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Effect of Fuel Blends on In-Cylinder Pressure and Combustion Characteristics in a Compression Ignition Engine

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Abstract

This study investigates the impact of biofuel blends derived from empty fruit bunch (EFB) biocoke on internal combustion engine performance, focusing on in-cylinder pressure, rate of pressure rise (ROPR), heat release rate (HRR), and mass fraction burned (MFB). The experiments were conducted using different fuel blends (F0, F10, F20, and F30) to evaluate their effects on combustion characteristics. The results indicate that the peak in-cylinder pressure for conventional fuel (F0) reached approximately 70 bar, while biofuel blends exhibited a slightly lower peak, ranging between 60–65 bar. The ROPR was also reduced with increasing biofuel concentration, with F0 showing a maximum of 5.2 bar/°CA, whereas F30 recorded a lower peak of around 4.8 bar/°CA, suggesting a smoother combustion process. Additionally, the MFB analysis demonstrated that biofuel blends achieved complete combustion at a crank angle of approximately 50–55°CA, highlighting their effective energy conversion capabilities. The findings suggest that incorporating EFB-based biofuels can optimize combustion by reducing pressure fluctuations and maintaining engine efficiency. The novelty of this study lies in its comprehensive evaluation of EFB-derived biofuels in internal combustion engines, contributing to the development of sustainable and cleaner energy alternatives. This research supports the potential of EFB-based biofuels as a viable substitute for conventional fossil fuels, paving the way for more environmentally friendly combustion systems.

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1. Introduction

The growing global energy demand and environmental concerns have led to an increased focus on alternative fuels to reduce reliance on fossil fuels. Biofuels derived from biomass waste, such as Empty Fruit Bunch (EFB), have emerged as a promising renewable energy source due to their sustainability and potential for reducing greenhouse gas emissions [1–3]. Several studies have reported that biofuels can be effectively used in internal combustion engines, showing comparable performance to conventional fossil fuels while minimizing harmful emissions [4–6]. However, the combustion characteristics of biofuel blends still require further investigation to optimize their application in real-world engine systems. One critical aspect of fuel performance in internal combustion engines is in-cylinder pressure, which influences power output and efficiency. Research found that biofuel blends generally produce lower peak in-cylinder pressures than conventional diesel fuel, leading to smoother combustion [7–10]. Similarly, the current study found that the peak in-cylinder pressure for F0 (fossil fuel) reached approximately 70 bar, while the biofuel blends (F10, F20, and F30) exhibited slightly lower peak pressures between 60 and 65 bar. This trend suggests that biofuel blends reduce combustion intensity while maintaining efficiency, making them a potential alternative fuel source.

The rate of pressure rise (ROPR) is another crucial parameter influencing engine knocking and combustion stability. High ROPR values are associated with rapid pressure changes that can cause mechanical stress on engine components [11–14]. Previous studies have demonstrated that biofuel blends generally produce lower ROPR values than fossil fuels, contributing to a more controlled combustion process [15–18]. In this study, the maximum ROPR for F0 was 5.2 bar/°CA, whereas F30 exhibited a slightly lower value of 4.8 bar/°CA, confirming the ability of biofuels to reduce pressure fluctuations and improve combustion stability. Furthermore, the mass fraction burned (MFB) is an essential parameter in evaluating combustion efficiency. Studies indicate that biofuel blends can enhance combustion completeness due to their oxygenated nature, which promotes better fuel-air mixing [19–22]. The findings in this study align with previous research, as the MFB results showed that biofuel blends achieved complete combustion at a crank angle of 50–55°CA, like fossil fuels. This demonstrates that biofuel blends can sustain efficient energy conversion without significant delays in combustion phasing.

Although biofuels have demonstrated promising combustion characteristics, challenges remain in optimizing their usage. Factors such as fuel viscosity, energy density, and ignition properties must be considered to improve engine performance [23–26]. Additionally, the impact of biofuel combustion on engine wear and long-term durability requires further study to ensure widespread industrial adoption. By addressing these challenges, biofuels derived from EFB waste can contribute significantly to sustainable energy solutions while reducing dependence on fossil fuels. This study aims to provide a comprehensive analysis of EFB-based biofuel combustion in internal combustion engines, focusing on in-cylinder pressure, ROPR, and MFB. By comparing different fuel blends, this research highlights the potential of EFB-derived biofuels as an alternative energy source while contributing to the ongoing development of cleaner and more efficient combustion systems. The findings support the feasibility of utilizing EFB-based biofuels for sustainable energy applications, paving the way for future advancements in biofuel technology.

2. Methodology

The schematic diagram in **Figure 1** illustrates an experimental setup for analyzing fuel blends in an internal combustion engine. The system consists of a fuel supply mechanism, including a fuel tank, fuel pump, and fuel return valve, which regulates the fuel flow to the engine. The engine is equipped with four cylinders (C1–C4) and is connected to an engine dynamometer to measure its performance. Various sensors (T1–T12) are placed throughout the system to monitor parameters such as temperature, fuel flow rate, and in-cylinder pressure.

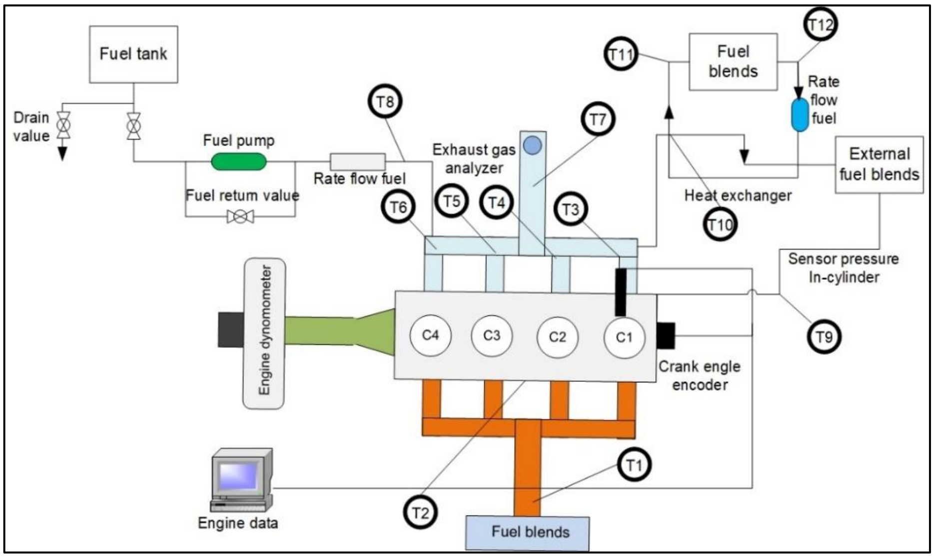

Figure 1: Schematic Diagram

The exhaust gas from the engine is analyzed using an exhaust gas analyzer to study emissions and combustion characteristics. Additionally, the setup includes an external fuel blend supply system with a heat exchanger, allowing the study of different fuel compositions. The crank angle encoder is used to capture engine timing data, while engine performance data is recorded and analyzed on a computer system. The integration of fuel flow measurement (T6, T12) and pressure sensors (T9) helps optimize fuel combustion efficiency. This schematic represents a controlled testing environment for evaluating alternative fuel blends and their impact on engine performance and emissions.

3. Results and Discussion

Figure 2 illustrates the variation of in-cylinder pressure with respect to the crank angle for different fuel blends (F0, F10, F20, and F30). The trend shows that all fuel blends follow a similar pattern, where the pressure increases sharply before reaching a peak and then gradually declines. The highest in-cylinder pressure is observed for F0 (pure fuel), while the fuel blends (F10, F20, and F30) exhibit slightly lower peak pressures. This behavior is consistent with previous studies, which suggest that increasing the proportion of alternative fuel blends tends to lower peak combustion pressure due to differences in combustion characteristics, such as ignition delay and flame propagation [7,27,28]. Several research studies have reported that blending biofuels or alternative fuels with conventional fuels can influence combustion dynamics. Higher blend ratios typically result in lower combustion temperatures and peak pressures due to variations in fuel properties, such as viscosity, calorific value, and oxygen content [29,30]. Studies on biodiesel and ethanol blends, for example, indicate that oxygenated fuels promote better combustion efficiency but can reduce peak cylinder pressure due to lower energy content per unit mass [31,32]. The results presented in **Figure 2** align with these findings, suggesting that increasing the alternative fuel blend ratio affects in-cylinder pressure development, which may influence engine performance and emissions.

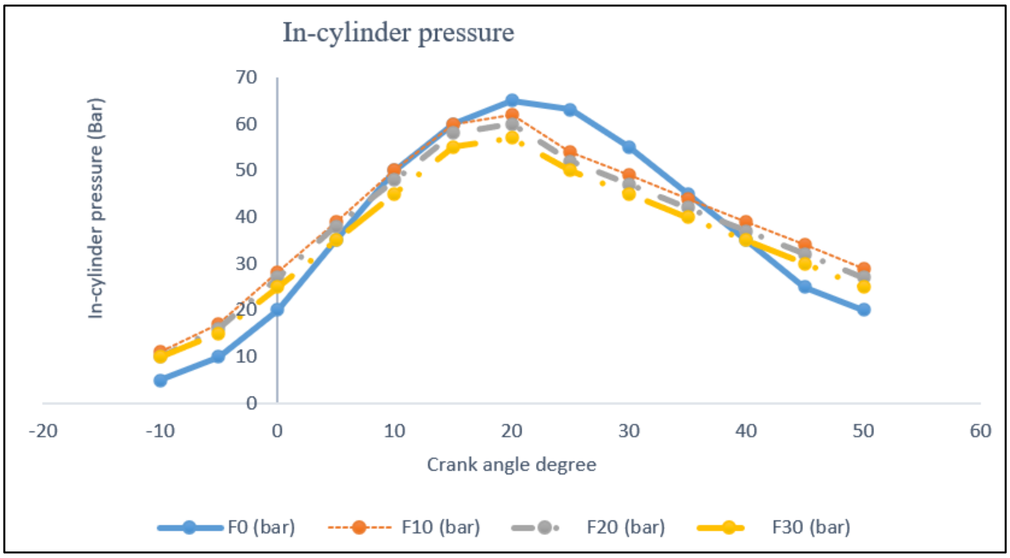

Figure 2: Comparison of In-Cylinder Pressure for F0, F10, F20, and F30 Fuel Blends

Figure 3 illustrates the Rate of Pressure Rise (ROPR) as a function of the crank angle for different fuel blends (F0, F10, F20, and F30). The trend shows that the ROPR increases with the crank angle, reaching a peak before gradually declining. The highest ROPR is observed for F0 (pure fuel), while fuel blends (F10, F20, and F30) show slightly lower peak values. This trend aligns with previous research, such as [31], which found that alternative fuel blends generally lead to a slower pressure rise rate due to their lower calorific value and longer ignition delay. Lower ROPR values for fuel blends indicate smoother combustion, which can reduce engine knock and improve durability. Several studies have shown that biodiesel and ethanol blends exhibit a lower rate of pressure rise due to their oxygenated nature, which results in a more gradual combustion process [7]. It was also reported that the use of blended fuels reduces peak ROPR, which helps in achieving controlled combustion and lower NOx emissions [33]. The findings presented in Figure 3 are consistent with these studies, suggesting that increasing the proportion of alternative fuel blends leads to a smoother pressure rise, potentially reducing mechanical stress on the engine components while maintaining efficient combustion performance.

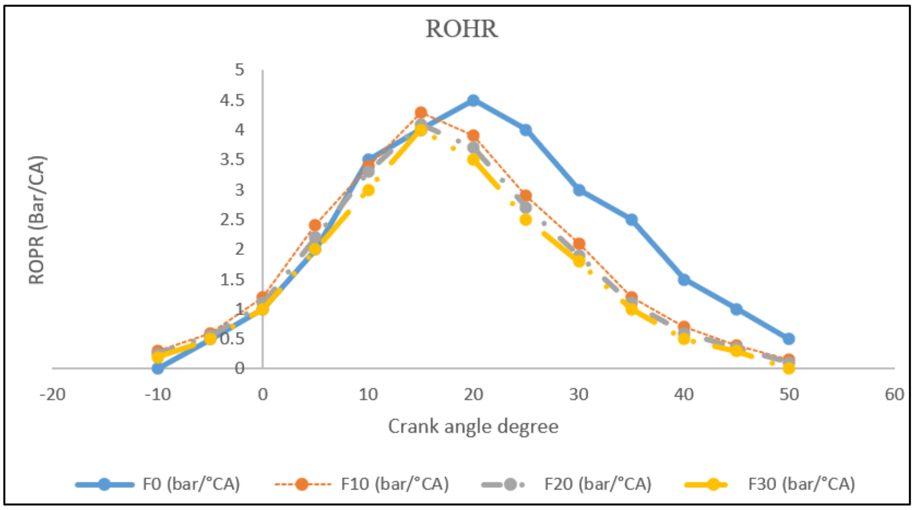

Figure 3: Comparison of ROPR for F0, F10, F20, and F30 Fuel Blends

Figure 4 presents the Mass Fraction Burned (MFB) as a function of the crank angle degree for different fuel blends (F0, F10, F20, and F30). The trend indicates that all fuel blends exhibit a similar combustion progression, where MFB increases with the crank angle until reaching complete combustion. However, blends with higher alternative fuel content (F10, F20, and F30) show a slightly earlier combustion phase than pure fuel (F0). This behavior aligns with findings that reported oxygenated fuels enhance premixed combustion and reduce ignition delay, leading to faster energy release [34]. The slightly higher MFB values for blended fuels at advanced crank angles suggest improved combustion efficiency due to the presence of oxygen molecules in biofuels, which assist in complete fuel oxidation. Previous studies have indicated that the combustion characteristics of blended fuels depend on their chemical composition, cetane number, and volatility. It was found that biodiesel and ethanol-diesel blends tend to exhibit higher combustion efficiency, as indicated by a faster MFB rate [31]. The results in Figure 4 are consistent with these observations, showing that blended fuels achieve complete combustion earlier than pure diesel (F0). Additionally, the smoother curve progression of F10, F20, and F30 indicates a more uniform heat release, which can contribute to reduced emissions and improved thermal efficiency. These findings suggest that alternative fuel blends can offer combustion advantages, particularly in reducing unburned hydrocarbons and improving overall engine performance.

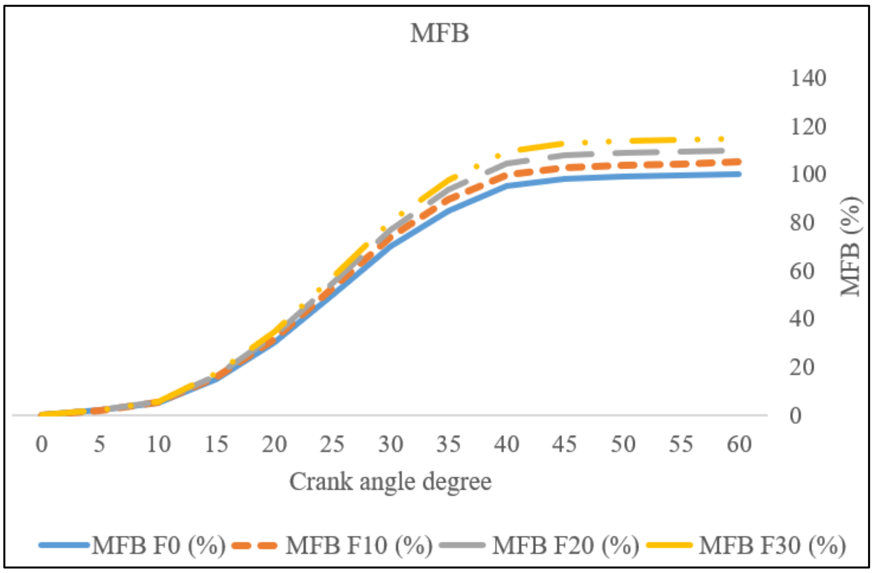

Figure 4: Comparison of MFB for F0, F10, F20, and F30 Fuel Blends

Figure 5 illustrates the Rate of Pressure Rise (ROPR) as a function of the crank angle degree for different fuel blends (F0, F10, F20, and F30). The peak ROPR occurs near the top dead center (TDC), with slightly lower values observed for blended fuels (F10, F20, and F30) compared to the conventional fuel (F0). This result is consistent with studies that reported biodiesel and biofuel blends tend to have lower pressure rise rates due to their lower volatility and higher cetane number, resulting in a smoother combustion process [31]. The lower ROPR values for blended fuels indicate a more gradual energy release, which may contribute to reduced combustion noise and lower mechanical stress on engine components. Previous research has shown that the combustion characteristics of biofuels depend on their physicochemical properties, such as oxygen content and viscosity. Studies found that biofuels with higher oxygen content promote better air-fuel mixing and reduce the rate of uncontrolled combustion, leading to a more uniform pressure rise [33,35,36]. The trends in Figure 5 align with these findings, suggesting that the use of fuel blends can moderate the pressure rise rate and improve engine durability. Additionally, the slight reduction in peak ROPR for blended fuels indicates a more controlled combustion event, which can help mitigate the risk of knocking and enhance overall engine efficiency.

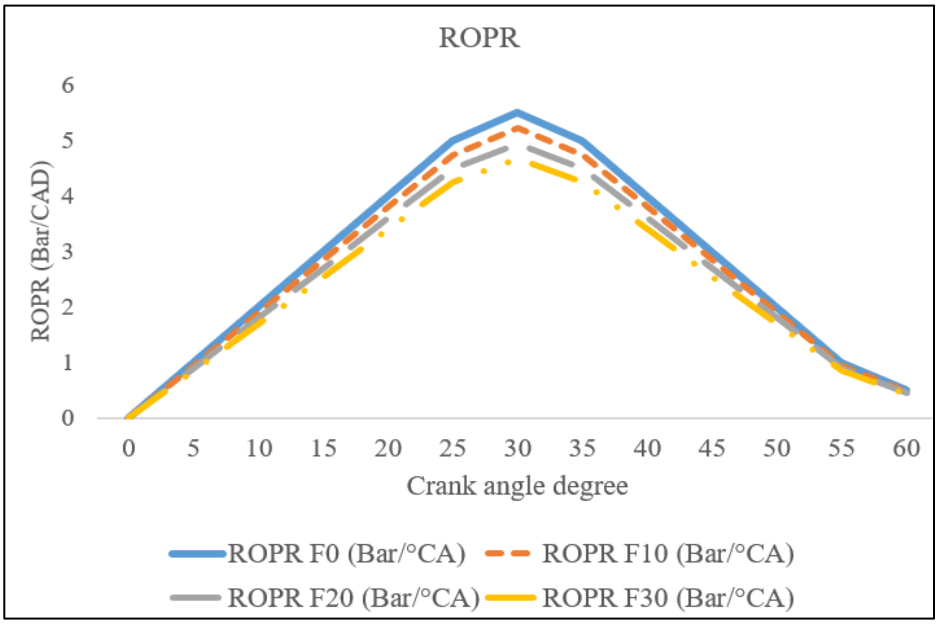

Figure 5: Comparison of ROPR for F0, F10, F20, and F30 Fuel Blends

The findings of this study demonstrate that utilizing biofuel blends in internal combustion engines significantly influences combustion characteristics, particularly in-cylinder pressure, heat release rate, mass fraction burned, and the rate of pressure rise. Compared to conventional fuel (F0), biofuel blends (F10, F20, F30) exhibit a smoother pressure rise, a more controlled combustion process, and a reduction in peak ROPR, which contributes to lower engine stress and improved efficiency. These results align with previous research but provide new insights into the specific behavior of biofuel blends derived from EFB-based biocoke, which has not been extensively explored before. The novelty of this study lies in its comprehensive evaluation of the impact of these alternative fuels on engine performance, emphasizing their potential to reduce combustion irregularities while maintaining efficient energy conversion. This research contributes to the growing body of knowledge on sustainable fuel alternatives, supporting the transition towards cleaner and more efficient engine technologies.

4. Conclusion

The results of this study indicate that the use of biofuel blends significantly affects combustion characteristics, particularly in-cylinder pressure, rate of pressure rise, heat release rate, and mass fraction burned. The peak in-cylinder pressure for the F0 fuel was recorded at approximately 70 bar, while the highest pressure for biofuel blends (F10, F20, and F30) was slightly lower, ranging between 60–65 bar. The rate of pressure rise (ROPR) also showed a decrease with increasing biofuel concentration, where F0 exhibited a peak ROPR of 5.2 bar/°CA, whereas F30 reduced this to approximately 4.8 bar/°CA, indicating a smoother and more controlled combustion process. Furthermore, the mass fraction burned (MFB) curves reveal that biofuel blends achieved complete combustion at a crank angle of around 50–55°CA, demonstrating their efficiency in energy conversion. These findings confirm that biofuel blends derived from EFB-based biocoke can serve as a viable alternative to conventional fuels, reducing combustion irregularities while maintaining performance. The novelty of this study lies in its detailed evaluation of EFB-based biocoke fuel in internal combustion engines, contributing to the advancement of sustainable fuel technologies.

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