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Sustainable Transport using New Generations Engine and Fuels: An Experimental Study of Emissions with Biodiesel as Fuel in RCCI Engine

Suresh D. Mane[1] and Chinna Bathula[2]
[1]D Y Patil Prathisthan's College of Engineering, Kolhapur, India 416007
Email: mane.suresh@gmail.com
[2]Dongkukk University, Seoul, South Korea
Email: chinnuchem@gmail.com

Abstract*— The increasing environmental concerns and depletion of fossil fuel reserves have necessitated the transition towards sustainable transport solutions. Biodiesel, derived from renewable sources, presents a viable alternative due to its carbon-neutral nature and compatibility with existing diesel engines. However, conventional diesel engines operating on high-temperature combustion cycles contribute significantly to nitrogen oxides (NOx) and particulate matter (soot) emissions, posing serious environmental and health challenges. To address these limitations, this study explores the use of biodiesel in a Reactivity Controlled Compression Ignition (RCCI) engine configuration, aimed at achieving cleaner combustion. A conventional compression ignition (CI) engine was retrofitted in the laboratory to function as an RCCI engine. This was accomplished by integrating a Multi-Point Fuel Injection (MPFI) system for port injection of gasoline, while biodiesel was directly injected into the combustion chamber. The experiments were conducted at three different compression ratios—16:1, 17:1, and 18:1—to evaluate the influence of compression on combustion and emissions. A programmable open-source Engine Control Unit (ECU) was employed to control the port fuel injection durations, varied at zero, three, four, and five milliseconds. The emission analysis revealed a marked reduction in NOx and unburned hydrocarbons (HC), indicating more efficient and cleaner combustion with the RCCI strategy. The dual-fuel approach facilitated better control over combustion phasing and temperature, thereby minimizing the formation of NOx while retaining the advantages of biodiesel usage. Emissions including NOx, CO, HC, CO2, and O2 were analyzed. Results indicate that NOx emissions increase sharply with load and compression ratio, while CO and HC emissions decrease, suggesting improved combustion. Fuel type significantly influences emission profiles, with some blends yielding notably higher HC and NOx. These findings help identify optimal operating conditions and highlight the trade-offs between efficiency and emissions. These findings demonstrate the potential of RCCI engines as a transitional solution in the move towards sustainable transportation. The combination of biodiesel and advanced combustion strategies can pave the way for cleaner, low-emission engines without major alterations to existing engine platforms, thereby offering a practical and scalable pathway toward carbon-neutral mobility.

***Index Terms*— Biodiesel, RCCI engine, NOx Emissions, Sustainable Transport, IC Engine.**

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I. INTRODUCTION

India's escalating vehicular emission regulations, such as the Bharat Stage VI norms and Real Driving Emissions (RDE) testing, underscore the urgent need for advanced combustion technologies [1]. These stringent standards aim to bridge the gap between laboratory and real-world emissions, ensuring vehicles maintain low pollutant levels under actual driving conditions [2]. To comply, manufacturers are exploring innovative combustion methods [3]. Homogeneous Charge Compression Ignition (HCCI) is one such technology, blending features of gasoline and diesel engines to achieve higher efficiency and lower emissions. HCCI operates by compressing a uniform fuel-air mixture until it auto-ignites, reducing peak combustion temperatures and thus minimizing nitrogen oxide (NOx) and particulate matter emissions [4]. Additionally, the adoption of flex-fuel vehicles (FFVs), capable of running on varying ethanol-gasoline blends, presents a viable path forward [5]. India's push towards ethanol-blended fuels not only reduces dependence on fossil fuels but also supports agricultural economies [6]. Implementing these technologies necessitates significant investment in research and development, as well as infrastructure upgrades. However, the long-term benefits include improved air quality, energy security, and alignment with global sustainability goals [7]. As India advances its emission standards, embracing such combustion innovations is imperative for a cleaner automotive future.

The accelerating depletion of fossil fuel reserves and the adverse environmental impact of conventional transportation systems underscore the urgent global need for sustainable and low-emission mobility solutions [8]. In alignment with the United Nations Sustainable Development Goals (SDGs), particularly those targeting clean energy (SDG 7), innovation (SDG 9), and climate action (SDG 13), this study explores the integration of biodiesel in a Reactivity Controlled Compression Ignition (RCCI) engine as a pathway to sustainable transport.

Biodiesel derived from Karanja oil, a non-edible and renewable resource, offers a carbon-neutral alternative to fossil diesel [9]. However, conventional CI engines generate high NOx and particulate emissions due to high-temperature combustion [10]. To address this, a standard diesel engine was modified into an RCCI configuration using a Multi-Point Fuel Injection (MPFI) system for port gasoline injection, combined with direct injection of a B20 biodiesel blend. This dual-fuel strategy promotes low-temperature, partially premixed combustion, offering a clean-burning alternative with high thermal efficiency.

II. LITERATURE REVIEW

Li, Jun et.a. (2010), examines how varying injection timing affects emissions in a heavy-duty diesel engine. Retarded injection timing was found to significantly reduce NOx levels by lowering peak in-cylinder temperatures. However, it also slightly increased HC emissions due to incomplete combustion. The findings stress the importance of precise control over injection strategies, Liu, Hai Xia et.al. 2024) investigated performance and emissions for different biodiesel-diesel blends under variable load. The results showed reduced CO and HC emissions for biodiesel blends due to better oxygenation. However, NOx emissions were higher compared to pure diesel, mainly due to elevated combustion temperatures and oxygen content in biodiesel. Tsolakis et al. (2013) highlights the interaction between EGR and biodiesel in reducing NOx emissions. While EGR was effective in lowering NOx, its improper use degraded combustion efficiency and raised HC emissions. A trade-off was observed between emission reduction and combustion quality, necessitating fine-tuning of EGR rates. Kumar, N. et.al. (2013) focused on how varying compression ratios influence NOx formation in diesel engines. Higher CRs led to increased thermal efficiency but also escalated NOx emissions due to greater combustion temperatures. The authors recommend CR optimization to maintain performance while limiting emissions.

Chen, Henglin, and Shize Ye (2019) developed a machine learning-based predictive model for diesel engine NOx emissions using real-time sensor data. The model demonstrated high prediction accuracy and offers a path toward intelligent emission control. It emphasized the feasibility of integrating AI tools for on-board diagnostics and emission forecasting, Mumtaz et. al. (2023) using neural networks, this research predicted NOx emissions based on injection duration, CR, and load. The model showed robustness in various operating conditions and outperformed traditional empirical models. The authors advocate AI-enhanced engine calibration to achieve optimal emission-performance trade-offs.

Okoji et. al. (2023) used a genetic algorithm for multi-objective optimization of engine parameters targeting both NOx and soot minimization. The algorithm identified optimal CR and injection parameters without sacrificing engine efficiency. This work underscores the value of evolutionary computation in emission control strategies Lee, Seokhwan (2020) examined the impact of renewable fuel blends on NOx emissions in diesel engines under full load. Alcohol-based blends increased NOx levels due to faster flame speeds and higher in-cylinder temperatures. The authors recommend integrating NOx mitigation methods when using high oxygen content. Dwivedi et. al (2013) compared diesel and biodiesel blends across varying injection timings. The study revealed that optimal injection near TDC minimizes both NOx and unburnt hydrocarbons. The results validate that biodiesel, with adjusted timing, can match diesel in emission performance under certain conditions. Wang, Haopeng et.al. (2024) used CFD simulations to analyse the effect of combustion chamber design on NOx formation. Their results showed that increased squish and tumble improve mixing but also raise localized temperatures. The study demonstrates the importance of chamber geometry in NOx control during high-pressure combustion.

III. METHODOLOGY

This study focuses on the utilization of a biodiesel–gasoline dual-fuel strategy in a modified compression ignition (CI) engine operated under Reactivity Controlled Compression Ignition (RCCI) mode. The methodology encompasses biodiesel production, fuel property characterization, engine modification, instrumentation setup, experimentation under varied operating conditions, and performance and emissions analysis. The entire approach has been developed in alignment with the goals of the United Nations Sustainable Development Goals (SDGs), specifically SDG 7 (Affordable and Clean Energy), SDG 9 (Industry, Innovation and Infrastructure), and SDG 13 (Climate Action).

A. Biodiesel Production

The biodiesel used in this research was derived from Pongamia pinnata (Karanja) oil, a non-edible feedstock widely available in India and suitable for sustainable energy applications. The transesterification process was employed to convert the raw Karanja oil into biodiesel (B100). This involved the reaction of Karanja oil with methanol in the presence of a sodium hydroxide (NaOH) catalyst under controlled temperature conditions (55–60°C).

The reaction was stirred continuously to ensure complete conversion to methyl esters. The biodiesel was then washed with hot water to remove residual soap and impurities and dried to eliminate moisture. The resulting biodiesel (B100) was blended with conventional diesel in a 20:80 ratio by volume to form B20. This blend was selected due to its widespread compatibility with existing diesel engines and good balance between emissions and performance. The physical and chemical properties of B100 and B20 were tested in accordance with ASTM D6751 standards at Apex Innovation Lab, Sangli. Parameters such as density, kinematic viscosity, calorific value, flash point, and fire point were evaluated and compared with standard diesel to ensure suitability for engine trials.

B. Fuel Property Characterization

The fuel properties were characterized for B20 and standard diesel fuels. Key parameters included:

- Density at 25°C: B20 (830 kg/m³), Diesel (816 kg/m³)
- Kinematic Viscosity at 40°C: B20 (3.64 cSt), Diesel (2.09 cSt)
- Lower Calorific Value: B20 (9794 cal/gm), Diesel (10235 cal/gm)
- Flash Point: B20 (60°C), Diesel (53°C)

These values indicated that B20 has a slightly higher viscosity and lower calorific value, consistent with typical biodiesel blends. The higher flash point also supports improved safety in handling and storage.

C. Engine Setup and Modification

The experiments were conducted on a single-cylinder, four-stroke, water-cooled CI engine (Kirloskar TV1 model) with a variable compression ratio (VCR) ranging from 12:1 to 18:1. The engine had a displacement of 661 cc, bore × stroke of 87.5 mm × 110 mm, and was operated at a constant speed of 1500 rpm using an eddy current dynamometer.

To enable RCCI operation, the standard diesel engine was modified with a Multi-Point Fuel Injection (MPFI) system for gasoline injection into the intake manifold. A programmable open-source Engine Control Unit (ECU) was used to control the port injection of gasoline with precise timing and duration. The injection durations tested were 0 ms (conventional CI), 3 ms, 4 ms, and 5 ms. Diesel or biodiesel (B20) was directly injected into the combustion chamber using the standard injection system.

The modified RCCI setup enabled dual-fuel operation where gasoline, a low-reactivity fuel, was port-injected and premixed with intake air, while biodiesel (high-reactivity fuel) was directly injected into the combustion chamber for controlled ignition.

IV. EXPERIMENTAL METHODOLOGY

The study followed a two-phase testing procedure. Initially, baseline performance and emission data were recorded for diesel and B20 fuels in conventional mode (0 ms port injection). In RCCI mode, gasoline was port-injected (3–5 ms) using an MPFI system, while B20 biodiesel was directly injected. ECU parameters were synchronized for dual injection, and tests were conducted at constant speed (1500 rpm) under variable loads and compression ratios (16:1, 17:1, 18:1). The parameters measured included carbon monoxide (CO % Vol), unburned hydrocarbons (HC ppm Vol), and nitric oxide (NO ppm Vol) using calibrated gas analyzers under steady-state operating conditions. Each test was performed after attaining thermal stability to ensure data accuracy. The obtained results, summarized in Table I, were analyzed to evaluate the influence of compression ratio and load on combustion efficiency and emission behavior of the RCCI engine operating on B20 biodiesel–gasoline blends. The trends and key observations derived from this dataset are discussed in the following section.

TABLE I. EMISSION CHARACTERISTICS OF RCCI ENGINE AT DIFFERENT LOADS AND COMPRESSION RATIOS

LOAD	CR	CO % Vol	HC ppm Vol	NO ppm Vol
0	18	0.19	484	22
3	18	0.26	255	76
6	18	0.08	164	571
9	18	0.23	577	46
12	18	0.14	309	327
0	17	0.14	562	25
3	17	0.22	878	54
6	17	0.18	468	298
9	17	0.27	998	115
12	17	0.18	468	298
0	16	0.17	966	31
3	16	0.17	877	64
6	16	0.18	876	185
9	16	0.2	729	287
12	16	0.17	569	433

SDG Integration: The experiment aligns with global sustainability goals: SDG 7 (clean energy through biodiesel use), SDG 9 (cost-effective innovation via RCCI retrofitting), SDG 12 (responsible fuel utilization and reduced emissions), and SDG 13 (climate action through lower NOx, HC, and CO_2 emissions).
The optimized setup at CR 17:1–18:1, injection duration 3–4 ms, and moderate load (6–9 kg) delivered the best trade-off between efficiency and emissions. NOx levels rose with higher CR and duration, while CO and HC were minimized, confirming the potential of RCCI operation for cleaner and more efficient combustion using biodiesel–gasoline blends.

V. RESULTS AND DISCUSSION

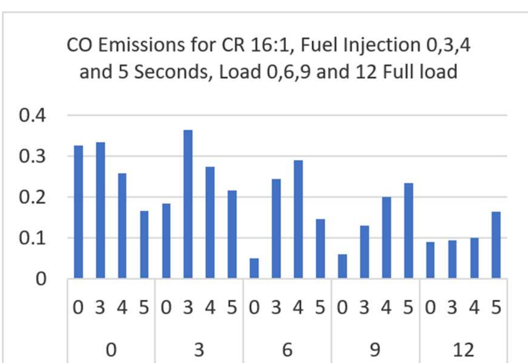

Fig. 1: Emission of CO for CR 16: 1

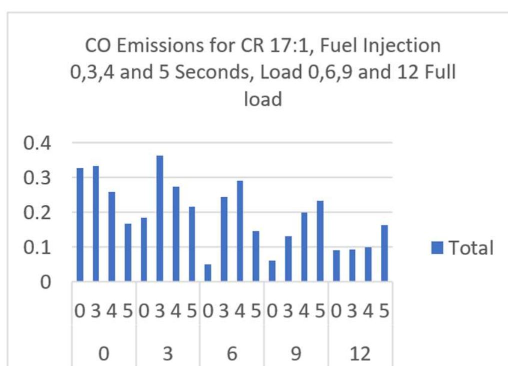

Fig. 2: Emission of CO for CR 17: 1

Effect of Load on Emissions As engine load increased, a clear trend of rising NOx emissions was observed, especially beyond 6 kg load. HC and CO initially decreased with load due to more complete combustion, but slightly increased at full load, suggesting mixture-rich zones. The carbon monoxide (CO) emission data for a compression ratio of 16:1 under varying fuel injection durations (0, 3, 4, and 5 seconds) and engine loads (0 to 12 kg) reveals a clear trend of decreasing CO emissions with increasing load. At idle and low loads (0–3 kg), CO levels are comparatively high, indicating incomplete combustion due to lower in-cylinder temperatures and poor fuel-air mixing. For instance, at 0 kg load, the CO emission is highest at 0.3267 for 0 seconds injection, reducing progressively with increased duration. As the load increases to 6 kg and above, CO emissions drop significantly, reaching a minimum average of 0.1117 at 12 kg load. This reduction is attributed to improved combustion efficiency at higher loads due to elevated temperatures and better oxidation of CO to CO_2.

Injection duration also plays a critical role. Shorter durations (0 and 3 seconds) tend to result in higher CO, especially under low load conditions, possibly due to poor atomization or incomplete burn. Longer injection durations (4 and 5 seconds) under moderate to high loads yield lower CO, suggesting enhanced mixing and combustion. Overall, the data indicates that a fuel injection duration of 4–5 seconds combined with higher load conditions minimizes CO emissions at CR 16:1.

For a compression ratio of 17:1, CO emission data across various fuel injection durations (0–5 seconds) and engine loads (0–12 kg) show a clear decline in CO levels with increasing load. At lower loads (0–3 kg), higher CO values indicate incomplete combustion due to low cylinder pressure and temperature—for instance, 0.3133 at 3 s and 0.2567 at 0 s injection. As load increases beyond 6 kg, CO emissions drop, reaching a minimum of 0.1067 at 12 kg (3 s injection), suggesting improved oxidation at higher temperatures. Injection durations of 3–4 s provide stable and efficient combustion, while longer durations (5 s) cause a slight CO rise due to over-fueling. Overall, for CR = 17:1, moderate to high loads (6–12 kg) with 3–4 s injection durations yield optimal combustion and minimum CO emissions.

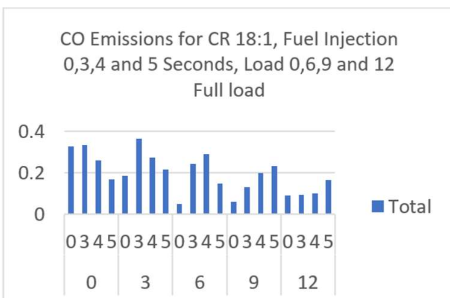

Fig. 3: Emission of CO for CR 18: 1

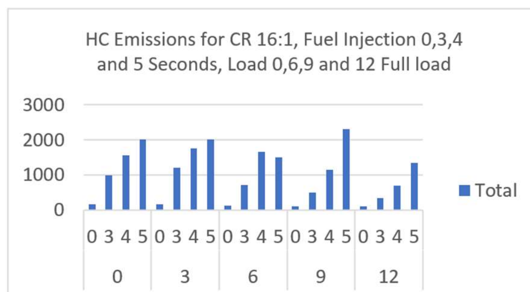

Fig. 4: Emission of HC for CR 16: 1

For CR 18:1, CO emissions decrease with increasing load, reaching a minimum of 0.1133 at 12 kg, indicating improved oxidation and combustion efficiency. Injection durations of 4–5 s perform best at medium to high loads (6–12 kg). For CR 16:1, HC emissions are high at low loads but drop sharply beyond 6 kg, showing enhanced combustion at higher pressures and temperatures. Optimal results occur with 3–5 s injection durations under higher loads, confirming better efficiency at elevated compression ratios.

For compression ratio (CR) 17:1, the hydrocarbon (HC) emission data show a consistent trend of decreasing average HC levels with increasing engine load, confirming improved combustion efficiency at higher loads. At no load (0 kg), the average HC emission is 392.75 ppm. Emissions increase with injection duration, from 53.67 ppm at 0 seconds to 670.67 ppm at 5 seconds, suggesting that excess fuel leads to incomplete combustion under low thermal conditions.

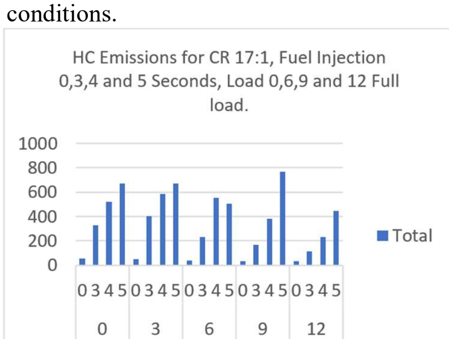

Fig. 5: Emission of HC for CR 17: 1,

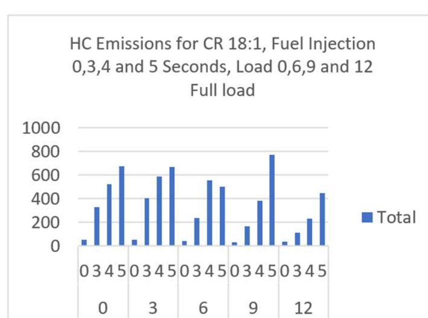

Fig. 6: Emission of HC for CR 16: 1

At 3 kg load, the average emission slightly increases to 427 ppm, primarily due to higher emissions at longer injection durations, again highlighting the challenge of achieving complete combustion at low to medium loads. From 6 kg load onwards, emissions gradually decline. At 6 kg, the average drops to 332.08 ppm, with significantly lower values at shorter injection durations. Further, at 9 kg load, HC emissions fall to 336.83 ppm, with the highest value observed at 5 seconds (768 ppm), indicating possible over-injection. The lowest average HC emission is seen at 12 kg (205.92 ppm), confirming optimal combustion under high-load conditions, particularly for 0- and 3-second injection durations. Overall, CR 17:1 demonstrates improved combustion efficiency with increasing load. However, longer injection durations at lower loads lead to elevated HC emissions, emphasizing the need for careful fuel injection control.

For CR 18:1, HC emissions decrease steadily with increasing load, confirming improved combustion efficiency. At low loads, emissions are high due to over-fueling and low temperatures, peaking at 595 ppm for 5-second injection. Beyond 6 kg, HC levels drop sharply, reaching a minimum of 170.58 ppm at 12 kg load. Overall, shorter injection durations ensure cleaner combustion, while longer durations increase unburned hydrocarbons.

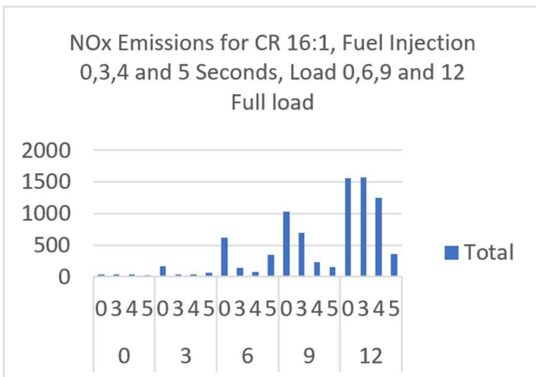

Fig. 7: Emission of NOx for CR 16: 1

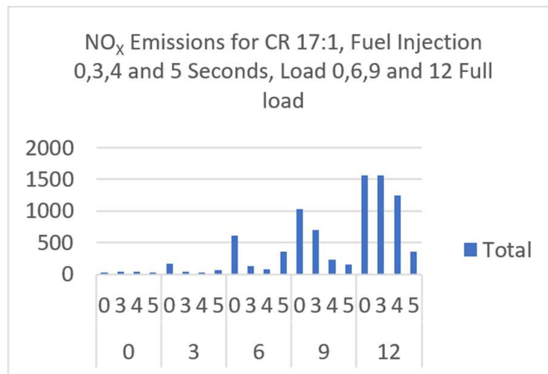

Fig. 8: Emission of NOx for CR 17: 1

For CR 16:1, NOx emissions rise steadily with increasing load due to higher combustion temperatures. At no load, levels are low (≈32 ppm), but increase sharply to 1181.83 ppm at 12 kg. Shorter injection durations (0–3 s) produce higher NOx because of leaner mixtures and peak temperatures, while longer durations reduce it. Overall, NOx formation is strongly influenced by load and injection timing, requiring optimization or EGR to control emissions.

For CR 17:1, NOx emissions increase steadily with load due to higher combustion temperatures, rising from about 32 ppm at no load to 1181.83 ppm at 12 kg. Shorter injection durations (0–3 s) produce higher NOx from advanced combustion, while longer durations (5 s) lower it by reducing peak temperature. The trend confirms thermal NOx dominance in high CR engines. Optimized injection timing and cooled EGR can effectively control these emissions.

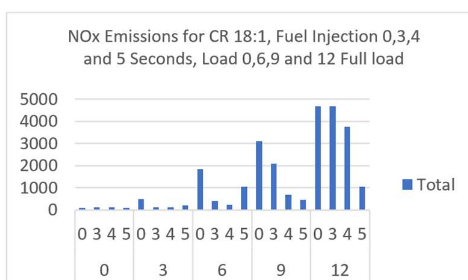

Fig. 9: Emission of NOx for CR 18: 1

For CR 18:1, NOx emissions rise sharply with increasing load and advanced injection timing, typical of thermal NOx formation. Values increase from about 78 ppm at no load to 14,182 ppm at 12 kg. Shorter injection durations (0–3 s) generate higher NOx due to elevated combustion temperatures, while longer durations (5 s) reduce it. Thus, retarded injection timing effectively limits NOx under high-load conditions.

TABLE II. KEY INSIGHTS

Area	CR	Emission Trend Summary	Injection Timing Effect	Load Effect	Key Observation
CO	16	Moderate CO levels, avg ~0.20	CO decreases with delayed injection	CO decreases with load increase	Lower CO at higher loads and delayed injection
	17	Slightly lower CO than CR16	Similar trend, delayed injection lowers CO	Load increase lowers CO	Emissions improve with CR increase and injection delay
	18	Lowest CO among three CRs	More pronounced decrease at 5 sec	Load increase reduces CO	Higher CR improves combustion, lowering CO
HC	16	High HC at low load and early injection	HC decreases significantly at 5 sec	HC decreases with load	Incomplete combustion at low load and early injection
	17	Lower HC than CR16	Same trend with injection delay	HC reduces with load	HC emissions improve with CR and delayed injection
	18	Lowest HC levels overall	Marked HC drop at 5 sec injection	Load increases reduce HC	CR18 yields better combustion, reducing HC
NOx	16	Lowest NOx levels, moderate increase with load	Early injection increases NOx	NOx increases sharply with load	NOx controlled better at lower CR
	17	Moderate NOx, higher than CR16	Early injection spikes NOx	NOx rises with load	NOx increases with CR and load
	18	Highest NOx values overall	Early injection leads to max NOx	Strong load-dependent NOx rise	High CR and load increase combustion temperature and NOx

In summary, for CR 18:1, NOx emissions increase significantly with load and are highest at early injection timings. Delaying injection reduces NOx by lowering combustion temperatures, underscoring the importance of optimizing injection timing to control NOx emissions in high CR engines. Table I, shows the key insights revealing, increasing the compression ratio from 16:1 to 18:1 enhances combustion efficiency as seen in the significant reduction of CO and HC emissions at higher CRs.

Delaying biodiesel and petrol injection timings (towards 5 seconds) consistently lowers CO and HC emissions across all CRs, indicating improved fuel-air mixing and more complete combustion. However, higher compression ratios (CRs) and loads enhance combustion efficiency but significantly increase NOx emissions due to elevated in-cylinder temperatures.

Early injection intensifies NOx formation, whereas delayed timing reduces CO and HC but needs support from EGR or after-treatment for effective NOx control. Optimal performance is achieved at CR 17:1–18:1 with 4–5 s injection, ensuring balanced combustion. Longer injection durations raise NOx, while intermediate durations (3–4 s) yield cleaner emissions.

Increasing CR from 16 to 18 lowers CO and HC but elevates NOx, with CR 17 offering the best trade-off. Overall, moderate loads (6–9 kg) and optimized injection timing ensure efficient and cleaner biodiesel-petrol engine operation.

VI. CONCLUSION

The study explores the application of biodiesel in low-temperature combustion (LTC) engines as a sustainable method to reduce nitrogen oxide (NOx) emissions, a key pollutant from conventional diesel engines. While Selective Catalytic Reduction (SCR) systems effectively lower NOx, they are costly and complex, making them unsuitable for small diesel engines widely used in India. Biodiesel's higher oxygen content and superior cetane rating enable more efficient combustion at lower temperatures, naturally suppressing NOx and particulate matter formation without requiring expensive after-treatment. However, achieving stable performance demands precise control over ignition timing, air–fuel mixing, and blend standardization due to variations in biodiesel feedstock's. Minor hardware modifications may also be needed to address issues related to viscosity and cold-weather operation.

Economically, biodiesel derived from non-edible oils, waste cooking oil, and agricultural residues offers dual benefits—reducing the transport sector's carbon footprint and strengthening rural economies through feedstock production. Supported by India's National Policy on Biofuels, the integration of biodiesel with LTC technology provides a cost-effective, clean, and scalable alternative to traditional diesel systems. With further advancements in combustion optimization and infrastructure development, biodiesel-powered LTC engines can play a transformative role in achieving sustainable mobility and energy security.

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