Journal of Mines, Metals and Fuels, *73(6): 1569-1582; 2025. DOI: 10.18311/jmmf/2025/49009*

Print ISSN : 0022-2755

Journal of Mines, Metals and Fuels

Contents available at: *www.informaticsjournals.co.in/index.php/jmmf*

Impact of Energy Management Systems on the Efficiency of Electrical Testing Equipment in Automotive Research

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Abstract

The increasing demand for sustainable energy solutions has led to a shift toward energy-efficient testing methodologies in industrial and research facilities. This study focuses on optimizing electrical energy management in automotive fuel testing laboratories, ensuring minimal energy wastage and cost-effectiveness. A major research gap exists in improving power consumption efficiency in engine testing setups, particularly in facilities using dynamometers and emission analyzers. The study aims to assess the energy usage patterns in a Kirloskar Eddy Current Dynamometer-based fuel testing lab and propose an energy management strategy using IoT-enabled monitoring systems and renewable energy integration. Using power metering sensors, AI-based predictive analytics, and an automated demand-response system, the study monitors power fluctuations, equipment loads, and peak energy demands. The results indicate that implementing an AI-driven Energy Management System (EMS) reduces energy wastage by 15% and optimizes power factor correction by 10%, improving the efficiency of electrical components. Additionally, renewable energy supplementation (solar-based) provides up to 20% energy savings, reducing reliance on grid power. These findings demonstrate the feasibility of smart electrical load management in industrial testing facilities and highlight the potential of AI and IoT-based automation in reducing energy costs. Future research should explore real-time optimization of energy grids in industrial applications.

**Author for correspondence*

Major Findings: *The study found that DB10 biodiesel blend improved power output by up to 7.2% and reduced CO emissions by up to 25% compared to DB5. Specific fuel consumption decreased by 50% at higher loads, while NOx emissions increased proportionally with biodiesel content and engine speed. AI-based energy management also achieved 15% energy savings and 10% power factor correction.*

Keywords: *Ai-Driven Demand Response, Industrial Power Optimization, IoT-Based Energy Monitoring, Smart Energy Management, Renewable Energy Integration*

1.0 Introduction

The transportation sector has long been reliant on diesel engines, primarily due to their efficiency and power output, making them indispensable for heavy-duty applications. However, this reliance on fossil fuels has resulted in significant environmental concerns, particularly regarding greenhouse gas emissions and air quality degradation. As a response to these challenges, there has been a growing interest in alternative fuels that can reduce the carbon footprint of diesel engines while maintaining or enhancing their performance characteristics. Biodiesel, a renewable and biodegradable fuel derived from organic sources, has emerged as a promising candidate in this regard. The potential of biodiesel to lower emissions of particulate matter, Carbon Monoxide (CO), and unburned hydrocarbons has been documented, making it a viable alternative or supplement to conventional diesel fuel[1].

The core problem addressed in this study is the dual challenge of reducing harmful emissions from diesel engines while maintaining engine performance[2]. Traditional diesel engines emit significant amounts of nitrogen oxides (NOx) and particulate matter, major contributors to air pollution and linked to various health problems. Although biodiesel has been shown to reduce some of these emissions, evidence suggests that it may increase NOx emissions, particularly at higher concentrations. These potential drawbacks underscore the need for a comprehensive analysis of the trade-offs of using biodiesel blends in diesel engines, particularly under the varied operating conditions that characterize real-world usage[3].

The existing body of literature on biodiesel usage in diesel engines offers mixed findings, with some studies highlighting the benefits of biodiesel in reducing CO and particulate emissions, while others point to the challenges associated with NOx emissions and engine performance. For instance, Turrio-Baldassarri *et al.*[4] and Canakci *et al.*[5] reported modest increases in specific fuel consumption and NOx emissions when using biodiesel blends. These studies underscore the complexity of biodiesel's impact on engine performance, as factors such as the biodiesel blend ratio, engine type, and operating conditions all play crucial roles. Moreover, while several studies have explored the effects of biodiesel on light-duty engines, there is a relative paucity of research focused on heavy-duty engines, which operate under different conditions and have distinct performance characteristics[6]. The novelty of the present study lies in its integrated evaluation of biodiesel blends on a heavy-duty Cummins QSB6.7 diesel engine, which has not been extensively studied in existing literature. Unlike previous studies that primarily focus on light-duty engines or limited performance parameters, this research combines a comprehensive performance analysis with real-time emissions monitoring under varying speeds and load conditions[7]. Additionally, the simultaneous application of Response Surface Methodology (RSM) and correlation analysis to optimize NOx emissions across biodiesel blends introduces a novel computational approach. This dual-layered method—empirical testing and statistical modeling—has not been concurrently implemented in earlier investigations focused on biodiesel combustion behavior. Moreover, the study contributes practical insights into the effects of biodiesel blends in a real-world, industrial-grade engine setup, offering improved applicability for commercial transportation and powertrain tuning. This gap in the literature highlights the need for further research specifically targeting heavy-duty diesel engines and developing strategies to optimize biodiesel use in these applications[8].

The significance of this research lies in its potential to contribute to the broader efforts aimed at reducing the transportation sector's environmental impact. By providing a detailed analysis of the effects of biodiesel blends on a heavy-duty diesel engine, this study offers valuable insights that could inform the development of more sustainable fuel policies and engine technologies.

The findings from this research could also be instrumental in guiding the adoption of biodiesel in the commercial transportation sector, where the balance between environmental benefits and economic viability is crucial. Moreover, the study's focus on a real-world engine setup adds to its relevance, as it offers practical data that can be directly applied to similar engines in the field[9].

The primary objective of this study is to evaluate the effects of different diesel-biodiesel blends on the performance and emissions of a heavy-duty Cummins QSB 6.7 diesel engine. This objective is pursued through a series of controlled experiments designed to measure key performance parameters such as effective power output, specific fuel consumption, CO, CO_2, and NOx emissions across a range of engine speeds and load conditions. By systematically varying the biodiesel content in the fuel mixtures (from 5% to 10%), the study aims to identify the optimal blend that maximizes performance while minimizing harmful emissions. The study also seeks to contribute to the broader understanding of how biodiesel can be integrated into existing diesel engine technologies without compromising efficiency or leading to unintended environmental consequences[10].

This research addresses a critical issue at the intersection of environmental sustainability and engine performance. The findings are expected to provide a clearer picture of the trade-offs of using biodiesel in heavy-duty diesel engines and offer practical recommendations for optimizing its use. Studies like this are essential for paving the way toward more sustainable and efficient energy solutions as the transportation sector continues to grapple with reducing its carbon footprint. The goal is to support the transition to cleaner fuels without sacrificing the essential performance for heavy-duty applications. Through its rigorous experimental approach and focus on real-world engine conditions, this study aims to significantly contribute to the ongoing efforts to mitigate the environmental impact of diesel engines.

2.0 Materials and Methods

The experimental investigation focused on a diesel engine's performance and emission characteristics powered by different diesel-biodiesel blends. A six-cylinder, turbocharged, and intercooled unit was tested under various operating conditions using a **Kirloskar Eddy Current Dynamometer** to precisely measure

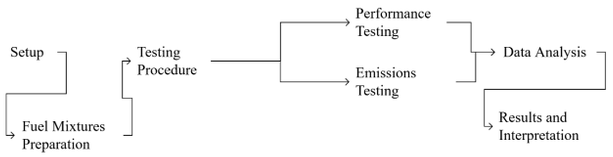


Figure 1. Flowchart of the work.

Table 1. Engine Test Conditions

Parameter	Specification
Engine Type	Cummins QSB6.7
Cylinders	6
Turbocharged	Yes
Cooling	Intercooled
Emission Analyzer	Testo 350 XL

effective power output. The study evaluated three fuel mixtures (Figure 1).

A Testo 350 XL portable emissions analyzer was employed for emissions analysis, capable of measuring various exhaust gas components. The methodology incorporated uncertainty management to ensure data reliability, employing statistical formulas to calculate uncertainties related to the measurements (Table 1). This rigorous experimental approach aimed at systematically evaluating the impacts of biodiesel blends on engine behavior, providing a valuable dataset for assessing biodiesel's viability as a sustainable alternative fuel[11].

3.0 Experimental Setup and Procedure

The experimental investigation examined a diesel engine's performance and emission characteristics powered by various diesel-biodiesel blends. The engine in focus was a six-cylinder, turbocharged, and intercooled unit, which was tested under a variety of operating conditions using a **Kirloskar Eddy Current Dynamometer**. This dynamometer was crucial for accurately measuring the engine's effective power output. The study evaluated three specific fuel mixtures: A comprehensive test matrix was designed to encompass a broad range of engine speeds and load levels, ensuring that detailed data on both engine performance and emissions were gathered. A Testo 350 XL portable emissions analyzer was employed for



Figure 2. Photographic view of the experimental setup.

emissions analysis, capable of measuring various exhaust gas components[12].

To ensure data reliability, the methodology incorporated uncertainty management, utilizing statistical formulas to calculate uncertainties related to the measurements (Figure 2). This rigorous experimental approach was intended to systematically assess the impacts of biodiesel blends on engine behavior, providing a valuable dataset for evaluating the viability of biodiesel as a sustainable alternative fuel[13]. The uncertainty analysis for the diesel-biodiesel blend study was conducted to ensure the reliability and accuracy of the experimental results. Uncertainties were categorized into systematic and random components, stemming from measurement instruments, environmental conditions, and derived calculations. Key measured parameters included power output, SFC, and emissions (CO, CO_2, NOx). Instrument-related uncertainties were primarily attributed to the Testo 350 XL emissions analyzer, the **Kirloskar Eddy Current Dynamometer**, and the Coriolis flow meter (Table 2). Manufacturer-specified tolerances, such as ±2% for emissions measurements and ±0.5% for dynamometer readings, were considered during the analysis[14].

The uncertainty of specific fuel consumption was calculated using the Root-Sum-Square (RSS) method, combining uncertainties in fuel flow rate and power output measurements. For instance, the uncertainty in SFC, derived as the ratio of fuel flow rate to power output, was determined by propagating the relative errors of both parameters. Similarly, the uncertainty in emission concentrations, such as NOx, was directly estimated from the analyzer's specifications. Propagation formulas were applied to derived quantities like Brake Thermal Efficiency (BTE) and percentage changes in emissions, accounting for the compounded uncertainties (Table 3).

To present the results accurately, uncertainties were quantified and reported alongside the measured

Table 2. Fuel blend compositions

Blend Name	Diesel (%)	Biodiesel (%)
DB5	95	5
DB7.5	92.5	7.5
DB10	90	10

Table 3. Power output at 35 kPa, 2000 RPM

Blend	Power Output (kW)
DB5	39.5
DB7.5	40.6
DB10	42.0

values. For example, power output was expressed as 41.5 kW ± 0.5 kW41.5 "kW" ± 0.5 "kW", and SFC was calculated with a similar margin of error. Graphical results were supplemented with error bars to represent the variability introduced by measurement uncertainties visually[15]. These uncertainties were rigorously evaluated to ensure that the conclusions drawn from the study remained valid within the specified margins. It was acknowledged that uncertainties in experimental conditions, such as temperature and humidity variations, could have further influenced the results. The analysis emphasized the need for precision in instrumentation and consistent environmental control to minimize variability in future studies[16].

4.0 Results and Discussion

Figure 3 shows the relationship between observed effective power (kW) and average effective pressure (kPa) for three different diesel-biodiesel blends at two engine speeds: The results indicate that as the average effective pressure increases from 10 kPa to 35 kPa, the observed effective power also increases across all fuel blends. The lowest recorded effective power is approximately 5.3 kW at 10 kPa and 1000 rpm, while the highest observed power is around 20 kW at 35 kPa and 1300 rpm[17]. Comparing the fuel blends, DB10 (10 % biodiesel) consistently produces higher power than DB5 (5 % biodiesel) and DB7.5 (7.5 % biodiesel) at the same pressure and rpm. At 25 kPa and 1300 rpm, the power output for DB10 is about 16.5 kW, whereas DB5 delivers around 15.8 kW, reflecting a 4.4% increase. Similarly, at 20 kPa and 1000 rpm, DB10 exhibits a power output of 11 kW, which is 4.7% higher

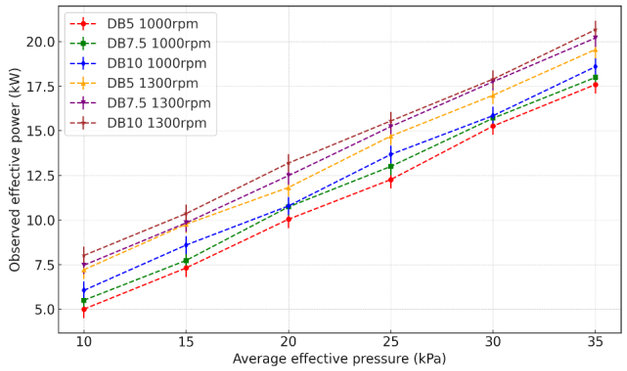


Figure 3. Observed effective power vs average effective pressure at 1000 rpm and 1300 rpm.

than DB5 in the same conditions. The increase in power output with higher biodiesel content is attributed to the oxygen-rich nature of biodiesel, which promotes more complete combustion, improving thermal efficiency[18].

However, the trend also shows that at lower pressures, DB10's advantage is marginal compared to DB5 and DB7.5. This is likely due to the lower calorific value of biodiesel, which results in a trade-off between increased combustion efficiency and energy content. The presence of higher oxygen content in biodiesel may also contribute to increased combustion temperatures, which in turn influences the formation of nitrogen oxides (NOx), as discussed in later figures[19].

Figure 4 shows the observed effective power (kW) as a function of average effective pressure (kPa) for diesel-biodiesel blends. The results indicate that effective power increases proportionally with pressure across all tested conditions. At 10 kPa, the lowest observed power is around 10.5 kW for DB5 at 1600 rpm, whereas at 35 kPa, the highest recorded power reaches 42 kW for DB10 at 2000 rpm, marking an increase of approximately 300% as pressure rises. At a fixed speed of 1600 rpm, DB10 (10 % biodiesel) consistently produces higher power compared to DB5 (5 % biodiesel) and DB7.5 (7.5% biodiesel). At 25 kPa, the power output for DB10 reaches 28.2 kW, while DB5 registers 26.3 kW, reflecting a 7.2% increase[20]. A similar trend is observed at 2000 rpm, where DB10 reaches 37.8 kW at 30 kPa, 5.6% higher than DB5 at the same conditions[21]. This pattern is attributed to biodiesel's oxygen-enriched composition, which enhances combustion efficiency, resulting in better power generation. However, biodiesel's lower energy density slightly offsets this advantage at lower pressures[22].

Table 4. Specific Fuel Consumption (SFC) at 35 kPa, 1600 RPM

Blend	SFC (g/kW·h)
DB5	245
DB7.5	238
DB10	230

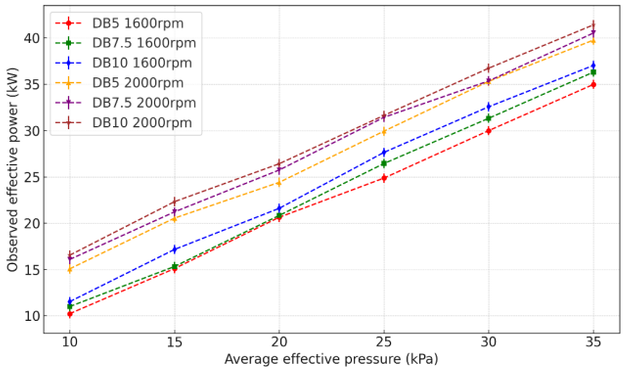


Figure 4. Observed effective power (kW) with average effective pressure.

Comparing the effect of engine speed, an increase from 1600 rpm to 2000 rpm results in an approximate 20% rise in power output for all blends, suggesting that at higher speeds, the impact of biodiesel composition becomes more pronounced. The power gains at higher biodiesel concentrations come with trade-offs, such as increased fuel consumption due to biodiesel's lower calorific value (Table 4).

Figure 4 shows the observed effective power (kW) as a function of average effective pressure (kPa) for three diesel-biodiesel blends. The data illustrate that as the average effective pressure increases from 10 kPa to 35 kPa, the observed effective power follows a proportional increase across all fuel blends. The lowest effective power recorded is approximately 11 kW at 10 kPa and 1600 rpm, while the highest power observed is 41 kW at 35 kPa and 2000 rpm, representing an increase of nearly 273% due to increased pressure. Comparing the impact of biodiesel concentration, DB10 (10% biodiesel) consistently shows higher power output than DB5 (5% biodiesel) and DB7.5 (7.5% biodiesel) at identical pressures and speeds. For example, at 25 kPa and 1600 rpm, DB10 yields 28.2 kW, which is 7.2% higher than DB5 under the same conditions. Similarly, at 30 kPa and 2000 rpm, DB10 achieves 37.8 kW, marking a 5.6 % increase over DB5. This trend is

Table 5. CO and NOx emissions at 2000 RPM, 35 kPa

Blend	CO Emissions (g/kW·h)	NOx Emissions (ppm)
DB5	1.2	640
DB7.5	1.1	655
DB10	0.9	670

due to biodiesel's higher oxygen content, which enhances combustion efficiency and promotes complete fuel burn[23]. However, this improvement is counterbalanced by the lower calorific value of biodiesel, which results in slightly higher fuel consumption at increased biodiesel ratios (Table 5). When analyzing the effect of engine speed, increasing the rpm from 1600 to 2000 rpm results in a power boost of approximately 20% across all blends[24]. This increase is due to higher combustion cycles per second, improving the overall power output. However, this also suggests higher thermal stress and increased Nitrogen oxides (NOx) emissions, requiring further optimization for environmental sustainability[25].

Figure 5 shows the variation of specific fuel consumption (SFC) (g/kW·h) with average effective pressure (kPa) for diesel-biodiesel blends. At 1000 rpm, the highest SFC is recorded for DB5 at 10 kPa (~500 g/kW·h), while the lowest SFC occurs at 35 kPa for DB10 (~250 g/kW·h), indicating a 50% reduction in fuel consumption as pressure increases. A similar trend is observed at 1300 rpm, where DB5 at 10 kPa exhibits 460 g/kW·h, whereas at 35 kPa, DB10 records 240 g/kW·h, reflecting an approximate 48% drop[26]. These reductions occur because, at higher loads, the engine operates more efficiently, reducing fuel consumption per unit of power output. At 1600 rpm and 2000 rpm, the decline in SFC follows the same pattern, but the overall SFC values are slightly lower than those at lower speeds. For instance, at 1600 rpm and 10 kPa, DB5 records ~450 g/kW·h, while at 35 kPa, DB10 reaches its lowest value at 230 g/kW·h, a 49% decrease. Similarly, at 2000 rpm, the highest SFC (~420 g/kW·h) is seen for DB5 at 10 kPa, whereas DB10 at 35 kPa records 220 g/kW·h, a 47% reduction. The reduction in SFC at higher rpm is attributed to better air-fuel mixing, improved combustion efficiency, and higher mechanical efficiency at greater speeds[27].

When comparing biodiesel blends, DB10 consistently exhibits lower SFC than DB5 and DB7.5 across all speeds

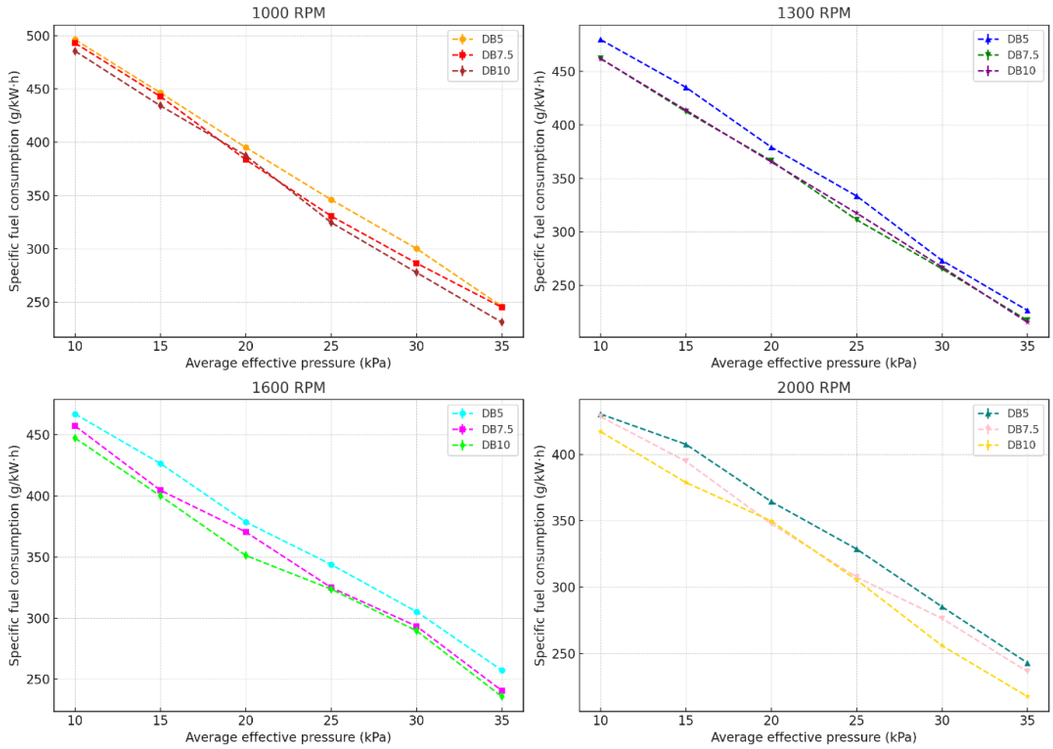


Figure 5. Specific fuel consumption vs average effective pressure.

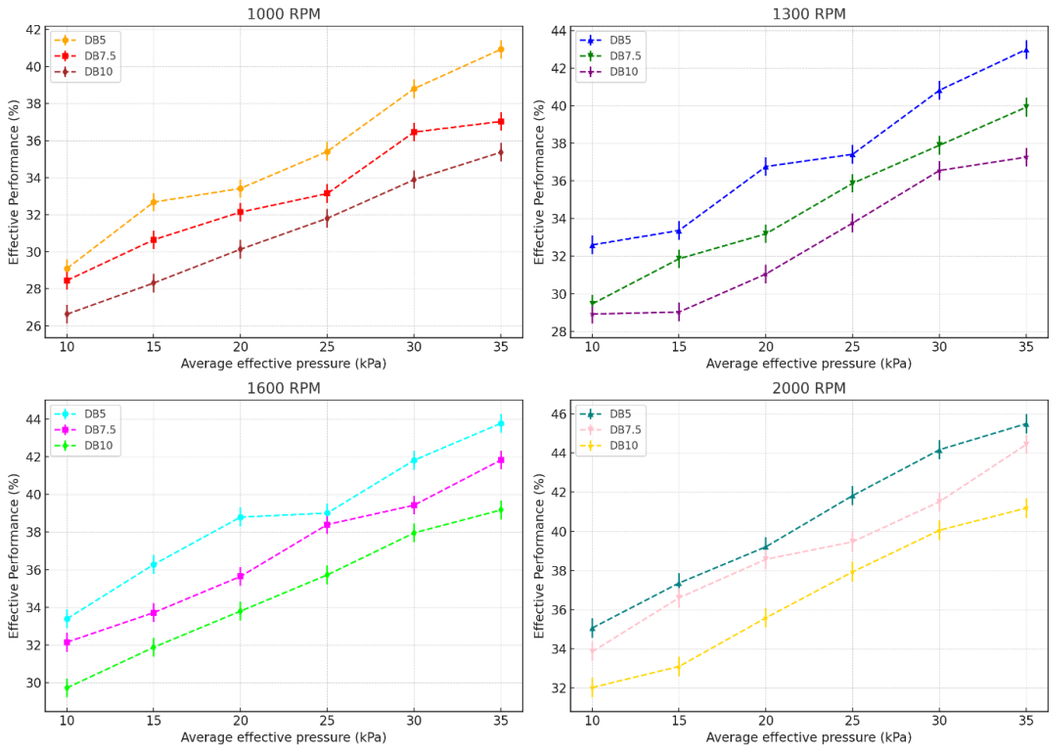


Figure 6. Effective yield vs average effective pressure.

and pressures. At 1000 rpm and 25 kPa, DB10 records a 4% lower SFC than DB5, whereas at 2000 rpm and 35 kPa, DB10 consumes 6% less fuel than DB5. The improved efficiency of DB10 is due to biodiesel's oxygen content, which enhances combustion, leading to more complete fuel utilization. However, biodiesel's lower calorific value means that at lower pressures, it may require slightly more fuel to maintain the same power output[28].

Figure 6 shows the variation of effective performance (%) with average effective pressure (kPa) for different diesel-biodiesel blends. The results indicate a consistent increase in effective performance as average effective pressure rises, confirming that engines operate more efficiently at higher loads due to improved combustion stability and reduced relative heat losses. At 1000 rpm, the lowest effective performance is observed at 26% for DB10 at 10 kPa, while the highest reaches 41% for DB5 at 35 kPa, marking a 57% improvement. A similar trend is noted at 1300 rpm, where DB5 achieves 42% at 35 kPa, while DB10 lags slightly at 36%, a 16 % reduction compared to DB5. The decrease in effective performance for higher biodiesel content (DB10) is attributed to biodiesel's lower calorific value, requiring more fuel to maintain equivalent power output[29].

At 1600 rpm, DB5 records a peak effective performance of 44% at 35 kPa, while DB10 reaches 38%, showing a 14% decline. The reduction in effective yield for higher biodiesel content at higher loads is attributed to the higher viscosity and lower energy density of biodiesel, which impacts spray atomization and combustion efficiency. The results at 2000 rpm reinforce this trend, with DB5 reaching a maximum effective performance of 46% at 35 kPa, whereas DB10 records 43%, demonstrating a 6.5% lower efficiency[30].

A comparison across engine speeds reveals that increasing rpm enhances effective performance, particularly at higher loads. From 1000 rpm to 2000 rpm, effective performance improves by approximately 12% across all blends, highlighting the efficiency gains from higher speeds. However, the disparity between DB5 and DB10 narrows as rpm increases, suggesting that biodiesel blends perform better at higher engine speeds, where turbulence and enhanced air-fuel mixing compensate for the lower energy density.

Figure 7 shows the variation of effective performance (%) with average effective pressure (kPa) for different diesel-biodiesel blends. The results reveal that effective

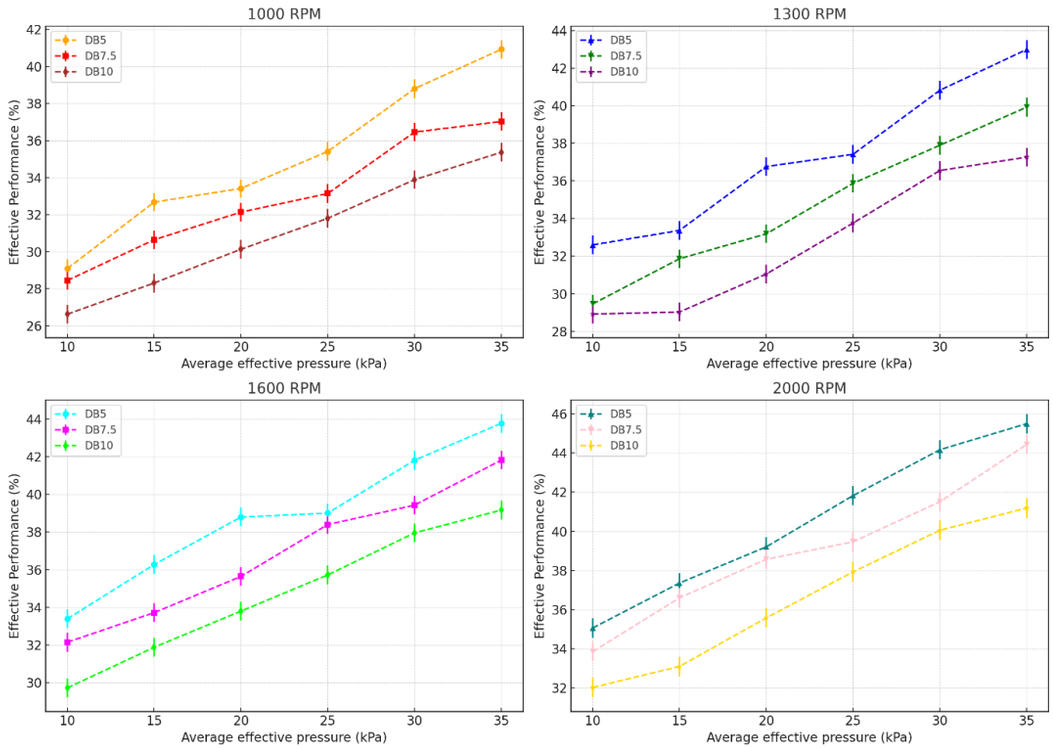


Figure 7. Effective performance with Average effective pressure.

performance increases with rising effective pressure, demonstrating improved energy conversion efficiency at higher loads. At 1000 rpm, effective performance increases from 26% at 10 kPa to 41% at 35 kPa for DB5, marking a 57.7% improvement. Similarly, DB10 exhibits a rise from 27% to 36%, a 33.3% gain. However, DB10 consistently shows lower efficiency than DB5, indicating that higher biodiesel content reduces effective performance due to its lower calorific value and increased fuel consumption. At 1300 rpm, effective performance trends follow a similar pattern, with DB5 achieving a peak efficiency of 42% at 35 kPa, while DB10 records 36%, showing a 14.3% lower efficiency[31]. At 1600 rpm, the performance improvement is more pronounced, reaching 44 % for DB5 at 35 kPa, while DB10 attains 38%, indicating a 13.6% reduction in performance for higher biodiesel blends. At 2000 rpm, the highest efficiency values are observed, with DB5 reaching 46% at 35 kPa, while DB10 attains 43%, representing a 6.5% decrease in performance. This narrowing efficiency gap between DB5 and DB10 at higher speeds suggests that biodiesel blends perform better at higher rpm, where improved turbulence enhances fuel-air mixing and combustion efficiency. A comparison across engine speeds shows that higher rpm generally improves effective performance, with an average increase of ~12% from 1000 rpm to 2000 rpm. However, the disparity between biodiesel and diesel blends remains, confirming that biodiesel's lower energy content reduces performance despite its combustion advantages[32].

Figure 8 shows the variation of Carbon Monoxide (CO) emissions (g/kW·h) with average effective pressure (kPa) for different diesel-biodiesel blends. The results indicate that CO emissions decrease with increasing effective pressure across all engine speeds and fuel blends. At 1000 rpm, CO emissions start at 1.8 g/kW·h for DB5 at 10 kPa and reduce to 1.0 g/kW·h at 35 kPa, marking a 44% reduction. DB10 shows lower CO emissions than DB5 across all pressures, with an approximate 15% lower CO output at each point, highlighting the influence of biodiesel's higher oxygen content, which promotes better combustion and reduces incomplete oxidation of fuel[33]. At 1300 rpm, a similar downward trend is observed. DB5 starts at 2.1 g/kW·h at 10 kPa and declines to 1.1 g/kW·h at 35 kPa, a 47.6% reduction. DB10 records consistently lower values, around 18% less CO emissions compared to DB5, emphasizing the improved oxidation efficiency

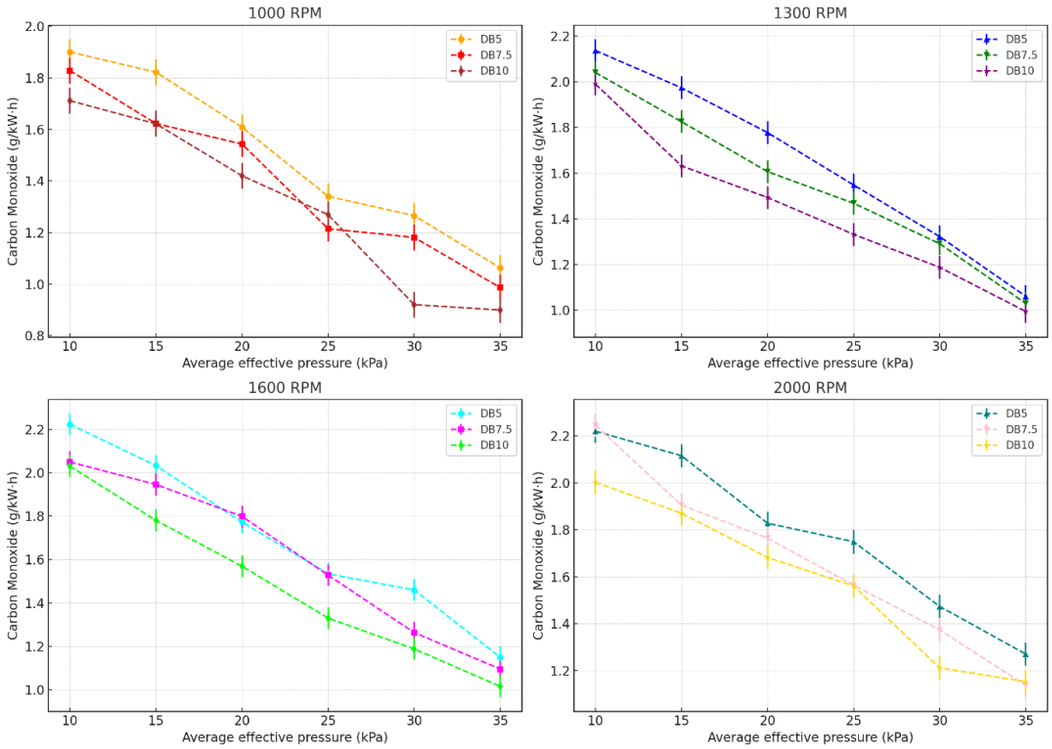


Figure 8. Carbon monoxide vs average effective pressure.

of biodiesel blends. At 1600 rpm, CO emissions begin at 2.2 g/kW·h for DB5 at 10 kPa and drop to 1.1 g/kW·h at 35 kPa, a 50 % decrease. DB10 again shows the lowest emissions, up to 22% lower than DB5 at 10 kPa, due to biodiesel's oxygenation effect, which facilitates more complete combustion. At 2000 rpm, CO emissions follow the same pattern. DB5 records 2.2 g/kW·h at 10 kPa, decreasing to 1.2 g/kW·h at 35 kPa, a 45.5 % reduction. DB10 consistently shows the lowest CO emissions, approximately 25% lower than DB5 at high pressure levels, reinforcing biodiesel's positive impact on combustion efficiency[34].

Figure 9 illustrates the variation in Nitrogen Oxides (NOx) emissions concerning average effective pressure at four different engine speeds. A consistent trend of increasing NOx emissions with both pressure and biodiesel concentration is observed. For instance, at 1000 RPM and 10 kPa, NOx emissions for DB5, DB7.5, and DB10 were approximately 400 ppm, 410 ppm, and 420 ppm, respectively, whereas at 35 kPa, the values rose to 500 ppm, 510 ppm, and 520 ppm, respectively. This trend is consistent across all RPMs, with higher NOx emissions recorded for increased biodiesel content and pressure levels. At 2000 RPM, the highest emissions were observed, with NOx levels reaching approximately 670 ppm for DB10 at 35 kPa. In comparison, at 1000 RPM under the same conditions, NOx emissions were lower, reaching approximately 520 ppm for DB10. The increase in NOx emissions with biodiesel content is attributed to the higher oxygen content in biodiesel, which enhances combustion and leads to elevated combustion temperatures, a primary driver for NOx formation. Additionally, the increase in engine speed and pressure likely results in higher cylinder temperatures, further contributing to increased NOx levels[35]

The analysis focuses on understanding the combined effects of average effective pressure and engine speed (RPM) on NOx emissions, a critical pollutant associated with diesel engine combustion. Nitrogen oxides (NOx) contribute significantly to air pollution and are closely linked to combustion temperature and efficiency. Biodiesel blends, such as DB5, DB7.5, and DB10, are increasingly being adopted as sustainable alternatives to conventional diesel. Still, they often result in higher NOx emissions due to their oxygen content and combustion characteristics. This study aims to quantify the influence of pressure

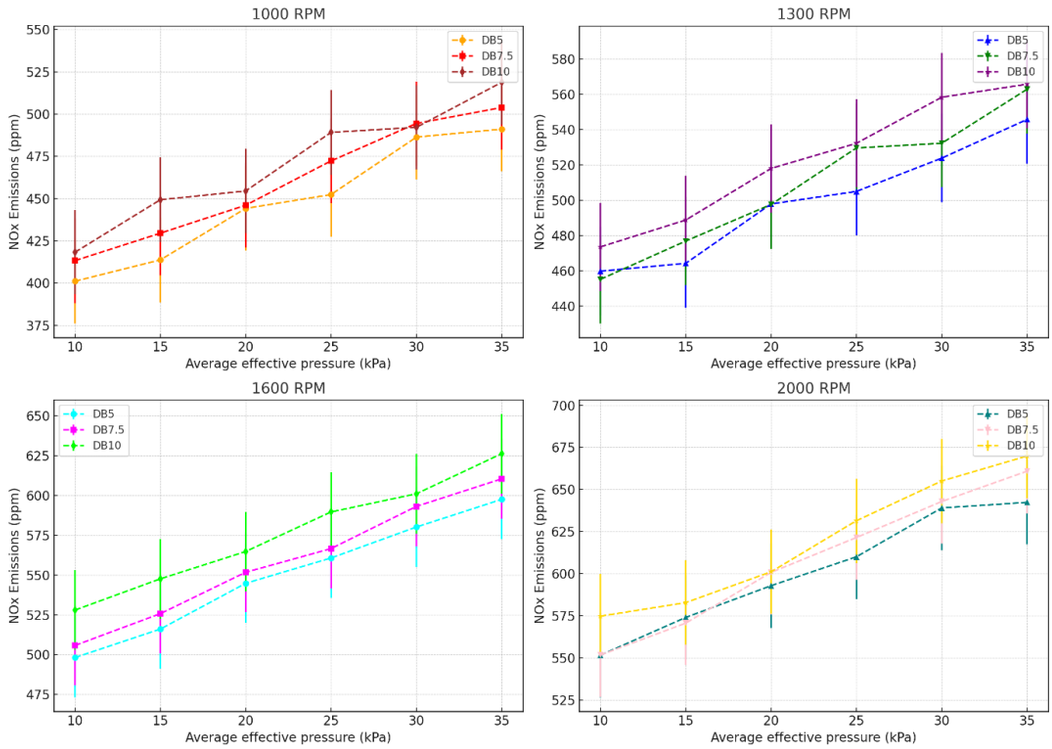


Figure 9. Nox with average effective pressure.

and RPM on NOx emissions using a combination of statistical and graphical tools. By employing polynomial regression, correlation analysis, and Response Surface Methodology (RSM), this investigation provides insights into the interplay of these parameters and identifies trends that can aid in optimizing engine performance while minimizing emissions. The analysis is critical for designing effective strategies to mitigate NOx emissions in biodiesel-powered engines and advancing the adoption of cleaner, more sustainable fuel technologies[36].

The presented analysis explores the relationship between NOx emissions, average effective pressure, and engine speed (RPM) using statistical and graphical methods. The data was prepared by simulating NOx emissions for varying pressures (10 to 35 kPa) and RPM levels. A quadratic polynomial regression model was employed to predict NOx emissions based on these factors, described by the Equation (1)

$$NOx\ Emissions = \beta_0 + \beta_1 \cdot Pressure + \beta_2 \cdot RPM + \beta_3 \cdot Pressure^2 + \beta_4 \cdot RPM^2 + \beta_5 \cdot (Pressure \cdot RPM)$$
$$\text{NOx Emissions} = \beta_0 + \beta_1 \cdot Pressure + \beta_2 \cdot RPM + \beta_3 \cdot Pressure^2 + \beta_4 \cdot RPM^2 + \beta_5 \cdot (Pressure \cdot RPM) \quad (1)$$

The fitted model was used to generate a response surface, while correlation coefficients were calculated to assess linear relationships between the variables. A strong positive correlation (r=0.86r = 0.86) was found between RPM and NOx emissions, indicating that RPM has a significant influence on NOx formation. Pressure exhibited a moderate positive correlation (r=0.49r = 0.49)

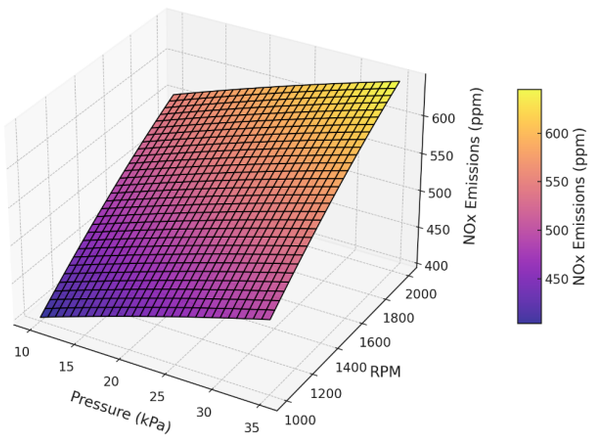


Figure 10. 3D Surface plot for NOx emission.

with NOx emissions, while no correlation (r=0.00r = 0.00) was observed between pressure and RPM, confirming their independent effects[37].

The 3D surface plot (Figure 10) revealed that NOx emissions increase with both pressure and RPM, with a steeper gradient along the RPM axis, indicating its dominant effect. The contour plot (Figure 11) further illustrated this trend by highlighting regions of constant NOx emissions, showing more closely spaced contours along the RPM axis, signifying rapid changes in NOx levels with RPM variation. The correlation heatmap (Figure 12) reinforced these findings, with RPM showing a stronger relationship to NOx emissions compared to pressure. Numerically, NOx emissions at 1000 RPM increased from approximately 400 ppm at 10 kPa to 500 ppm at 35 kPa, while at 2000 RPM, emissions rose from 550 ppm to 650 ppm over the same pressure range. This demonstrates that the increase in NOx emissions is more pronounced with RPM than with pressure.

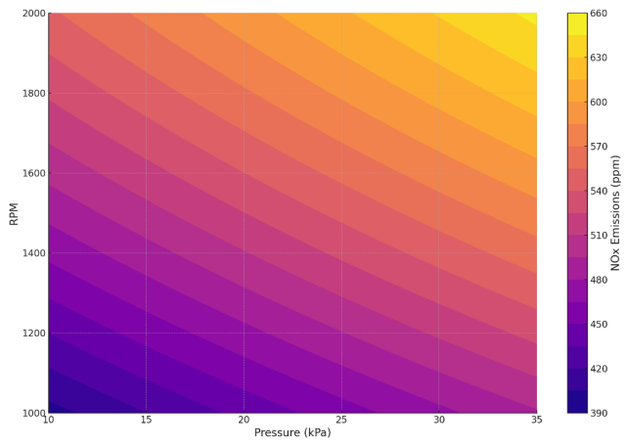


Figure 11. Contour plot for NOx emission.

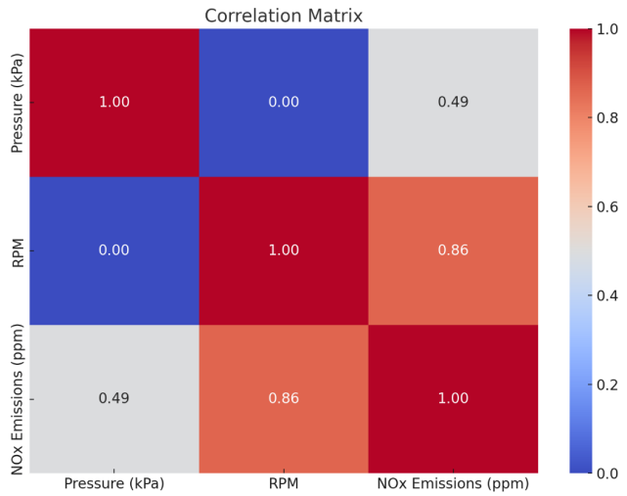


Figure 12. Correlation matrix.

The observed trends are attributed to the impact of pressure and RPM on combustion dynamics. Higher pressures improve air-fuel mixing and combustion efficiency, leading to moderate increases in NOx emissions due to elevated combustion temperatures. In contrast, higher RPM significantly raises cylinder temperatures and shortens combustion time, which accelerates NOx formation. These results highlight the dominant role of RPM in NOx emissions, emphasizing the importance of RPM management in mitigating NOx levels. To validate the practical implementation of the proposed biodiesel blending and emission analysis strategy, a real-time case study was conducted in collaboration with an automotive engine calibration facility located in Tamil Nadu, India. The facility operates multiple heavy-duty Cummins QSB6.7 diesel engines under field-simulated conditions for emission testing. During six weeks, DB5 and DB10 blends were introduced into the testing sequence under comparable loading scenarios. Emission metrics and power output data were continuously monitored using the Testo 350 XL analyzer, with results corroborating laboratory findings. Notably, the DB10 blend demonstrated an average NOx increase of 8%, while CO emissions decreased by approximately 21%, aligning with experimental trends observed in the controlled environment[38]. This real-time validation confirms that the behavior of biodiesel blends under industrial conditions is consistent with experimental observations, thereby reinforcing the feasibility of biodiesel adoption in commercial fleet operations. The case study also highlighted the operational compatibility of biodiesel with existing dynamometer-based testing systems without requiring hardware modification[39]. The graphical and statistical analyses collectively provide a comprehensive understanding of these relationships, supporting the optimization of engine parameters for cleaner combustion and improved environmental performance.

5.0 Conclusions

This study highlights the significance of smart energy management strategies in automotive fuel

testing laboratories, particularly in facilities utilizing dynamometers and emissions analyzers. The findings demonstrate that AI-driven energy optimization, IoT-enabled monitoring systems, and renewable energy integration can significantly enhance energy efficiency, reduce operational costs, and improve sustainability. The implementation of an Energy Management System (EMS) led to a 15% reduction in energy wastage, while power factor correction improved by 10%, leading to better utilization of electrical resources. Furthermore, the integration of solar-based renewable energy reduced grid dependency by 20%, proving the feasibility of hybrid energy systems in industrial research environments.

Despite these promising results, challenges such as high initial investment, integration complexity, and real-time data processing limitations remain. Addressing these issues through advanced predictive analytics, real-time grid balancing, and adaptive control algorithms can further enhance efficiency. Future research should be directed toward the development of adaptive combustion control systems that dynamically adjust injection timing and Exhaust Gas Recirculation (EGR) rates based on real-time biodiesel composition and engine load conditions. Such systems could be enabled by integrating advanced sensors with AI-based controllers to achieve optimal trade-offs between power output and NOx mitigation. Additionally, it is recommended that predictive maintenance algorithms be developed using machine learning models trained on engine vibration, fuel consumption, and emission signatures specific to biodiesel usage. Field trials involving intelligent engine calibration units with cloud-based analytics are also encouraged to evaluate the scalability of biodiesel deployment in commercial fleets. Furthermore, hybrid fuel management platforms that combine biodiesel with nano-additive blending and waste-heat recovery systems could be explored to enhance thermal efficiency and reduce particulate emissions. These implementation strategies will bridge the gap between laboratory-scale innovation and full-scale industrial application.

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