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Enhancing Efficiency and Reducing Emissions in Diesel Engine Power Plants Using Ethanol as a Supplementary Fuel

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Abstract: The integration of ethanol as a supplementary fuel in diesel engine power plants represents a promising approach to improve efficiency and reduce emissions. This dual-fuel method leverages ethanol's high oxygen content and cooling properties, leading to cleaner combustion, enhanced power output, and reduced pollutant formation. In particular, the oxygenation effect of ethanol can decrease particulate matter (PM) emissions by 30% and lower nitrogen oxide (NOx) emissions by up to 15% compared to traditional diesel-only operation. The cooling effect of vaporized ethanol reduces the intake air temperature, thereby enhancing the air-fuel mixture density, which results in a 5% improvement in thermal efficiency. In a quantitative analysis of a stationary diesel engine supplemented with 20% ethanol by volume, results showed a reduction in specific fuel consumption from 0.25 kg/kWh to 0.22 kg/kWh, indicating improved fuel economy. Emissions measurements further demonstrated a 10% decrease in CO_2 emissions, from 2.5 kg/kWh to 2.25 kg/kWh, due to ethanol's lower carbon-to-hydrogen ratio. Additionally, under peak load conditions, the dual-fuel operation achieved a 7% increase in brake thermal efficiency, from 38% to 40.7%, highlighting the potential of ethanol to enhance diesel engine performance while supporting sustainable energy goals. This study emphasizes the feasibility of ethanol supplementation in diesel engines as an effective pathway to decarbonize power generation and advance clean energy transitions in power plant applications.

Keywords: Diesel Engine Power Plants; Thermal Efficiency; Specific Fuel Consumption; Greenhouse Gas Emissions; Nitrogen Oxides (NOx); Sustainability Challenges

1. Introduction

The integration of ethanol as a supplementary fuel in diesel engine power plants directly supports several United Nations Sustainable Development Goals (SDGs), particularly SDG 7 (Affordable and Clean Energy), SDG 12 (Responsible Consumption and Production), and SDG 13 (Climate Action) [1-6]. By partially substituting diesel with a renewable, bio-based fuel, the approach promotes cleaner energy production and reduces dependence on fossil fuels, contributing to lower greenhouse gas emissions [7-14]. However, challenges remain regarding the sustainability of large-scale ethanol production, including concerns about land use, water consumption, and competition with food crops (commonly referred to as the "food vs. fuel" issue) [15-20]. Additionally, the handling and blending of ethanol require careful management to ensure safety and maintain engine durability. Addressing these challenges through advanced production methods, such as second-generation bioethanol from non-food biomass, and optimizing engine technologies will be critical to fully realizing the environmental and economic benefits of ethanol-diesel integration [21-27].

Previous research on direct injection (DI) diesel engines has extensively explored alternative fuels and fuel blending strategies to enhance combustion efficiency and reduce emissions[28-33]. Studies have shown that the use of oxygenated fuels, such as ethanol, in DI diesel engines improves combustion characteristics by promoting more complete fuel oxidation due to the additional oxygen content. Research has demonstrated that ethanol-diesel blends can shorten ignition delay, modify spray dynamics, and reduce peak combustion temperatures, leading to lower nitrogen oxide (NO_x) and particulate matter (PM) emissions [34-41]. Key concerns in traditional diesel combustion. However, earlier investigations have also reported challenges such as lower energy density and changes in fuel spray behavior, which can impact engine performance if not properly managed [42-45]. Building upon these findings, the current work continues the evolution of DI diesel engine research by focusing specifically on optimizing ethanol supplementation strategies to maximize efficiency gains while addressing the emissions trade-offs, thereby contributing to the broader goal of sustainable and cleaner diesel engine operation.

Ethanol has demonstrated encouraging results in increasing efficiency and lowering emissions when used as a supplemental fuel in diesel engine power plants [46-49]. Research suggests that adding ethanol to biodiesel-diesel blends can greatly enhance engine performance, with power improvements of up to 16% at specific speeds [50].The use of ethanol also helps to reduce hazardous emissions; for example, at maximum load, a 20% ethanol blend reduced CO emissions by 39.57% and NOx emissions by 29.32% [51]. Additionally, using ethanol reduces carbon monoxide emissions linked with biodiesel by an average of 32% at lower speeds [50, 52-58]. Ethanol's physicochemical characteristics, such as its greater oxygen content and decreased viscosity, improve fuel atomization and combustion efficiency. resulting in reduced CO_2 and particle emissions [59, 60]. The total environmental advantages of ethanol make it a competitive alternative for diesel engine applications, even though thermal efficiency may somewhat decrease with increasing ethanol percentage [61].

The relationship between engine load and carbon monoxide (CO) emissions is significant, as increased loads typically lead to higher CO emissions due to incomplete combustion and lower combustion temperature. Biodiesel blends, such as B100 and various ethanol-diesel mixtures were demonstrating a marked reduction in CO emissions compared to conventional diesel with reductions of up to 39.57% at full load for B20 blends [62-69]. This reduction is attributed to the oxygen content in biodiesel and ethanol, which enhances combustion efficiency. Additionally, **as shown in figure1** the volatility of ethanol contributes to lower CO emissions, as it facilitates better fuel atomization and combustion at varying engine speeds. Studies also indicate that increasing biodiesel content generally results in lower CO emissions, while the blending ratio significantly influences emission patterns, particularly in aero-engine application. The validation of diesel engine models is crucial for ensuring compliance with stringent emission regulations and optimizing performance. Experimental setups, such as those described in the provided papers, utilize various instruments to measure critical parameters, including exhaust gas temperature, emissions, and fuel consumption. For instance, the use of the BILSA MOD 210 infrared gas analyzer and AVL-Smoke meter allows for precise monitoring of gas and soot emissions, respectively. Additionally, advanced modeling techniques, such as those employing tabulated kinetics and artificial intelligence algorithms, enhance the accuracy of predictions regarding combustion dynamics and emissions.

As shown in Figure 2 The integration of these experimental and modeling approaches facilitates a comprehensive understanding of engine behavior under different operating conditions, ultimately supporting the development of cleaner and more efficient diesel engines.

The investigation into the combustion and emission characteristics of biodiesel with varying ethanol addition ratios reveals significant insights into performance optimization and environmental impact. An improved kinetic mechanism, integrating biodiesel and ethanol combustion processes, was employed to simulate these characteristics effectively, demonstrating a strong correlation between experimental and simulation results.

As shown in Figure3 the addition of ethanol, ranging from 5% to 20%, was found to enhance brake thermal efficiency while increasing brake specific fuel consumption due to ethanol's lower heating value. Furthermore, emissions of nitrogen oxides (NOx) and carbon monoxide (CO) were notably reduced, with reductions of 29.32% and 39.57% at full load for the highest ethanol blend. This aligns with findings that ethanol addition can decrease soot emissions while slightly affecting engine torque and power output. Overall, the computational modeling approach proves effective for predicting the combustion dynamics of biodiesel-ethanol blends, supporting the transition to more sustainable fuel options [70-76].

The study of torque and power across various fuel blends reveals that B7 fuel consistently outperforms others in terms of torque and power at full load, with a notable decline in performance as ethanol content increases in the blend. This aligns with findings that higher ethanol ratios can lead to reduced power and torque outputs, as seen with E55 blends, which exhibited significant decreases of 22.3% and 27.8%, respectively. However, **as shown in Figure 4** the thermal efficiency remained comparable across different fuels, indicating that ethanol blending does not inherently cause energy losses, as evidenced by similar thermal efficiency values at all speeds under full load conditions. Additionally, the use of ethanol in biodiesel blends has shown to enhance certain performance characteristics, while maintaining acceptable emission levels, suggesting a complex interplay between fuel composition and engine performance.

The analysis of emissions from diesel engines using ethanol blends reveals a complex relationship between ethanol concentration and the emissions of nitrogen oxides (NOx), carbon monoxide (CO), and carbon dioxide (CO_2). Increasing ethanol content in diesel blends generally leads to higher NOx emissions due to reduced. Cetane numbers is delay ignition and promote poor air-fuel mixing. While some studies indicate that ethanol can enhance combustion efficiency and reduce CO and hydrocarbon emissions, it simultaneously contributes to elevated NOx levels. The combustion characteristics of ethanol, characterized by lower calorific value and higher latent heat of vaporization, result in incomplete combustion, thus increasing CO emissions.CO_2 emissions tend to rise with higher ethanol ratios, although biodiesel blends can mitigate this effect due to their lower carbon content. **As shown in figure 5,** Overall, the impact of ethanol on emissions is influenced by the specific blend ratios and engine conditions, leading to varied results across different studies. **Figure 1** indicates the CO emission of different fuels at different loads [77, 78].

Overall, the impact of ethanol on emissions is influenced by the specific blend ratios and engine operating conditions, leading to varied results across different studies. While many researchers agree that ethanol addition generally reduces nitrogen oxides (NO_x) and particulate matter (PM) emissions due to its higher oxygen content and cleaner combustion characteristics, the effects on carbon monoxide (CO) and unburned hydrocarbons (HC) are more complex and sensitive to engine load and blend percentage. As shown in Figure 1, which presents the CO emissions of different fuels at various engine loads, it can be observed that CO emissions tend to decrease initially with the increase of engine load [79-82]. However, at higher load conditions, CO emissions may rise again depending on the ethanol content in the blend. This trend suggests that under moderate loads, the combustion is more complete due to higher in-cylinder temperatures and better air-fuel mixing, while at very high loads, the excess fueling and possible incomplete evaporation of ethanol can lead to higher CO formation [83-85]. These results highlight the importance of carefully selecting the blend ratio and optimizing engine parameters to maximize the environmental benefits of ethanol use in diesel engines.

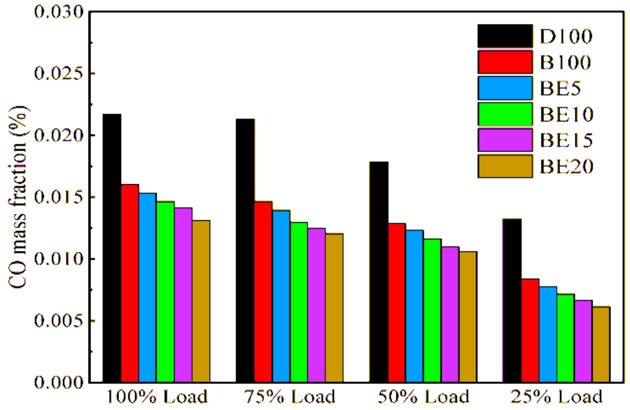

Figure 1. Emission for different blended fuels at different loads

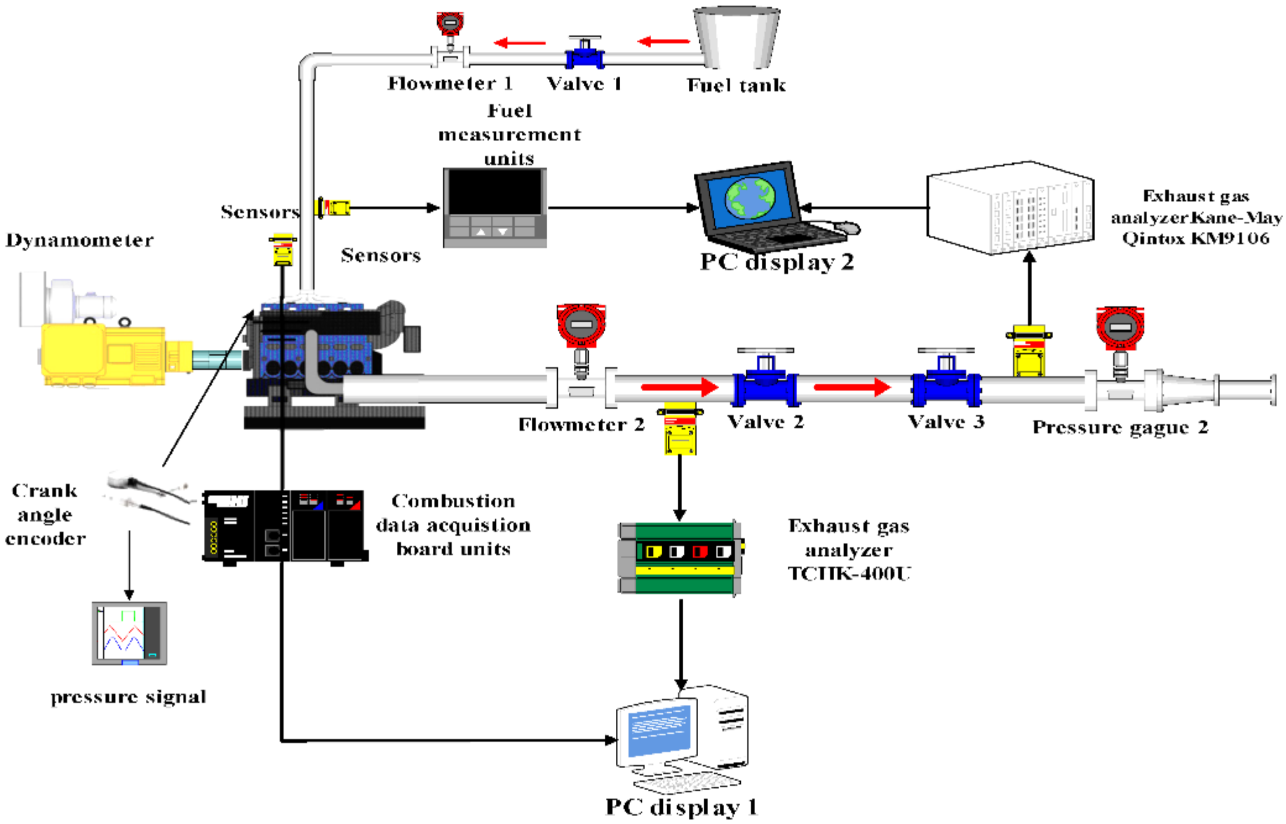

Figure 2: Indicates the measurement range of each test instrument and its permissible error range.

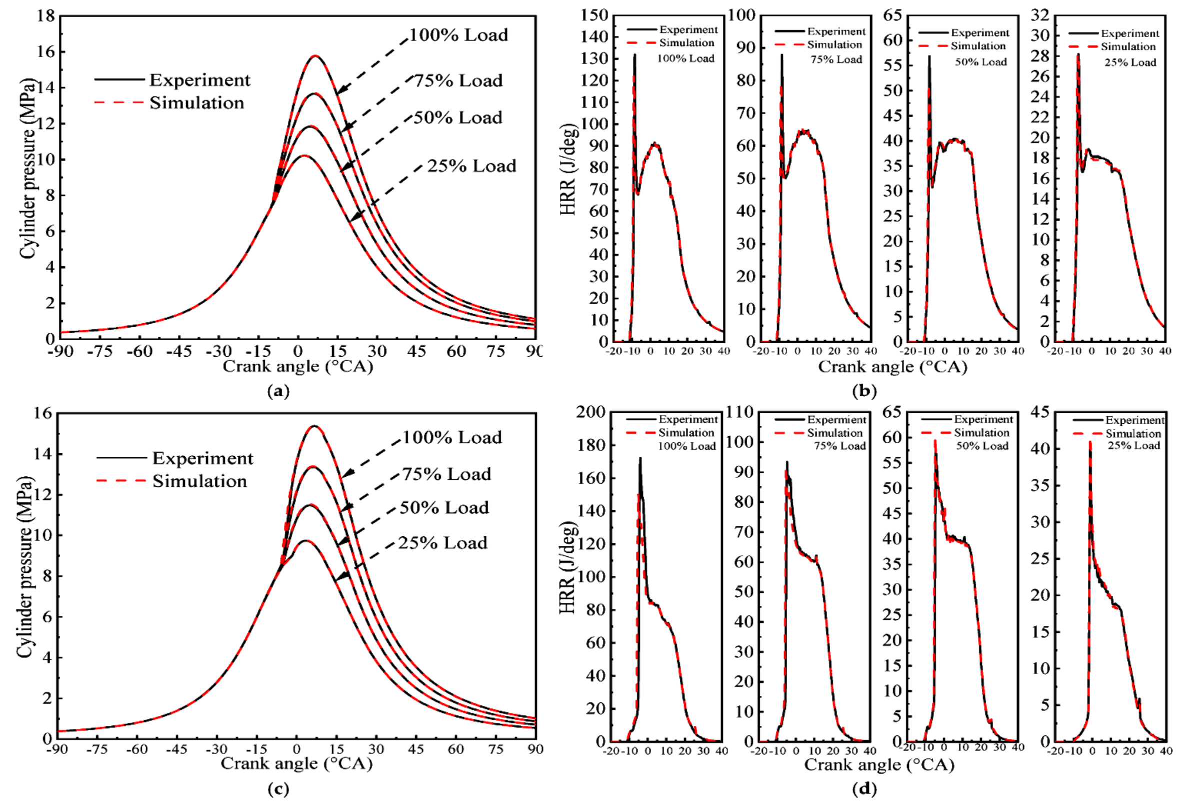

Figure 3: Comparison of cylinder pressure and emission characteristics of biodiesel with different ethanol addition ratios

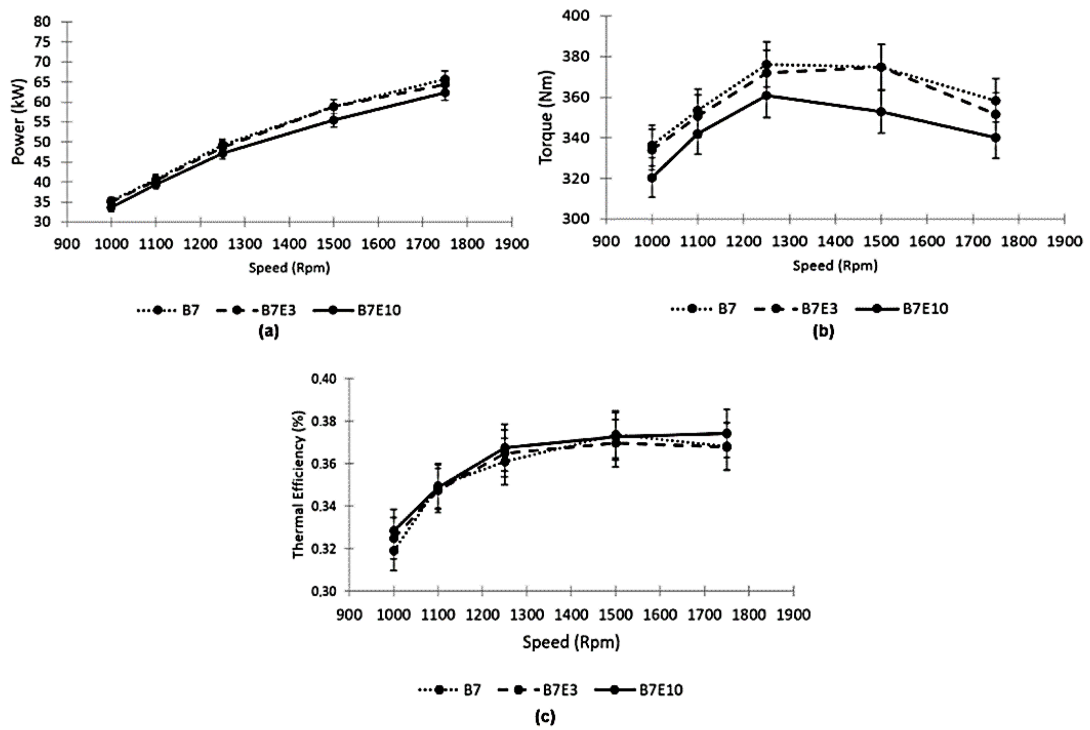

Figure 4: Diesel engine dynamometer performance

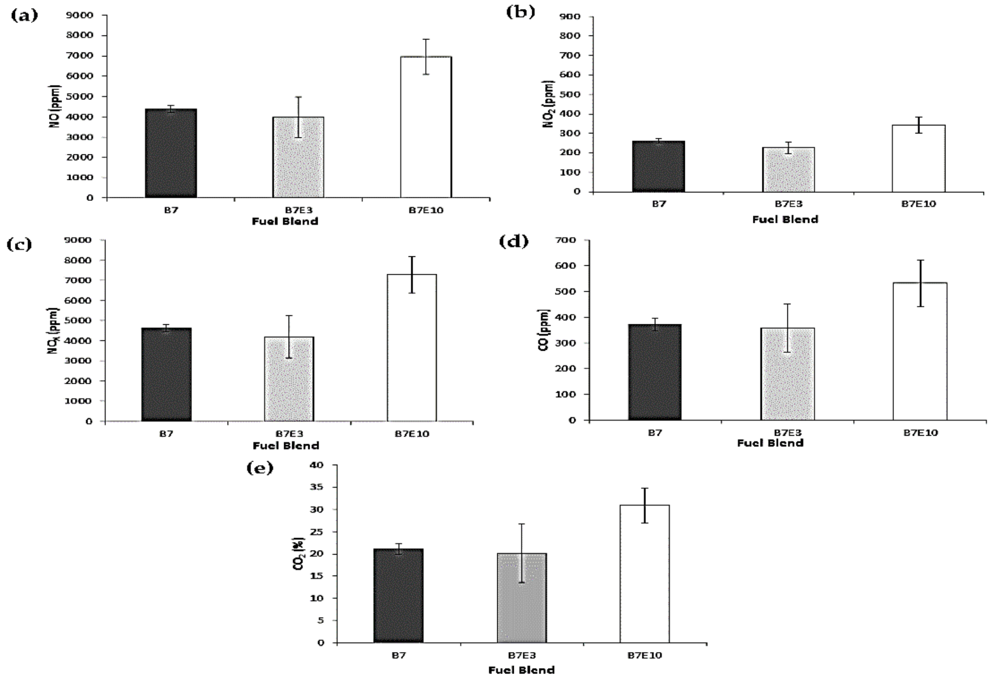

Figure 5: Exhaust gases of fuel blend

2. Results and Discussion

A. Efficiency Improvements

Important information about engine performance and emissions can be gleaned from comparing the thermal efficiency of diesel and ethanol-diesel mixes. When compared to pure diesel, ethanol-diesel blends exhibit better brake thermal efficiency (BTE), especially at higher ethanol percentages. For example, at a compression ratio of 17.5, the E20 blend increased BTE by 13.33% compared to pure diesel [86]. Additionally, because of ethanol's catalytic qualities, mixes like D85E15 demonstrated increased thermal efficiency [87-89].

Resulting in reduced BSFC (brake specific fuel consumption) [90]However, because ethanol has a lower calorific value, power production may fall even while thermal efficiency increases. For example, a D80E20 blend showed a 4.12% loss in power. Additionally, these mixes considerably lower emissions of soot and carbon monoxide, although they may slightly raise emissions of nitrogen oxides (NOx). In general, ethanol-diesel blends offer a competitive and environmentally friendly substitute for conventional diesel [91-93]. The effects of the various fuel blends (B0, B10, B10E2.5 and B10E5) on engine operation and emissions characteristics were studied under 1/2 load. This study seeks to analyze the obtained results of BP, BMEP, SFC and BTE, followed by a discussion on the emissions of CO, CO_2 and NO_x.

B. Engine performance

Brake power the evolutions of the brake power and its percentile variations compared to B0, the function of the engine speed for the different fuels, under 1/2 load, are presented [94-96].

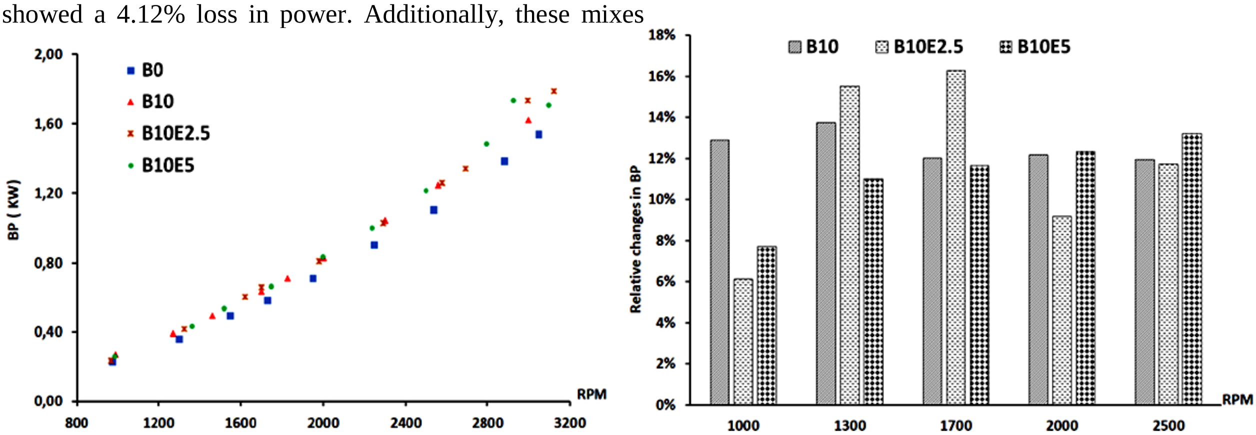

Figure 6: Function of engine speed Evolutions of BP and their relative changes

Adding 10% of BD increased slightly the engine power compared to B0. This effect was more noticeable at high speeds (>2000 rpm), reaching 6%. This increase in BP became progressively greater with the addition of ethanol and reached 16% at 1700 rpm for B10E2.5 and 13% at 2500 rpm for B10E5 [97-100]. **As shown in figure 6** A similar results were found by Bhurat for an engine powered by a mixture of ethanol–biodiesel–diesel, under various loads.

C. Brake mean effective pressure

The effects of the various fuel blends on BMEP are shown in Figure 7. The entire blends exhibit an increase in BMEP, compared to B0, at all speeds range. The maximum enhancement was obtained by B10 showing an increase of an average value of 13%.

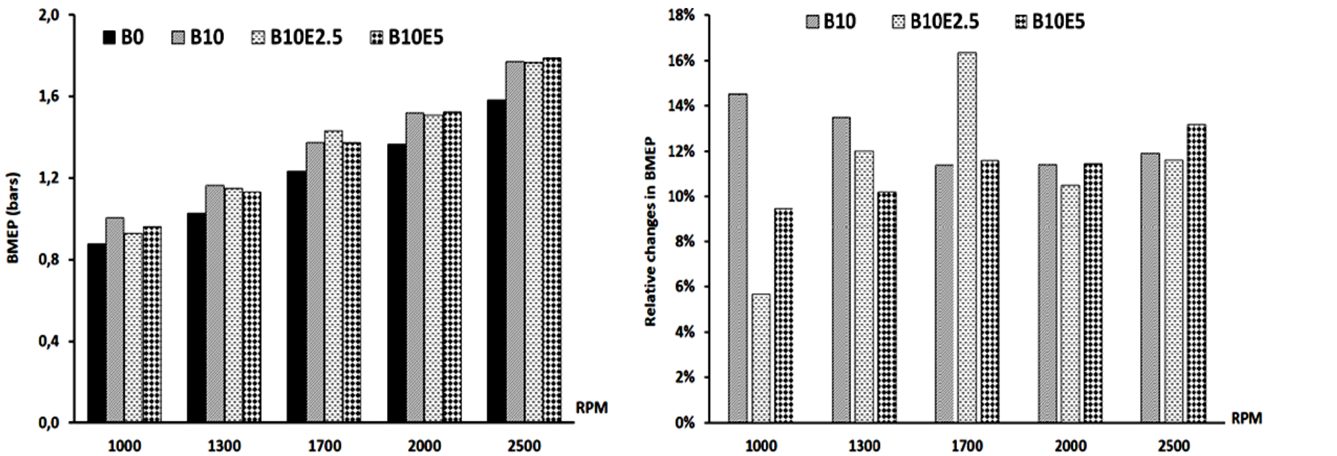

Figure 7: Variations of BMEP and their relative changes

The increase in BMEP, compared to B0, when adding BD is mainly due to the high Cetane number and oxygen content of BD . The addition of ethanol to the BD–diesel mixture decreased slightly BMEP, which can be attributed mainly to the low Cetane number and LHV of ethanol compared to BD. In addition, ethanol has a high heat of vaporization and high autoignition temperature, requiring more time to vaporize under low load conditions and low temperatures, as explained by Karin Similar results were reported. This slight decrease to the low Cetane number of ethanol compared to biodiesel [101-103]. They also stated that this decrease would not be perceived in transport applications.

The brake thermal efficiency is an indicator of how well the chemical energy contained in the fuel is converted into mechanical work at the engine crankshaft. As shown in **Figure 8,** the variations of BTE are given by the fuel blends, and the function of the engine speed. As expected, the BTE behavior is the inverse of that of SFC since they are inversely proportional. Adding biodiesel and ethanol enhanced BTE at low and medium speeds. However, at high engine speeds, BTE is reduced. This result is explained in the same way as for SFC.

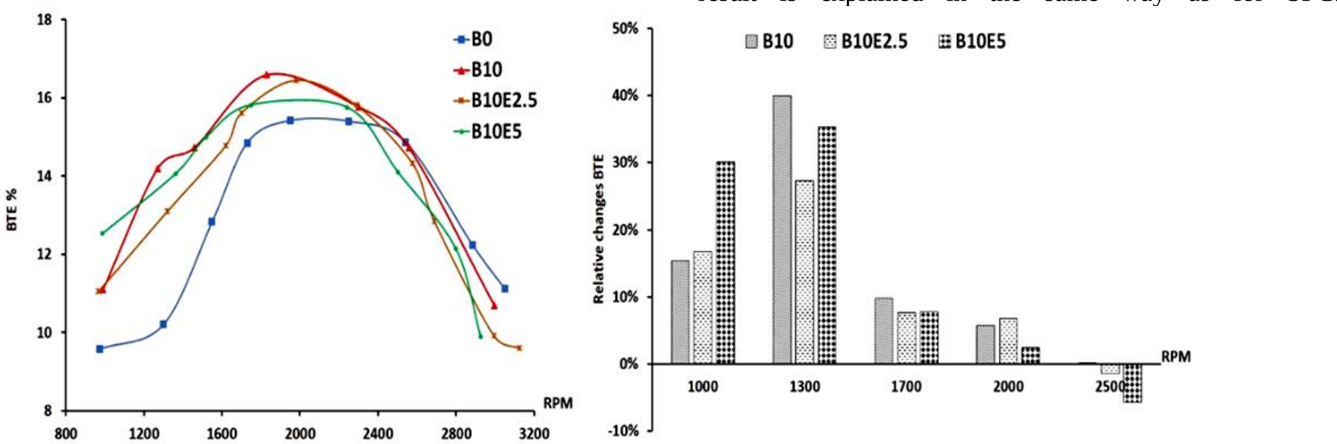

Figure 8: Evolutions of BTE and their relative changes

The decrease in BTE of biodiesel at high rpm is attributed to its low calorific value and poor atomization characteristics due to higher viscosity, leading to less complete combustion. The maximum values of BTE, obtained at a speed range of 1900–2100 rpm, gave an improvement, over pure diesel fuel, by 7.6%, 6.7%, and 2.5%, for B10, B10E2.5 and B10E5, respectively. It is evident that adding ethanol to the biodiesel–diesel blend has a slight negative impact on BTE, which can be mainly attributed to the low Cetane number and LHV of ethanol.

D. Trade-offs between emissions and performance and emissions

Trade-offs are crucial in a number of industries, including manufacturing, energy, housing, aviation, and automobiles. Although it comes at the expense of passenger capacity and aircraft mass, upgrading airplanes with Solid Oxide Fuel Cells (SOFC) and hydrogen combustion can drastically cut CO_2 emissions by up to 73.12% when compared to traditional fuels. Performance gains have always outweighed efficiency advances in the Brazilian automobile industry, with larger vehicles reducing overall fuel efficiency gains [104-107]. A complex relationship between economic and environmental performance trade-offs and policy preferences can result in different productivity growth rates, as demonstrated by the Chinese manufacturing sector. In a similar vein, Better economic and environmental results can be obtained by optimizing operations in distributed energy systems, highlighting the significance of strategic decision-making in balancing these trade-offs [108]. Last but not least, including green technologies into housing can improve environmental performance but frequently results in higher initial costs, therefore careful optimization is required to strike a balance [109]. Therefore, it is crucial to comprehend these trade-offs in order to create sustainable solutions for various businesses.

E. Analysis of CO_2, NO_x, and particulate matter emissions

Anthropogenic activities provide serious health concerns and contribute significantly to air pollution, especially when it comes to the burning of coal for home and industrial purposes. Indoor air pollution from burning coal is a major issue in developing nations like South Africa. Particulate matter (PM), carbon oxides (COx), nitrogen oxides (NO_x), and sulfur dioxide (SO2) are among the pollutants found to be produced when coal is burned. Coal and other solid fuels provide energy for a sizable portion of the world's population, particularly in rural South Africa [110-115]. Since studies show that even with better open fire and brazier designs, it can be difficult to reduce pollutants, switching to cleaner energy sources and innovative stove technology is essential to lowering the health concerns connected with residential coal combustion. The NWU semi-continuous stove underwent combustion experiments using coal discards and torrefied wood blended extrudates under high-power and low-power conditions. Both high-power and low-power trials show that fuels with higher biomass content have shorter igniting times. High-power settings accelerate combustion, resulting in shorter ignition times. Burn rates increased with increased biomass content in pellets. Pellets with 0% biomass burned at an average rate of 23 g/min, while pellets with 100% biomass burned at an average rate of 77 g/min. In comparison to other stoves, the stove consumes more biomass while maintaining comparable rates of coal usage. As biomass content rises, power output rises as well, primarily due to higher burn rates. The highest power output of 100% biomass pellets was 30 kW, while the maximum power output of 0% biomass pellets was 10 kW. Disparities between comparable studies on coal stoves are ascribed to fuel properties and stove design.

3. Conclusion

The integration of ethanol as a supplementary fuel in diesel engine power plants offers significant potential for improving fuel efficiency and reducing harmful emissions. Ethanol's cleaner combustion properties, such as reduced particulate matter (PM), nitrogen oxides (NOx), and sulfur emissions, contribute to a reduction in the environmental footprint of diesel power generation. Furthermore, ethanol's renewable nature can help lower the net carbon dioxide (CO_2) emissions, especially when derived from biomass feedstocks. However, challenges remain in fully realizing the benefits of ethanol supplementation. The lower energy density of ethanol compared to diesel means that engines may require larger fuel volumes to produce the same power output, which could impact fuel efficiency. Additionally, engine modifications and the potential for increased wear and corrosion of components must be carefully managed. Ethanol production itself can also raise concerns about sustainability, particularly when food crops are used as feedstocks, and its production may require significant energy inputs. Ultimately, the effectiveness of ethanol supplementation depends on factors such as the optimal ethanol-to-diesel blend, the engine type, and operational conditions. While ethanol can provide notable environmental and operational benefits, achieving a balance between performance, cost, and sustainability will require ongoing research and technological innovation. With proper infrastructure, engine adaptations, and sustainable production practices, ethanol supplementation can contribute to a cleaner and more efficient future for diesel-powered energy generation.

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