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Impact of Biodiesel-Diesel Blends and EGR on Emissions and Performance of a Single-Cylinder Diesel Engine at Constant Speed

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Abstract: This study investigates the impact of biodiesel-diesel blends and exhausts gas recirculation (EGR) on the emissions and performance of a single-cylinder, direct injection diesel engine operating at a constant speed of 1600 rpm. Four biodiesel blends 15%, 30%, 45%, and 60% by volume were tested to evaluate their effects on nitrogen oxide (NOx), hydrocarbon (HC), carbon monoxide (CO), and smoke opacity emissions, as well as engine performance. The results showed that a 45% biodiesel blend at medium load significantly reduced NOx emissions by 65%, highlighting the blend's potential to enhance the renewable fraction of fuel. Further reductions were achieved by applying EGR rates of 15%, 30%, and 40%, leading to a maximum NOx reduction of 81.57% at medium load and 78.22% at high load. While moderate EGR rates (30-40%) slightly increased smoke opacity, levels remained manageable; however, opacity rose sharply beyond these rates for all blends. The study demonstrated that both NOx and smoke emissions could be simultaneously minimized using biodiesel blends and moderate EGR, with only a minor improvement in engine performance. Additionally, the tests indicated a slight reduction in HC emissions and a minimal rise in CO emissions across all blends compared to pure diesel under EGR conditions. Long-term durability tests confirmed the suitability of biodiesel blends (45-60%) for continuous operation without engine modifications or significant wear. This research aligns with global sustainability goals, particularly Sustainable Development Goals (SDGs) 7 (Affordable and Clean Energy) and 13 (Climate Action), by promoting renewable energy use and reducing harmful emissions in diesel engines. The findings support the development of eco-friendly, renewable fuel strategies for cleaner and more sustainable transportation system.

Keywords: EGR; Sustainable Development Goals; biodiesel-diesel blends; Single-Cylinder Diesel Engine

I. INTRODUCTION

Despite their high fuel efficiency and power output, diesel engines remain significant contributors to greenhouse gas emissions, which harm the environment and release carcinogens that threaten human health. Growing public concern over global warming and energy security has driven increased interest in bio-derived fuels as alternatives to conventional petroleum-based fuels [1-5]. Modifying fuel properties has gained attention as a way to meet stringent emission regulations, as these adjustments often require little to no changes to existing engine systems[6-10]. Blending alcohols or alternative fuels with diesel offers a promising solution to both the energy crisis and environmental concerns, as biofuels can be produced from renewable resources and their oxidizing properties help reduce harmful emissions[11-18]. However, using alcohols in compression ignition engines presents challenges due to their low Cetane number, high latent heat of vaporization, and extended ignition delay. Additionally, issues such as low calorific value, poor miscibility, instability during mixing, and inadequate lubricating properties complicate their use in diesel engines. Various technologies, including vaporization, dual injection systems, and blending alcohols or biofuels with diesel, have been explored to overcome these challenges [19-24].

In recent years, the use of higher concentrations of biofuels in diesel engines has gained significant attention due to their potential to enhance engine efficiency, lower fuel consumption, and reduce the cost of converting oils into biofuels[20, 21, 25, 26]. Research has shown that blending biofuels with pure diesel can substantially decrease emissions of soot and carbon monoxide, while also improving engine performance. Studies indicate that biofuels blends containing up to 60%–80% pure diesel can be used without modifying the engine or causing any visible damage to its components. Chen et al. demonstrated that combining high-purity diesel with biofuels and an exhaust gas recirculation (EGR) rate of 30%–40% can significantly reduce both nitrogen oxides (NOx) and soot emissions[27-32]. In our ongoing research, we are exploring the addition of catalytic alcohols, such as toluene, for use in low-temperature combustion (LTC). This advanced strategy employs high EGR rates to reduce both smoke and NOx emissions by extending the ignition delay, promoting better fuel-air mixing, and lowering combustion temperatures. Toluene, with its low Cetane number, can delay ignition and increase fuel mixing, while its rapid evaporation may enhance the overall mixing process. This makes it a promising candidate for achieving LTC in diesel engines [33-38]. Recently, researchers have also investigated the potential of n-pentanol, a 5-carbon straight-chain alcohol, as a diesel blending component.

Table 1 Show the studied alcohols like ethanol, methanol, and butanol, including higher energy density, greater Cetane number, better blending stability, and lower hygroscopicity. Moreover, its physical properties such as latent heat of vaporization, density, and viscosity are closer to those of diesel, making it an attractive renewable alternative. It can be produced from biological processes like microbial fermentation [34-39].

Limited studies have examined the use of pentanol in diesel engines, but early research is promising. Campos-Fernandez et al. evaluated blends of 10%, 15%, 20%, and 25% pentanol with diesel in a direct-injection diesel engine. They observed minor power losses, a slight increase in fuel consumption, and improved brake thermal efficiency. The study concluded that blends containing up to 25% pentanol can be used in diesel engines without the need for modifications. Meanwhile, Li et al. investigated pure pentanol combustion in a single-cylinder diesel engine and found that both NOx and soot emissions could be reduced without the use of EGR[40].

EGR is a well-established technology for reducing flame temperatures and oxygen levels within the combustion chamber, helping to minimize NOx emissions. In our current study, we explored the impact of EGR on the performance and emissions of four biodiesel-diesel blends (15%, 30%, 45%, and 60%) under three different EGR rates: 15%, 30%, and 40%. The results were compared with baseline diesel operation, showing that increasing the EGR rate led to NOx reductions of up to 81.57% at medium load and 78.22% at high load. While smoke opacity increased slightly with EGR up to 40%, it rose significantly beyond this point for all fuel blends. The study demonstrated that a combination of biodiesel-diesel blends and moderate EGR rates (30-40%) could effectively reduce both NOx and smoke emissions, with only a minor impact on engine performance. Additionally, hydrocarbon (HC) emissions decreased slightly, and carbon monoxide (CO) emissions showed a minimal increase compared to pure diesel under EGR conditions. Overall, the study concluded that biodiesel blends of 45%–60% can be used safely in diesel engines without modifications, and no significant wear or damage was observed during long-term durability testing[41].

Table 1. Properties of Diesel fuel, Fuel properties of diesel, ethanol, Toluene and n-pentanol[42].

Properties	Diesel	Ethanol	n-Pentanol	Toluene
Chemical formula	$C12H26–C14H30$	$C2H5OH$	$C5H11OH$	C_7H_8
Cetane number	52	11	20	5
Low heating value (MJ/kg)	43	27	32	95
Latent heat of vaporization (kJ/kg)	256	918	308	110.6
Density (kg/m3) (kg/m3)	850	789.4	809.7	870

II. EXPERIMENTAL TEST FACILITY

The testing facility features a fully automated test bench equipped with measuring and control devices for various engine parameters, including engine speed, load, and temperatures of both water and lubricating oil[43-49]. The engine is a single-cylinder, water-cooled unit connected to an electric DC dynamometer, allowing for precise measurement and control during operation. This engine can operate on different principles: the Otto cycle (spark ignition), direct injection (compression ignition), or indirect injection diesel, with configurations easily adjustable through modifications to the crankshaft gear mechanism [50-55].

Tests were conducted on a naturally aspirated, air-cooled, single-cylinder diesel engine with direct injection, operating at a constant speed of 1600 rpm [56-59]. The engine was connected to a hydraulic dynamometer, mounted on bearings within a rigid frame designed for swinging field-type loading. The engine has output power was measured by capturing the reaction torque using a strain gauge load cell [60-62]. To monitor the combustion process, pressure inside the combustion chamber was recorded with an AVL GH12D miniature pressure transducer, providing precise data for analysis[63].

A. *OPERATING MACHINE EGR COMPONENTS*

Figure 1 the schematic diagram of the operating machine, illustrated in this study, an external cooled EGR (Exhaust Gas Recirculation) system was employed to reduce NOx emissions. By cooling the recirculated exhaust gases, the intake air charge temperature is lowered, which in turn decreases the peak in-cylinder temperatures, thereby inhibiting NOx formation. Additionally, cooling increases the density of the exhaust gases, allowing for a higher proportion of EGR to be utilized[64]. A portion of the exhaust gas is directed through an EGR cooler, which is a heat exchanger where the cooling water is maintained at a constant temperature to absorb heat from the exhaust gases before they are mixed with fresh intake air in the manifold. It is important to note that the temperature of the recirculated exhaust gas is kept cooler than the engine exhaust but warmer than the intake air charge. In this experiment, the exhaust gas is cooled to 35°C. The EGR flow rate is controlled by an EGR valve, and an orifice is used to measure the flow rate of the exhaust gas. Thorough mixing of the fresh intake air and the recirculated exhaust gas is achieved in the mixing chamber before the mixture is introduced into the combustion chamber. The EGR quantity is expressed as a percentage and calculated using the following formula[65].

$$EGR\% = \left[\frac{CO_{2\,intake}}{(CO_2)_{exhaust}}\right] \times 100 \quad (1)$$

In provides a clear layout of its components. A single cylinder, direct injection, four strokes, vertical, water cooled engine is selected, the specification of which is given in the made at the intake air manifold of the engine. Diesel flow is governed by the governor and the acetylene flow rate is varied manually with the help of gas flow meter. Acetylene gas is continuously inducted at fixed flow rate. The compression ratio of the engine is varied by raising and lowering the bore and the head of the engine [66].

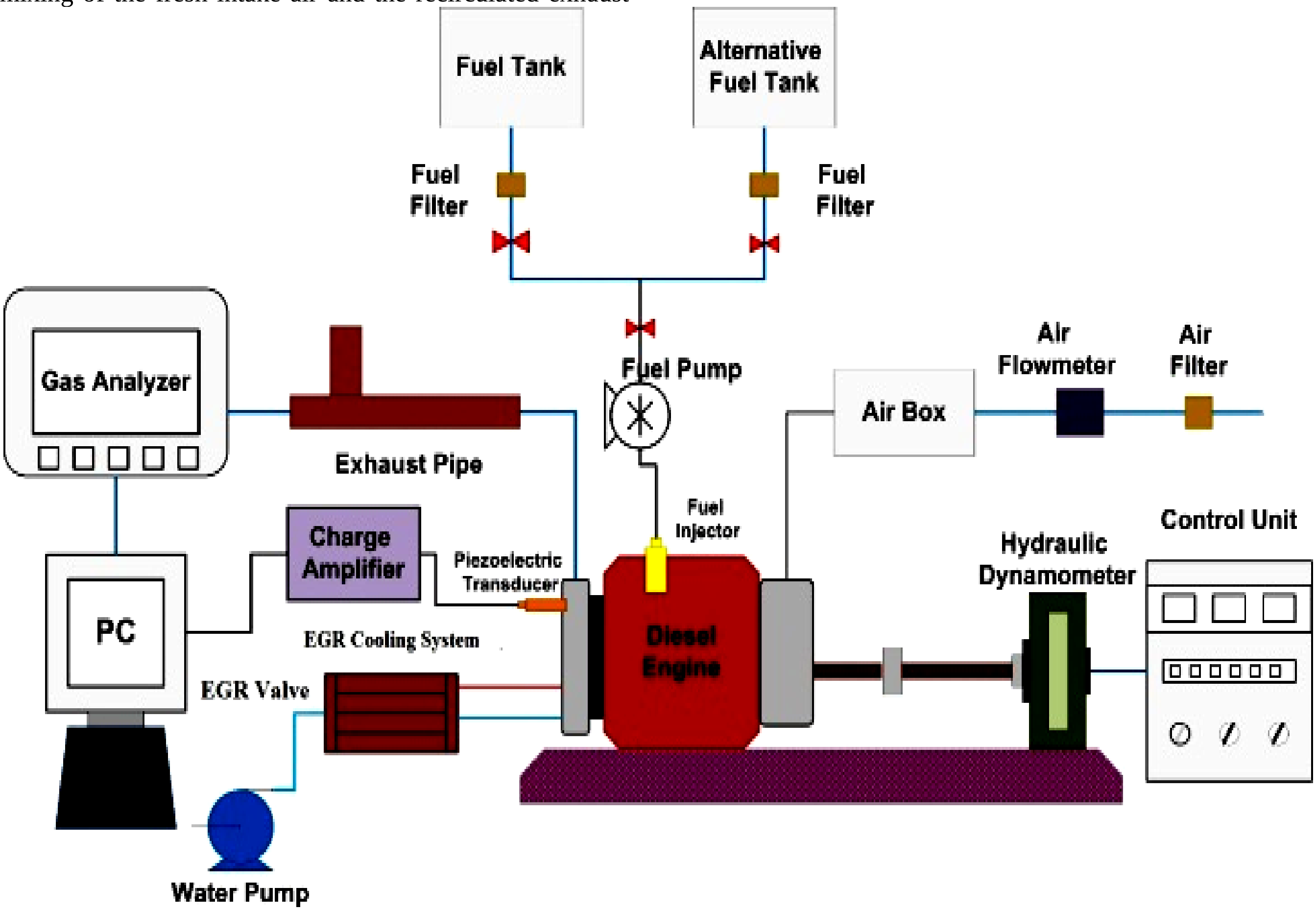

Figure 1. Schematic the operating machine diagram

Figure 2 presents a photographic view of the test setup. The facility is equipped with a fully automated test bench designed for engine testing, featuring precise control and monitoring of key engine parameters such as speed, load, and water and oil temperatures. The test engine is a single-cylinder, water-cooled model connected to a DC dynamometer, allowing for accurate performance measurements. This engine supports multiple operational modes, including the Otto cycle (spark ignition), direct injection (compression ignition), and indirect injection diesel, with easy adaptability achieved by altering the crankshaft gear mechanism. Cylinder pressure data is captured using a flush-mounted quartz pressure sensor, and the signals are logged on a computer system. Specialized software analyzes the pressure data over 100 consecutive engine cycles to calculate the heat release rate and other combustion characteristics. This calculation is based on the First Law of Thermodynamics, using the corresponding equation[67].The software calculates heat release rate on the basis of Ist law of thermodynamics using Eq[68].

$$\frac{dQ_n}{d\theta} = \frac{\gamma}{\gamma-1} p \frac{dV}{d\theta} + \frac{1}{\gamma-1} V \frac{dp}{d\theta} \quad \text{Equ. (2)}$$

Figure 1. Photographic view of test engine

B. *ERROR ANALYSIS*

The errors associated with various measurements and calculations of parameters are computed in this section. The maximum possible error in calculations was estimated by using the method proposed by Moffat[50, 69-73]. Errors were estimated from minimum values of the output and accuracy of the instrument. If an estimated quantity S, depends on independent variables, then the error in the value of S is calculated by using Since brake thermal efficiency (BTE) is calculated from fuel consumption, errors associated with it can be represented by the following [74].

$$\left(\frac{\partial BTE}{BFCE}\right) = \left(\left(\frac{\partial Torque}{Torque}\right)^2 + \left(\frac{\partial rpm}{rpm}\right)^2 + \left(\frac{\partial time}{time}\right)^2\right)^{\frac{1}{2}}$$

C. *TEST INSTALLATION DESCRIPTION*

The dynamometer facilitates load absorption and operational capabilities, equipped with a load cell for torque measurement[75]. Two electric sensors monitor speed and torque, transmitting signals The control panel is designed with indicators and a control unit[75]. That facilitates real-time monitoring and adjustment of various engine parameters. Operators can manipulate the dynamometer settings to regulate speed and load using intuitive control knobs[76-81]. Additionally, the injection timing can be automatically calibrated through a dedicated switch on the panel, ensuring optimal engine performance. The circulation of coolant and lubricating oil is efficiently managed by electrically powered pumps, which maintain consistent fluid flow. To regulate temperatures, water-fed heat exchangers play a crucial role, supported by a secondary cooling system that enhances the overall heat management process, ensuring the engine operates within ideal thermal conditions, developed in-house, consists of a large water tank and an additional heat exchanger. Heaters ensure that oil and coolant temperatures remain stable during warm-up and light load conditions [78-83]. Thermometers placed at critical points throughout the engine display readings on an electronic multi-point temperature indicator [84-88].

The engine's exhaust system connects to a custom-built muffler system[89]. Air intake is monitored using an Alcock viscous laminar flow meter to measure the airflow entering the engine. For fuel consumption measurement, a flow metering tank system is employed. A glass biuret of known volume is positioned parallel to the tank, and the time taken for the complete evacuation of the fuel sample feeding the engine is recorded. The system is designed with pipes and valves for rapid drainage of the fuel sample, including return fuel from the pump and injector, allowing for the quick refilling of the metering system with fresh fuel samples [90].

D. THE EXHAUST GAS ANALYSIS SYSTEM

Figure 3 show The exhaust gas analysis system comprises a set of instruments designed to measure soot (smoke), nitrogen oxides (NOx), carbon monoxide (CO), and total unburned hydrocarbons (HC)[91-95]. Soot levels in the exhaust are assessed using a Bosch RTT-100 opacity meter, which provides readings in Hartridge units (% opacity) or as equivalent soot density (mg of soot per cubic meter of exhaust gas). NOx concentration, measured in parts per million (ppm) by volume, is determined using a chemiluminescence analyzer (CLA) equipped with a thermostatically controlled heated line [96-99]. The CO concentration (ppm) is measured with a non-dispersive infrared analyzer (NDIR). Total unburned hydrocarbons (ppm) are detected using a flame ionization detector (FID), also featuring a thermostat-controlled heated line for accuracy[51-55, 100-102].

Figure 3. The Exhaust gas analysis and smoke meter of a machine.

E. *FUELS PROPERTIES*

Table 2 In this study, corn oil was blended with pure diesel fuel in volume ratios of 15/85%, 30/70%, 40/55%, and 60/40%, forming the primary fuel mixtures for the analysis. The vegetable oils were processed in a specialized treatment system in the laboratory at the Faculty of Engineering, Tanta University, where biodiesel was produced via transesterification using methanol and sodium hydroxide as a catalyst[103-109]. The properties of diesel fuel, vegetable oils, and biodiesel used in this study are summarized in Table 1.These values are typical and referenced from various sources, while the actual density was measured in the lab[110]. It is important to note that the kinematic viscosity and Cetane number values provided are for guidance only and were not used in the calculations. They are intended to offer qualitative insight into the performance and emission characteristics of the different fuel blends. Tests were conducted using each fuel blend, with the engine operating at a constant speed of 1600 rpm and under low, medium, and full load conditions [111]. To account for differences in calorific value and oxygen content among the fuel blends, comparisons the tests were conducted at a consistent engine load, determined by the average effective brake pressure, rather than focusing on a uniform mass of fuel or a specific air-to-fuel ratio. During each test, various parameters were meticulously measured, including volumetric fuel consumption, exhaust smoke density, and regulated emissions such as nitrogen oxides (NOx), carbon monoxide (CO), and total unburned hydrocarbons (HC) [112-116]. These measurements enabled the calculation of specific fuel consumption and brake thermal efficiency by utilizing the recorded fuel density and lower calorific value. This approach ensures that the results accurately reflect the engine's performance and emissions under controlled conditions [117]. The experimental work began with an initial test using pure diesel fuel to establish the baseline engine performance and emission levels. Subsequent tests with the fuel blends were compared to this baseline to assess changes in performance and emissions [118].

Table 2. Properties of Diesel fuel, vegetable oils and bio-diesels [89].

Fuel properties	Density at 15 _C (kg/m3)	Kinematic viscosity at 40 _C (mm2/s)	Lower calorific value (kJ/kg)	Cetane number (–)
Diesel fuel	837	3	42,700	50
Sunflower oil	920	34	36,500	37
Corn oil	915	35	36,300	38
Soybeanoil methyl ester	885	4.1	37,300	51
Olive kernel oil	925	32	37,000	39

F. *BIODIESEL PRODUCTION*

- **Step 1: The alcohol and catalyst mixture are prepared as follows**

Figure 4 Show the alcohol and catalyst mixture are prepared in the fuel laboratory at the Faculty of Engineering at Tanta University. Methanol is utilized as an alcohol that is purchased from laboratory chemicals, for trading chemicals in Tanta, Egypt, while sodium hydroxide is used as a catalyst, which is bought from Tanta, Egypt, from Al-Pharaohs company for trade and import at laboratory chemicals.

In the beginning, take a quantity of NaOH and weigh it on an electronic balance to estimate the weight required [119-123]. For example, in this paper, we need 49 gm for every 6 liters of oil, then grind the parts of NaOH till they turn into a powder [for every 1 liter of oil, use 7 gm of NaOH, then for every 6 liters of oil, use 49 gm of NaOH][124-128]. After that, fill an empty beaker with 1500 milliliters, which is equal to 1.5 liters of methanol with 49 gm of NaOH [for every 1 liter of oil, use 250 milliliters [0.25 liters] of methanol, then for every 6 liters of oil, use 1500 milliliters [1.5 liters] of methanol]. Finally, place the beaker of NaOH with methanol mixtures on a mixer instrument for 10 minutes to obtain the mixture of alcohol and catalyst [NaOH + Methanol][129-134].

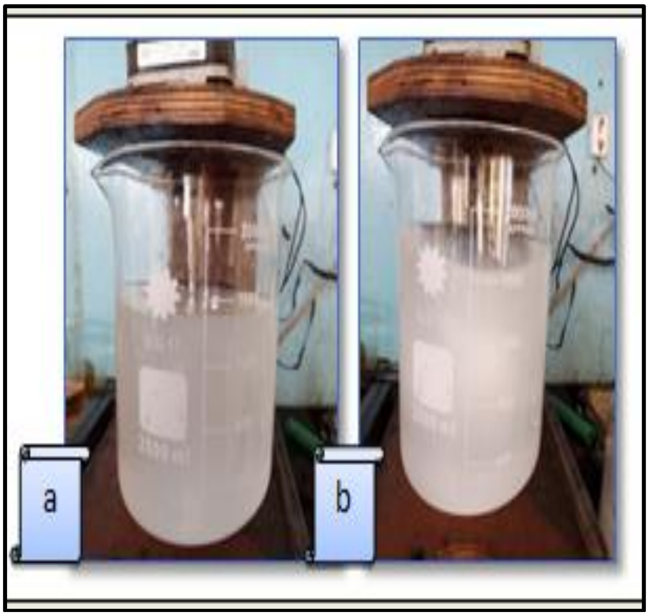

Figure 4. Preparation of an alcohol and catalyst mixture [Methanol + NaOH].

- **STEP 2: The biodiesel is prepared as follows in two stages**

Figure 5 Show Biodiesel is prepared at the fuel laboratory at the Faculty of Engineering at Tanta University. Table [9] contains the list of used components during the experiment, such as stirring machine components, electric heater, mixer instrument, electric kettle, 2 liters [2000 milliliters] beaker, and 1 liter [1000 milliliters] beaker.

Use corn oil mixture in biodiesel production in two stages: A. separation process stage and B. washing process stage by transesterification process. Moreover, the total quantity of usage oil is 25 liters, which is divided on the experiment into two phases, including the first phase for the first 6 liters and the second phase for the remaining 6 liters, while the washing process is done three times in phase 1 and twice in phase 2[135]. Furthermore, the biodiesel yield is about 90%, which is a result of the sum of the biodiesel production quantities at phase 1 [11 liters] and phase 2 [11 liters], respectively, with the overall biodiesel production quantity equal to 22 liters[136].

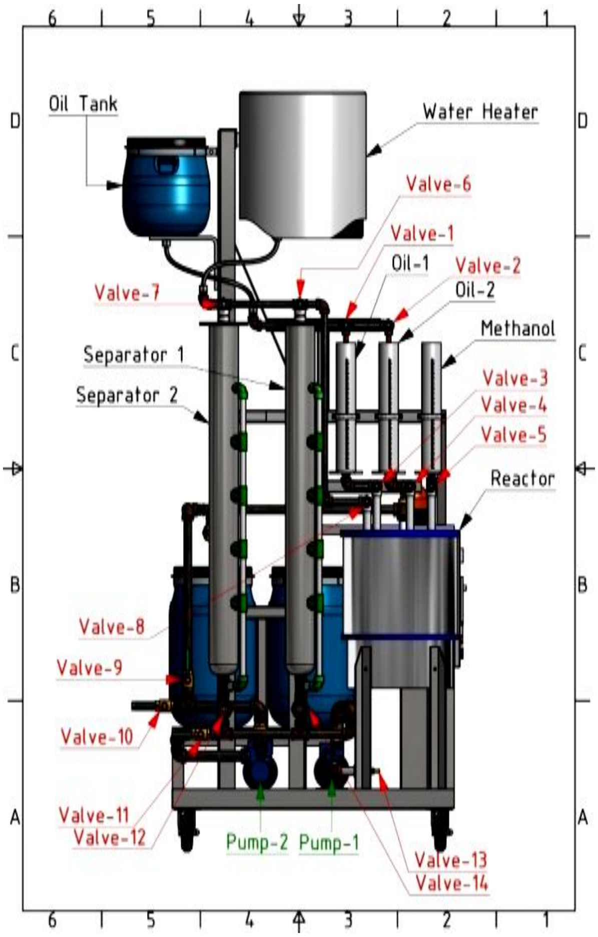

Figure 5, a: Schematic the operating machine diagram.

Figure 5, b: Photographic view of machine biodiesel production.

- **STEP 3: Prepare four various biodiesel and diesel blends**

Figure 6 Show After the biodiesel manufacturing process is completed, the preparation of biodiesel and diesel blends will begin in this paper. Furthermore, employ a variety of biodiesel and diesel percentages mixed, such as 15% biodiesel plus 85% diesel, 30% biodiesel plus 70% diesel, 45% biodiesel plus 55% diesel, and 60% biodiesel plus 40% diesel. Fill an empty 1 liter [1000 milliliters] beaker with an experimental concentration of biodiesel and diesel blend, then transfer the blend to an empty 2 liters [2000 milliliters] beaker to ensure that the blend does not come out of the beaker during the mixing process, and finally set it on the mixer instrument for 1 hour to create the blend[137-140]. The above steps should be repeated for each concentration. The outcomes of blends are clarified further[141].

Figure 6. Four biodiesel/diesel blends

III. III. Results and discussion

A. Engine exhaust performance analysis

Analyzing engine exhaust performance with Exhaust Gas Recirculation (EGR) involves evaluating several key parameters, including NOx emissions, particulate matter (PM), fuel consumption, engine power, and combustion efficiency[142-144]. The goal is to understand how EGR impacts these aspects to balance emission reduction with optimal engine performance. Here's a breakdown of key considerations in engine exhaust performance analysis with EGR[145]:

- **Engine Power Output:**
  EGR has a generally minor but noticeable impact on engine power output, especially under high-load conditions. Since EGR lowers combustion temperature and oxygen levels, this can lead to a reduction in maximum power. Power performance analysis often shows a slight drop in engine output at higher EGR levels, which may be more pronounced in diesel engines operating at high loads or speeds[145].
- **Combustion Stability and Temperature:**
  With EGR, peak combustion temperatures decrease, resulting in slower and sometimes less complete combustion. Performance analysis may include an assessment of in-cylinder combustion characteristics such as peak pressure, temperature profiles, and heat release rates. Lower combustion temperatures contribute to NOx reduction but can lead to misfires or unstable combustion at high EGR rates. This analysis helps in determining the optimal EGR rate that balances NOx reduction without compromising combustion stability[145].
- **Engine Cooling Load:**
  EGR increases the thermal load on the engine's cooling system since recirculating exhaust gases raise intake and in-cylinder temperatures. A comprehensive performance analysis includes monitoring coolant temperature and evaluating cooling system performance. Ensuring the cooling system can handle this additional thermal load is essential for maintaining engine reliability under various operating conditions.

B. Brake specific fuel consumption (B.S.F.C) with EGR

Figure 7 the impact of varying Exhaust Gas Recirculation (EGR) rates on Brake Specific Fuel Consumption (BSFC) is demonstrated for biodiesel-diesel blends at high engine loads. The general trend indicates that BSFC increases as EGR rates are elevated, with this effect being particularly noticeable at lower engine loads. The main reason behind this rise in fuel consumption is the decrease in combustion chamber temperature due to the introduction of cooled exhaust gases through the EGR system. When EGR is applied, a portion of the exhaust gases is recirculated into the intake, displacing some of the fresh air. Since these recirculated gases are inert and carry less oxygen, they dilute the fuel-air mixture, leading to a reduction in combustion temperature[146].

The lower temperature inside the cylinder results in incomplete combustion because there is insufficient heat and oxygen to fully burn the fuel. This incomplete combustion not only reduces the efficiency of the engine but also forces the engine to consume more fuel to generate the same power output as before. Essentially, the engine becomes less efficient because it is burning fuel less effectively[147].

Moreover, as more exhaust gases are recirculated, the overall quality of combustion diminishes, since the cooled gases slow down the combustion process. The engine has to compensate for this loss in efficiency by increasing fuel consumption. This is why BSFC rises with higher EGR rates.

In simpler terms, increasing EGR introduces cooler, inert gases into the combustion chamber, which weakens the combustion process. The engine must then burn more fuel to make up for the lost energy, resulting in a higher BSFC. This trade-off highlights one of the challenges in managing emissions and fuel efficiency in diesel engines, especially when using biodiesel blends. While EGR helps in reducing nitrogen oxide (NOx) emissions, it comes at the cost of higher fuel consumption due to the lowered combustion efficiency[148].

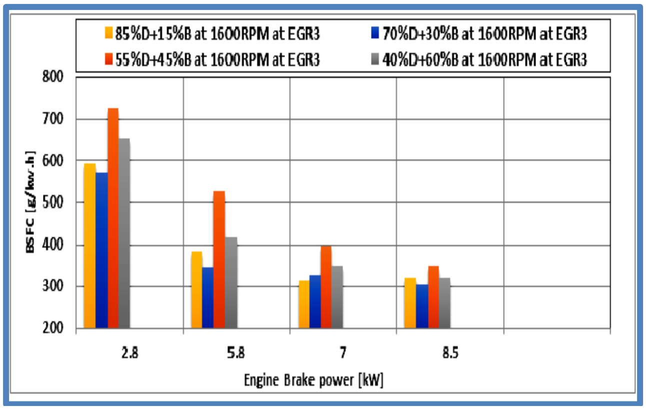

Figure 7. Illustrates the brake specific fuel consumption (b.s.f.c) blends at various engine brake power levels (loads) with EGR.

C. BRAKE THERMAL EFFICIENCY (BTE) WITH EGR

Figure 8 Show the effect of increasing Exhaust Gas Recirculation (EGR) rates on the performance of biodiesel-diesel blends at high engine loads is presented. It shows that the Brake Thermal Efficiency (BTE) experiences only a slight decrease across all biodiesel-diesel blends as EGR rates rise, particularly at lower engine loads. This is because higher EGR rates introduce more exhaust gases into the combustion chamber, which in turn disrupts the normal combustion process and slows down the burning rate of the fuel mixture. The lower combustion temperature, due to the dilution of the air-fuel mixture with inert exhaust gases, contributes to less efficient combustion[148].

Moreover, the increase in EGR rates leads to higher emissions of carbon monoxide (CO) and unburned hydrocarbons (HC). These emissions are typically the result of incomplete combustion, as the oxygen available in the cylinder is reduced, further impairing the combustion process. This incomplete combustion causes energy losses, reducing engine efficiency.

However, despite these drawbacks, the use of higher biodiesel blends with diesel shows improved performance. Biodiesel tends to have better lubricating properties and higher oxygen content, which can partially offset the negative effects of EGR. These benefits help to maintain a relatively stable engine performance, even with increased EGR rates, when compared to using pure diesel fuel alone[149].

In summary, while increasing EGR rates generally reduces combustion efficiency and leads to higher CO and HC emissions, the negative impact on performance is minimized when higher biodiesel blends are used, thanks to biodiesel's inherent advantages such as its oxygenated nature and improved combustion characteristics.

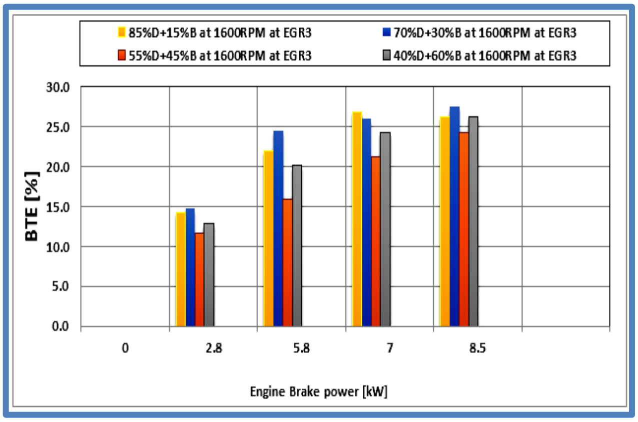

Figure 8. Change in brake thermal efficiency (BTE) blends at various engine brake power levels (loads) with EGR.

D. EXHAUST GAS TEMPERATURE (EGT) WITH EGR

Figure 9 Show the effect of increasing Exhaust Gas Recirculation (EGR) ratios on exhaust temperatures for various biodiesel-diesel blends at high engine loads is illustrated. The figure shows that as the EGR rate increases, the exhaust temperature decreases, particularly at higher engine loads. This trend is more pronounced as the proportion of biodiesel in the blend increases. The data reveal that the blend with the highest biodiesel content, 60%, exhibits the lowest exhaust temperature at high load conditions[150].

The decrease in exhaust temperature is due to several factors. First, the increase in EGR introduces more cooled exhaust gases into the combustion chamber, which reduces the overall combustion temperature. This reduction in peak combustion temperature is directly linked to the lower formation of nitrogen oxides (NOx), but it also causes a cooling effect that lowers the exhaust gas temperature.

Additionally, the higher evaporation rate of biodiesel during combustion plays a significant role in further reducing the exhaust temperature. As biodiesel evaporates more readily than diesel, it absorbs more heat from the combustion process, which contributes to the overall cooling effect. This combination of lower combustion temperatures and higher evaporation rates leads to a noticeable decrease in exhaust temperatures as the EGR rate increases and as the biodiesel content in the fuel blend rises[150].

In summary, increasing EGR ratios is resulting in lower exhaust temperatures for all biodiesel-diesel blends, with the most significant temperature reductions observed in blends with higher biodiesel content, particularly at high engine loads. This is due to the cooling effect of EGR, which reduces combustion temperatures, as well as the enhanced evaporation characteristics of biodiesel.

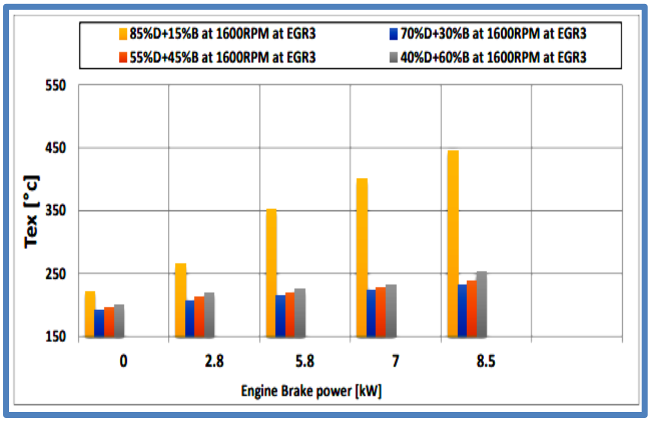

Figure 9. Changes in Exhaust Gas Temperature at various engine brake power levels (loads) with EGR.

E. Engine exhaust emissions analysis

Exhaust Gas Recirculation (EGR) is a key technique for controlling nitrogen oxide (NOx) emissions in diesel engines. When discussing the combustion of fuel blends in diesel engines with EGR applied, it is crucial to consider the unique fuel properties and operating conditions within the engine cylinder. Diesel fuel blends with relatively low blending ratios (15%, 30%, 45%, and 60% by volume) maintain injection rates and spray characteristics that closely match those of pure diesel under similar operating conditions, including injection timing, speed, and load (expressed as brake mean effective pressure).

Biodiesel and vegetable oils have slightly higher compressibility than diesel, potentially leading to a slight advance in injection timing; however, this effect is minimal and does not significantly alter combustion behavior, as the crank angle shift is negligible. The Cetane number, which indicates the ignition quality of the fuel, plays a role in ignition delay. Biodiesel generally has a higher Cetane number than diesel, which reduces ignition delay and shortens the initial premixed combustion phase, thereby lowering NOx emissions, particularly when EGR is used. Conversely, vegetable oils have a lower Cetane number, which increases ignition delay and extends the premixed combustion phase, leading to higher NOx formation. However, this increase is somewhat balanced by the absence of aromatic compounds in vegetable oils, which typically contributes to lower NOx formation overall.

The most notable difference between these fuels lies in the atomization process. Biodiesel and vegetable oils produce larger fuel droplets compared to diesel, with vegetable oil having much higher viscosity, which significantly slows down evaporation and impacts combustion. Under mixing-controlled combustion conditions, biodiesel and vegetable oils can improve combustion efficiency due to their higher oxygen content. However, in evaporation-controlled combustion, the high viscosity and slower evaporation of vegetable oils may hinder the combustion process[151].

The application of EGR reduces combustion temperatures by recirculating a portion of the exhaust gas, thereby reducing NOx emissions. In the engine used, where high compression ratios and advanced injection timing are present, diesel and biodiesel blends exhibit predominantly mixing-controlled combustion. In contrast, vegetable oil blends tend toward evaporation-controlled combustion due to slower atomization and evaporation characteristics. The absence of sulfur in biodiesel reduces particulate matter (PM) emissions, while EGR application helps balance reductions in NOx with managing particulate emissions, especially when using vegetable oil blends[145].

F. Unburned Hydrocarbon [HC]:

Figure 10 illustrates the variation in hydrocarbon emissions from an engine operating with diesel-biodiesel blends compared to pure diesel. A noticeable increase in hydrocarbon emissions is observed with lower biodiesel blend ratios (e.g., 15% biodiesel and 85% diesel), particularly under low engine load conditions. This increase is attributed to the lower Cetane number of these blends, which causes a longer ignition delay, weakening the fuel's auto-ignition properties. As a result, a quenching effect occurs in the lean mixture zones within the cylinder, leading to higher levels of hydrocarbon emissions in the exhaust[63].

Figure 10 demonstrates the effect of a higher blend ratio (60% biodiesel and 40% diesel) combined with Exhaust Gas Recirculation (EGR) on hydrocarbon emissions. Hydrocarbon emissions decrease at high loads; however, as the EGR rate increases, these emissions rise significantly. This increase is due to the reduction in flame temperature caused by higher EGR levels, creating larger flame quenching zones within the cylinder where complete combustion is challenging, thus increasing hydrocarbon levels in the exhaust. Results showed that hydrocarbon emissions rose from 23 parts per million (ppm) to 35 ppm when a 40% EGR rate was used with the biodiesel-diesel blend[145].

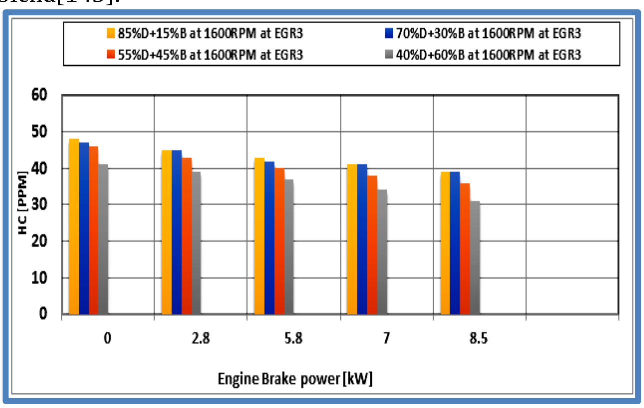

Figure 10. The emissions of total unburned hydrocarbons (HC) blends at various engine brake power levels (loads) with EGR.

- **CARBON DIOXIDE [CO2]:**

Figure 11 illustrates the data reveal distinct trends in CO2 emissions with EGR based on fuel type and blend ratios. For pure diesel, CO2 emissions increase with increasing engine loads and EGR ratios. This trend is expected, as increasing loads burn more fuel, resulting in increased CO2 production as a by-product of complete combustion. The Effect of Exhaust Gas Recirculation (EGR) on Carbon Dioxide (CO2) Emissions Exhaust Gas Recirculation (EGR) is a technology used in internal combustion engines to reduce nitrogen oxide (NOx) emissions. However, it also has notable effects on carbon dioxide (CO2) emissions. Below is an explanation of how EGR influences these emissions Reduction of Combustion Temperature How It Happens When exhaust gas is reintroduced into the combustion chamber, it lowers the flame temperature. Impact on Emissions the decrease in temperature can negatively affect combustion efficiency, leading to incomplete combustion and increased CO2 emissions. Impact on the Optimal Fuel-Air Ratio: The use of EGR can lead to changes in the mixture composition, affecting combustion efficiency. Increase in CO2 Emissions: Inefficient combustion because of EGR usage may lead to the production of more unburned carbon, thus increasing CO2 emissions. Pure Diesel: For pure diesel, CO2 emissions increase with higher loads and EGR rates, as the engine needs to combust more fuel to meet power requirements. Typically show lower CO2 emissions due to the high oxygen content that promotes complete combustion. Vegetable Oil Blends In contrast, vegetable oil blends tend to produce higher CO2 emissions due to higher viscosity and lower combustion efficiency. Exhaust Gas Recirculation affects CO2 emissions in a complex manner. On one hand, it may lead to increased emissions due to incomplete combustion; on the other hand, it helps reduce NOx emissions. Therefore, a comprehensive assessment of diesel engine performance and environmental impact using EGR technology is required, considering all factors associated with the types of fuel used[152].

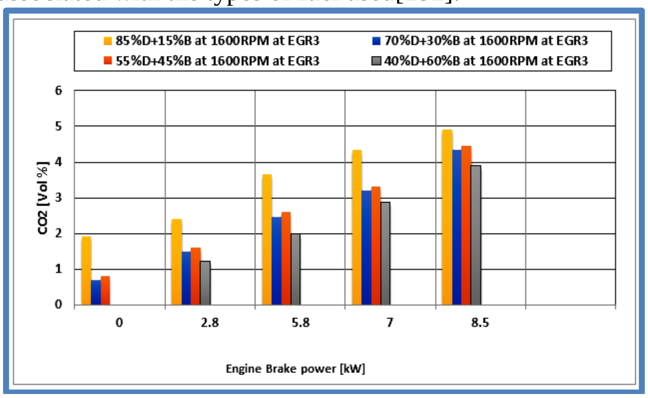

Figure 11. The emissions of carbon dioxide (CO_2) blends at various engine brake power levels (loads) with EGR.

- **CARBON MONOXIDE [CO]:**

Figure 12 illustrates the variations in carbon monoxide (CO) emissions for biodiesel/diesel blends compared to pure diesel fuel. The results indicate that CO emissions generally increase at high loads, while they decrease at lower loads. This is attributed to the fact that in-cylinder temperatures rise with increased load, leading to more efficient combustion and reduced CO formation under low-load conditions.

Previous studies have reported an increase in CO emissions when using a biodiesel/diesel blend with a blending ratio of 85%. However, it can be observed that CO emissions decrease as the biodiesel ratio in the blend increases compared to pure diesel. This reduction is due to the distinctive thermal properties of biodiesel, which has a high latent heat of vaporization, leading to lower in-cylinder temperatures and aiding in improving the combustion process. This cooling effect can enhance CO formation, highlighting that combustion conditions play a crucial role in its emissions[19]. Furthermore, the introduction of Exhaust Gas Recirculation (EGR) reduces CO oxidation due to the lower oxygen concentration within the combustion chamber. As a result, CO emissions may increase slightly with rising EGR rates, particularly at 40%, as shown in Figure 12.

Overall, these results suggest that CO emissions from biodiesel blends are significantly influenced by blending ratios and operating conditions. This underscores the importance of monitoring CO emissions to enhance the efficiency of internal combustion engines and reduce their environmental impact[63].

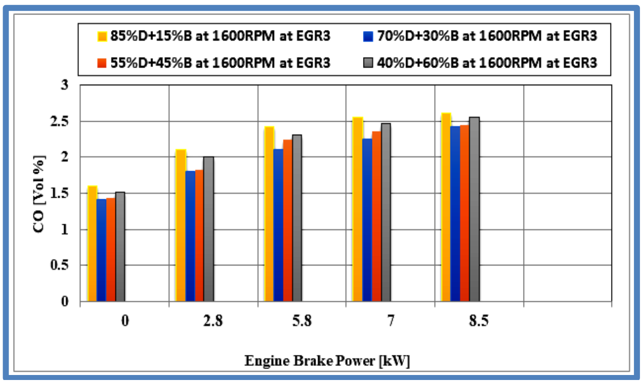

Figure 12. illustrates the carbon monoxide (CO) emissions blends at various engine brake power levels (loads) with EGR.

- **NITROGEN OXIDE [NOX]:**

Figure 13 illustrates the effect of blends on nitrogen oxide (NOx) emissions under different load conditions with the use of Exhaust Gas Recirculation (EGR). Overall, NOx emissions decreased with increasing engine load for all blends, similar to the behavior of pure diesel fuel.

Effect of Biodiesel Percentage: Under low to medium load conditions, it was observed that NOx emissions decreased as the biodiesel percentage in the blends increased compared to pure diesel. This reduction can be attributed to the lower heating value and the high latent heat of vaporization of biodiesel, which reduces in-cylinder temperatures, thereby leading to lower thermal NOx formation[19].

At high engine loads, NOx emissions were found to be elevated, as reported previously with biodiesel/diesel blends. This behavior may result from the dominant effect of the high oxygen content in biodiesel and the lower cetane number, which leads to longer ignition delays. Consequently, more of the fuel blend is injected into the cylinder during this period, and when this larger quantity of fuel burns during the pre-mixed combustion phase, it leads to increased gas temperatures, resulting in higher NOx emissions[145].

The effects of different EGR percentages on NOx emissions for all biodiesel/diesel blends at medium and high loads are discussed. Increasing EGR rates leads to a reduction in flame temperature and oxygen concentration, resulting in lower NOx emissions. As previously noted, NOx emissions are generally lower for biodiesel/diesel blends at medium loads compared to diesel, and with the introduction of EGR, further reductions were achieved for all tested EGR rates. From Figure 13, it can be inferred that at medium loads, the blends exhibited a maximum reduction of up to 62% in NOx emissions with 40% EGR, whereas pure diesel showed a reduction of 30% under similar conditions.

Overall, at high loads and elevated EGR rates, the concentration of inert gases present in the recirculated exhaust is higher, which absorbs the energy released from combustion and reduces peak temperatures within the combustion chamber. From the figure, it can be concluded that at higher loads, NOx emissions decreased by 41.8% with a 40% EGR rate for the blend, while a 30% reduction was observed with pure diesel under similar conditions[149]. The difference in reduction percentages between medium loads (62%) and high loads (41.8%) indicates that NOx emissions are less sensitive to EGR at high loads compared to medium loads. In summary, NOx emissions decreased by 62% and 42% for the blend at a 40% EGR rate at medium and high loads, respectively, compared to operating pure diesel without EGR.

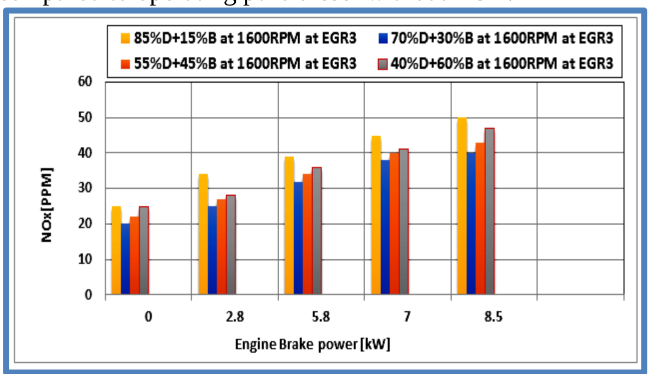

Figure 13. the nitrogen oxide (NOx) blends at various engine brake power levels (loads) with EGR.

- ## SMOKE INTENSITY [SOOT]:

Figure 14 the data show compares the differences in smoke opacity for all biodiesel blends relative to pure diesel under different load conditions with the use of Exhaust Gas Recirculation (EGR). It is observed that smoke opacity increases with higher engine loads, being significantly elevated at high loads. This is due to the combustion of larger amounts of fuel to produce higher energy output[19].

The data show that smoke emissions are lower with all biodiesel blends compared to pure diesel fuel. This reduction can be explained by the presence of oxygen atoms in biodiesel, which help reduce soot formation and prevent smoke appearance. The oxygen content in biodiesel contributes to improved combustion efficiency, resulting in smoke reduction of up to 80.9% compared to running pure diesel under EGR conditions[33].

When examining the effects of different EGR percentages, the figure shows that smoke opacity remains low for all blends at any EGR rate compared to pure diesel. This is likely due to the dominant effect of increased oxygen ratio and lower overall equivalence ratio, which enhances EGR effectiveness[63]. Similar effects have been reported when using blends at high EGR rates. It is evident from Figure 14 that smoke emissions only increase by 17% at a certain EGR rate, after which smoke emissions for all blends rise.

Increasing EGR rates leads to a decrease in oxygen concentration and an increase in the local equivalence ratio, which may cause incomplete combustion and enhance soot formation. With a higher EGR rate, the cylinder temperature decreases, promoting smoke formation. Studies have shown that soot emissions increase significantly with rising EGR rates, especially when the rate exceeds a certain level of 40%[66]. There is a peak in soot emissions within a specific range of EGR rates, making these emissions sensitive to changes and complicating combustion control. The results show that smoke opacity increases with higher engine loads, similar to when using EGR, where incomplete combustion and elevated soot levels are more pronounced[65].

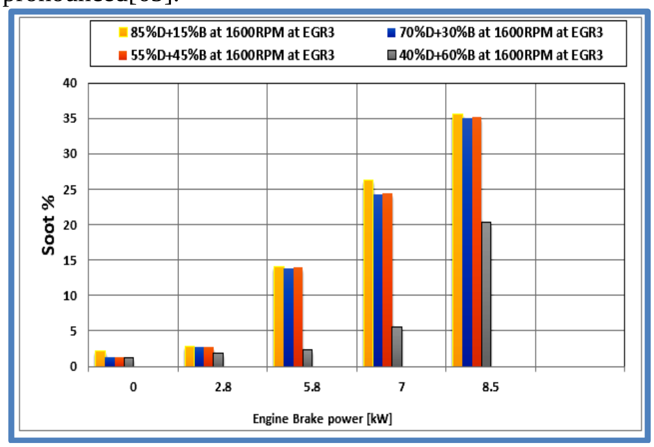

Figure 14. Illustrates the density of the soot (smoke) blends at engine brake power (loads) with EGR.

Overall, the reduction in smoke emissions for biodiesel blends compared to pure diesel can be attributed to the presence of oxygen atoms, which reduce soot formation and enhance combustion efficiency, leading to lower opacity.

G. Analysis of the Experimental Findings and Their Interpretation

The blend values of 15%, 30%, 45%, and 60% (by volume) for both biodiesel and vegetable oil are presented side by side, organized to show the corresponding values for different engine loads. Figure 1 illustrates the smoke (soot) density, expressed in milligrams per cubic meter of exhaust gas, for neat diesel fuel, biodiesel blends, and vegetable oil blends. The bar chart clearly demonstrates that the soot emissions from all biodiesel blends are significantly lower than those from neat diesel fuel. This reduction in soot emissions becomes more pronounced as the percentage of biodiesel in the blend increases. The decrease in soot is attributed to the mixing-controlled combustion of biodiesel blends, similar to that of neat diesel fuel, but with the added benefit of oxygen molecules inherently present in the biodiesel. In contrast, vegetable oil blends emit higher levels of soot compared to neat diesel, with soot emissions increasing as the vegetable oil content in the blend rises. This is primarily due to the evaporation-controlled combustion process of vegetable oil, which hinders the full utilization of the fuel-bound oxygen during combustion. The slower evaporation of vegetable oil, combined with its higher viscosity, leads to less efficient mixing with air, particularly under higher loads, resulting in increased soot emissions. Figure 14. shows nitrogen oxides (NOx) emissions, measured in parts per million (ppm), for neat diesel fuel, biodiesel blends, and vegetable oil blends. The data indicate that NOx emissions from all biodiesel blends are generally higher than those from neat diesel. This increase is attributed to the higher combustion temperatures associated with biodiesel due to its oxygen content, which promotes a more complete and hotter combustion process. However, the exact increase in NOx depends on the blend ratio and load conditions, with higher blend percentages typically resulting in greater NOx emissions[153].

On the other hand, NOx emissions for vegetable oil blends tend to be lower compared to biodiesel and, in some cases, even neat diesel. This is due to the lower combustion temperatures caused by the longer ignition delay and slower evaporation rates of vegetable oil. These factors reduce the peak combustion temperatures, which are critical for NOx formation, resulting in relatively lower NOx emissions from vegetable oil blends, especially at higher blend ratios[154].

IV. Conclusions

The study investigated the impact of using biodiesel-diesel blends at varying ratios (15%, 30%, 45%, and 60%) on the performance and emissions characteristics of a direct injection diesel engine. The biodiesel blends were compared to pure diesel, and the effects of increasing Exhaust Gas Recirculation (EGR) rates up to 40% were also evaluated. The primary goal of incorporating EGR was to mitigate the high nitrogen oxides (NOx) emissions that occur during high engine loads when using biodiesel-diesel blends. Based on the experimental results, the following conclusions were drawn [155]:

Key Findings:

1. **Engine Compatibility:** The direct injection diesel engine was able to operate successfully with biodiesel blends at ratios of 15%, 30%, 45%, and 60% with pure diesel, along with EGR. No engine modifications were necessary, and there were no visible signs of damage to the engine components. However, long-term durability testing is required before recommending biodiesel blends as a regular fuel source.
2. **Ignition Delay:** For all tested biodiesel-diesel blends, the ignition delay was found to increase across all EGR rates. This extended ignition delay is due to the lower cetane number of biodiesel, which leads to slower ignition compared to pure diesel.
3. **Brake Thermal Efficiency (BTE):** BTE improved for all biodiesel-diesel blends as the EGR rates increased, reaching up to 40%. The maximum observed reduction in BTE, compared to pure diesel, was 8.4% at high engine loads. Additionally, Brake Specific Fuel Consumption (BSFC) decreased for biodiesel blends with rising EGR rates, indicating improved fuel efficiency under these conditions.
4. **NOx Emissions:** NOx emissions were significantly reduced, with a 75% decrease observed at 40% EGR for medium and high engine loads compared to pure diesel operation. This is a notable improvement in controlling NOx emissions, which are typically higher in biodiesel blends.
5. **Smoke Opacity:** Smoke opacity decreased for all biodiesel-diesel blends up to 40% EGR. The oxidative properties of biodiesel helped maintain lower smoke levels. However, beyond 40% EGR, smoke opacity began to increase across all blends, likely due to incomplete combustion caused by excessive recirculation of exhaust gases.
6. **Simultaneous Reduction of NOx and Smoke:** Moderate EGR rates (up to 40%) combined with biodiesel blends of up to 60% were effective in simultaneously reducing both NOx and smoke emissions. This was achieved with only a minor impact on engine performance, making this approach a promising strategy for cleaner combustion.
7. **Hydrocarbon (HC) and Carbon Monoxide (CO) Emissions:** Both HC and CO emissions increased as the EGR rates rose across all biodiesel-diesel blends. This is likely a result of incomplete combustion, which is more prevalent at higher EGR rates due to reduced oxygen availability in the combustion chamber.

Processing corn oil into biodiesel has shown great potential as a next-generation biofuels. It can be blended with diesel to reduce emissions and improve fuel efficiency in diesel engines without requiring significant modifications. Moreover, its use could enhance energy security and promote environmental sustainability. However, further research is needed, especially in the areas of low-temperature combustion and long-term durability, to fully realize the potential of biodiesel in modern diesel engines[156].

The theoretical principles of diesel engine combustion, combined with the unique physical and chemical characteristics of biodiesels and vegetable oils in contrast to conventional diesel fuel, offered a solid foundation for understanding the engine behaviors that were observed[157]. In summary, with the exception of the minor increase in smoke emissions associated with vegetable oil blends, all tested biodiesel and vegetable oil blends, regardless of the raw feedstock, can be utilized safely and effectively in diesel engines. This is particularly applicable for blends with lower ratios of biofuels mixed with conventional diesel, demonstrating the potential for these renewable alternatives in reducing emissions while maintaining engine performance[158].

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