

# Optimization of Fuel Injection Parameters in LHR Engines Using Fish Oil Methyl Ester Blends for Enhanced Performance and Emission Reduction

B. Raja Narender<sup>1\*</sup>, S. Narasimha Kumar<sup>2</sup>, B. Hadya<sup>3</sup>

## Abstract

*The need for alternative fuels has become increasingly critical due to the depletion of petroleum resources, growing automobile usage, and environmental concerns. Fish oil methyl ester, derived from fish oil, presents a promising alternative biodiesel, which can be produced from both edible and non-edible oils as well as animal fats. Diesel engines are valued for their efficiency, reliability, and durability, with performance and emissions being influenced significantly by factors such as fuel injection pressure and timing. This study examines how different fuel injection pressures and timings affect the performance and emissions of a Low Heat Rejection (LHR) engine running on blends of fish oil methyl ester, diethyl ether, and butanol. Results indicate that optimizing the injection pressure up to 230 bar enhances engine performance, fuel efficiency, and emission control. However, higher pressures show diminishing benefits, and fine-tuning the injection timing to 29° before top dead center further improves efficiency and reduces emissions. This research highlights the crucial role of optimizing injection parameters to maximize engine performance and reduce emissions when using alternative fuels.*

**Keywords:** FOME, DEE, butanol, injection pressure, injection timing

## INTRODUCTION

Due to the depletion of petroleum reserves, the rising number of automobiles, and increasing environmental pollution, finding alternative fuels is crucial. Biodiesel can be produced from a range of sources, including non-edible oils, edible oils, and animal fats. Fish oil methyl ester, derived Fish oil, stands out as a viable alternative among various options. Despite advancements, challenges remain, particularly with high-viscosity biodiesels like SAME. For instance, studies have shown that the high viscosity of biodiesel causes inefficient combustion and poor atomization, requiring additional optimization.

Automobile engines today must meet stringent environmental standards, which necessitates maximizing performance while minimizing emissions. CI engines, favored for their fuel efficiency, reliability, and durability, outperform Spark Ignition engines by consuming less fuel. Key factors influencing CI engine performance include fuel injection pressure, timing, duration, quantity, position, angle, and nozzle size. The fuel injection system is crucial for achieving optimal atomization and combustion. Low fuel injection pressure can lead to wider fuel particle diameters, increased

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Received Date: October 03, 2024

Accepted Date: October 14, 2024

Published Date: October 24, 2024

**Citation:** B. Raja Narender, S. Narasimha Kumar, B. Hadya. Optimization of Fuel Injection Parameters in LHR Engines Using Fish Oil Methyl Ester Blends for Enhanced Performance and Emission Reduction. Journal of Thermal Engineering and Applications. 2024; 11(3): 18–35p.

ignition delay, reduced performance, and higher CO, HC, and smoke emissions. Conversely, higher injection pressures enhance atomization, improve air-fuel mixing, and reduce emissions while boosting engine performance [1].

Research supports that increasing fuel injection pressure improves performance and combustion characteristics. For instance, studies have shown that high injection pressures can reduce NO<sub>x</sub> and soot emissions without compromising fuel economy. Optimization techniques like Central Composite Design (CCD) suggest that adjustments in injection parameters enhance brake thermal efficiency and reduce fuel consumption. High pressures, such as 600 bar, have been found to improve efficiency with certain fuel mixtures. Additionally, post-injection methods can decrease soot emissions significantly, while various fuel blends, including diesel-tung oil-ethanol mixtures, have shown performance improvements due to reduced combustion periods and higher pressure and heat release rates. Studies on injection timing have revealed mixed results, such as improved efficiency and reduced emissions with specific timings, but also the need for further investigation into optimal conditions. Overall, continuing research and optimization are essential for enhancing the performance and emission characteristics of engines using alternative fuels.

This study aims to optimize the timing and fuel injection pressure for a Low Heat Rejection (LHR) Compression Ignition (CI) engine that runs on a blend of 35% butanol, 15% diethyl ether (DEE), and 50% fish oil methyl ester (FOME) [2–7].

The aim is to enhance engine performance metrics such as BTE and SFC while minimizing harmful emissions including NO<sub>x</sub>, CO, HC, smoke opacity, and aldehydes. By fine-tuning these injection parameters, the study seeks to achieve an optimal balance between efficiency and emissions, demonstrating the viability of this alternative fuel blend for sustainable diesel engine operation [8–16].

## EXPERIMENTAL CONFIGURATION AND PROCEDURE

Figure 1a shows the experimental arrangement used to study LHR diesel engines with different fuel blends, and Table 1 lists the engine configurations.

A compression-ignition engine with an aluminium alloy piston and cylinder parameters of 80 mm in diameter and 110 mm in stroke length was used in the experiment. It ran at a rotational speed of 1500 rpm with a rated output of 3.68 kW. The burette method was used to measure fuel usage, and an AVL 5-Gas analyzer system was used to track air consumption. The schematic diagram and a picture of the experimental setup are shown in Figure 1a.

The water-cooling system of the naturally aspirated engine used controlled flow rates to keep the incoming water temperature at 30°C. The tests were carried out at 1500 rpm, with a compression ratio of 16.5:1, a cranking angle of 27°, and a fuel injection pressure of 190 psi. Before reaching steady-state functioning, the engine was manually started and originally fueled with diesel. About 9 l/m of water flow was maintained to the cooling jacket. Several test fuels were added from a different tank after stability was attained [17–20].

Using an eddy current dynamometer, load conditions were controlled, rising by 20% for each experimental cycle from 0 to 100%. FOME, FOME85+DEE15, FOME50DEE15+BTN35, and FOME25+DEE15+BTN60 were among the fuel blends that were assessed. Important variables including engine load, fuel consumption, and manometer readings were routinely documented during the experimental processes. We investigated those in 190, 230, and 270 bar injection pressures to examine how injection pressure affected performance and pollution. Engine timings 27°, 29°, and 31° bTDC were employed in this work. The experimental setup is schematically diagrammed in Figure 1a.

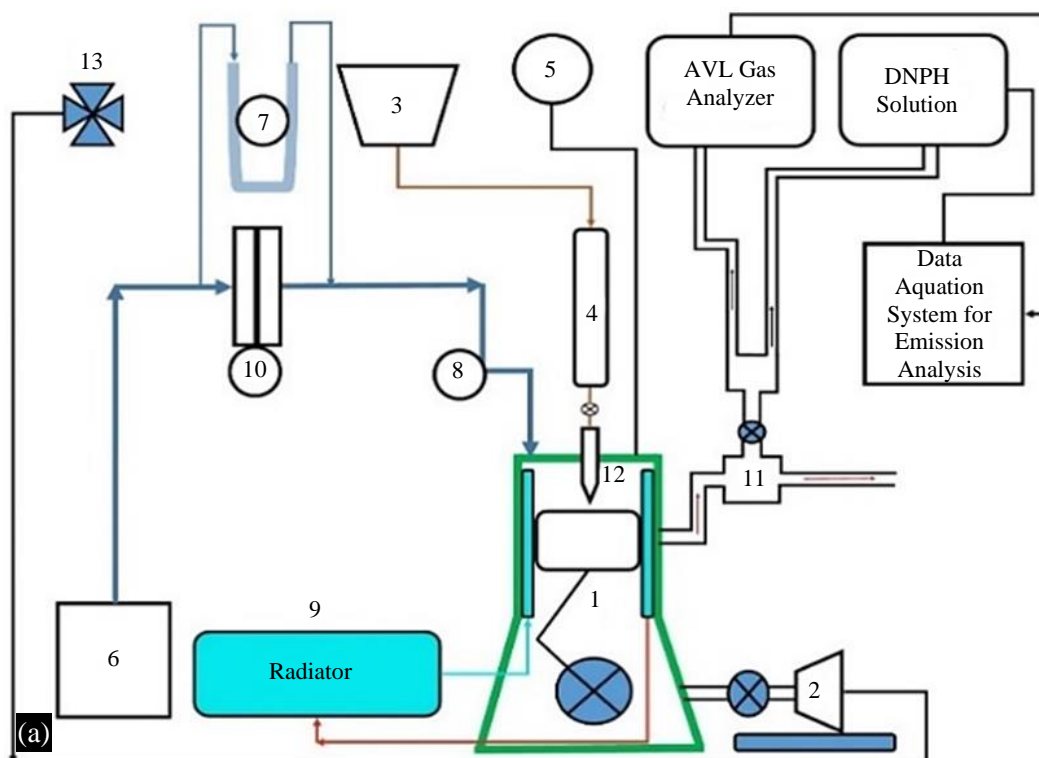
The piston of the LHR CI Engine was made up of two components: a 5 mm thick top crown made of a low thermal conductivity material (Ni90) and an aluminium piston body. When the Ni90 insert was attached to the engine crown, it had a 3 mm air gap, which was shown to be the best arrangement for improving engine performance. According to the study, the most efficient thickness for enhancing engine performance was this air gap. The air and Ni90 thermal conductivities at 500°C are found to be 0.057 and 20.92 W/mk, respectively. Figure 1b shows a representation of the Ni90 insert with the air-gap piston.

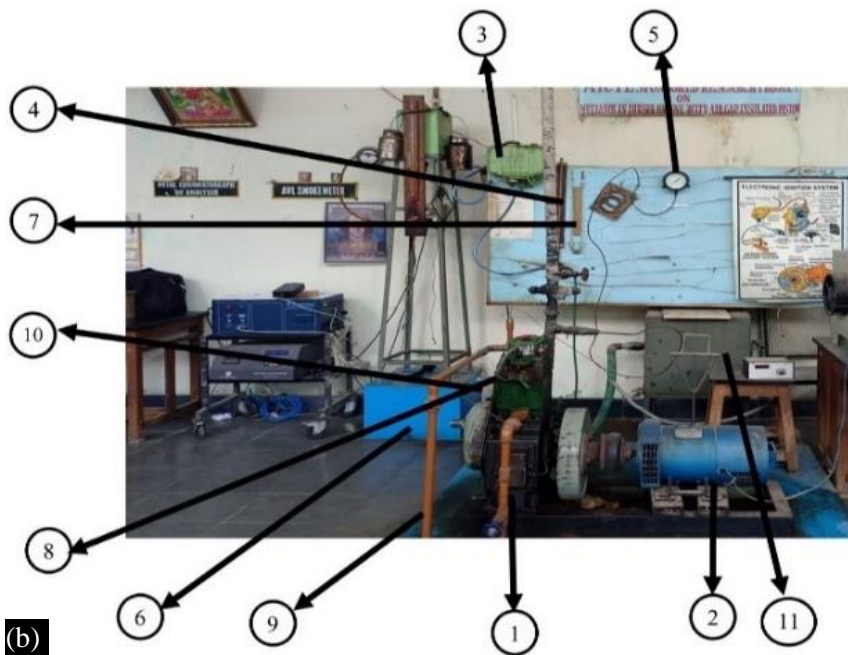
Aldehydes, such as formaldehyde and carcinogenic acetaldehyde, were tested for their health concerns in research utilizing a mixture of FOME, DEE, and butanol. By passing engine exhaust through a DNPH solution to create hydrazones, the DNPH (2,4-dinitrophenyl hydrazine) method was used to quantify these aldehydes.

These were then extracted into chloroform and analyzed using HPLC to determine their concentrations accurately.

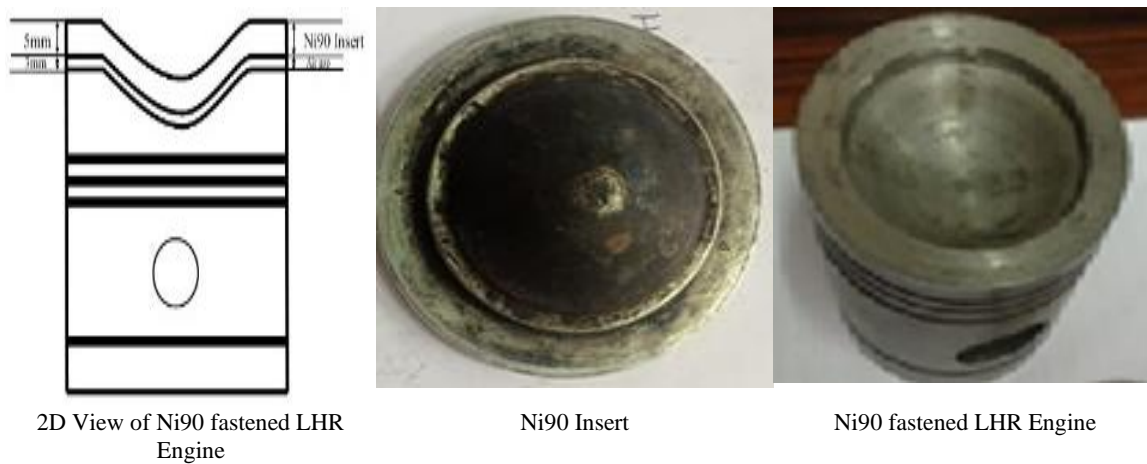
**Table 1.** Testing Engine Technical details.

Engine parameters		Specifications
Engine Type		4-stroke single cylinder, constant speed, direct injection CI Engine
Manufacturer		Kirloskar
Rated power		3.68 kW at 1500 rpm
Bore		80 mm
Stroke		110 mm
Specific volume		0.552 l
Compression ratio		16.5:1
Cooling type		Water cooling
Insulated insert	Material	Ni90
	Thickness	5 mm





**Figure 1a.** Experimental setup. (a) Schematic layout, (b) Photographic view.  
 1. Engine, 2. Electrical Dynamo meter, 3. Fuel tank, 4. Burette, 5. Piezo-electric pressure transducer  
 6. Air box, 7. U-tube water manometer, 8. Air inlet, 9. Outlet-jacket water flow, 10. Orifice meter  
 11. Exhaust gas sampling collection, 12. Fuel Injector, 13. Dynamometer control



**Figure 1b.** LHR Engine Piston.

## RESULTS AND DISCUSSION

Optimizing fuel injection pressure and timing is crucial for enhancing CI engine performance and reducing emissions. This study examines a CI engine using a blend of 50% Fish Oil Methyl Ester (FOME), 15% Diethyl Ether (DEE), and 35% Butanol, each contributing unique benefits. By varying these parameters, we analyze the impact on metrics like BTE, SFC and emissions including  $NO_x$ , CO, HC, smoke opacity, and aldehydes.

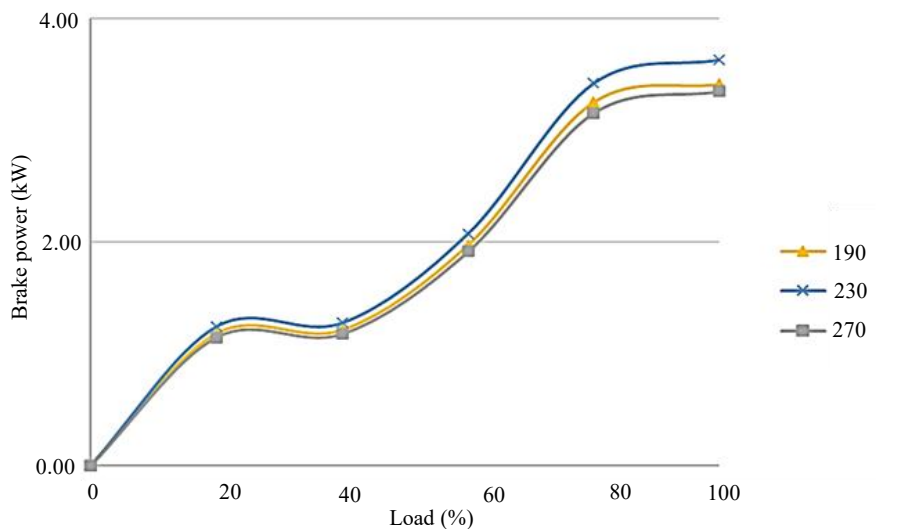
### Optimizing the Fuel Injection Pressure

Fuel atomization is improved by increasing injection pressure, which results in more effective combustion. Testing different pressures helps find the optimal level for better spray patterns and combustion efficiency. For engines using biofuel blends to operate better and emit less emissions, this optimization is essential.

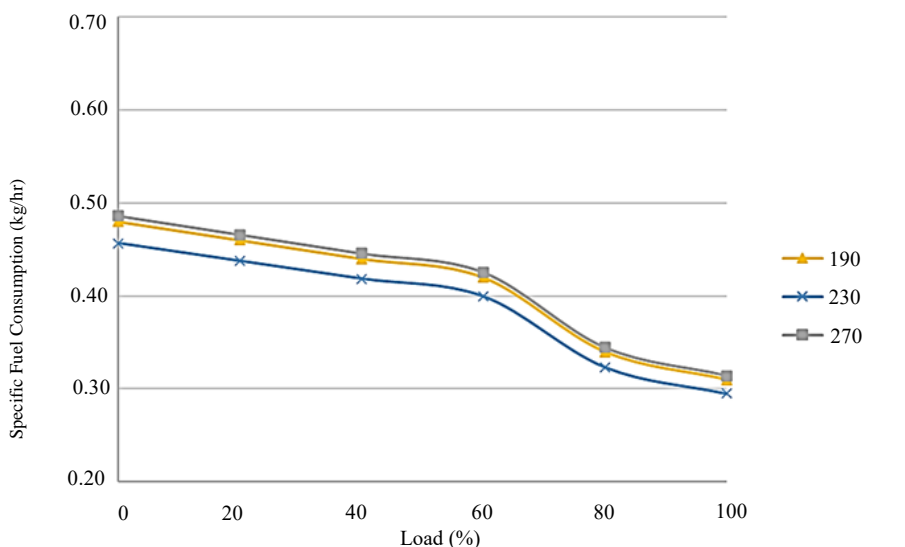
The performance analysis of a Low Heat Rejection (LHR) engine using a blend of 50% FOME, 15% DEE, and 35% butanol reveals significant findings by varying injection pressure. At 190 bar, brake power is low, described in Figure 2, due to poor atomization and incomplete combustion. The optimal pressure is 230 bar, where brake power is 4.62% higher than the baseline, providing the best performance across all loads. However, at 270 bar, over-penetration causes mechanical losses, reducing brake power by 2.5%.

SFC also varies with injection pressure. At 190 bars, fuel consumption is higher due to poor atomization. In contrast, at 230 bars, the lowest fuel consumption is observed, indicating optimal efficiency. As shown in Figure 3, at 270 bars, fuel consumption increases by 5% compared to 230 bars, highlighting diminishing returns beyond the optimal pressure range [23–25].

Similarly, Brake Thermal Efficiency (BTE) is low at 190 bar due to incomplete combustion, peaks at 230 bars with an 8.52% increase, and slightly decreases at 270 bar by 2.4% due to increased mechanical losses, as shown in Figure 4.



**Figure 2.** Variation of Brake power with respect to load.



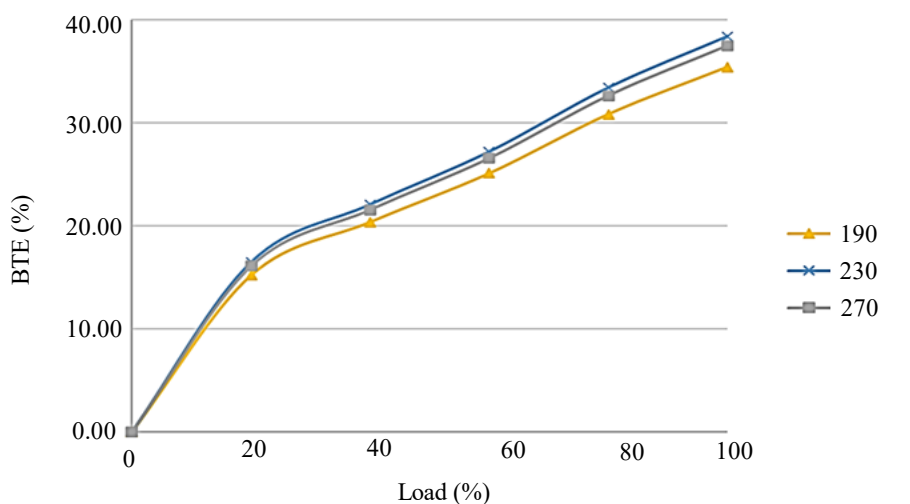
**Figure 3.** Variation of SFC with respect to load.

Mechanical Efficiency follows a similar trend as shown in Figure 5. At 190 bar, reduced mechanical efficiency is attributed to higher friction losses, while at 230 bar, optimal mechanical efficiency shows a 6.9% increase. At 270 bars, efficiency is reduced by 9.9% due to mechanical losses.

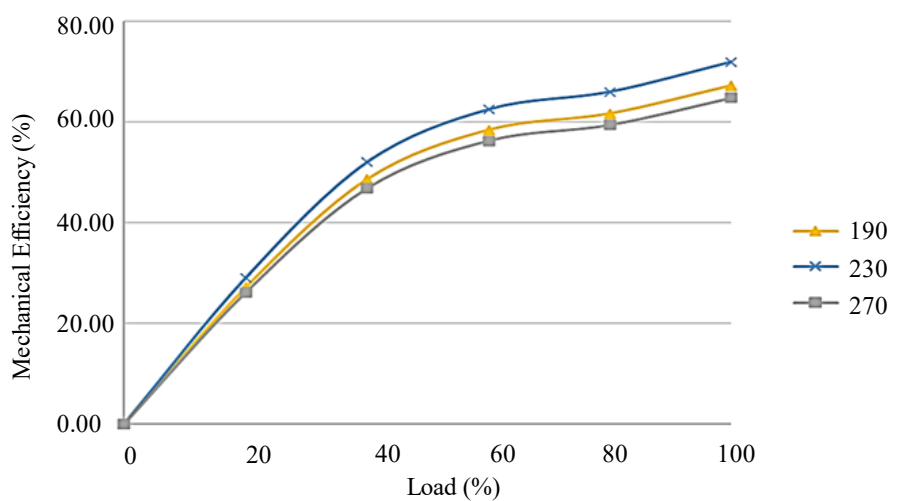
The Air-Fuel Ratio (AFR) at 190 bar leads to richer mixtures and incomplete combustion, whereas 230 bar provides an optimal AFR for efficient combustion. At 270 bar, over-penetration causes a slight reduction in AFR.

Volumetric Efficiency is impacted by injection pressure as well. At 190 bar, incomplete cylinder filling reduces efficiency, but at 230 bars, there is a 6.8% improvement shown in Figure 6. However, at 270 bars, the efficiency decreases by 2.9% due to elevated temperatures and over-penetration. Emission analysis indicates significant levels.

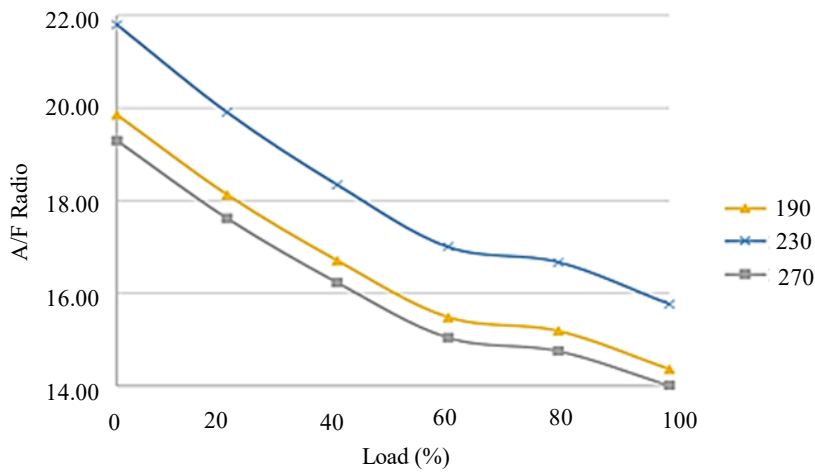
Figure 7 shows CO emissions at different injection pressures: at 190 bar, emissions are high due to incomplete combustion. At 230 bars, emissions decrease by 17% due to improved combustion efficiency. However, at 270 bar, CO emissions increase by 35% because of rich mixtures and over-penetration of fuel.



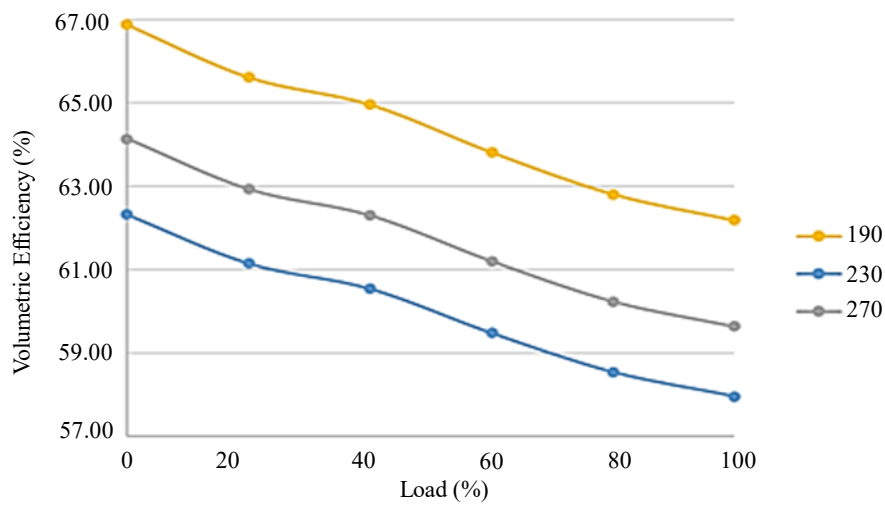
**Figure 4.** Variation of BTE with respect to load.



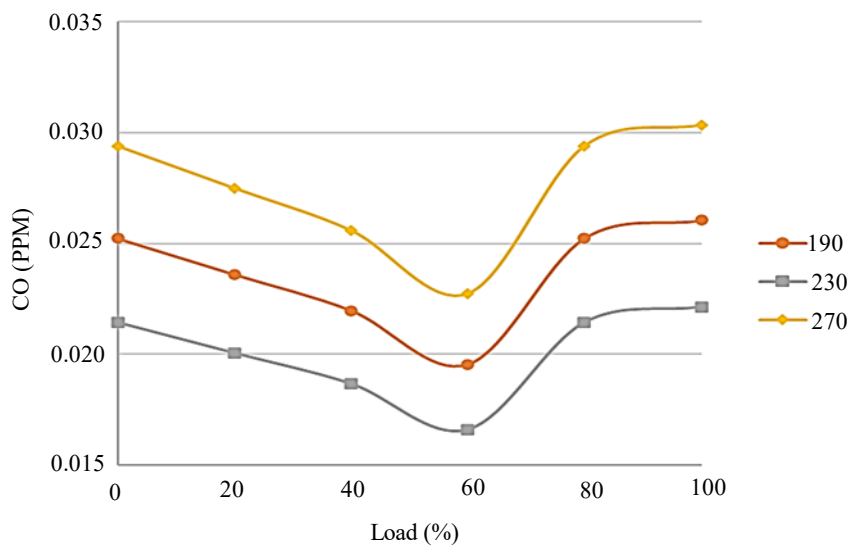
**Figure 5.** Variation of Mechanical Efficiency with respect to load.



**Figure 6.** Variation of A/F ratios with respect to load.



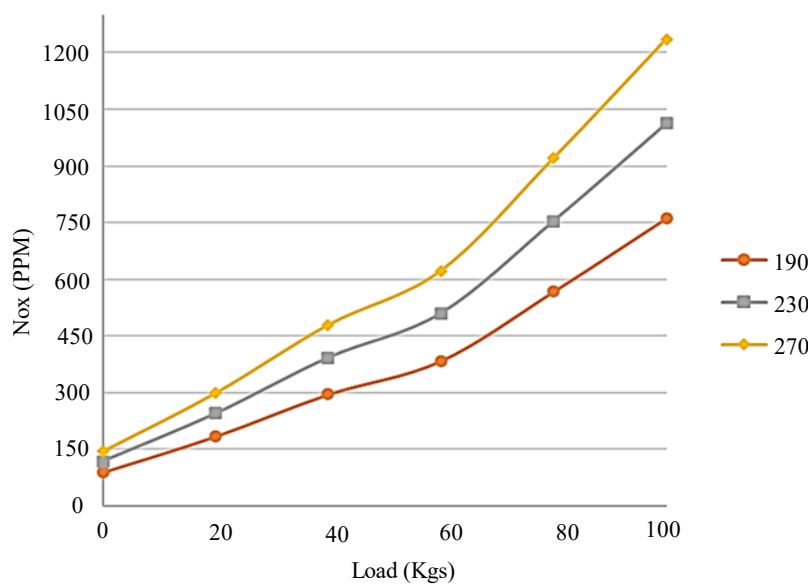
**Figure 7.** Variation of Volumetric Efficiency with respect to load.



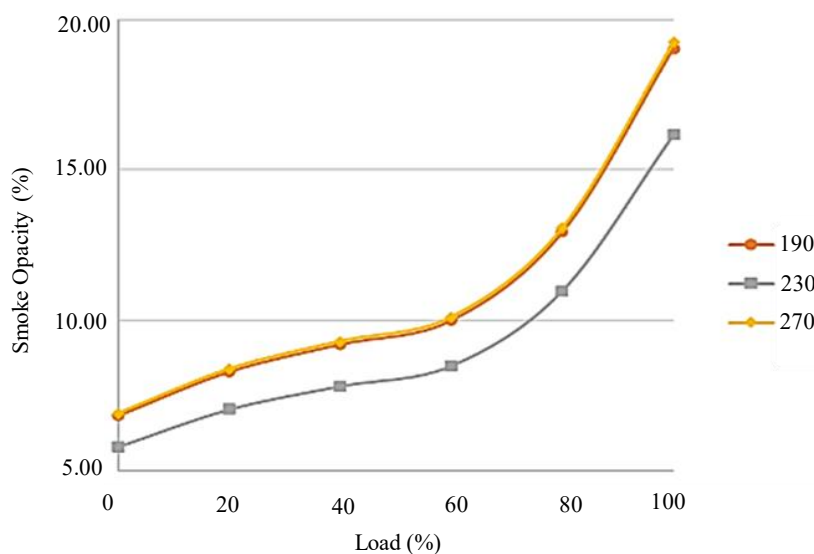
**Figure 8.** Variation of CO emission for LHR engine with optimized blend by varying the fuel injection pressure.

Oxides of nitrogen emissions are lower at an injection pressure of 190 bar, as shown in Figure 8, due to suboptimal atomization, which leads to incomplete combustion and lower combustion temperatures. However, when the injection pressure is increased to 230 bar, the fuel atomizes more effectively, leading to more efficient combustion and higher temperatures, causing NO<sub>x</sub> emissions to rise by 33.15%. At an even higher pressure of 270 bar, the NO<sub>x</sub> emissions continue to climb by another 21.94%, as the combustion temperatures further increase [21–26].

From Figure 9, Smoke Opacity, an indicator of soot in the exhaust, is initially high at 190 bar due to incomplete combustion and poor atomization. When the injection pressure is optimized to 230 bar, smoke opacity decreases by 15.03% because of better atomization and more complete combustion. However, at 270 bars, the over-penetration of the fuel causes incomplete combustion again, increasing smoke opacity by 19.06%.



**Figure 9.** Variation of NO<sub>x</sub> emission for LHR engine with optimized blend by varying the fuel injection pressure.

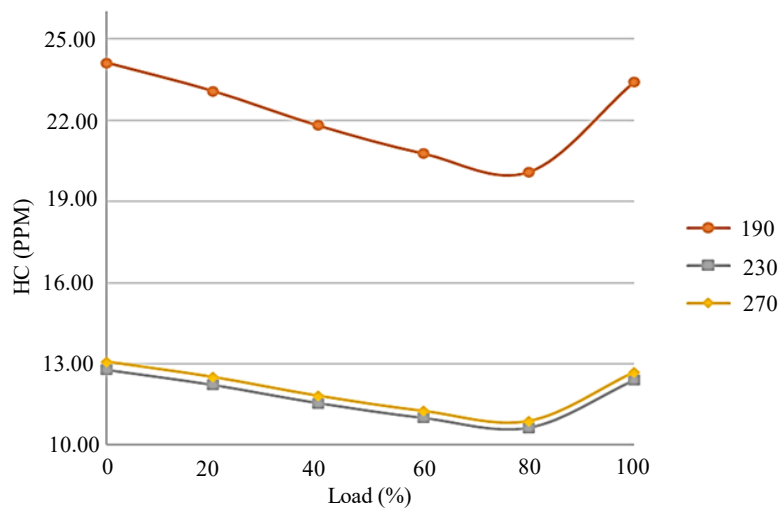


**Figure 10.** Variation of Smoke opacity emission for LHR engine with optimized blend by varying the fuel injection pressure.

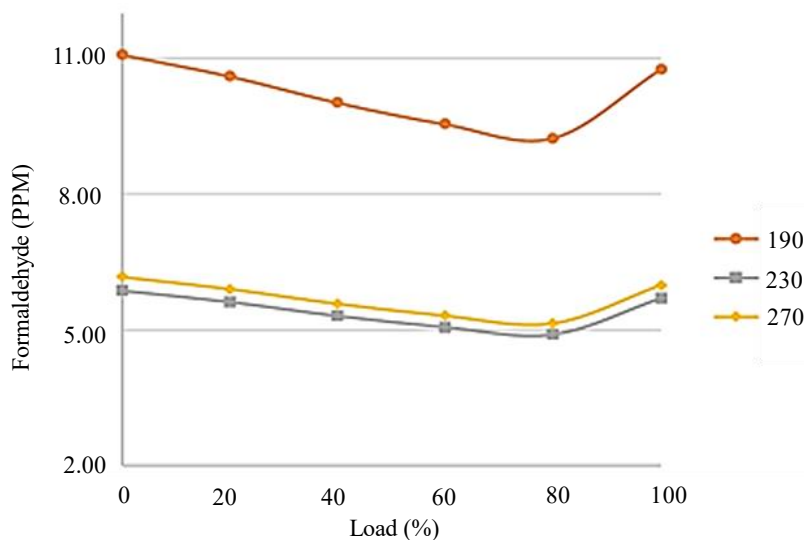
Figure 10 describes that variation of Hydrocarbon (HC) emissions are significantly elevated at 190 bars because of incomplete combustion resulting from poor atomization. When the injection pressure is increased to 230 bar, HC emissions are reduced by 47% due to more efficient combustion. At 270 bar, HC emissions are further reduced by 44.6% compared to the baseline, as the fuel continues to burn more completely.

Formaldehyde emissions are high at 190 bar due to incomplete combustion and lower combustion temperatures shown in Figure 11. At 230 bar, these emissions are reduced by 47.06% because the higher injection pressure improves combustion efficiency. However, at 270 bar, formaldehyde emissions see a slight increase of 5.2% compared to 230 bar, likely due to over-penetration and subsequent combustion inefficiencies, as shown in Figure 12.

Acetaldehyde emissions follow a similar trend, as described in Figure 13. They are high at 190 bar due to poor combustion. Acetaldehyde emissions decrease by 47% at 230 bars as the combustion process improves.



**Figure 11.** Variation of Hydrocarbon emission for LHR engine with optimized blend by varying the fuel injection pressure.

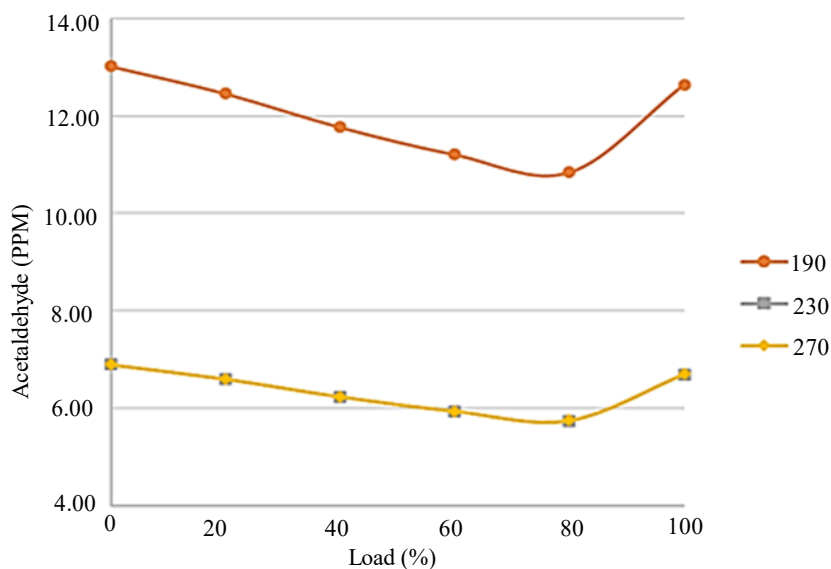


**Figure 12.** Variation of Formaldehyde emission for LHR engine with optimized blend by varying the fuel injection pressure.

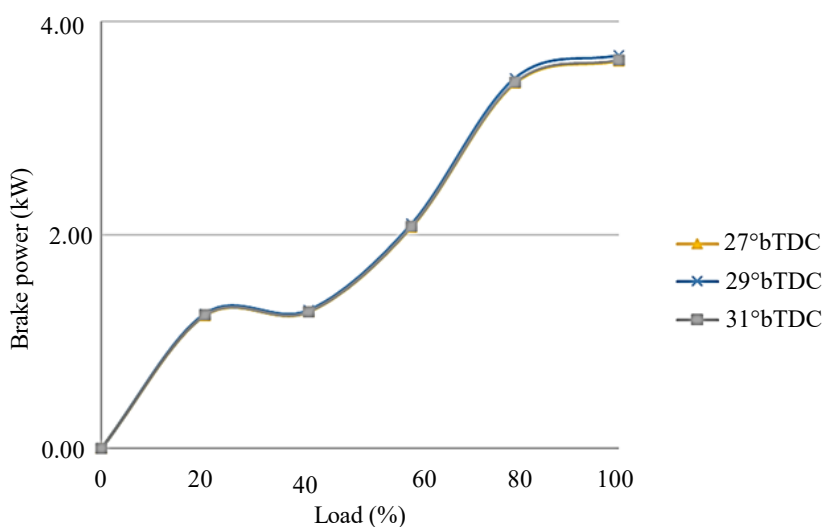
At 270 bar, there is a slight increase of 0.15% in acetaldehyde emissions compared to the levels at 230 bar, again due to less efficient combustion at this higher pressure.

The optimization of injection timing is crucial for maximizing the performance and reducing emissions of a LHR engine running on a blend of 50% FOME, 15% Diethyl Ether (DEE), and 35% butanol, with an injection pressure of 230 bar. This analysis evaluates how varying the injection timing affects the engine's performance and emissions, focusing on brake power, SFC, BTE, mechanical efficiency, and emissions such as CO,  $NO_x$ , smoke opacity, hydrocarbons (HC), formaldehyde, and acetaldehyde.

At lower loads (0–40%), brake power remains relatively low due to suboptimal fuel atomization and incomplete combustion. As the engine load increases, brake power also increases, but it remains less effective compared to higher injection timings. At 27° bTDC, inadequate atomization leads to larger fuel droplets and less efficient combustion, impacting brake power at lower loads.



**Figure 13.** Variation of Acetaldehyde emission for LHR engine with optimized blend by varying the fuel injection pressure.



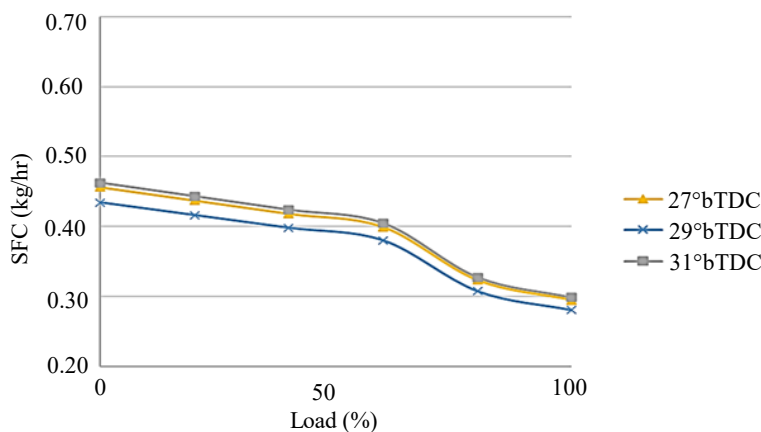
**Figure 14.** Variation of Brake power with respect to load.

Changing the injection timing to  $29^\circ$  bTDC improves fuel atomization and combustion efficiency, increasing brake power by 1.14% compared to the baseline timing. However, advancing the timing to  $31^\circ$  bTDC results in mechanical losses and fuel over-penetration, reducing brake power by 1.12% at average loads, as shown in Figure 14.

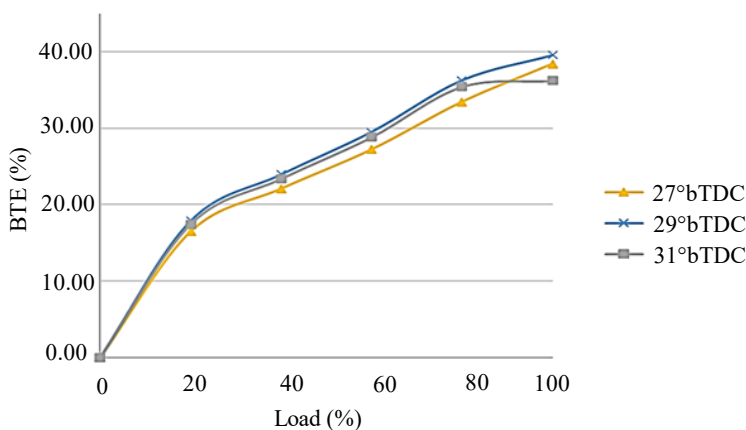
At  $27^\circ$  bTDC, poor atomization leads to incomplete combustion and higher fuel consumption, increasing SFC. Adjusting the timing to  $29^\circ$  bTDC improves atomization and combustion efficiency, reducing SFC by 4.9%. However, advancing the timing further to  $31^\circ$  bTDC increases SFC by 6.5% relative to  $29^\circ$  bTDC due to over-penetration and mechanical losses is shown in Figure 15. Consequently, the best temperature for reducing fuel use and increasing fuel economy is  $29^\circ$  bTDC.

At  $27^\circ$  bTDC, poor atomization and incomplete combustion result in lower BTE, especially at lower loads. Adjusting the timing to  $29^\circ$  bTDC significantly improves atomization and combustion efficiency, increasing BTE by 6.97%. Further advancing the timing to  $31^\circ$  bTDC decreases BTE by 4.02% due to increased mechanical losses and potential fuel over-penetration. Thus,  $29^\circ$  bTDC is optimal for achieving the highest BTE, as shown in Figure 16.

At  $27^\circ$  bTDC, suboptimal atomization leads to increased friction losses and reduced mechanical efficiency. Adjusting the timing to  $29^\circ$  bTDC improves mechanical efficiency by 7%, enhancing fuel atomization and combustion efficiency. However, further advancing the timing to  $31^\circ$  bTDC reduces mechanical efficiency by 10.01% due to additional mechanical losses and fuel over-penetration. Therefore,  $29^\circ$  bTDC is optimal for maximizing mechanical efficiency, as shown in Figure 17.

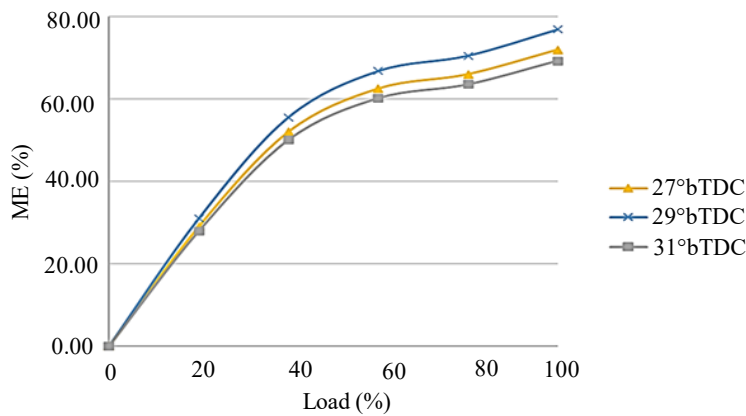


**Figure 15.** Variation of SFC with respect to load.

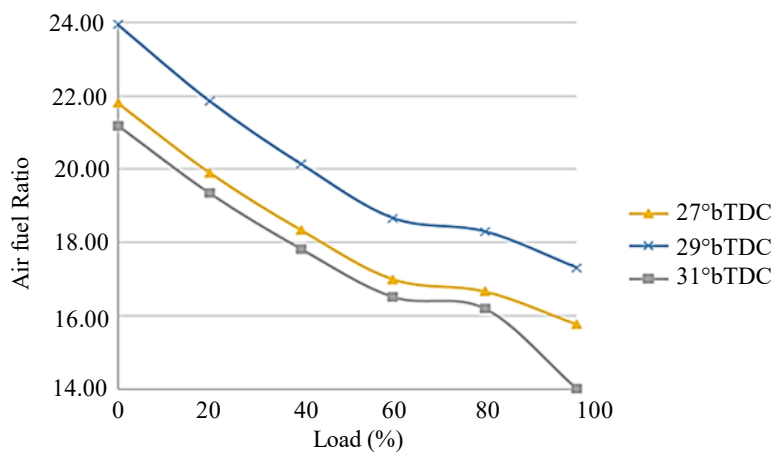


**Figure 16.** Variation of BTE with respect to load.

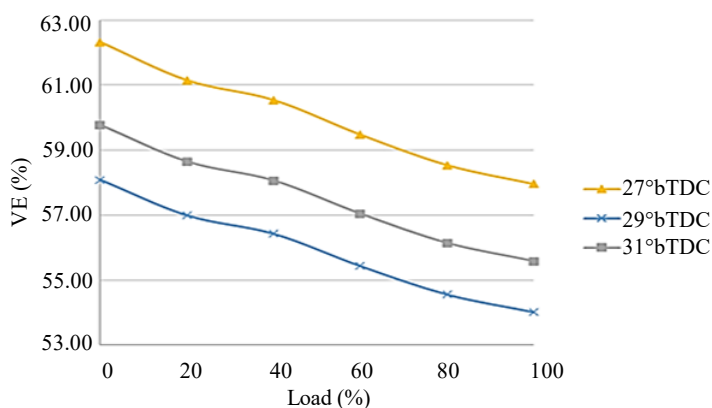
The air-fuel ratio (AFR) is vital for engine performance and emissions control. This study examines AFR variations with load and injection timing in an LHR engine using a blend of 50% FOME, 15% DEE, and 35% butanol, as shown in Figure 18. At 27° bTDC, poor atomization results in a richer mixture and higher emissions. Adjusting timing to 29° bTDC improves atomization, achieving an optimal AFR with efficient combustion and enhanced performance. Further increasing timing to 31° bTDC raises AFR, leading to less efficient combustion. Thus, 29° bTDC is optimal for balancing air-fuel mixing and engine efficiency, as shown in Figure 19.



**Figure 17.** Variation of Mechanical Efficiency with respect to load.



**Figure 18.** Variation of A/F ratios with respect to load.

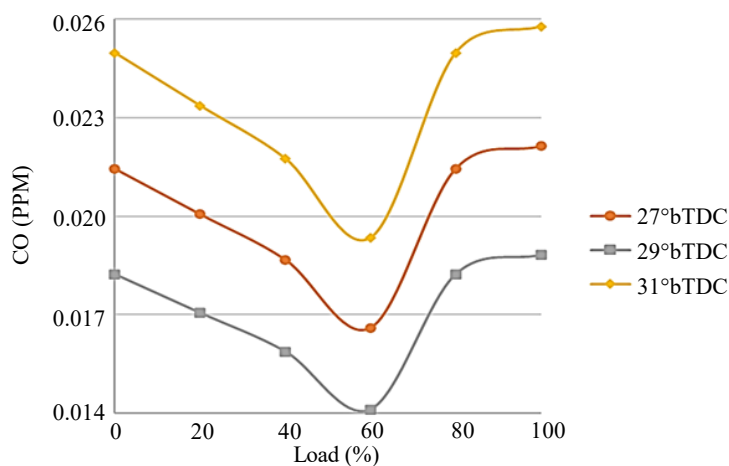


**Figure 19.** Variation of Volumetric Efficiency with respect to load.

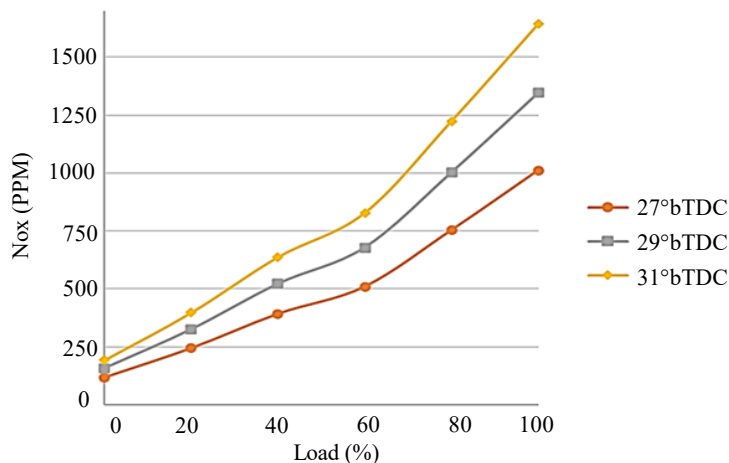
Volumetric efficiency, indicating an engine's ability to fill its cylinders with an air-fuel mixture, varies with load and injection timing in an LHR engine using a blend of 50% FOME, 15% DEE, and 35% butanol. At 27° bTDC, suboptimal atomization reduces efficiency. Optimal efficiency is achieved at 29° bTDC, improving intake and atomization. Further increasing timing to 31° bTDC decreases efficiency due to higher temperatures and fuel over-penetration. Thus, 29° bTDC offers the best balance for maximum volumetric efficiency.

At an injection timing of 27° before Top Dead Center (bTDC), carbon monoxide (CO) emissions are relatively high because the fuel atomization is inadequate, leading to incomplete combustion. This poor atomization results in larger fuel droplets that do not burn completely, generating higher levels of CO.

When the injection timing is advanced to 29° bTDC, the CO emissions are significantly reduced by 15%. This reduction is attributed to the improved atomization and combustion efficiency. At this timing, the fuel is better mixed with the air, allowing for more complete combustion and thus lowering CO emissions. However, advancing the timing further to 31° bTDC results in a 37% increase in CO emissions. This increase is due to over-penetration of the fuel into the combustion chamber, which creates localized areas with rich fuel mixtures. These areas do not burn completely, leading to higher CO emissions, as shown in Figure 20.



**Figure 20.** Variation of CO emission for LHR engine with optimized blend by varying the fuel injection timing.

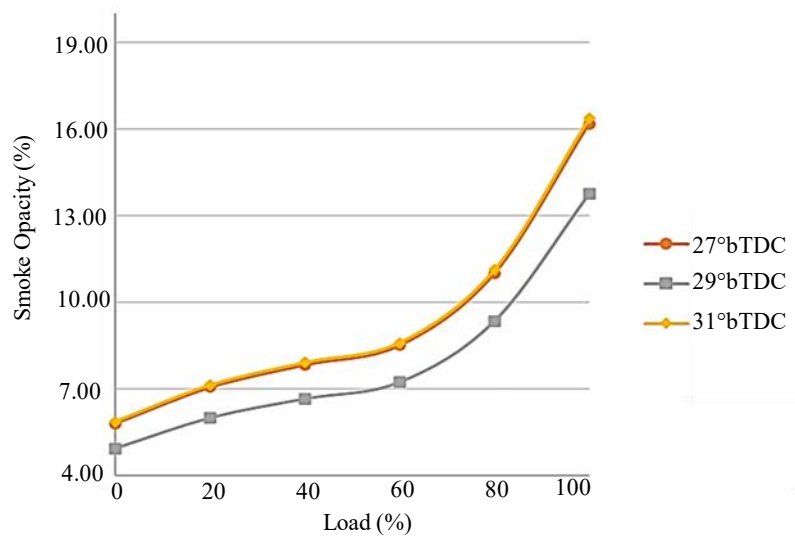


**Figure 21.** Variation of  $NO_x$  emission for LHR engine with optimized blend by varying the fuel injection timing.

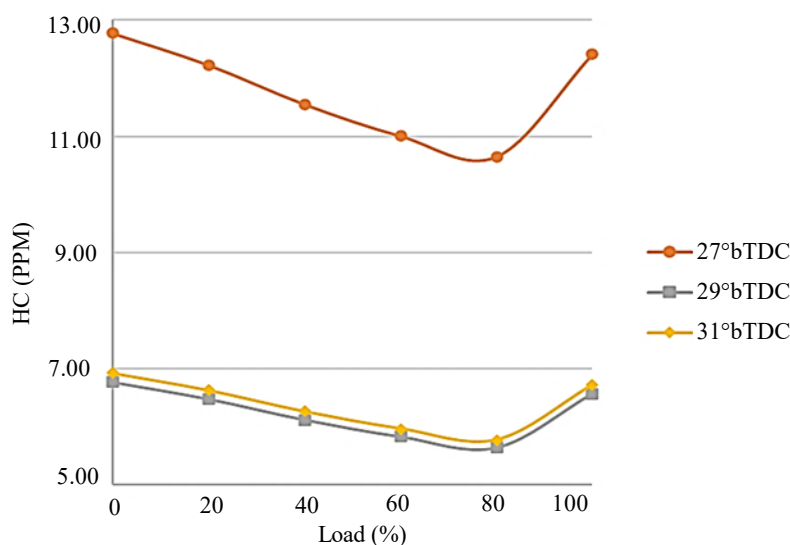
Nitrogen oxides (NO<sub>x</sub>) emissions increase with more advanced timing because the combustion temperatures are higher. At 29° bTDC, NO<sub>x</sub> emissions rise by 33% due to the higher peak temperatures achieved during combustion. When the timing is advanced to 31° bTDC, NO<sub>x</sub> emissions increase further by 22%, as the combustion temperatures continue to rise, as shown in Figure 21.

Smoke opacity, which indicates the level of particulate emissions, decreases at 29° bTDC because the improved combustion leads to fewer soot particles. However, at 31° bTDC, smoke opacity increases again, likely due to the formation of rich fuel zones that produce more soot.

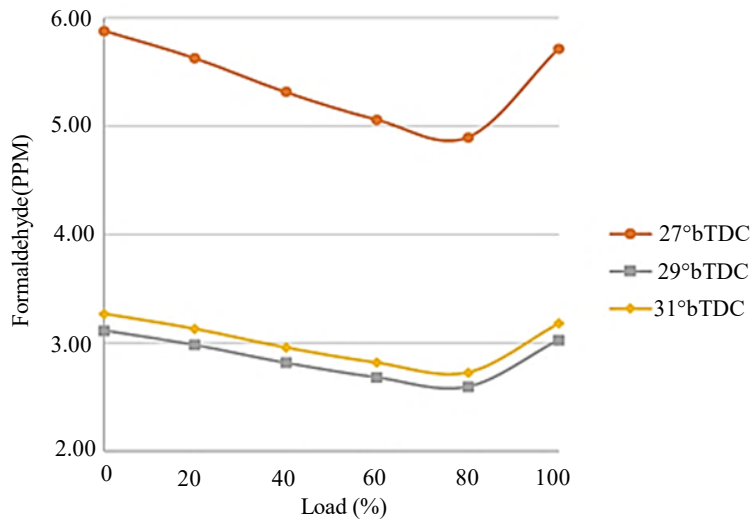
Hydrocarbon (HC) emissions, which are also indicative of incomplete combustion, decrease at 29° bTDC due to the more complete burning of the fuel. However, there is a slight rise in HC emissions at 31° bTDC, possibly because of the same localized rich mixtures that increase CO emissions, as shown in Figure 22.



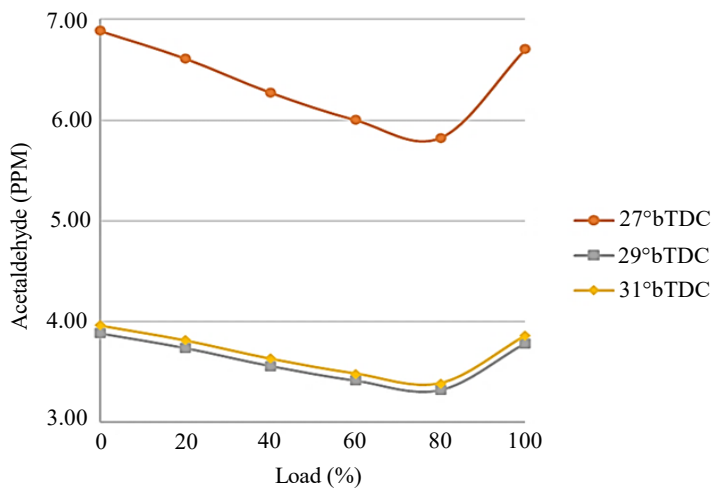
**Figure 22.** Variation of Smoke opacity emission for LHR engine with optimized blend by varying the fuel injection timing.



**Figure 23.** Variation of Hydrocarbon emission for LHR engine with optimized blend by varying the fuel injection timing.



**Figure 24.** Variation of Formaldehyde emission for LHR engine with optimized blend by varying the fuel injection timing.



**Figure 25.** Variation of Acetaldehyde emission for LHR engine with optimized blend by varying the fuel injection timing.

Formaldehyde and acetaldehyde emissions follow similar trends to CO and HC emissions. The timing of 29° bTDC is optimal for minimizing these emissions, as it represents a balance between improved atomization and avoiding over-penetration. At this timing, combustion is more complete, reducing the formation of these harmful compounds, as shown in Figures 23–25.

## CONCLUSION

Optimizing fuel injection pressure and timing is essential for maximizing the performance and minimizing emissions of CI engines, particularly when using alternative fuel blends. This study highlights the significant benefits of using a blend of 50% Fish Oil Methyl Ester (FOME), 15% Diethyl Ether (DEE), and 35% Butanol. Each component contributes to improved combustion characteristics, and by fine-tuning the injection parameters, it is possible to enhance Brake Thermal Efficiency (BTE), reduce Specific Fuel Consumption (SFC), and lower emissions of NO<sub>x</sub>, CO, HC, smoke opacity, and aldehydes. The findings underscore the importance of precise injection parameter optimization in leveraging the advantages of alternative fuels for CI engines.

- Increasing injection pressure enhances fuel atomization and combustion efficiency in biofuel engines. For a LHR engine with a 50% FOME, 15% DEE, and 35% butanol blend, the optimal

pressure is 230 bar, improving brake power by 4.62%, while 270 bar causes a 2.5% decrease due to over-penetration.

- Specific Fuel Consumption (SFC) is highest at 190 bar and lowest at 230 bar, indicating optimal efficiency, while Brake Thermal Efficiency (BTE) peaks at 230 bar with an 8.52% increase but slightly drops at 270 bar. Mechanical Efficiency also peaks at 230 bar with a 6.9% improvement, decreasing by 9.9% at 270 bar.
- Volumetric Efficiency improves by 6.8% at 230 bar but decreases by 2.9% at 270 bar. CO emissions are highest at 190 bar, reduced by 17% at 230 bar, and rise by 35% at 270 bar. NO<sub>x</sub> emissions increase by 33.15% at 230 bar and by 21.94% at 270 bar.
- Smoke opacity decreases by 15.03% at 230 bar and increases by 19.06% at 270 bar. HC emissions drop by 47% at 230 bar and slightly more at 270 bar, while Formaldehyde emissions are reduced by 47.06% at 230 bar but increase by 5.2% at 270 bar.
- Optimizing injection timing is key for performance and emission control in LHR engines. At 29° bTDC, brake power improves by 1.14%, SFC decreases by 4.9%, and BTE increases by 6.97%, while at 31° bTDC, performance metrics generally decline.
- CO emissions decrease by 15% at 29° bTDC but increase by 37% at 31° bTDC, NO<sub>x</sub> emissions rise by 33% at 29° bTDC and by 22% at 31° bTDC. Smoke opacity and HC emissions show similar trends, decreasing at 29° bTDC but increasing at 31° bTDC. Formaldehyde and acetaldehyde emissions are minimized at 29° bTDC.

The experiments conducted revealed that optimizing the injection pressure up to 230 bar and fine-tuning the injection timing to 29° bTDC resulted in the best overall engine performance and emission characteristics. The findings underscore the importance of precise control over fuel injection parameters to achieve the desired balance between efficiency, performance, and environmental impact when using alternative fuel blends in CI engines. Table 2 shows abbreviations and nomenclatures.

**Table 2.** Abbreviations and Nomenclatures.

CI	Compressed ignition
SAME	safflower methyl ester
BTE	Brake thermal efficiency
SFC	Specific Fuel Consumption
HPLC	High-performance liquid chromatography
A/F ratio	Air fuel ratio
LHR	Low heat rejected
bTDC	before top dead centre

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