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A Critical Review of Performance Improvement Techniques in Compression Ignition Engines

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***Abstract*— Compression ignition engines play a critical role in various industrial and transportation applications; however, their environmental impact remains a major concern. Continuous research efforts have been directed toward optimizing engine performance to enhance efficiency and reduce emissions. This paper reviews key strategies that have been investigated for performance optimization, primarily focusing on combustion chamber geometry, fuel attributes, and advanced combustion strategies. Each of these factors significantly influences the combustion process, thereby affecting engine performance and emission characteristics. While no single method has proven sufficient to fully resolve all challenges associated with these engines, combustion chamber geometry optimization has demonstrated potential in improving efficiency and reducing pollutant emissions. More notably, integrating multiple optimization techniques appears to offer a more effective pathway toward achieving substantial improvements in overall engine performance.**

Keywords— Combustion chamber geometry, Compression ignition engines, Emission, Renewable fuel

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I. INTRODUCTION

Internal combustion engines (ICEs) have proven to be one of the most transformative technological innovations in modern history. The transportation sector has significantly benefited from their invention, which revolutionized mobility by enabling faster and more efficient movement of people and goods. However, the impact of ICEs is not limited to transportation alone; They are also essential contributors to the energy, agriculture, and construction sectors. Thus, it is reasonable to state that internal combustion engines have partially contributed to the acceleration of globalization [1].

Despite their widespread utility, ICEs powered by fossil fuel derivatives are associated with significant environmental concerns. Emissions from engines, including carbon monoxide (CO), hydrocarbons (HC), nitrogen oxides (NOx), and fine particulate matter (PM), are widely acknowledged as significant contributors to global warming and climate change. As a result, internal combustion engines remain under continuous scrutiny in the context of environmental sustainability [2].

Given the critical importance of ICEs in human activities and their adverse environmental effects, numerous studies have focused on optimizing engine performance to enhance fuel efficiency and reduce harmful emissions.

These strategies include modifications to combustion chamber geometry, utilization of renewable fuels, optimization of fuel injection strategies, and implementation of advanced combustion modes. Studies indicate that these interventions can significantly improve combustion efficiency and emission profiles [3].

For instance, adjustments to combustion chamber geometry have been shown to enhance air-fuel mixture turbulence and accelerate flame propagation, thereby improving thermal efficiency and reducing particulate emissions [4]. Similarly, the use of renewable fuels, such as biodiesel, bioethanol, and synthetic fuels (e-fuels), has demonstrated potential in lowering carbon emissions and toxic pollutants.

The implementation of innovative combustion strategies, such as Homogeneous Charge Compression Ignition (HCCI), Low Temperature Combustion (LTC), and Reactivity Controlled Compression Ignition (RCCI), has also produced encouraging outcomes in cutting NOx and particulate matter emissions without compromising high efficiency [5] [6] [7]. The view that these technologies may serve as long-term solutions for cleaner combustion systems.

Additionally, optimizing fuel injection parameters such as injection timing, pressure, and multi-injection strategies has been found to significantly improve fuel atomization and air-fuel distribution uniformity [8]. These findings collectively suggest that integrating multiple optimization techniques yields better outcomes than relying on a single approach.

Based on this background, this study aims to provide a comprehensive review of intervention methods used in the performance optimization of internal combustion engines. By analyzing recent developments and empirical evidence, this paper contributes to the understanding of how ICE technology can evolve toward greater efficiency and environmental compatibility.

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II. METHOD

A. Literature Review

This study's backbone is a comprehensive literature review. This approach was chosen for its systematic way of gathering, analyzing, and synthesizing findings from a variety of pertinent academic works. The goal To deeply assess interventions aimed at boosting performance and reducing emissions from compression ignition (CI) engines, which are more widely known as diesel engines. Our review zeroes in on three key intervention areas that have been extensively explored by researchers.

B. Analyzing Combustion Chamber Geometry

The first intervention we dove into involves modifications to combustion chamber geometry. This method hinges on a fundamental idea: the combustion process inside an internal combustion engine is heavily shaped by how fluids move within the cylinder [9] [15]. And that fluid movement It's directly controlled by the combustion chamber's design and layout. This review specifically dissects how different piston crown shapes impact two crucial aspects.

The Combustion Process: How various geometric forms influence the mixing of air and fuel, which is significantly governed by swirl (rotational motion) and squish (squeezing motion) within the cylinder. Optimizing this mixing is absolutely vital for efficient and complete combustion [10].

Physical Parameters: The impact they have on in-cylinder pressure and temperature, where the maximum combustion pressure directly controls the engine’s power production, while combustion temperature influences the creation of undesirable combustion byproducts, particularly pollutant emissions [11].

The studies we examined looked at various piston bowl designs, whether common or still in development, such as Grooved, Hemispherical, Multi-Chambered, Re-entrant, Shallow depth, Toroidal, Trapezoidal, Truncated cone [12] [13]. Each design possesses unique traits that influence airflow patterns, fuel distribution, and ultimately, combustion efficiency and emission profiles.

C. Analyzing Fuel Usage

The second area we thoroughly analyzed was the impact of fuel type on engine performance. This method stems from the understanding that a fuel's physical and chemical properties are incredibly significant factors determining a CI engine's overall performance and emission characteristics [14]. Our review focused on:

Fuel Properties: An analysis of how various physical and chemical fuel properties like density, viscosity, heat content (calorific value), and oxygen content play a role [15]. Each property is crucial in dictating the fuel's injection, atomization, vaporization, and combustion processes, which ultimately affect efficiency and emissions.

Renewable Fuels: This review paid special attention to renewable fuels, particularly biodiesel, as it's the most common and widely researched option for CI engines in efforts to lessen reliance on fossil fuels and the emissions they produce. We evaluated the performance of several biodiesel types found in the reviewed literature, including Canola, Jatropha, Pongamia, Waste Cooking Oil, Karanja, Palm Oil, and Soybean. Furthermore, the use of other promising renewable fuels like Di-Methyl Ether (DME) and alcohols (ethanol, methanol), along as the incorporation of metal additives in biodiesel, were also scrutinized to grasp their potential in boosting performance and cutting emissions [16].

D. Analyzing Advanced Combustion Modes

The third intervention explored was the implementation of advanced combustion modes. This technology was developed in response to the urgent need for more eco-friendly engines, primarily aiming to drastically cut down on toxic pollutant emissions like nitrogen oxides (NO_X) and particulates (PM). Advanced combustion modes strive for cleaner, more efficient combustion through highly precise control over the combustion process [17]. The methods examined in this category include:

Homogeneous Charge Compression Ignition (HCCI) and Low Temperature Combustion (LTC): Both modes aim for more homogeneous combustion at lower temperatures, effectively reducing NO_X and soot formation [18].

Exhaust Gas Recirculation (EGR): This method returns part of the exhaust gases to the combustion chamber to reduce combustion temperatures and suppress NOx production. [19].

Reactivity Controlled Compression Ignition (RCCI): This approach employs two fuels with distinct reactivities to manage the heat release rate and attain highly efficient, low-emission combustion [20].

Premixed Charged Compression Ignition (PCCI): Similar to HCCI, PCCI involves pre-mixing fuel and air before compression to achieve more controlled combustion.

For each combustion mode discussed, this review meticulously assessed its impact on fuel efficiency (specific fuel consumption, thermal efficiency) and the reduction of toxic waste emissions from internal combustion engines. This analysis examines the impact of each mode on the formation of NOx, particulates, carbon monoxide (CO), and unburned hydrocarbons (UHC).

III. RESULTS AND DISCUSSION

This chapter provides and critically examines research findings related to the effects of combustion chamber design, renewable fuel application, and advanced combustion strategies on engine performance and emission levels. The discussion centers on a thorough analysis of various design modifications, evaluating their effects on key parameters such as pressure, temperature, combustion efficiency, and exhaust emission levels. The data presented are drawn from validated experimental and simulation results, offering a clear perspective on both the potential benefits and inherent challenges of each approach in advancing cleaner and more efficient engine technologies.

A. Combustion Chamber Geometry

The geometry of the combustion chamber plays a fundamental role in governing the in-cylinder thermodynamic behavior during the combustion process in compression ignition engines. Specifically, it exerts a significant influence on key physical properties such as in-cylinder pressure and temperature, both of which are critical to engine performance and emission characteristics. While pressure determines the brake power output, the temperature governs the chemical kinetics and composition of combustion by-products, including NO_x, CO, HC, and particulate matter [21].

Several studies have confirmed that the formation of these emission species is highly sensitive to the interaction between combustion chamber geometry and engine operating speed. Additionally, the effectiveness of air–fuel mixing, which directly impacts combustion efficiency, is largely dictated by the swirl motion generated by piston bowl geometry and intake flow dynamics.

Although conventional research has predominantly utilized cylindrical or hemispherical piston designs, recent investigations have expanded to incorporate non-cylindrical configurations such as toroidal, re-entrant, stepped-lip, and truncated cone bowls. These alternative geometries are engineered to enhance in-cylinder turbulence, improve fuel–air mixing, and optimize the spatial distribution of temperature and pressure fields during combustion. For instance, toroidal and stepped-lip designs have been shown to produce more uniform turbulence fields, which contribute to increased thermal efficiency and lower carbon emissions, albeit sometimes at the expense of elevated NO_x levels.

A range of performance enhancement strategies based on combustion chamber modification are systematically summarized in Table 1, while selected visual representations of piston bowl geometries are provided in Figure 1, illustrating the diversity of approaches undertaken to improve both combustion stability and environmental compliance.

Figure 1. Several piston geometries a) hemispherical [22] b) toroidal [23] c) trapezoidal [24] d) truncated cone [25] e) cylindrical [24] f) re-entrant [26]

TABLE 1.
EFFECTS OF DIFFERENT COMBUSTION CHAMBER SHAPES ON ENGINE PERFORMANCE

Combustion Chamber	Outcome
Hemispherical combustion chamber piston	The engine exhibited lower performance and emission characteristics compared to the cylindrical piston bowl, except for NOx emissions, where it performed better [28]. Similarly, engines equipped with a hemispherical piston bowl demonstrated inferior performance and emission characteristics relative to those with a toroidal piston bowl, except in the case of NOx emissions [29].
Truncated cone combustion chamber piston	When the base cone angle of the piston crown is set at an optimal value, the engine's performance characteristics and emissions show significant improvement. The use of a truncated cone-shaped piston crown demonstrates better performance and emission levels compared to the commonly used standard piston crown [30] [31].
Toroidal combustion chamber piston	The utilization of a toroidal-shaped piston bowl has been shown to enhance the performance characteristics of internal combustion engines compared to a standard piston bowl. Moreover, engine emissions are generally reduced relative to those of a standard piston crown, except for NOx emissions [28].
Re-entrant combustion chamber piston	The engine performance exhibited a decline, as did its emission characteristics, except for nitrogen oxides (NOx). Nevertheless, previous studies have indicated that employing a re-entrant piston bowl, compared to a cylindrical piston bowl, can enhance engine performance, albeit with an accompanying increase in NOx emissions [32].
Trapezoidal combustion chamber piston	The engine exhibited lower performance and emission characteristics compared to the cylindrical piston bowl, except for NOx emissions, which showed improved results. Among the various combustion chamber designs investigated, engines equipped with trapezoidal piston bowls demonstrated the lowest performance [32].
Cylindrical combustion chamber piston	The use of a cylindrical piston bowl in the combustion chamber of internal combustion engines can enhance turbulence, which aids the mixing of air and fuel, thereby potentially improving combustion efficiency and overall engine performance. However, this increased turbulence may also lead to higher combustion temperatures, potentially resulting in elevated nitrogen oxide (NOx) emissions, despite a tendency for reduced particulate matter and unburned hydrocarbon emissions [33].
Multi-chambered piston crown	The use of a multi-chambered piston crown significantly enhances engine performance and reduces emissions compared to a standard piston. This specific design creates optimal air turbulence, which leads to a more perfect mixing of fuel and air. Consequently, this results in higher thermal efficiency, increased power and torque, and lower fuel consumption. Regarding emissions, the more complete combustion substantially reduces particulate matter (soot/smoke) as well as hydrocarbon (HC) and carbon monoxide (CO) emissions. However, the resulting increase in combustion temperature can potentially elevate NOx emissions, an effect that must be balanced through design optimization [34].
Grooved piston crown	The use of a grooved piston crown has been proven to significantly improve engine performance and reduce emissions compared to a conventional piston. These grooves are specifically designed to optimize the air movement within the cylinder, resulting in a more uniform fuel-air mixture. This has a positive impact on thermal efficiency, leading to increased power and torque, as well as reduced fuel consumption. This more complete combustion is also effective in suppressing harmful emissions like soot (particulates), hydrocarbons, and carbon monoxide. It is important to note, however, that the resulting increase in combustion temperature can lead to a rise in nitrogen oxide (NOx) emissions [35].

B. Fuels

Fuel properties have long been recognized as a pivotal factor in enhancing engine performance and curbing emissions, particularly in the context of modern internal combustion systems. Among the wide array of variables that govern engine operation, the chemical and physical characteristics of the fuel used are often the most decisive in influencing combustion behavior and emission formation. As such, a nuanced understanding of fuel behavior under dynamic engine conditions is critical to achieving performance optimization without compromising environmental standards.

Key attributes including density, viscosity, heating value, and oxygen content are known to substantially influence combustion efficiency and the generation of pollutants such as NO_x, CO, HC, and particulate matter. For instance, fuel viscosity directly affects the atomization quality during injection, which in turn governs how well the fuel mixes with air in the combustion chamber. Inadequate atomization caused by high viscosity may result in incomplete combustion and lower thermal efficiency, whereas excessively low viscosity can impair lubrication and lead to component wear, particularly in high-pressure common rail systems.

In parallel, the calorific value of the fuel its inherent energy content determines how much useful work can be extracted per unit mass of fuel. Fuels with higher heating values typically reduce brake-specific fuel consumption (BSFC), thereby improving overall fuel economy. Meanwhile, brake thermal efficiency (BTE) is often correlated with the oxygen content in the fuel. Fuels enriched with molecular oxygen, such as certain biodiesels and oxygenated synthetic blends, tend to support more complete combustion, lowering the emissions of unburned hydrocarbons and carbon monoxide.

However, the presence of oxygen within the fuel also introduces complexity. While it enhances oxidation reactions and facilitates soot reduction, it can simultaneously elevate local combustion temperatures thereby increasing NO_x formation, especially under lean-burn or high-load conditions. Therefore, a careful balance must be achieved to exploit the benefits of oxygenated fuels without exacerbating thermal NO_x emissions.

Furthermore, the oxygen content plays a key role in particulate matter (PM) reduction. Improved oxidation of residual carbon leads to cleaner exhaust gas, particularly when coupled with optimized injection strategies and combustion chamber design. Nonetheless, the impact of these fuel characteristics is not isolated it interacts significantly with engine geometry, injection timing, and combustion mode.

The properties of fuels play a critical role in determining the operational performance and environmental impact of internal combustion engines. Given their profound influence on engine behavior ranging from combustion efficiency to the nature and quantity of emissions fuel characteristics have become a central subject of investigation in recent research efforts. In particular, there has been a noticeable shift toward utilizing renewable fuels, especially biofuels, as part of broader strategies aimed at improving thermal performance while simultaneously reducing harmful exhaust emissions.

Although synthetic fuel technologies are still undergoing significant development and have yet to be widely adopted in commercial applications, certain types such as Dimethyl Ether (DME) have long been known and studied for their potential as cleaner-burning renewables. DME, in particular, has attracted interest for its favorable combustion properties, though its widespread use remains limited by current production and infrastructure constraints.

A variety of fuels have been tested and implemented in efforts to optimize engine performance, as outlined in Table 2. Among these, biodiesel has emerged as a dominant focus, primarily because of its widespread availability and compatibility with compression ignition (CI) engines. Biodiesel's renewable nature and relatively clean-burning profile make it one of the most extensively researched and applied renewable fuels in diesel engine configurations.

Alongside biodiesel, alcohol-derived fuels like ethanol and methanol have been utilized to lower emissions by enabling cleaner and more complete combustion. These alcohols offer advantages in terms of enhanced air–fuel mixing, higher oxygen content, and lower soot formation, which together contribute to reduced levels of carbon monoxide (CO) and unburned hydrocarbons (HC) in the exhaust gases.

More recently, there has been growing scholarly attention toward the incorporation of metallic additives into biodiesel blends, prompted by promising outcomes from early-stage studies. These metallic compounds often in the form of oxides or nanoparticles have demonstrated the ability to improve thermal conductivity, enhance the rate of heat transfer, and promote more complete oxidation during combustion. As a result, engines fueled with such enhanced biodiesel blends have shown notable improvements in performance metrics and reductions in emissions, particularly in terms of particulate matter and incomplete combustion by-products.

TABLE 2.
IMPACT OF RENEWABLE FUELS ON ENGINE PERFORMANCE

Renewable Fuels	Outcome
Palm Oil biodiesel	Significant reductions in CO, HC, and smoke/PM emissions are attributed to the inherent oxygen content and higher cetane number of PME. Several studies have reported substantial decreases, with reductions of up to ~87% in CO, ~14% in HC, and ~68% in smoke under specific test conditions [36].
Pongamia biodiesel	In the case of Pongamia biodiesel–diesel blends, a reduction in thermal efficiency and an increase in specific fuel consumption were observed. Nevertheless, CO and HC emissions were found to be lower than those of conventional diesel, whereas NO_x emissions were comparatively higher [37].
Soybean biodiesel	The use of SME leads to a decrease in thermal efficiency and engine power, accompanied by an increase in brake specific fuel consumption of approximately −2%, −3%, and +12%, respectively, when compared with neat diesel. Moreover, NO_x emissions were observed to increase by more than 28% for all SME blends relative to neat diesel [38].
Karanja biodiesel	The use of KME blends up to B20 resulted in an improvement in brake thermal efficiency (BTE) under high-load conditions, accompanied by reductions in CO and smoke emissions. However, an increase in NO_x emissions was observed under nearly all loading conditions[39].
Di-Methyl Ether (DME)	Dimethyl ether (DME) exhibits a high cetane number and excellent volatility, which promote rapid and clean combustion. Compared to conventional diesel, DME shows a distinct heat release rate (HRR) profile, necessitating optimization of injector design and injection timing to enhance efficiency while mitigating NO_x emissions. In contrast, CO and HC emissions are generally reduced due to the more complete combustion process facilitated by the inherent molecular oxygen content of DME [40] [41].
Jatropha biodiesel	Smoke decreased ↓21%, HC ↓17.9%, and CO ↓16%. NO_x increased ↑3.8% at full load. The thermal efficiency decreased by about 2.8% and BSFC slightly increased, but still within acceptable limits [42].
Canola biodiesel	BSFC increased by up to 6.56%, while BTE decreased by up to 4.2% at high load with a 20% blend. Combustion exhibited a shorter ignition delay, along with reductions in the maximum heat release rate, in-cylinder pressure, and rate of pressure rise. NO_x increased by 8.9%, whereas smoke, CO, and THC emissions decreased. CO_2 levels were slightly higher under all load conditions [43].
Waste Oil biodiesel	BSFC is higher, particularly at low loads (with an increase of up to 42% at 25% load). BTE is slightly higher than diesel at 50–100% load, but lower at 25%. HC and NO_x emissions show a slight reduction, although the results vary depending on the operating conditions [44].

C. Advanced Combustion Mode

The growing demand for fuel-efficient and environmentally responsible propulsion systems has placed advanced combustion technologies for compression ignition (CI) engines at the center of academic and industrial interest. Diesel engines, while celebrated for their excellent thermal efficiency and long service life, are likewise associated with the release of hazardous emissions, notably nitrogen oxides (NO_x) and particulate matter (PM), both of which contribute significantly to air quality degradation and public health concerns.

To address these limitations, researchers have explored and developed advanced combustion concepts that aim to balance performance with emissions control. Among the most prominent innovations are Homogeneous Charge Compression Ignition (HCCI) and Low Temperature Combustion (LTC) both representing a paradigm shift from traditional diesel combustion strategies. These combustion techniques are specifically designed to limit peak temperatures and promote more uniform combustion, thereby minimizing the formation of NO_x and soot without compromising overall engine efficiency.

HCCI operates by premixing the fuel and air to create a homogeneous charge that auto-ignites under compression. This process leads to rapid and simultaneous combustion across the chamber, resulting in low combustion temperatures and cleaner exhaust gases. On the other hand, LTC focuses on managing the timing and temperature of combustion through optimized injection strategies and air–fuel mixing, effectively reducing high-temperature zones that typically generate NO_x.

Numerous interventions based on these advanced combustion strategies are outlined in Table 3, highlighting a diverse range of research directions. One of the most extensively studied approaches involves the use of biodiesel, a renewable and oxygenated renewable fuel that has gained traction due to its compatibility with CI engines and reduced carbon footprint. Its inherent oxygen content enhances combustion efficiency, making it a suitable candidate for use in advanced combustion modes.

A well established complement to these strategies is the Exhaust Gas Recirculation (EGR) system, which has proven effective in reducing peak combustion temperatures and improving thermal efficiency, particularly under partial load conditions [64–65]. EGR works by reintroducing a portion of exhaust gases into the intake air, diluting the oxygen content and absorbing combustion heat further suppressing the production of thermal NO_x.

In addition to biodiesel, alcohols such as ethanol and methanol have also been employed as supplementary fuels to lower engine-out emissions. Their higher volatility and oxygen-rich molecular structure facilitate better air–fuel mixing and more complete combustion, contributing to reductions in carbon monoxide and unburned hydrocarbons.

Recent years have also witnessed increased attention toward the use of metal-based fuel additives, particularly in biodiesel applications. These metallic additives, often in nanoparticle or oxide form (e.g., cerium oxide, copper oxide), have demonstrated significant potential in enhancing combustion kinetics, thermal conductivity, and mixture stability. Experimental evidence suggests that these additives can improve engine performance indicators while simultaneously decreasing the emission of particulates and incomplete combustion by-products.

TABLE 3.
EFFECTS OF ADVANCED COMBUSTION MODES ON ENGINE PERFORMANCE

Advanced Combustion Modes	Outcome
Reactivity Controlled Compression Ignition (RCCI)	Reactivity Controlled Compression Ignition (RCCI) has been shown to simultaneously achieve ultra-low NO_x and soot emissions compared to conventional diesel combustion (CDC), often accompanied by higher thermal efficiency. However, an increase in unburned hydrocarbons (UHC) and carbon monoxide (CO) may occur due to quenching or over-mixing effects, thereby necessitating precise injection control strategies and the application of appropriate after-treatment systems [45].
Homogenous Charge Compression Ignition (HCCI)	Compared to conventional diesel engines, HCCI operation exhibits higher thermal efficiency due to a combustion process that more closely approaches the ideal thermodynamic cycle and reduced wall heat losses. Numerous studies have also reported lower brake specific fuel consumption (BSFC), reflecting improved fuel economy. Nevertheless, combustion stability remains a critical limitation at high load and low-speed conditions, where the occurrence of knocking or misfire can be significant [46] [47] [48]
Premixed Charged Compression Ignition (PCCI)	Premixed Charge Compression Ignition (PCCI) integrates the benefits of premixed combustion with the precise injection control of conventional diesel engines. This strategy enables rapid ignition with charge stratification, thereby preserving combustion phasing, lowering combustion noise, and enhancing thermal efficiency. Compared to conventional diesel combustion, and in many cases even to HCCI operation, PCCI achieves substantial reductions in NO_x and soot emissions due to its moderated combustion temperature and staged ignition process. Nevertheless, elevated levels of unburned hydrocarbons (HC) and carbon monoxide (CO) are frequently observed, which are primarily attributed to incomplete combustion and quenching effects near wall regions under early injection conditions [49] [50].
Exhaust Gas Recirculation (EGR)	An increase in the EGR ratio leads to a reduction in peak cylinder pressure and combustion temperature. Consequently, Brake Specific Fuel Consumption (BSFC) increases, while Brake Thermal Efficiency (BTE) exhibits a declining trend, primarily due to reduced in-cylinder temperature and oxygen concentration. The implementation of EGR, however, results in a significant reduction in nitrogen oxide (NO_x) emissions [51] [52].

IV. Conclusion

Compression ignition (CI) engines remain indispensable across numerous sectors of the global economy, particularly in industries reliant on heavy-duty and long-duration power applications. While their robustness and superior fuel efficiency are well documented, their environmental drawbacks most notably the emission of nitrogen oxides (NO_x) and particulate matter pose a continuing challenge in light of increasingly stringent emission regulations.

In this context, the present study has synthesized findings from various interventions aimed at improving the environmental and operational performance of CI engines. These interventions fall into three primary categories: combustion chamber geometry modifications, renewable fuel utilization, and advanced combustion methodologies.

With regard to combustion chamber geometry, changes in piston bowl shape have been shown to influence in-cylinder dynamics significantly. Most design configurations achieved higher brake thermal efficiency and reduced specific fuel consumption. Nevertheless, certain geometries such as re-entrant, hemispherical, and trapezoidal bowls showed variable results, suggesting that the shape itself is not enough without being optimally integrated into the overall combustion approach.

In terms of fuel-related interventions, the adoption of biodiesel particularly from sources such as canola and jatropha has yielded measurable improvements in thermal efficiency and emissions reduction. Alcohol-based fuels also demonstrated value, primarily due to their favorable combustion properties and oxygen content, which facilitate more complete oxidation and reduce unburned hydrocarbons.

In terms of combustion methods, technologies such as Homogeneous Charge Compression Ignition (HCCI) have demonstrated success in minimizing NO_x production through the suppression of maximum flame temperatures. The use of Exhaust Gas Recirculation (EGR) further contributes to emission control by diluting oxygen concentration and absorbing heat within the combustion chamber.

Despite these advancements, no single intervention provides a complete solution. The emission targets set for the near future, particularly concerning greenhouse gases, will likely require a combination of the strategies outlined above. Among them, fuel innovation especially the development and deployment of synthetic, carbon-neutral fuels at commercial scale offers the most forward-looking potential. Such fuels could radically alter the emissions profile of CI engines and support broader climate goals.

In summary, a multifaceted approach that integrates combustion design optimization, renewable fuel adoption, and advanced combustion control appears to be the most pragmatic pathway toward achieving cleaner and more efficient CI engine operation. Continued research in this direction holds significant promise for balancing energy demands with environmental sustainability.

References

[1] M. Effendy, I. M. R. A. Mulyono, M. C. W. S. Kusuma, and F. R. P. K. Wardana, "Performance and smoke opacity of compression-ignition engine using used-waste oil," *Case Stud. Therm. Eng.*, vol. 27, p. 101292, 2021.

[2] T. T. Olugasa, M. L. Adekanbi, and S. K. Fasogbon, "Performance and emission characteristics of compression ignition engine running on a blend of cashew nut shell liquid and biodiesel produced from orange peel," *Eur. J. Sustain. Dev. Res.*, vol. 6, no. 4, p. em0197, 2022.

[3] Y. Lin, S. Zhang, G. Li, S. Cai, and J. Wu, "Effects of piston bowl geometry on combustion and emissions of a four-stroke heavy-duty diesel marine engine," *Appl. Sci.*, vol. 12, no. 24, p. 13012, 2022.

[4] S. Suryawanshi and V. Deshmukh, "Influence of combustion chamber shapes and nozzle geometry on performance, emission, and combustion characteristics of CRDI engine powered with biodiesel blends," *Sustainability*, vol. 13, no. 17, p. 9613, 2021.

[5] J. Wang et al., "The impact of alternative fuels on ship engine emissions and aftertreatment systems: A review," *J. Mar. Sci. Eng.*, vol. 12, no. 2, p. 138, 2022.

[6] H. Xu et al., "An in-depth review on advanced low temperature combustion modes for internal combustion engines," *Renew. Sustain. Energy Rev.*, vol. 155, p. 111818, 2022.

[7] Semin & Octaviani N. S., "Performance Investigation of Dual Fuel Engine: A Technical Review", *ARPN J. Eng. Appl. Sci*., vol. 14, Special Issue 8, pp. 2393–2397, 2019.

[8] G. Li, B. Cui, C. Zhang, L. Chang, and L. Chen, "Formulation of a jet fuel surrogate and its kinetic chemical mechanism by emulating physical and chemical properties of real jet fuel," *Sustainability*, vol. 15, no. 18, p. 13792, 2023.

[9] M. J. Tuner and J. M. Williams, "Advanced research on internal combustion engines and engine fuels," *Energies*, vol. 10, no. 9, p. 1307, 2023.

[10] İ. Kalay, Ö. Cihan, and M. Karabektas, "Numerical analysis of various combustion chamber bowl geometries on combustion, performance, and emissions parameters in a diesel engine," *Int. J. Automot. Eng. Technol*., vol. 1351644, 2024.

[11] Semin & Bakar R. A., "Analysis of the Effect of Intake Valve Fin Adding of Dual Fuel Engine on the Performance-Based Experiment", *Int. J. Adv. Sci. Eng. Inf. Technol., vol. 10, no. 5, pp. 1939–1945, Okt. 2020.*

[12] H. E. Gulcan and M. Ciniviz, "Effect of piston bowl geometry on combustion performance and pollutant emissions of methane-diesel common rail dual-fuel engine," *Fuel*, vol. 345, p. 128175, 2023.

[13] D. Hariharan et al., "Effects of piston bowl geometry and injector included angle on dual-fuel and single-fuel RCCI," *J. Eng. Gas Turbines Power*, vol. 143, no. 11, p. 111013, 2021.

[14] M. Seddiq et al., "Piston bowl geometry and diesel injection timing in a heavy-duty diesel/syngas RCCI engine," *J. Energy Resour. Technol.*, 2023.

[15] E. C. W. Pribadi, S. Semin, A. Santoso, B. Cahyono, A. Iswantoro, H. Prasutiyon, and F. M. Felayati, "Lateral Swirl Combustion System Development of Dual Fuel Diesel Engine Piston to Improve Efficiency and Reduce NO_x Emission: a Brief Review," *Int. J. Eng. Appl. Sci. (IREA)*, vol. 12, no. 4, pp. 218–225, Jul. 2024.

[16] K. SivaPrasad et al., "Enhancement of mixture homogeneity for DI-CI engine to achieve HCCI combustion: a numerical approach," *Energy Sources, Part A: Recovery, Utilization, and Environmental Effects*, vol. 44, no. 2, pp. 4318–4333, 2022.

[17] M. Idris et al., "Engine performance using blended fuels of biodiesel and eco diesel," *Energy Eng*., vol. 120, no. 1, pp. 107–123, 2023.

[18] A. Chen et al., "Effects of alcohol and bio-based fuel additives on engine combustion and emissions: A review," *Fuel*, vol. 306, p. 121632, 2021.

[19] M. Y. Kim et al., "Integrated optimization of injection strategy

and combustion chamber geometry for reducing emissions in a diesel engine," *Energy Convers. Manag*., vol. 260, p. 115646, 2022.

[20] Frontiers in Energy Research, "The combustion and emission improvements for diesel–biodiesel hybrid engines based on response surface methodology," *Front. Energy Res*., vol. 11, p. 1201815, 2023.

[21] E. C. W. Pribadi, S. Semin, A. Santoso, M. I. S. Saihilmi, "Static Structural Simulation on A 47-mm-Crown-Diameter Lateral Swirl Combustion System (LSCS) Piston Modified," *Advances in Science, Technology & Innovation, Springer Nature*, 2025.

[22] A. Ramesh and R. S. Kamoji, "Comparative investigation of the effect of hemispherical and toroidal piston bowl geometries on diesel engine combustion characteristics," *Energy*, vol. 197, p. 117235, Apr. 2020. doi: 10.1016/j.energy.2020.117235.

[23] P. K. Devan, S. Mahalingam, and V. Jayaraj, "Effects of combustion vestibule configuration on the competence, emissions and combustion attributes of direct injection diesel prime mover powered with diesel and corn oil methyl ester (CROME)," *Renewable Energy*, vol. 158, pp. 1046–1058, Oct. 2020. doi: 10.1016/j.renene.2020.06.076.

[24] M. Senthil Kumar, A. Ramesh, and B. Nagalingam, "Effect of combustion chamber shapes on the performance of mahua and neem biodiesel operated diesel engines," *Renewable Energy*, vol. 34, no. 12, pp. 2703–2708, Dec. 2009. doi: 10.1016/j.renene.2009.05.013.

[25] S. O. Oyejide, A. M. Adelekan, and E. M. Attabo, "Experimental investigation of the performance and emission characteristics of a CI engine equipped with a modified truncated cone piston crown operated on diesel and shea-butter biodiesel," *Case Studies in Thermal Engineering*, vol. 37, p. 102315, Dec. 2022. doi: 10.1016/j.csite.2022.102315.

[26] V. R. Ayodhya, P. V. R. Babu, and K. Kishore Kumar, "Influences of re-entrant combustion chamber geometry on the performance of Pongamia biodiesel in a DI diesel engine," *Fuel*, vol. 267, p. 117213, Mar. 2020. doi: 10.1016/j.fuel.2020.117213.

[27] A. Ramesh and R. S. Kamoji, "Comparative investigation of the effect of hemispherical and toroidal piston bowl geometries on diesel engine combustion characteristics," *Energy*, vol. 197, p. 117235, Apr. 2020. doi: 10.1016/j.energy.2020.117235.

[28] C. M. Channappagoudra, K. Ramesh, and G. Manavendra, "Comparative investigation of the effect of hemispherical and toroidal piston bowl geometries on diesel engine combustion characteristics," Biofuel Res. J., vol. 5, no. 3, pp. 854-862, 2018.

[29] B. Pathak and N. Patel, "Thermodynamic Performance of an Engine by Modifying Piston Bowl Geometries Fuelled by SME-100, LA-100, KB-100 Biodiesel Blends, and Diesel," J. Adv. Res. Fluid Mech. Therm. Sci., vol. 102, no. 1, pp. 1-13, 2023.

[30] O. A. Towoju, A. A. Dare, and S. K. Fashogbon, "Experimental investigation of the performance and emission characteristics of a CI engine equipped with a modified truncated cone piston crown operated on diesel and shea-butter biodiesel," European Journal of Engineering and Technology Research, vol. 3, no. 10, pp. 32-44, 2018.

[31] S. Kumar, "Piston Crown Profile Modifications for Various Combustion Mode Strategies of Modified GDI Engine towards NOx and PM Reduction," International Journal of Automotive Science And Technology, vol. 4, no. 4, pp. 289-294, 2020.

[32] Y. Lin *et al.*, "Investigation of the effect of piston bowl geometry on the combustion and emissions of a common-rail diesel engine," *Fuel*, vol. 182, pp. 461-470, 2016.

[33] P. K. Saravanan, G. Dhandapani, P. Saravanan, and J. M. Subramanian, "Impact of piston bowl geometry on performance and emission characteristics of a biodiesel-fueled diesel engine," *Fuel*, vol. 270, Art. no. 117565, Jun. 2020.

[34] H. Yang, Z. Zhao, H. Xu, and Z. Chen, "Combined effects of piston bowl geometry and spray pattern on combustion and emissions in a heavy-duty diesel engine," Fuel, vol. 269, p. 117451, Mar. 2020, doi: 10.1016/j.fuel.2020.117451.

[35] A. Khalife, M. P. Ebrahimi, and B. Khalife, "Investigation of pollutants formation in a diesel engine using computational fluid dynamics: The effect of piston bowl shape," Journal of the Brazilian Society of Mechanical Sciences and Engineering, vol. 43, no. 5, pp. 1–14, May 2021, doi: 10.1007/s40430-021-02884-5.

[36] M. E. M. Soudagar, H. M. Khan, T. M. Yunus Khan, L. Razzaq, T. Asif, M. A. Mujtaba, … M. R. Safaei, "Experimental Analysis of Engine Performance and Exhaust Pollutant on a Single-Cylinder Diesel Engine Operated Using Moringa Oleifera Biodiesel," Applied Sciences, vol. 11, no. 15, 2021, Art. no. 7071, doi: 10.3390/app11157071.

[37] R. Thirunavukkarasu, R. Tamilselvan, T. Karthickmunisamy, M. Veeramanikandan, dan D. Sathish, "Experimental Investigation of Performance and Emissions Characteristics of a Diesel Engine with Pongamia Biodiesel and Diesel Blends," Applied Mechanics and Materials, vol. 877, pp. 397–402, Feb. 2018, doi: 10.4028/www.scientific.net/AMM.877.397

[38] M. F. Al-Dawody, "Effect of Soybean Oil Biofuel Blending on the Performance and Emissions of Diesel Engine Using Diesel-RK Software," International Journal of Engineering Science and Technology, vol. 3, no. 6, pp. 4539–4555, Jun. 2011.

[39] R. L. Patel dan C. D. Sankhavara, "Investigation of performance and emissions of diesel engine run on biodiesel produced from karanja oil in a single-step transesterification process using heterogeneous catalyst (lithium-impregnated calcium oxide)," Biofuels, vol. 11, no. 4, pp. 421–430, 2020, doi: 10.1080/17597269.2017.1370883.

[40] S. H. Park, H. J. Kim, dan C. S. Lee, "Effects of dimethyl-ether (DME) spray behavior in the cylinder on the combustion and exhaust emissions characteristics of a high speed diesel engine," Fuel Processing Technology, vol. 91, no. 5, pp. 504–513, May 2010, doi: 10.1016/j.fuproc.2009.12.013.

[41] M. Prabhahar, S. Prakash, B. Karpaga Vinayagam, D. Dhanraj, dan H. Zhang, "Investigating the Impact of Oxygenated Additives (DEE, DME & MTBE) on Engine Performance and Emission Reductions in Simarouba Methyl Ester Blends," International Research Journal of Multidisciplinary Technovation, online. Available: asianresassoc.org/journals/index.php/irjmt/article/view/2781.

[42] S. Jaichandar dan K. Annamalai, "Jatropha oil methyl ester as diesel engine fuel – an experimental investigation", International Journal of Automotive and Mechanical Engineering, vol. 13, no. 1, pp. 3248–3261, Dec. 2022. doi: 10.15282/ijame.13.1.2016.11.0271

[43] Ö. Can, E. Öztürk, dan H. S. Yücesu, "Combustion and exhaust emissions of canola biodiesel blends in a single cylinder DI diesel engine," Renewable Energy, vol. 109, pp. 73–82, 2017, doi: 10.1016/j.renene.2017.03.017.

[44] H. An, W. M. Yang, A. Maghbouli, J. Li, S. K. Chou, dan K. J. Chua, "Performance, combustion and emission characteristics of biodiesel derived from waste cooking oils," Applied Energy, vol. 112, pp. 493–499, 2013, doi: 10.1016/j.apenergy.2012.12.044.

[45] A. Paykani, A. García Martínez, M. Shahbakhti, P. Rahnama, dan R. D. Reitz, "Reactivity controlled compression ignition engine: Pathways towards commercial viability," Applied Energy, vol. 282, no. Part A, Art. no. 116174, Jan. 2021, doi: 10.1016/j.apenergy.2020.116174.

[46] X. Lu, D. Han, and Z. Huang, "Fuel design and management for the control of advanced compression-ignition combustion modes," Progress in Energy and Combustion Science, vol. 37, no. 6, pp. 741–783, Dec. 2011, doi: 10.1016/j.pecs.2011.03.002.

[47] R. H. Thring, "Homogeneous-charge compression-ignition (HCCI) engines," SAE Transactions, vol. 96, pp. 1923–1931, 1987, doi: 10.4271/892068.

[48] K. B. Arun, C. K. Saravanan, and R. Nagarajan, "Experimental investigations on a homogeneous charge compression ignition (HCCI) engine fueled with ethanol and gasoline blend," Applied Energy, vol. 95, pp. 116–123, Jul. 2012, doi: 10.1016/j.apenergy.2012.02.015.

[49] M. Murugesa Pandian dan K. Anand Krishnasamy, "Comparison of different low temperature combustion strategies in a light duty air cooled diesel engine", Applied Thermal Engineering, vol. 142, pp. 380–390, Jul. 2018, doi: 10.1016/j.applthermaleng.2018.07.047.

[50] Q. Hao, "A Review of Low Temperature Combustion Mode of

Engine", Trends in Renewable Energy, vol. 9, no. 2, pp. 180–191, Jul. 2023, doi: 10.17737/tre.2023.9.2.00160.

[51] H. Huang, J. Tian, J. Li, dan D. Tan, "Effects of Different Exhaust Gas Recirculation (EGR) Rates on Combustion and Emission Characteristics of Biodiesel–Diesel Blended Fuel Based on an Improved Chemical Mechanism," Energies, vol. 15, no. 11, Art. no. 4153, Nov. 2022, doi: 10.3390/en15114153.

[52] S. M. Ashrafur Rahman, I. M. Rizwanul Fattah, H. C. Ong, dan M. F. M.-A. Zamri, "State-of-the-Art of Strategies to Reduce Exhaust Emissions from Diesel Engine Vehicles," Energies, vol. 14, no. 6, Art. no. 1766, Mar. 2021, doi: 10.3390/en14061766.