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Assessing the Impact of Exhaust Gas Recirculation on the Emission Profile of a Diesel Engine Operating on Mohua Oil: An Experimental Study

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Abstracts

The growing concern over vehicular emissions has intensified research into alternative fuels and emission control technologies. This study presents an experimental analysis of the influence of Exhaust Gas Recirculation (EGR) on the emission characteristics of a diesel engine fueled with Mohua oil biodiesel. The investigation was conducted on a single-cylinder, direct-injection diesel engine operating at a compression ratio of 17.5:1, a constant speed of 1500 rpm, and an injection pressure of 80 bar. Various EGR rates (4%, 7%, 12%, and 14%) were employed to assess their impact on key exhaust emissions, including Nitrogen Oxides (NO_x), smoke opacity, exhaust gas temperature, and other combustion by-products. The results indicate a significant reduction in NO_x emissions with increasing EGR rates, primarily due to the lowered in-cylinder temperatures and dilution of oxygen concentration. However, a marginal increase in smoke opacity and unburned hydrocarbon emissions was observed at higher EGR percentages, attributed to incomplete combustion. Notably, Mahua oil biodiesel exhibited a distinct emission pattern compared to conventional diesel, with enhanced combustion efficiency at lower EGR rates but a tendency toward higher particulate emissions under excessive recirculation. The study underscores the potential of Mohua oil as a sustainable alternative fuel while highlighting the need for optimised EGR strategies to balance emission reduction and engine performance. The findings contribute to the ongoing efforts to develop cleaner combustion technologies for future diesel engines.

Major Findings: *The study found that implementing EGR significantly reduced NO_x emissions in a diesel engine fueled with Mohua oil biodiesel, with up to a 46% reduction at higher EGR rates. However, increased EGR led to a slight rise in smoke opacity and unburned hydrocarbons due to incomplete combustion. Optimised EGR strategies are crucial for balancing emission control and engine performance.*

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Keywords: *Exhaust Gas Recirculation, Diesel Engine, Exhaust Gas Analysis, Mohua Oil*

1.0 Introduction

1.1 Origin of Study

The increasing energy demand and environmental concerns have led to extensive research into alternative fuels and emission reduction strategies for internal combustion engines. Diesel engines, widely used in transportation and industrial applications, are known for their high efficiency and durability. However, their emissions, particularly NO_x and Particulate Matter (PM), pose significant environmental and health challenges[1]. Biodiesel, derived from renewable sources, has emerged as a promising alternative to conventional diesel fuel due to its biodegradable nature, lower sulfur content, and potential for reducing greenhouse gas emissions[2]. Among various biodiesel feedstocks, non-edible oils such as Mahua (*Madhuca indica*) have gained significant attention due to their availability, cost-effectiveness, and non-competition with food resources[3].

Mahua oil biodiesel exhibits fuel properties comparable to diesel, making it suitable for use in conventional diesel engines with minimal modifications. However, its combustion characteristics, emission profile, and overall performance depend on factors such as fuel blend ratio, injection parameters, and emission control technologies[4]. One of the most effective techniques for reducing NO_x emissions in diesel engines is EGR, which recirculates a portion of the exhaust gases into the intake manifold to lower combustion temperatures and suppress NO_x formation[4]. Although EGR is effective in lowering NO_x emissions, it may lead to an increase in PM and Hydrocarbon (HC) emissions. Therefore, optimising the EGR rate is essential to maintain a balance between emission reduction and engine performance.

Several studies have explored the effects of EGR on the emission characteristics of biodiesel-fuelled diesel engines. Research indicates that applying EGR to diesel engines operating with Mahua biodiesel can lead to a significant reduction in NO_x emissions while moderately affecting combustion efficiency and particulate formation[6]. Furthermore, advancements such as catalytic enhancement, injection timing optimization, and low-heat rejection engine configurations have been investigated to improve the combustion characteristics of Mahua biodiesel blends[7]. However, there remains a need for comprehensive experimental analysis to determine the optimal EGR conditions for minimising emissions without compromising engine performance. This study investigates the impact of EGR on diesel engine emissions using Mahua oil biodiesel. It analyzes varying EGR rates on NO_x, CO, HC, and particulate matter while assessing thermal efficiency and combustion characteristics. The findings support cleaner diesel technologies by optimising biodiesel-EGR integration for improved environmental performance.

2.0 Literature Review

The integration of EGR in diesel engines has been extensively studied to mitigate Nitrogen Oxide (NO_x) emissions. Concurrently, the utilization of biodiesel derived from non-edible oils, such as Mahua oil (*Madhuca indica*), has garnered attention due to its renewable nature and potential to reduce greenhouse gas emissions. This literature review examines the experimental analyses of the influence of EGR on the exhaust emission characteristics of diesel engines operating with Mahua oil-based biodiesel.

2.1 Mahua Oil Biodiesel as an Alternative Fuel

Mahua oil, derived from *Madhuca indica* seeds, is a promising non-edible biodiesel feedstock. Research shows that Mahua biodiesel can power diesel engines without major modifications. *Yadav et al.*,[8] examines the impact of critical process parameters etchant concentration, etching duration, and temperature on the machining characteristics of thin copper sheets using PCM. Puhan *et al.*[9] found that Mahua Oil Ethyl Ester (MOEE) offered similar brake thermal efficiency to diesel while reducing CO, HC, NO_x, and smoke emissions by 58%, 63%, 12%, and 70%, respectively. Godiganur *et al.* studied Mahua Oil Methyl Ester (MOME) in a Kirloskar HA394 engine, concluding that up to 20% MOME blends performed comparably to diesel, with notable CO and HC emission reductions, making Mahua biodiesel a viable alternative fuel.

2.2 Impact of EGR on Emissions with Mahua Biodiesel

EGR is a method used to reduce NO_x emissions by recirculating exhaust gases into the combustion chamber,

lowering combustion temperatures. Senthil *et al.*[10] studied EGR with Mahua biodiesel and red mud as a catalyst, finding it improved fuel properties and reduced pollution. Praveena *et al.*[11] optimised Mahua biofuel blends and EGR rates, concluding that a 20% Mahua oil blend with an optimal EGR rate effectively lowered NO_x, unburned hydrocarbons, carbon monoxide, and soot emissions. These findings highlight the potential of Mahua biodiesel and EGR integration in enhancing diesel engine performance while minimising environmental impact.

2.3 Performance and Emission Trade-Offs

While the application of EGR in diesel engines running on Mahua biodiesel effectively reduces NO_x emissions, it is essential to consider the trade-offs. Studies have reported that higher EGR rates can lead to increased Particulate Matter (PM) emissions and a slight decrease in thermal efficiency. Therefore, optimising the EGR rate is crucial to balance the reduction of NO_x emissions with the potential increase in PM emissions and the impact on engine performance. Comparative analyses have been conducted to evaluate the performance of Mahua biodiesel against other non-edible oil-based biodiesels. For example, studies have shown that Mahua biodiesel exhibits comparable performance and emission characteristics to Jatropha and Karanja biodiesels. However, the specific fatty acid composition of Mahua oil may result in distinct combustion and emission profiles, necessitating tailored engine calibration and EGR strategies. Recent studies have explored advanced combustion techniques to further improve the emission characteristics of diesel engines fueled with Mahua biodiesel. For instance, the use of Low Heat Rejection (LHR) engines has been investigated. Reddy *et al.*[7] conducted experimental investigations on exhaust emissions of a low-heat rejection diesel engine with crude Mahua oil. The study found that the LHR engine configuration led to a reduction in particulate emissions compared to a conventional engine.

2.4 Energy and Exergy Analysis

An energy and exergy analysis provides a comprehensive understanding of the performance of biodiesel blends. Puhan *et al.*[3] performed such an analysis on a compression ignition engine using Mahua biodiesel blends with diesel. The study revealed that the energy efficiency was 28% for diesel, while for a 20% Mahua biodiesel blend (B20), the efficiency was 65.74% higher than that of diesel. The exergy analysis indicated that the input availability of diesel fuel was 1.46% more than that of B20.

2.5 Catalyst Utilization in Biodiesel Production

The use of catalysts in the production of Mahua biodiesel has been explored to improve fuel properties and reduce production costs. Senthil *et al.*[10] investigated the use of red mud as a catalyst in the transesterification process of Mahua oil. The study concluded that red mud is an effective and economical catalyst, enhancing the fuel properties and reducing environmental pollution.

3.0 Optimization of Injection Parameters

Optimising fuel injection parameters is essential for enhancing diesel engine performance and reducing emissions when using Mahua biodiesel. Praveena *et al.*[11] investigated the impact of different injection pressures on engine performance and emissions with Mahua biodiesel blends. Their study found that an injection pressure of 230 bar with a 20% Mahua biodiesel blend provided improved efficiency and reduced emissions compared to other settings. These findings highlight the significance of fine-tuning injection parameters to achieve optimal combustion, making Mahua biodiesel a more viable and environmentally friendly alternative fuel for diesel engines.

The research on biodiesel, particularly from Mahua and Jatropha oils, offers valuable insights into renewable energy alternatives for diesel engines. Puhan *et al.*[12] and Sukumar Puhan *et al.*[13] explore the performance and emissions of Mahua oil ethyl ester in diesel engines, demonstrating its potential as a sustainable fuel. Similarly, Godiganur *et al.*[14] investigate Mahua oil methyl ester, highlighting its efficiency and emission characteristics in a Kirloskar diesel engine. Senthil *et al.*[15] further examine EGR with Mahua biodiesel, using red mud as a catalyst to reduce harmful emissions. Praveena *et al.*[16] focus on optimising Mahua biofuel blends and EGR to control NOx emissions in diesel engines. Reddy and Ramesh[17] conduct parametric studies to enhance Jatropha

oil-fuelled engine performance, while Kannan and Anand[18] analyse injection timing and pressure adjustments for biodiesel from waste cooking oil, showing improved efficiency. Reddy and Maheswar[19] investigate crude Mahua oil in low heat rejection engines, assessing its impact on exhaust emissions. Murugesan *et al.*[20] provide a comprehensive review of biodiesel production from non-edible oils, covering key benefits and challenges. Chauhan *et al.*[21] and Sanjid *et al.*[22] explore Jatropha and palm biodiesel blends, analyzing their effects on engine performance, emissions, and noise levels. Similarly, Nabi *et al.*[23] evaluate cottonseed biodiesel, emphasising its impact on efficiency and emissions.

Raheman and Phadatare[24] study Mahua methyl ester blends, demonstrating their feasibility for diesel engines with reduced emissions. Bhale *et al.*[25] address the low-temperature limitations of biodiesel, proposing methods to improve fuel properties. Lastly, Bora *et al.*[26] evaluate Mahua Oil Methyl Ester (MOME) in diesel engines, reaffirming its viability as a cleaner alternative fuel. The study by Patil *et al.*[27] highlights the effectiveness of Al_2O_3 nanofluids in MQL grinding, improving cooling and friction reduction for sustainable machining. Kirpekar *et al.*[28] explore I-Cool materials in vehicles, demonstrating their role in reducing internal temperatures and enhancing energy efficiency. Parkar *et al.*[29] introduce an algorithmic approach for HVACR duct design, improving accuracy and efficiency. Yadav *et al.*[30,31] examine the impact of overlapping angles on welded curved plates, optimising structural strength and evaluating fuzzy logic-controlled five-phase induction motors, showing improved efficiency and responsiveness. Another study by Yadav *et al.*[32] compares mono-composite and metal leaf springs, confirming weight reduction and enhanced durability in composites. Shelat and Patel[33] investigate waste plastic fuel blends in CI engines, proving their potential for sustainable fuel alternatives. Purandare *et al.*[34] compare coil heat exchangers, highlighting coil geometry's effect on heat transfer. Lastly, Patil *et al.*[35] explore coconut shell ash for corrosion control in concrete, demonstrating its eco-friendly benefits for infrastructure durability. These studies collectively emphasise innovation, efficiency, and sustainability across various engineering applications along with emphasising the potential of biodiesel as an eco-friendly alternative, balancing performance, emissions, and sustainability in the pursuit of greener energy solutions.

4.0 Experimental Setup

The experimental setup (Figure 1) comprises a state-of-the-art Direct Injection (DI) diesel engine housed in the Internal Combustion (I.C.) engines laboratory, meticulously instrumented for precision testing. A custom-engineered EGR system, fabricated in-house, facilitates the controlled recirculation of predefined fractions of cooled exhaust gases, effectively displacing a portion of the intake air. The experimentation is conducted under varying engine loads, dynamically regulated via an advanced eddy current dynamometer, enabling real-time acquisition of cylinder pressure data. This data is subsequently processed to compute heat release rates as a function of the crank angle. Comprehensive engine performance metrics are captured to evaluate both operational efficiency and emissions characteristics.

The experimental analysis encompasses key pollution indicators, including smoke opacity measured in Hartridge Smoke Units (HSU), exhaust gas temperatures, and detailed compositional breakdowns of emitted gases. The study systematically investigates EGR rates of 4%, 7%, 12%, and 14%, with their respective impacts on engine performance and emissions rigorously quantified. The precise EGR percentages are derived using a standardised computational formula, ensuring repeatability and accuracy in experimental evaluation.

5.0 Result and Discussion

Figure 2 illustrates the intricate relationship between engine load and Nitrogen Oxide (NO_x) emissions,

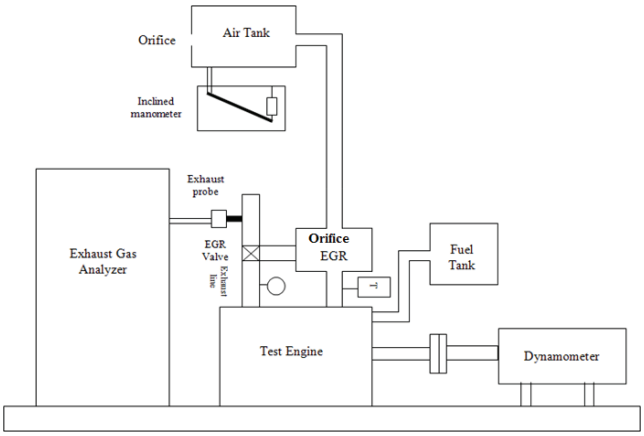


Figure 1. Experimental setup with EGR system.

offering valuable insights into the impact of fuel blends on combustion characteristics. The graphical representation highlights a distinct correlation pattern, where specific biodiesel blends—B2, B15, and B100—exhibit a stronger relationship between load variation and NO_x emissions compared to diesel, B5, and B10. This suggests a more pronounced influence of these fuel compositions on combustion dynamics and thermal efficiency.

The experimental results were obtained under controlled conditions, with the engine operating at a Compression Ratio (CR) of 17.5, a fixed speed of 1500 rpm, and an injection pressure of 80 bar. The higher correlation observed in B2, B15, and B100 blends can be attributed to variations in combustion temperature, oxygen content within the fuel, and the resulting flame propagation characteristics. Biodiesel, known for its inherent oxygen content, tends to promote more complete combustion, leading to elevated in-cylinder temperatures and subsequently higher NO_x formation. Conversely, the weaker correlation observed for diesel, B5, and B10 suggests a relatively moderated combustion process, likely due to lower oxygen availability and a more controlled heat release rate. Figure 3 illustrates the impact of incorporating an EGR system on NO_x emissions across varying engine loads. In contrast to the trends observed in Figure 2, the introduction of EGR brings a noticeable shift, particularly in the case of B100 with EGR, where NO_x emissions are significantly reduced—dropping to approximately 100 ppm compared to the earlier 185 ppm recorded without EGR. A similar emission reduction trend is evident for B15 with EGR, indicating the effectiveness of recirculated exhaust gases in moderating combustion temperatures and suppressing NO_x formation.

For other fuel blends, the NO_x emission patterns largely mirror those observed in the non-EGR scenario, albeit with a slight reduction when operating under a 20% EGR condition. This suggests that while EGR effectively curtails peak combustion temperatures in oxygen-rich biodiesel blends, its influence on conventional diesel and lower biodiesel mixtures is relatively moderate. The findings reinforce the role of EGR as a strategic emission control technique, particularly for higher biodiesel concentrations, in achieving a more environmentally sustainable combustion process without compromising overall engine performance.

Lowering the combustion temperature to less than 1200°C controls the generation of NOx, which is highly temperature-dependent. Using biodiesel and its mixes would be particularly beneficial because it also helps to mitigate the increased NOx emissions that have been noticed for these fuels. Figures 4 and 5 indicate that biodiesel-containing fuels outperform pure diesel, even in the absence of EGR. Increased oxygen levels in biodiesel fuel may cause incomplete combustion, resulting in increased hydrocarbon emissions. The use of EGR leads to

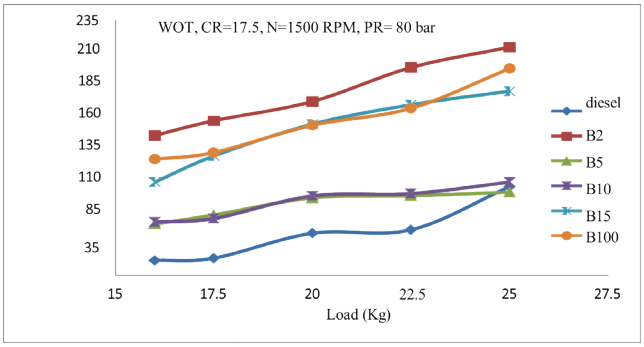


Figure 2. NOx (ppm.) vs load (kg).

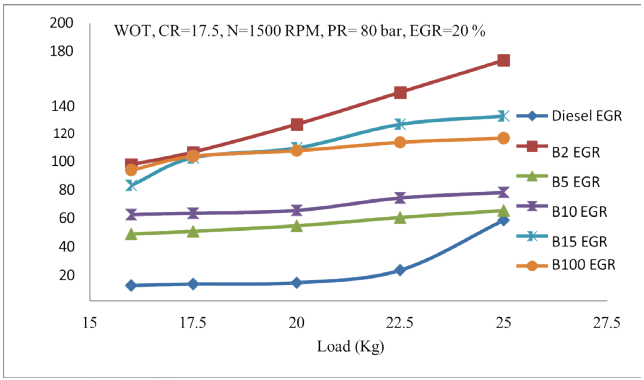


Figure 3. NOx (ppm.) vs load (kg) EGR.

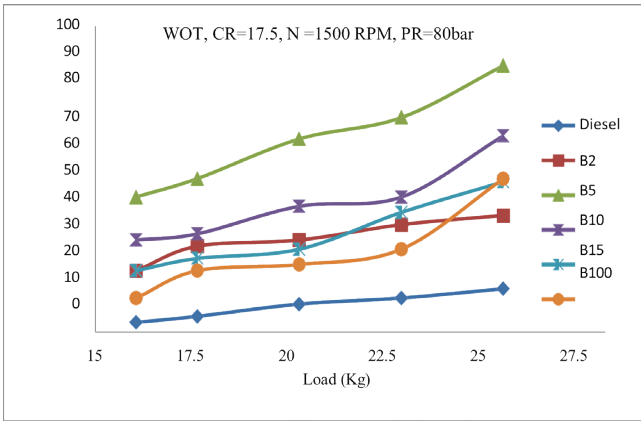


Figure 4. HC (ppm) vs load (kg).

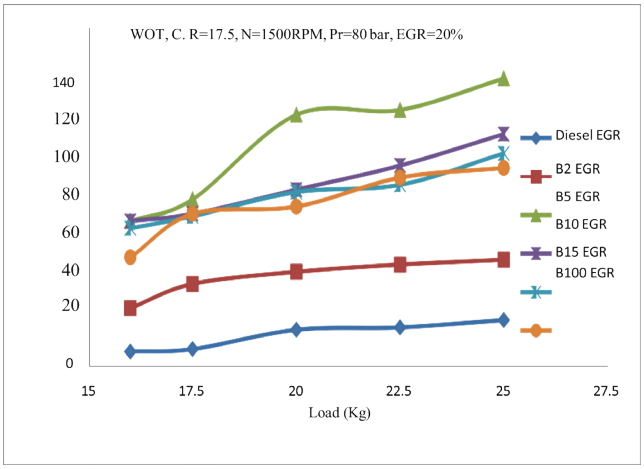


Figure 5. HC (ppm) vs load (kg) EGR.

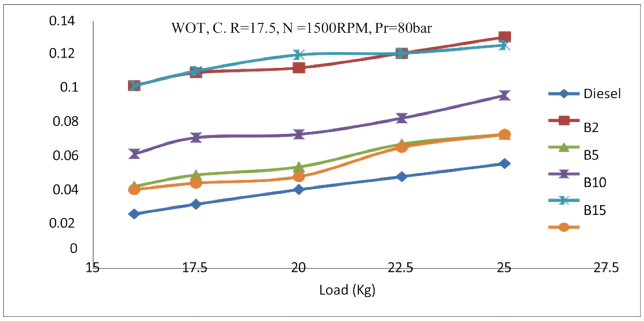


Figure 6. CO (ppm) vs load (kg).

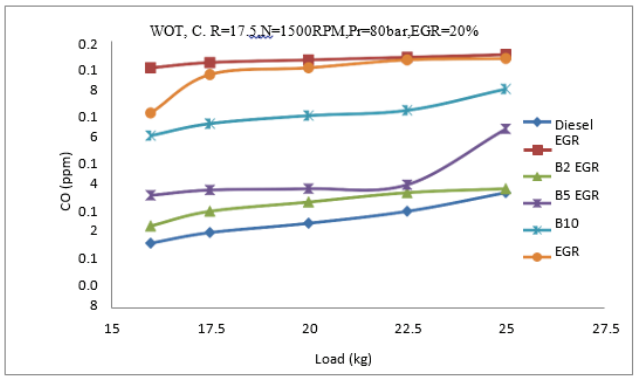


Figure 7. CO(ppm) vs load(kg) EGR.

higher HC emissions. Recirculated exhaust gases reduce the concentration of oxygen in the combustion chamber, slowing the process and preventing total combustion. This leads to increased HC emissions.

Similarly, Figures 6 and 7 show that the usage of biodiesel and its mixes produces significantly higher CO emissions than pure diesel. It even increases when EGR is used. It is primarily because the available oxygen to be consumed for combustion was reduced due to the usage of recirculated exhaust gas, resulting in incomplete combustion and increased CO production. Although EGR helps to lower NOx emissions, it also increases HC and CO emissions in the process. Thus, there is an indirect trade-off between emission control measures.

6.0 Conclusion

Exhaust Gas Recirculation (EGR) is an effective technique for reducing NO_x emissions by recirculating a portion of the exhaust gases into the combustion chamber. This process lowers combustion temperatures, thereby decreasing NO_x formation. However, research indicates that biodiesel blends tend to produce higher NO_x emissions compared to conventional diesel. This increase is attributed to the higher oxygen content and distinct combustion properties of biodiesel. Despite this, EGR remains a valuable strategy to counteract the NO_x rise associated with biodiesel use. Studies have shown that increasing the EGR rate effectively reduces NO_x emissions for both pure diesel and biodiesel blends, including those derived from cooking oil esters. However, while EGR helps in NO_x reduction, its impact on other emissions, such as carbon monoxide (CO) and hydrocarbons (HC), follows a different trend.

Higher biodiesel concentrations in the fuel blend tend to reduce CO and HC emissions due to improved combustion characteristics. However, as the EGR flow rate increases, CO and HC emissions tend to rise, particularly in both diesel and lower biodiesel blends like B5. This suggests a trade-off when optimising EGR rates—while a higher EGR rate effectively lowers NO_x emissions, it can lead to increased CO and HC emissions. Therefore, achieving an optimal balance between NO_x reduction and CO/HC control is essential for improving overall emission performance when integrating biodiesel and EGR technology in diesel engines.

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