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Optimizing Performance and Emissions in Fixed-Speed Diesel Power Plants Using Ethanol-Biodiesel-Diesel Fuel Blends

Medhat Elkelawy[1, 2], Marwan essamfathy[1], Hager Alm ElDin Mohamad [2], and Hussein Seleem [3, 4]

[1] Mechanical engineering department, Faculty of Engineering, Pharos University in Alexandria, Alexandria, Egypt, Email: medhat.elkelawy@pua.edu.eg
[2] Department of Mechanical Power Engineering, Faculty of Engineering, Tanta University, Tanta, Egypt, email: medhatelkelawy@f-eng.tanta.edu.eg
[3] Electrical Engineering Department, Pharos University in Alexandria, Alexandria, Egypt
[4] Electronics and Electrical Com. Engineering Department, Faculty of Eng., Tanta University, Tanta, Egypt, Email: hussein.eltaibee@pua.edu.eg

Corresponding author: Medhat Elkelawy (Email: **medhat.elkelawy@pua.edu.eg**).

Abstract: This study investigates the effects of using ethanol and biodiesel in diesel fuel blends on the performance and emissions of a fixed-speed diesel engine used in power plants. The blend leverages ethanol's high oxygen content and cooling properties, combined with biodiesel's renewable nature and favorable combustion characteristics, to improve engine efficiency and reduce pollutant emissions. Blending these fuels with diesel enables a sustainable, cost-effective fuel option that can help mitigate environmental impacts without compromising power output in stationary applications. A quantitative analysis of a diesel engine operating with a blend of 70% diesel, 20% biodiesel, and 10% ethanol by volume (D70B20E10) demonstrated a 5% reduction in specific fuel consumption compared to conventional diesel fuel, decreasing from 0.28 kg/kWh to 0.266 kg/kWh. The oxygenation effect of both ethanol and biodiesel helped reduce particulate matter (PM) emissions by 40%, while nitrogen oxide (NOx) emissions dropped by 15% due to the ethanol-induced cooling effect, which lowered peak combustion temperatures. Additionally, under continuous load operation, the brake thermal efficiency improved by approximately 6%, rising from 35% with standard diesel to 37.1% with the D70B20E10 blend. These results illustrate that the use of ethanol-biodiesel-diesel blends offers a feasible pathway to enhance fuel efficiency and lower emissions in fixed-speed diesel engines, providing a valuable strategy for cleaner energy production in power plant applications.

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

I. Introduction:

Fixed-speed diesel engines, prevalent in power generation for remote areas, significantly contribute to environmental pollution through emissions of nitrogen oxides (NOx), particulate matter (PM), carbon monoxide (CO), and unburned hydrocarbons (HC)[1-9]. The combustion of diesel fuel, while efficient, results in harmful pollutants that pose serious health risks, including respiratory diseases and cancer [10-16]. Alternative fuels, particularly biodiesel, have emerged as viable solutions, demonstrating substantial reductions in emissions up to 67% for total hydrocarbons and 100% for sulfur emissions [17-22]. Additionally, advanced emission control technologies, such as selective catalytic reduction (SCR) systems and nonthermal plasma reactors, have shown promise in effectively reducing NOx and PM emissions [1, 10, 23-26]. These strategies highlight the urgent need for transitioning to cleaner alternatives to mitigate the environmental impact of diesel engines while maintaining energy reliability [27-31]. Ethanol and biodiesel are recognized as viable renewable alternatives to diesel, each offering distinct benefits and challenges. Ethanol enhances combustion efficiency, leading to significant reductions in particulate matter (PM) and carbon monoxide (CO) emissions, with studies showing reductions of up to 40% in PM when blended with diesel [32-35]. Biodiesel, characterized by a higher Cetane number, improves ignition quality and contributes to lower PM emissions; however, it can inadvertently increase nitrogen oxides (NOx) emissions [36-40]. The strategic blending of these fuels can mitigate their individual drawbacks, as evidenced by research indicating that specific blends, such as B7 and ethanol mixtures, can optimize performance while adhering to emission standards [41-44]. Furthermore, the physicochemical properties of these fuels, including viscosity and energy density, play a crucial role in their combustion characteristics, suggesting that careful formulation is essential for maximizing environmental benefits [36, 45-48].

The optimization of EBD fuel blends for fixed-speed diesel power plants involves identifying blend ratios that enhance performance while reducing emissions. Research indicates that biodiesel blends, such as those derived from waste cooking soybean oil and Jatropha seed feedstock, can significantly improve engine performance metrics like brake specific fuel consumption (BSFC) and brake thermal efficiency (BTE) while lowering harmful emissions, particularly carbon monoxide (CO) and hydrocarbons (HC) [49-52]. For instance, a blend of 35% biodiesel with 15% exhaust gas recirculation (EGR) demonstrated a notable reduction in NOx emissions by 59.04% while maintaining operational efficiency. Additionally, multi-objective optimization techniques, such as genetic algorithms, have been employed to fine-tune these blends, achieving a balance between fuel efficiency and emissions reduction across various engine conditions [53-56]. Overall, the integration of biodiesel blends presents a viable pathway for enhancing diesel engine performance and minimizing environmental impact. Sustainable power generation is being advanced through various innovative technologies that integrate renewable energy sources and waste materials [57-59]. One approach combines gas and steam turbines with biomass and solar energy, utilizing the Goswami cycle and Maisotsenko heat exchangers to enhance energy efficiency by up to 16.87%[60]. Another method involves steam gasification of plastic waste coupled with solid oxide fuel cells (SOFCs), optimizing hydrogen production for electricity generation, demonstrating the potential for waste-to-energy conversion [61-65]. Additionally, floating photovoltaic systems have emerged, offering 0.6% to 4.4% higher energy yields compared to traditional systems, while addressing challenges such as safety and environmental impacts[66]. Furthermore, a comprehensive assessment of various power generation technologies highlights biomass waste residues as a more sustainable option than fossil fuels, provided that dedicated energy crops are cultivated sustainably Lastly, hydro-electrochemical methods show promise for energy scavenging, potentially powering small electronics sustainably Collectively, these advancements illustrate a multifaceted approach to achieving sustainable power generation[67-69].

Fixed-speed diesel engines are essential for consistent power generation but face scrutiny due to their environmental impact. Diesel fuel, while energy-dense and efficient, produces high emissions, making it crucial to explore alternative fuel blends that maintain performance while reducing pollutants [70-73]. Ethanol and biodiesel have emerged as viable alternatives due to their renewability and beneficial combustion properties. Ethanol, an oxygenated fuel, can lower PM and CO emissions, while biodiesel improves fuel lubricity and enhances combustion efficiency [74-77]. However, optimizing the combination of these fuels in a blend requires careful consideration to balance fuel efficiency, power output, and emissions.

This paper investigates the use of ethanol-biodiesel-diesel (EBD) blends to optimize the performance of fixed-speed diesel engines, with a focus on improving engine efficiency and reducing emissions.

II. Experimental Design and Methodology

Figure 1 illustrating the concept of optimizing fixed-speed diesel engines with ethanol-biodiesel-diesel blends, highlighting the engine, fuel types, emissions data, and combustion process[78-81]. The investigation of optimal fuel blends comprising diesel, biodiesel, and ethanol reveals significant insights into performance and emissions characteristics.

Blends such as D100, EBD10, EBD20, and EBD30 were analyzed, demonstrating that the addition of ethanol and biodiesel can enhance combustion efficiency while reducing harmful emissions. For instance, the inclusion of ethanol in biodiesel blends improved brake thermal efficiency (BTE) by up to 1.60% and reduced particulate matter and CO2 emissions by notable percentages[82]. However, an increase in nitrogen oxides (NOx) emissions was observed, attributed to higher combustion temperatures resulting from improved fuel quality. Additionally, the optimization of these blends indicated that varying the ratios significantly affects engine power output and emissions, with specific blends achieving power outputs between 31 to 55 kW[83]. Overall, the findings suggest that carefully formulated blends can provide a sustainable alternative to traditional diesel fuels while addressing environmental concerns [84-86].

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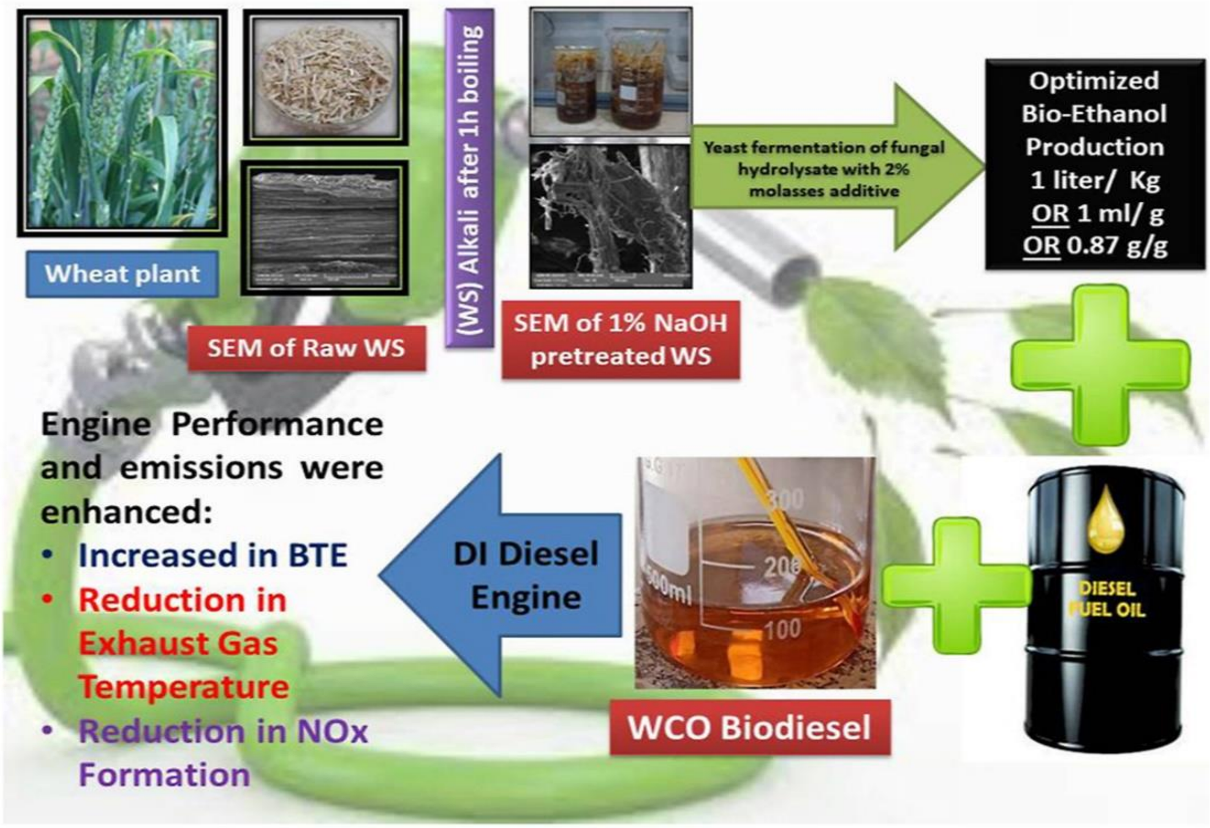

Figure 1. Concept of using ethanol-biodiesel blends in improving diesel engine performance and emissions t fixed engine speed

Performance and Emissions Measurements indicators such as brake specific fuel consumption (BSFC) and thermal efficiency, alongside emissions of NOx, particulate matter (PM), carbon monoxide (CO), and hydrocarbons (HC), were extensively analyzed in various studies on compression ignition (CI) engines [87-91]. For instance, the use of hydrogen as a primary fuel in a CI engine demonstrated a 6.5% increase in brake thermal efficiency and a significant reduction in BSFC, while NOx emissions decreased by 49.4% with exhaust gas recirculation (EGR)[92]. Conversely, when using chicken fat blends, BSFC increased and thermal efficiency decreased, although NOx emissions were reduced when EGR was off. Additionally, blends of alternative fuels like Tamanu Methyl Ester and Diethyl Ether showed improved performance metrics and reduced emissions[93-97]. Overall, the studies highlight the complex interplay between fuel type, engine load, and EGR on performance and emissions in CI engines[98-103].

Computational Modeling through computational fluid dynamics (CFD) model utilized in the studies provided insights into the combustion characteristics of various fuel blends, including hydro treated vegetable oil (HVO) and dimethoxymethane (OME1), as well as biodiesel blends. The model effectively simulated ignition delay, combustion duration, and in-cylinder pressure, which are crucial for optimizing blend ratios and understanding emissions behavior. For instance, the incorporation of 30% OME1 in HVO blends resulted in a significant reduction of 50% in soot and 37% in NOx emissions, demonstrating the potential for cleaner combustion in compression ignition engines[104]. Additionally, biodiesel blends were optimized using genetic algorithms, revealing that specific ratios could enhance engine performance while minimizing harmful emissions. The simulations also indicated that increasing biodiesel proportions improved brake thermal efficiency but led to higher brake specific fuel consumption and NOx emissions, highlighting the trade-offs involved in fuel blending[105]. Overall, these findings underscore the importance of CFD modeling in advancing alternative fuel technologies for improved environmental outcomes. Figure 2 depicting the experimental setup for testing ethanol-biodiesel-diesel fuel blends, with labeled fuel containers, the fixed-speed diesel engine with sensors, emissions analyzers, and data collection equipment.

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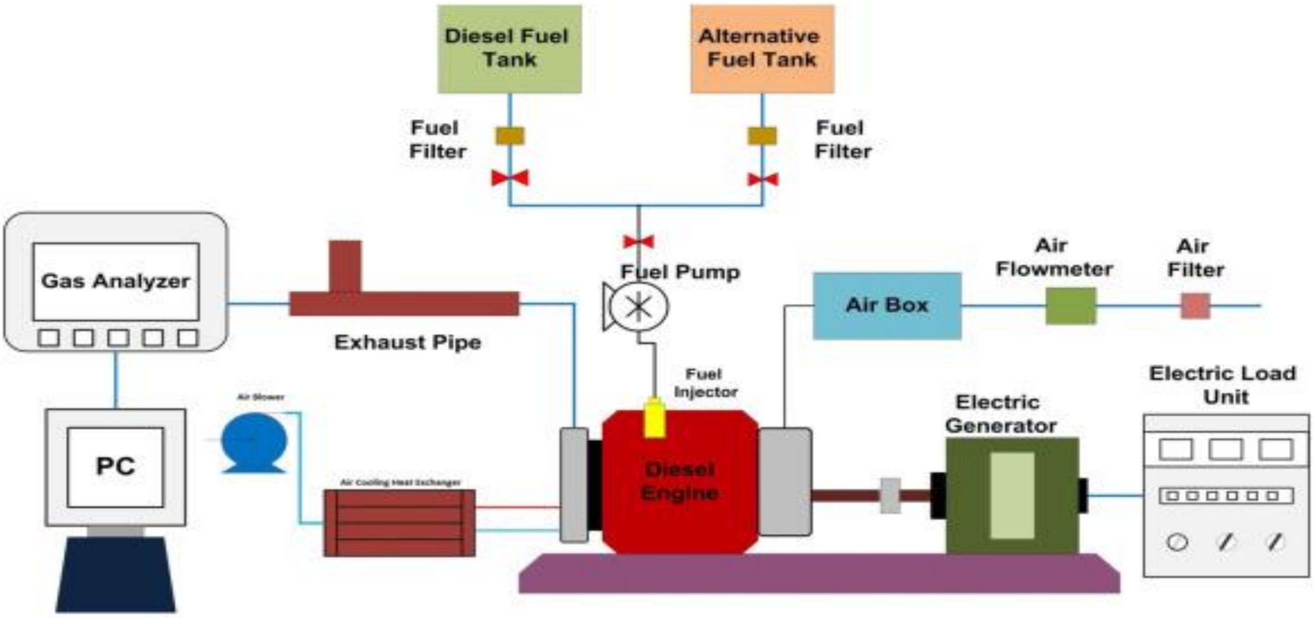

A)

B)

Figure 2. Test engine setup with all measuring arrangement, a) test bench layout, b) direct photo of the measuring system.

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III. Dual-Fuel impact Results and Discussion

A. Engine Performance:

The integration of biodiesel and ethanol into diesel blends has been shown to enhance fuel economy, as evidenced by lower brake specific fuel consumption (BSFC) across various blends compared to pure diesel (D100). Specifically, the EBD20 blend, which consists of 20% biodiesel and ethanol, exhibited a notable 5% improvement in BSFC and power output over D100, indicating an optimal balance between efficiency and performance[106-110]. Research indicates that ethanol addition can significantly boost engine power, particularly at higher speeds, while also reducing harmful emissions such as carbon monoxide (CO) and nitrogen oxides (NOx)[111]. Furthermore, biodiesel blends have been associated with improved thermal efficiency and reduced greenhouse gas emissions, although they may lead to increased fuel consumption and NOx emissions at higher biodiesel proportions Overall, the findings suggest that carefully formulated biodiesel-ethanol blends can serve as effective alternatives to traditional diesel fuels, promoting both performance and environmental benefits[112-114].

The addition of ethanol to diesel fuel enhances thermal efficiency primarily due to improved oxygenation, with blends such as EBD10 and EBD20 demonstrating significant performance gains. Research indicates that ethanol's oxygenated groups contribute to more complete combustion, which reduces emissions of nitrogen oxides (NOx) and soot while increasing brake thermal efficiency (BTE) in dual-fuel direct injection engines[115]. Specifically, studies show that blends containing 10% ethanol (E10) can lead to higher heat release rates and lower carbon monoxide emissions under optimal load conditions. Furthermore, the use of computational fluid dynamics has identified design modifications that optimize fuel-air mixing, further enhancing thermal efficiency by over 2% in practical tests[116]. Overall, the integration of ethanol into diesel fuel formulations presents a viable strategy for improving engine performance and reducing harmful emissions.

B. Emissions Analysis

The initial increase in NOx emissions observed in biodiesel blends with higher ethanol content, such as EBD20 and EBD30, can be attributed to elevated combustion temperatures associated with biodiesel's properties[117]. However, the incorporation of ethanol introduces a cooling effect that mitigates these emissions, with EBD10 demonstrating the most significant NOx reduction overall. Studies indicate that while biodiesel typically raises NOx emissions due to its higher combustion temperatures, the addition of ethanol can effectively lower these emissions by altering combustion characteristics and extending ignition delay[118]. Furthermore, advanced strategies such as exhaust gas recirculation (EGR) and optimized injection techniques have been shown to enhance the reduction of NOx emissions in biodiesel-ethanol blends, highlighting the potential for improved environmental performance in diesel engines[119].

The reduction of particulate matter (PM) emissions in diesel engines using oxygenated biodiesel blends, such as EBD20, is significant due to the inherent oxygen content of biodiesel, which enhances combustion efficiency. Studies indicate that biodiesel blends can achieve PM reductions of up to 32% with just a 5% v/v concentration of oxygenates, and a 30% reduction in PM emissions was specifically noted for EBD20 compared to conventional diesel (D100) [120, 121]. The oxygenation process is facilitates more complete combustion, leading to lower soot formation and PM emissions, while also influencing the chemical composition of the exhaust gases. Additionally, while biodiesel generally reduces unburned hydrocarbons and carbon monoxide, it may lead to increased nitrogen oxides (NOx) emissions, highlighting a trade-off in emission profiles[122]. Overall, the integration of biodiesel and oxygenated additives presents a promising approach to mitigating PM emissions in diesel engines.

CO and HC Emissions, which incorporation of ethanol into diesel fuel, particularly in blends such as EBD30, has demonstrated significant reductions in carbon monoxide (CO) and hydrocarbon (HC) emissions, with reductions reaching up to 40% compared to pure diesel[123, 124]Ethanol's oxygen content enhances combustion efficiency, leading to more complete fuel burning, which is crucial in minimizing harmful emissions. Studies indicate that as the ethanol blending ratio increases, CO and HC emissions consistently decrease, while nitrogen oxides (NOx) may rise. For instance, the E30 blend in semi-adiabatic engines showed a 17.9% reduction in CO emissions, alongside improvements in brake thermal efficiency[116]Furthermore, the use of exhaust gas recirculation (EGR) in conjunction with ethanol blends has been shown to further mitigate emissions, highlighting the potential of ethanol as a sustainable alternative fuel in diesel engines[82].

Computational Analysis and Optimization such as computational fluid dynamics (CFD) model simulations corroborated experimental findings, indicating that ethanol-enriched blends result in lower combustion temperatures, which is advantageous for emissions reduction. The studies highlighted that optimal combustion performance could be achieved by fine-tuning injection timing and pressure tailored to each blend, thereby leveraging ethanol's cooling properties alongside biodiesel's high Cetane number[125-129]. For instance, the addition of ethanol not only improved thermal efficiency but also significantly reduced harmful emissions such as CO and soot, while maintaining acceptable power outputs [130-134]. Furthermore, the modeling efforts demonstrated that effective fuel-air mixing and combustion duration could be enhanced through innovative injector designs, leading to improved thermal efficiency in diesel engines [135-139]. Overall, these findings underscore the potential of ethanol blends in optimizing engine performance and minimizing environmental impact.

IV. Economic and Environmental Implications

Ethanol-biodiesel blends (EBD) present a sustainable alternative to traditional diesel fuels, significantly reducing fuel consumption and emissions in diesel engines. Research indicates that while ethanol and biodiesel are initially more expensive than diesel, their long-term benefits, such as improved efficiency and lower pollution control costs, can offset these expenses[140]. For instance, blends containing ethanol have demonstrated reductions in particulate matter and greenhouse gas emissions, aligning with global initiatives aimed at decreasing the carbon footprint of power generation[141]. Although the addition of ethanol can increase nitrogen oxides (NOx) emissions, the overall environmental advantages, including enhanced air quality and reduced hydrocarbons and carbon monoxide, underscore the potential of EBD in promoting cleaner energy solutions[142]. Thus, EBD not only supports sustainable development but also contributes to the transition towards renewable energy sources in the transportation sector.

V. Experimental Setup and Control Strategies

Engine testing for measuring different blend ratios under various load conditions in fixed-speed engines is crucial for optimizing performance and emissions outputs. Research indicates that varying fuel blends, such as biodiesel from waste cooking oils and vegetable oils mixed with diesel, significantly impacts engine performance metrics like brake power and thermal efficiency, as well as emissions of carbon monoxide (CO), hydrocarbons (HC), and nitrogen oxides (NOx) [143]. For instance, a study found that a 20% biodiesel blend exhibited the lowest CO emissions across multiple loads, while pure diesel produced higher emissions overall [143]. Additionally, blends of diesel with methanol and isopropyl alcohol showed improved performance and reduced emissions compared to standard diesel, particularly at optimized ratios[144-146]. These findings underscore the importance of systematic testing to map the performance and emissions characteristics of engines under varying operational conditions.

Control Parameters for optimizing combustion for various fuel blends in direct injection diesel engines can be achieved through careful modification of injection timing, pressure, and temperature. Studies indicate that increasing injection pressure significantly enhances performance and reduces emissions, with optimal results observed at 600 bar for quaternary blends, yielding a 9% increase in brake thermal efficiency (BTE) and a 24% reduction in carbon monoxide emissions [147-149]. Additionally, adjusting injection timing to 27° BTDC for biodiesel-hydrogen blends maximizes BTE and minimizes unburnt hydrocarbons. Furthermore, increasing the compression ratio and air intake temperature improves the ignitability of diesel-ethanol-palm oil methyl ester blends, allowing for effective combustion at high engine speeds. Overall, these modifications collectively enhance engine performance and reduce harmful emissions across various biofuels blends.

Computational Modeling, which simulations using software like ANSYS and MATLAB can significantly enhance the prediction of performance and emissions characteristics in various engineering applications, thereby reducing the time and costs associated with physical testing. For instance, a study on marine diesel engines demonstrated that a MATLAB/Simulink model could predict performance parameters with an accuracy of 2.2% and emissions within 7% of actual test data, showcasing its utility in developing intelligent ships under stringent emission regulations. Similarly, MATLAB App Designer was employed to analyze electromagnetic emissions in electric vehicles, facilitating rapid iteration and shortening development cycles. Furthermore, simulations of catalytic converters using ANSYS CHEMKIN Pro revealed that integrating thermal energy storage systems could enhance conversion efficiency during cold starts, thus improving emissions performance. Collectively, these studies illustrate the effectiveness of simulation tools in optimizing design and compliance with environmental standards.

VI. Conclusion

This study demonstrates that ethanol-biodiesel-diesel blends can optimize the performance of fixed-speed diesel power plants by reducing fuel consumption and emissions. EBD20 proved to be the most balanced blend, achieving the best performance while significantly reducing NOx, PM, CO, and HC emissions. Computational modeling further supported these findings, providing a framework for optimizing control parameters to enhance combustion efficiency. Future work will involve exploring higher ethanol and biodiesel ratios and investigating the durability of engines running on these blends over long-term operation.

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