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Evaluating The Impact Of EGR On Butanol-Diesel Blends In A CRDI Engine: Performance And Emission Analysis

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The study evaluates the performance and emission characteristics of a single-cylinder CRDI research engine using Pure Diesel (PD) and butanol-diesel blends (B10, B20, and B30) under varying Exhaust Gas Recirculation (EGR) rates (0%, 10%, 20%, and 30%). Among the tested fuels, B20 exhibits the most balanced performance, achieving a favorable Brake Thermal Efficiency (BTE) while maintaining manageable emission levels. Although BTE generally decreases with higher butanol content due to its lower calorific value, B20 shows a moderate increase in Brake Specific Fuel Consumption (BSFC) compared to pure diesel, with less of a trade-off in efficiency than B30. Emission results indicate that HC and CO emissions increase with rising EGR rates and higher butanol percentages, but B20 maintains lower emissions compared to B30 across all EGR levels. Additionally, B20 effectively reduces NOx emissions due to the cooling effect of butanol and controlled combustion temperatures, particularly at higher EGR rates. Overall, B20 strikes an optimal balance between performance and emissions, demonstrating its potential as a viable alternative fuel blend for enhancing engine efficiency while minimizing environmental impact.

Keywords: Butanol, EGR, CRDI Diesel Engine.

1. Introduction:

Diesel engines, known for their efficiency and reliability, are significant contributors to harmful emissions, prompting research into alternative fuels that can reduce environmental impact without compromising performance. Water-emulsified diesel (WED) is one such alternative, offering improved combustion and reduced emissions, such as a 32.6% reduction in NOx and a 51.9% reduction in smoke emissions at higher injection pressures compared to conventional diesel[1]. Biodiesel, particularly from sources like palm oil and waste cooking oil, is another promising alternative. B30 biodiesel-diesel emulsions, for instance, have shown to increase brake thermal efficiency by up to 36% and reduce brake-specific fuel consumption by 8.70%, while also significantly lowering NOx, carbon monoxide, and smoke emissions [2].

The addition of nanoparticles, such as titanium oxide, to biodiesel can further enhance emission reductions, achieving a 25% reduction in carbon monoxide emissions [3]. The production of biodiesel using immobilized lipases from waste cooking oil has also been optimized to achieve high yields and meet international fuel standards [4]. Short carbon-chain alcohols like ethanol and 1-propanol, when blended with diesel, can reduce soot emissions due to their oxygen content, although they may increase noise emissions [5]. Lignocellulose-derived biofuels, such as furanic molecules, offer a carbon-neutral alternative, though they may increase NOx emissions and require careful blending to ensure stable combustion [6]. Renewable biofuels from waste cooking oils, such as Renewable Biofuel 100, provide a sustainable option with favorable fuel properties like viscosity and density [7]. Despite the potential of these alternatives, challenges remain, such as the need for engine calibration to optimize performance and emissions [9]. Overall, while each alternative fuel presents unique benefits and challenges, they collectively represent a significant step towards reducing the environmental impact of diesel engines [10]. The integration of various alcohols into diesel engines has been extensively studied to enhance performance and reduce emissions. Higher alcohols such as butanol, pentanol, and hexanol are promising due to their oxygen content, which improves combustion efficiency and reduces emissions like carbon monoxide (CO) and nitrogen oxides (NOx) [11]. Studies have shown that blends like DA5 and DA10, which include these alcohols, result in reduced brake power due to lower calorific values but also lead to decreased CO and NOx emissions due to the additional oxygen content and lower combustion temperatures[12]. Ethanol and isopropanol have also been evaluated, showing that while they can increase environmental impact and cost at low engine speeds, they reduce emissions at higher speeds and loads [13]. The use of n-propanol, n-butanol, and n-pentanol in high concentrations has been shown to significantly reduce polycyclic aromatic hydrocarbons (PAH) and toxic emissions, with n-butanol achieving the highest reduction in diesel blends [14]. Furthermore, the addition of ethanol to diesel, despite increasing brake-specific fuel consumption (BSFC) due to its low heating value, effectively reduces CO, NOx, and smoke emissions [15]. The use of co-solvents like tetrahydrofuran (THF) with ethanol in diesel blends has been found to enhance solubility and improve indicated thermal efficiency (ITE), especially under exhaust gas recirculation (EGR) conditions [16]. Additionally, the physical and chemical properties of alcohols, such as their cooling and dilution effects, influence combustion characteristics, with longer carbon-chain alcohols like hexanol showing significant soot reduction at high ambient temperatures [17]. Overall, higher alcohols offer a sustainable alternative to traditional diesel, addressing both environmental concerns and energy security, although challenges such as increased fuel consumption and phase separation need to be managed [18].

2. Materials and Methods:

2.1. Experimental Setup

The experiment utilized a Mahindra JEETO automotive research engine as the main testing platform. This engine, illustrated schematically in Figure 2 and thoroughly described in Table 2, is a single-cylinder, four-stroke, dual-fuel diesel engine specifically developed for research purposes. It features a water-cooling system that maintains consistent temperature levels, ensuring efficient operation even during prolonged testing periods. An open Engine Control Unit (ECU) is integrated into the setup to perform essential tasks, such as monitoring sensor data, calculating the precise fuel mass needed for optimal combustion, and controlling the injection timing and fuel pressure, which can be adjusted up to 1000 bar. The ECU also synchronizes the engine by detecting the Top Dead Center (TDC), manages the main relay for system functions, and regulates engine speed for accurate testing control. Additionally, the ECU includes communication capabilities to facilitate data transfer. Calibration of the ECU is carried out using PC-based software, which allows for configuring and fine-tuning ECU parameters while also logging engine data in real-time for continuous performance monitoring and analysis under different conditions. The specific model of the open ECU used is the MCS1-i7, connected to the data acquisition system through a Kvaser Leaf Light V2 CAN cable, enabling efficient data transmission and precise recording for comprehensive engine behavior analysis throughout the experiment.

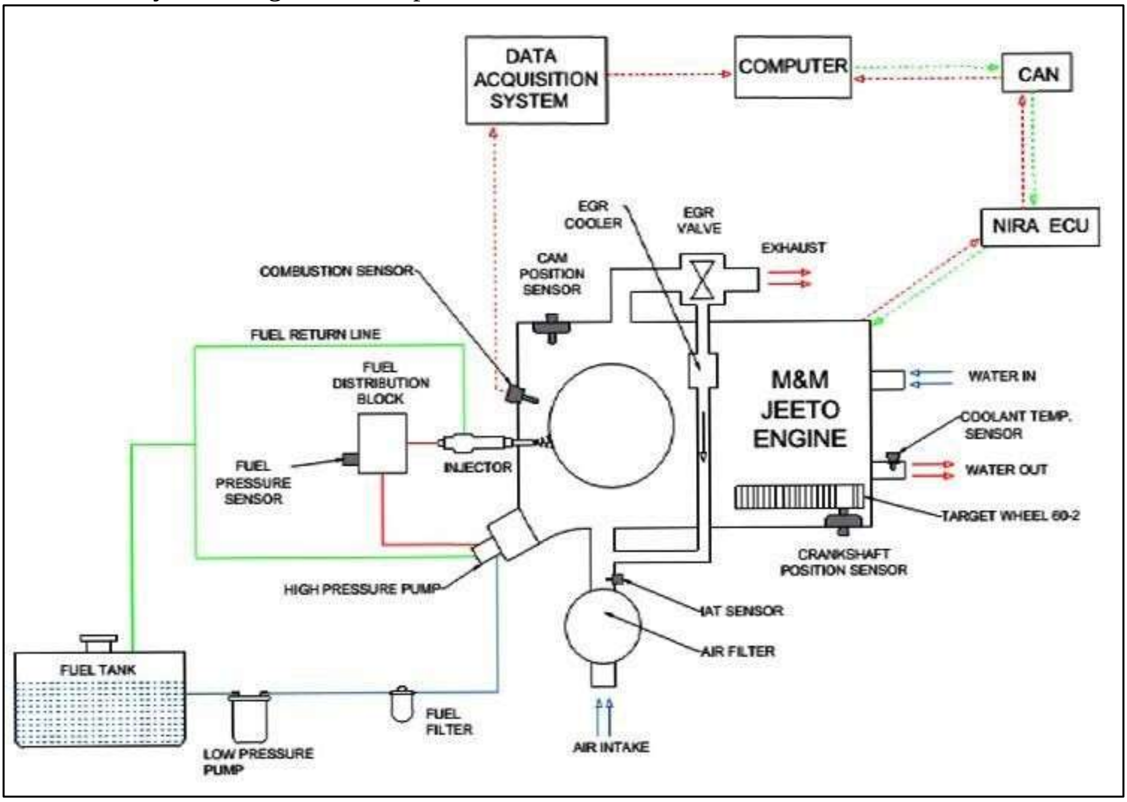

Figure 1: Line diagram of experimental set up1

Table 1. Properties of Test Fuel

Property	Diesel	Butanol
Chemical Formula	C10.8H18.7	C_4H_9OH

Lower heating value (kJ/kg)	42,600	33,100
Latent heat of vaporization	280	585
Research Cetane Number	45	5-8
Boiling Point(°C)	180-330	78
Stoichiometry A/F ratio	14.4	11.2
Kinematic Viscosity(cP at 20°C)	3.03	3.64
Density (g/cm^3 at 20°C)	0.84	0.789

Table 2. The research engine specifications

Description	**Specifications**
Make	Mahendra and Mahendra
No. of Cylinders	1
Engine capacity (cc)	625
Number of strokes	4
Compression Ratio	18:1
Bore (mm)	93.0 to 93.018
Stroke length (mm)	92
Application	Automotive (Multi speed)
Ignition	Compression Ignition
Nozzle diameter and holes	0.145 mm and 6 holes
Max. Power @RPM	9HP @ 3000 RPM
Max. Torque @RPM	30NM @ 1800 RPM
Cooling	Water Cooled
Number of Valves	2

Table 3. Specifications of Analyzers

Name of the analyzer	**Measuring Range**	**Precision**	**Resolution**
AVL Particulate Matter Analyzer	0-100 HSU	1 HSU	1 HSU
Netel Chromatograph NOx analyzer	0-5000 ppm	5 ppm	5 ppm

3. Results and Discussions

3.1. Brake Thermal Efficiency

The graph demonstrates the impact of Exhaust Gas Recirculation (EGR) on Brake Thermal Efficiency (BTE) for the blends B10 (10% Butanol + 90% Diesel), B20, and B30. For B10, the BTE slightly decreases as EGR levels rise. This happens because while the butanol enhances oxygen availability, higher EGR reduces oxygen concentration due to the influx of inert gases, leading to incomplete combustion. Additionally, the high latent heat of butanol lowers cylinder temperatures, affecting efficiency at higher EGR. In the case of B20, the blend shows higher BTE compared to B10 and B30 at moderate EGR levels, owing to a balanced oxygen content and energy density that supports combustion despite some EGR dilution. However, when EGR exceeds 20%, the presence of inert gases becomes dominant, resulting in reduced combustion efficiency and thus a drop in BTE. For B30, the decline in BTE with increasing EGR is more pronounced. The higher butanol percentage initially provides a greater oxygen boost, beneficial at low EGR, but butanol's lower calorific value and the reduced oxygen availability due to increased exhaust gas dilution lead to lower combustion efficiency as EGR levels rise. In summary, all blends show a decrease in BTE with higher EGR due to reduced oxygen availability, but the effect is most noticeable in B30 due to its composition and energy characteristics, while B20 offers the most balanced performance at moderate EGR levels.

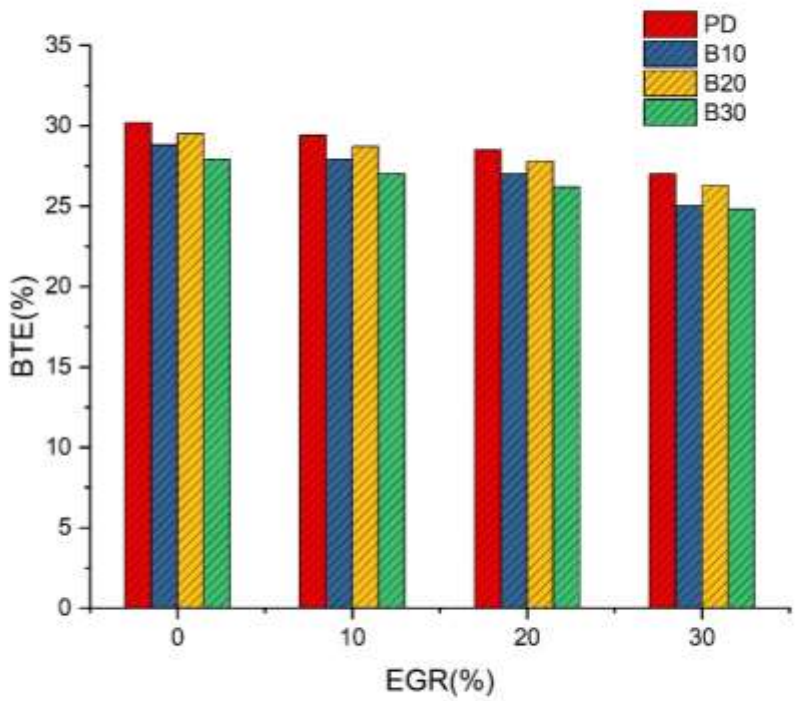

Figure 2: BTE vs various percentages EGR

3.2. Brake Specific Fuel Consumption

The graph illustrates the variations in Brake Specific Fuel Consumption (BSFC) with increasing Exhaust Gas Recirculation (EGR) percentages for different fuel blends, including pure diesel (PD), B10 (10% Butanol + 90% Diesel), B20, and B30. As the EGR percentage increases from 0% to 30%, the BSFC for all blends rises. This trend indicates that with higher EGR levels, the amount of fuel required to produce the same power output also increases. Among the blends, pure diesel consistently shows the lowest BSFC across all EGR levels, demonstrating its higher combustion efficiency compared to the butanol blends. For B10, the BSFC is slightly higher than pure diesel due to butanol's lower energy density. Similarly, B20 shows a moderate increase in BSFC, maintaining a balance between fuel efficiency and combustion properties. However, B30 exhibits the highest BSFC, as its increased butanol content, coupled with higher EGR, results in less efficient combustion and higher fuel consumption. Overall, the graph highlights that as the EGR percentage rises, BSFC increases for all fuel types, with blends containing higher amounts of butanol (B30) showing the most significant increase due to their lower calorific value and the effect of EGR on combustion efficiency

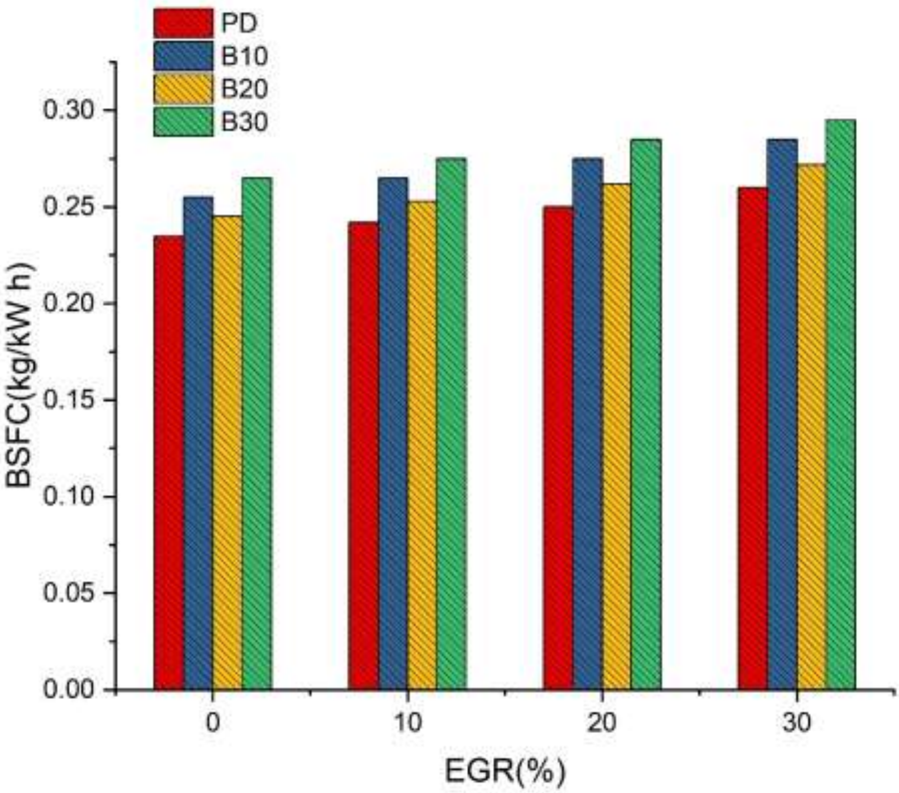

Figure 3: BSFC vs various percentages of EGR

3.3. HC Emissions

The graph depicts the variation of Hydrocarbon (HC) emissions in parts per million (ppm) with different levels of Exhaust Gas Recirculation (EGR) for various fuel blends: pure diesel (PD), B10 (10% Butanol + 90% Diesel), B20, and B30. As the EGR percentage increases from 0% to 30%, HC emissions rise across all blends. This increase occurs because EGR introduces more inert gases into the combustion chamber, which lowers the combustion temperature and leads to incomplete combustion, resulting in higher unburned hydrocarbons. Among the fuels, pure diesel exhibits the lowest HC emissions at all EGR levels, as its combustion properties are more favorable for complete burning. B10 shows a moderate increase in HC emissions compared to PD, while B20 displays slightly higher emissions due to a higher butanol content, which tends to lower flame temperatures. B30 has the highest HC emissions, as its elevated butanol content, combined with increased EGR, significantly reduces combustion efficiency. Overall, the graph highlights that increasing EGR percentages lead to greater HC emissions for all blends, with higher butanol concentrations (such as in B30) showing the most substantial increase due to the combined effects of fuel properties and reduced combustion efficiency.

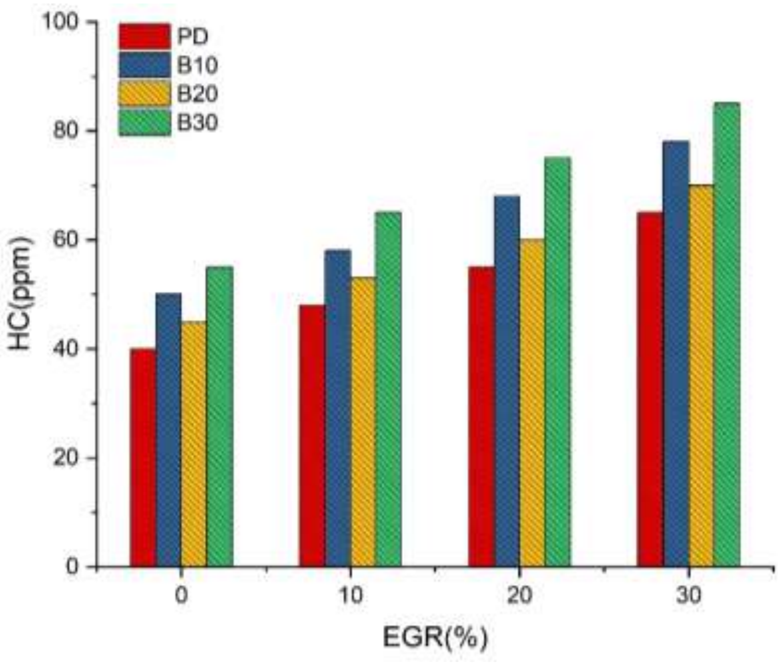

Figure 4: HC emissions vs various percentages of EGR

3.4. CO Emissions

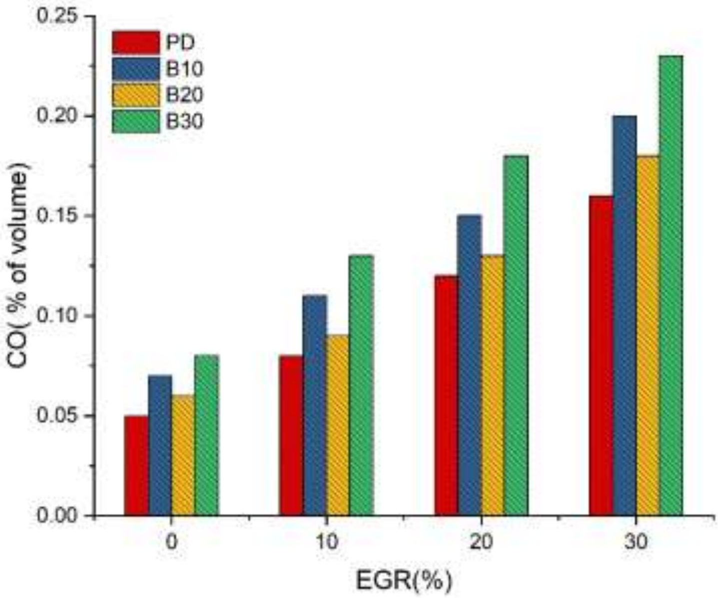

Figure 5: CO emissions vs various percentages of EGR

The graph illustrates the variation in carbon monoxide (CO) emissions (% of volume) for different butanol-diesel fuel blends (B10, B20, B30) and pure diesel (PD) at various exhaust gas recirculation (EGR) rates (0%, 10%, 20%, and 30%). As EGR percentage increases, CO emissions consistently rise for all fuel types. At 0% EGR, the CO emissions are minimal, with pure diesel (PD) showing the lowest emissions, followed by B10, B20, and B30 in increasing order. As the EGR percentage increases to 10%, 20%, and 30%, a significant rise in CO emissions is observed. Notably, B30 (30% butanol) shows the highest CO emissions at all EGR levels, while B10 (10% butanol) has comparatively lower emissions than B20 and B30 but still higher than PD. This trend indicates that blending diesel with higher concentrations of butanol leads to an increase in CO emissions. Additionally, the rise in EGR percentage exacerbates CO production for all fuel types. The highest CO emissions are recorded for the B30 blend at 30% EGR, indicating that both higher butanol content and higher EGR levels contribute to increased CO formation during combustion. This is likely due to incomplete combustion at higher EGR rates, which limits the availability of oxygen, particularly in blends with higher butanol content.

3.5. NOx Emissions

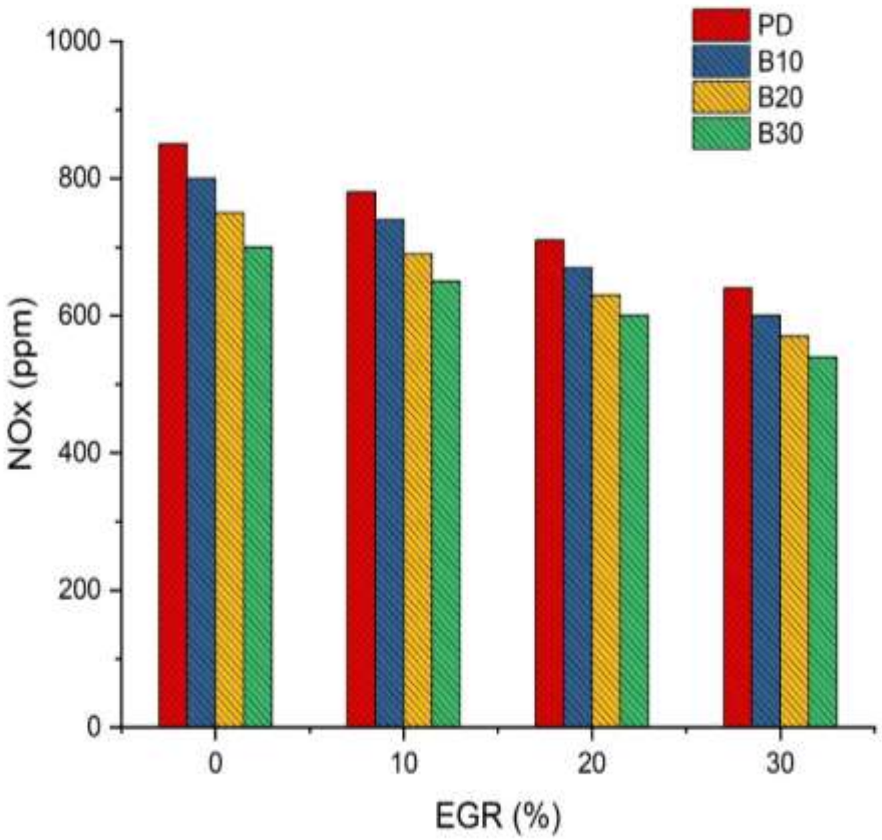

Figure 6: CO emissions vs various percentages of EGR

The graph illustrates the variations in nitrogen oxide (NOx) emissions (measured in parts per million, ppm) for different blends of butanol and diesel (B10, B20, B30) and pure diesel (PD) across varying exhaust gas recirculation (EGR) rates (0%, 10%, 20%, and 30%). As the EGR percentage increases, NOx emissions consistently decrease for all fuel blends. At 0% EGR, NOx emissions are highest, with pure diesel (PD) showing the greatest NOx output, followed by B10, B20, and B30 in descending order. As the EGR rate increases to 10%, 20%, and 30%, there is a noticeable decline in NOx emissions for all fuel types. B30, which contains 30% butanol, consistently shows the lowest NOx emissions at each EGR level, while pure diesel continues to have the highest emissions across all EGR settings. This pattern suggests that increasing EGR effectively reduces NOx emissions by lowering the combustion temperature and reducing oxygen availability, thereby limiting the formation of NOx. The higher the butanol content in the fuel blend, the lower the NOx emissions at any given EGR level, with B30 demonstrating the most significant reduction.

4. Conclusions:

This study investigated the effects of various Exhaust Gas Recirculation (EGR) rates on the performance and emission characteristics of butanol-diesel blends (B10, B20, B30) compared to pure diesel (PD) in a CRDI engine. The results show that increasing EGR leads to notable changes in both engine performance and emissions.

Performance: Brake Thermal Efficiency (BTE) generally decreases with increasing EGR due to the reduced oxygen availability and combustion temperatures. B20 provides the most balanced performance across the tested blends, maintaining higher BTE at moderate EGR levels, while B30 exhibits a more pronounced decline in BTE at higher EGR rates due to its lower calorific value. Brake Specific Fuel Consumption (BSFC) increases for all blends as EGR rises, with B30 showing the highest BSFC, indicating reduced combustion efficiency at higher butanol content and EGR levels.

HC and CO Emissions: Both hydrocarbon (HC) and carbon monoxide (CO) emissions increase as EGR levels rise across all blends. B30 consistently exhibits the highest emissions due to incomplete combustion, while B20 demonstrates more controlled emissions levels, making it a more favorable blend.

NOx Emissions: Nitrogen oxide (NOx) emissions decrease with increasing EGR for all fuel blends. B30 consistently shows the lowest NOx emissions, reflecting the cooling effect of butanol and the reduction in combustion temperatures, while pure diesel displays the highest NOx levels at each EGR rate.

In conclusion, B20 emerges as the most optimal blend, offering a favorable balance between engine performance, fuel consumption, and emissions control. It maintains moderate efficiency and reduced emissions, particularly at higher EGR levels, making it a promising alternative to pure diesel for reducing environmental impact while preserving engine performance.

Declarations:

Conflict of Interest

We have no conflict of interest to disclose**.**

Disclosure of Funding

No funding was received**.**

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