22%, 29%, 33%, and

37% at EGR rates of 0%, 10%, 20%, 30%, and 40%, respectively, compared to Diesel 100%. These findings confirm that biodiesel blended with diesel fuel, even under high EGR conditions, significantly reduces soot emissions, making it a promising solution for cleaner diesel engine operation.

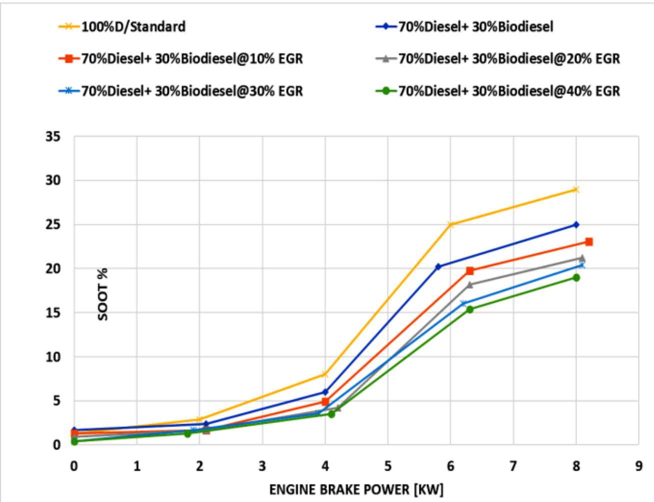

Figure 18. The variation of the soot level under various load conditions.

I. UNBURNED HYDROCARBONS-HC:

Unburned hydrocarbons (HCs) are a byproduct of incomplete combustion and are influenced by fuel type, air–fuel mixing, and combustion temperature. Biodiesel typically results in lower HC emissions than conventional diesel due to its higher oxygen content, which promotes combustion that is more complete and reduces the presence of unreacted hydrocarbons in the exhaust.

Exhaust Gas Recirculation (EGR) can slightly increase HC emissions, as it reduces combustion temperatures and slows down flame propagation, conditions that may prevent complete oxidation of hydrocarbons. When biodiesel is used in combination with EGR, the oxygen in the biodiesel helps compensate for the reduced combustion efficiency caused by EGR. As a result, HC emissions typically remain low and within acceptable limits, despite the presence of EGR.

Figure 18 shows the variation in unburned hydrocarbon emissions for Diesel 100% and the 70% diesel–30% biodiesel blend (B30) with EGR rates of 0%, 10%, 20%, 30%, and 40%, across different engine loads at a constant speed of 1500 rpm. The results indicate that for the B30 blend, average HC emissions decreased by 5%, 13%, 19%, 24%, and 9% at EGR levels of 0%, 10%, 20%, 30%, and 40%, respectively. These results demonstrate that the use of biodiesel with EGR maintains a low level of unburned hydrocarbons, confirming its potential for cleaner and more sustainable engine operation.

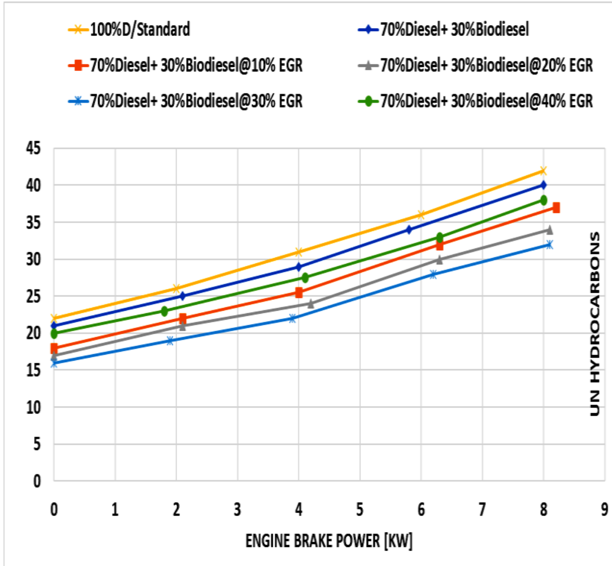

Figure 19. The variation of the UN hydrocarbons level under various load conditions.

IV. CONCLUSIONS:

This study evaluated the thermal efficiency, specific fuel consumption, and pollutant emissions of a diesel engine operated with 100% diesel and a blend of 70% diesel and 30% biodiesel (B30), under various Exhaust Gas Recirculation (EGR) rates of 0%, 10%, 20%, 30%, and 40%. The key findings are summarized as follows:

- **Brake Thermal Efficiency (BTE):**
  For the B30 blend at 10% EGR, the average BTE decreased by approximately **6%** compared to 100% diesel. This decline is attributed to EGR's dilution of the intake charge, which impairs combustion and reduces the burning rate.
- **Brake Specific Fuel Consumption (BSFC):**
  The average BSFC increased by about **7%** for B30 at 10% EGR. This rise is due to reduced oxygen availability from EGR, which affects combustion efficiency and increases fuel consumption.
- **NO_x Emissions:**
  NO_x levels decreased significantly across all EGR rates. Notably, at 40% EGR with B30, NO_x emissions were reduced by approximately **68%** compared to 100% diesel. This reduction is primarily due to lower combustion temperatures and reduced oxygen concentration.
- **Carbon Monoxide (CO):**
  CO emissions increased by around **33%** for B30 at 40% EGR, mainly due to incomplete combustion

caused by the oxygen-deficient environment created by high EGR rates.

- **Carbon Dioxide (CO_2):**
  CO_2 emissions increased by approximately **25%** for B30 at 40% EGR. This increase is a result of higher fuel consumption and the dilution effect of EGR, which lowers the effective oxygen concentration.
- **Oxygen (O_2):**
  Exhaust oxygen levels decreased by about **12%** at 40% EGR with B30, due to EGR introducing inert gases into the intake charge and reducing available oxygen.
- **Soot Emissions:**
  Soot levels were reduced by approximately **37%** for B30 at 40% EGR. This reduction is attributed to the inherent oxygen content in biodiesel, which promotes cleaner combustion.

Recommendation:

The use of Exhaust Gas Recirculation (EGR) is recommended, particularly in combination with biodiesel blends, as it effectively reduces NO_x emissions and exhaust temperatures. However, its impact on fuel efficiency and other emissions (such as CO and CO_2) must be carefully managed, especially at higher EGR rates.

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