Journal of Science and Engineering Applications Vol. 08, No. 1, pp. xx–xx, june 2026

Journal of Science and Engineering Applications

Contents are available at https://jsea.iujournals.com

A Review of Variable Compression Ratio Diesel Engines: Performance, Emissions, and Renewable Fuels

Karrar S. Hasan[1*], Hyder H. Balla [2]

[1] *Department of Mechanical Engineering, Al-Najaf Technical College, Al-Furat Al-Awsat Technical University, 54001, Iraq.*
[2] *Al- Najaf Technical Institute, Al-Furat Al-Awsat Technical University, 54001, Iraq*

ARTICLE INFORMATION

Received date: 17-04- 2026
Revised date: 31-05- 2026
Accepted date: 02-06- 2026

Keywords

Variable compression ratio (VCR)
Diesel engines
Biodiesel blends
Combustion characteristics
Emission characteristics
Renewable fuels.

ABSTRACT

Variable compression ratio (VCR) technology has received considerable attention as an effective approach to improving diesel engine efficiency, combustion characteristics, and exhaust emissions under different operating conditions. This review critically examines the effect of compression ratio variation on the performance and emission characteristics of diesel engines fuelled with biodiesel, renewable fuel blends, and alternative fuels. Different VCR implementation methods are comparatively analyzed based on combustion chamber integrity, mechanical complexity, control accuracy, and operational flexibility. In addition, recent experimental investigations conducted under various compression ratios and fuel compositions are systematically reviewed and discussed. The findings indicate that increasing the compression ratio generally improves brake thermal efficiency and combustion quality while reducing carbon monoxide (CO) and hydrocarbon (HC) emissions. However, excessively high compression ratios may increase nitrogen oxide (NOx) emissions because of elevated in-cylinder temperatures. The review further highlights the strong potential of integrating VCR technology with renewable fuels to achieve cleaner combustion and enhanced engine sustainability. Overall, the study provides a comprehensive technical assessment of VCR diesel engines and identifies promising directions for future low-emission and high-efficiency engine development.

1. Introduction

During the Industrial Revolution, significant scientific and technological advances occurred in many areas, including combustion-related applications important to power generation and transportation. Fuel's chemical energy is transformed into thermal energy and mechanical work. This principle forms the basis of external combustion systems, internal combustion engines, and boilers [1][2]. In response to growing concerns regarding global warming, countries have introduced strict regulations to improve energy efficiency, reduce emissions from various fossil fuels, and maintain a clean environment [3][4]. Switching to renewable and sustainable alternatives is crucial to mitigate potential shortages of fossil fuels, the current primary energy source. Therefore, considerable research effort has been devoted to developing sustainable fuels and cleaner combustion technologies [5][6][7]. There are two types of internal combustion engines: spark-ignition and compression-ignition (diesel) engines. Although the diesel engine can have a high thermal efficiency and torque, it generates pollutants such as NOx and PM [8]. The VCR technology allows the

* Corresponding authors: Department of Mechanical Engineering, Al-Najaf Technical College, Al-Furat Al-Awsat Technical University, Iraq
E-mail addresses: eng.karrarsalah.ask@gmail.com (Karrar S. Hasan)

compression ratio to be dynamically adjusted to enhance the combustion efficiency and reduce emissions under different operating conditions [9]. The idea of compression ignition, an alternative to the widely used steam engines of the time, was conceived by the inventor and engineer Rudolf Diesel in 1892 [10]. He presented his concept of using heat in internal combustion in a lecture on 16 June 1897, attended by a large number of scientists and academicians. It is known that diesel engines have high efficiency and durability, especially in heavy-duty transport and marine applications [11][12]. Diesel engines offer several benefits over spark-ignition engines, including the ability to achieve high compression ratios, which promote self-ignition of the fuel and increase efficiency. The high compression ratios (14:1–22:1) of diesel engines enable self-ignition of the fuel.

Under low-load conditions, a higher compression ratio improves fuel economy, whereas a lower compression ratio under high-load conditions reduces knocking tendency and NOx emissions [9][13]. Diesel engines are supported by advanced technologies such as EGR, SCR, and turbochargers [14][15]. The transition in combustion and flame stability properties in thermal and engine systems has been achieved through the use of alternative fuels (biodiesel, synthetic fuels, hydrogen, etc.) [16]. Alternative fuels enhance combustion and reduce carbon emissions [17][16]. Extensive research has been conducted to improve combustion technologies such as reactivity-controlled compression ignition (RCCI) and homogeneous compression ignition (HCCI) to achieve cleaner, lower-emission combustion [18][19]. These technologies are designed to reduce emissions by improving fuel/air mixing and lowering combustion temperatures. Although numerous studies have been conducted on VCR diesel engines and alternative fuels, there are very few review studies that have extensively explored the synergistic effects of LPG–diesel dual-fuel operation and hybrid nanoparticle additives under variable-compression-ratio operating conditions. The novelty of this manuscript lies in the extensive overview of the Variable Compression Ratio (VCR) technology and the unique combination of liquefied petroleum gas (LPG), diesel, and hybrid nanoparticles. This unique solution not only improves engine performance and reduces pollutant emissions but also provides a viable, scalable approach to meeting stringent environmental standards. This manuscript explores the synergistic integration of alternative fuels and advanced nanotechnology to improve diesel engine efficiency beyond the scope of previous review studies.

2. Variable Compression Ratios (VCR) in Diesel Engines

2.1 Concept and Mechanics of VCR

In diesel engines, variable compression ratio (VCR) technology dynamically adjusts the compression ratio in response to operating conditions. VCR technology addresses this difficulty by allowing the engine to adjust its compression ratio in real-time. An elevated compression ratio at minimal loads enhances fuel economy by improving combustion. A low compression ratio reduces the likelihood of knocking and allows the engine to produce more power under stress [9]. Comparative studies indicate that fuel efficiency can be increased by 10–15% with VCR technology under light-load conditions; higher compression ratios are most effective under these conditions. Besides, VCR engines can reduce their compression ratio in high-load situations to reduce knocking, combustion noise, and power output. Variable-compression-ratio systems can achieve this adaptability mechanically by altering the combustion chamber shape or modulating the piston stroke length. A prevalent technique entails adjusting the cylinder head clearance dimensions using hydraulic or mechanical actuators [20]. Many mechanical schemes have been suggested for implementing VCR systems, each offering specific advantages in terms of combustion chamber integrity, control accuracy, and mechanical complexity.

Figure 1 presents an author-developed classification and comparative illustration of the major VCR implementation mechanisms based on the reported literature [21][22][23][24]. VCR systems adjust the compression ratio mechanically or hydraulically to optimize combustion behavior under varying operating conditions.

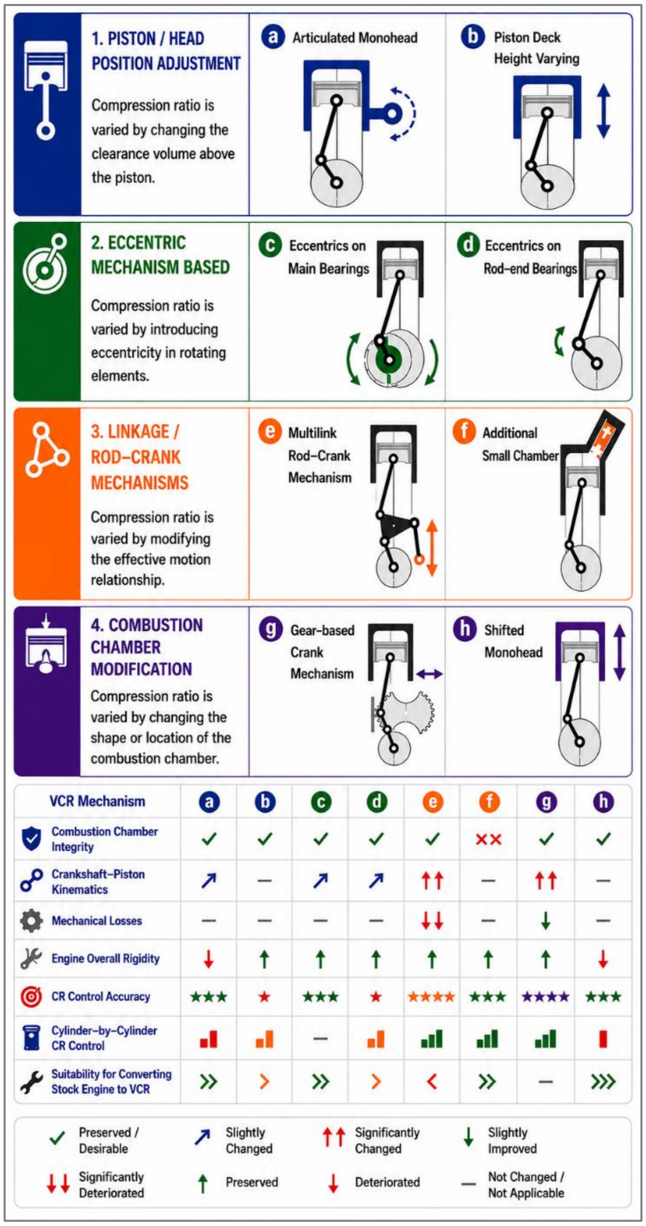

Figure 1. Classification and comparative features of major VCR implementation mechanisms developed based on the reported literature

Among the reported VCR mechanisms, eccentric-based and multilink systems demonstrated superior accuracy in controlling compression ratio. In contrast, piston deck height variation methods offered lower mechanical complexity and easier implementation in conventional diesel engines.

2.2 Advantages and Obstacles of Implementing VCR in Diesel Engines

The primary advantage of VCR technology in diesel engines is its ability to reduce emissions and fuel consumption across a range of operating conditions. Higher compression ratios improve fuel efficiency at low loads. Lower compression ratios at high load help reduce NOx emissions and combustion pressure [25]. Recent studies on hydrogen combustion also revealed a substantial trade-off between thermal efficiency and maximum engine load across various compression ratios. The indicated thermal efficiency increased by about 5.2% when the compression ratio was increased from 9.27 to 12.39. Still, the higher compression ratio was unable to achieve high peak-load operation due to higher maximum cylinder pressure limits [26]. This adaptability could significantly improve fuel efficiency and emissions management, enabling diesel engines to comply with more stringent environmental standards without compromising performance [13][27]. However, implementing VCR in diesel engines poses several technical challenges. Despite its advantages, VCR implementation increases system complexity and control requirements. Various methods have been proposed for VCR implementation, including piston modification, cylinder head adjustment, and eccentric crank mechanisms [28][29][30][31].

Table 1 summarises recent studies on the performance and emissions of VCR diesel engines operating under different fuel blends and conditions.

Table 1. Summary of Recent Studies on VCR Diesel Engines

Author	Fuel / Additive	Compression Ratio Range	Key Findings
Aravind et al.[32]	Hydrogen-Diesel/Algae blend	16.5 – 19.5	CR 18.5 improved efficiency and reduced emissions
Hou et al .[33]	Diesel	Optimised	Improved combustion and reduced NOx
Deb et al. [34]	Hydrogen-Biodiesel RCCI	Variable	Advanced injection improved combustion
Domínuez et al. [35]	Diesel-Hydrogen-Methanol	15.84 – 18.04	Higher CR improved thermal efficiency
Ramesh et al.[36]	Biodiesel blends	16 – 19	Higher CR increased BTE and reduced CO/HC
Yanhui Chen et al.[37]	Biodiesel blends	Variable	Higher CR reduces soot emissions

Yeneneh et al.[38]	Nano biodiesel blends	Various	Nano additives enhanced combustion

3. Performance Evaluation of VCR Diesel Engines

3.1 Comparative Analysis of Fixed and Variable Compression Ratios

Fixed compression ratio (FCR) engines are structurally simple and operate reliably, but are not very efficient when used at different operating conditions of the engine due to the fact that the compression ratio cannot vary with the load and operating speed. Variable compression ratio (VCR) engines, on the other hand, adjust the compression ratio dynamically to better control the combustion process over a wider range of operation [39]. Comparative tests have demonstrated that the fuel consumption of VCR technology can be reduced by about 10–15% under light load conditions, and under these conditions the higher the compression ratio the better the combustion and the higher the thermal efficiency. However, for high loads, decreasing the compression ratio will reduce the tendency to knock, lower combustion noise, and enhance engine durability [40]. In addition, at high load the compression ratio is reduced which also reduces in-cylinder peak temperature and thus emissions of nitrogen oxides (NOx) and particulate matter (PM). The above benefits confirm that VCR technology has great potential to provide an effective balance between engine performance, fuel economy and emission reduction in various operating conditions. Venkateswara Raoet al.[41] found that brake thermal efficiency (BTE) increased with the elevation of compression ratio for all fuels under all load conditions. The braking thermal efficiency (BTE) of blended fuel consistently lagged behind that of diesel due to biodiesel's lower calorific value. The increase in BTE was observed with a rise in compression ratio due to improved biodiesel mixing at higher temperatures, leading to complete fuel combustion.

3.2 Brake Thermal Efficiency (BTE)

BTE measures how efficiently an engine converts fuel energy into work. The engine's braking power output-to-fuel-input energy ratio is expressed as a percentage. Engine performance and fuel consumption depend on efficiency. Diesel pilot-ignited natural gas engines with exhaust gas recirculation (EGR) have been shown to improve emissions and brake thermal efficiency (BTE) [42][43][44]. Moreover, many studies have shown that intake throttling can enhance brake thermal efficiency (BTE) while decreasing THC and CO emissions [44][45][46]. Most studies reported that increasing the compression ratio improves brake thermal efficiency by enhancing air-fuel mixing, increasing in-cylinder temperature, and promoting more complete combustion. Silambarasan et al.[47] found that the BTE increased significantly with increasing compression ratio. At maximum load with the CR-19.5, the brake thermal efficiency (BTE) for A20 was 31.67%, practically identical to pure diesel fuel (30.47%). However, excessively low compression ratios reduce combustion quality and thermal efficiency. Similarly, Patel and Patel [48] reported that brake thermal efficiency increased by approximately 16% when using a neem biodiesel blend (NB30) at a compression ratio of 22:1 under moderate engine load conditions. The improvement was mainly attributed to enhanced combustion efficiency and improved fuel oxidation at higher compression ratios. Venkateswara Raoet al. [41] found that brake thermal efficiency (BTE) increased with the elevation of compression ratio for all fuels under all load conditions. The braking thermal efficiency (BTE) of blended fuel continuously lagged behind that of diesel due to the lower calorific value of biodiesel. The increase in BTE was observed with a rise in compression ratio due to improved biodiesel mixing at higher temperatures, leading to complete fuel combustion.

3.3 Brake-Specific Fuel Consumption (BSFC)

BSFC assesses an engine's fuel efficiency by linking fuel consumption to mechanical power output [45]. BSFC is commonly expressed in g/kWh. It is generally expressed as fuel consumption per unit of generated electricity. Brake-specific fuel consumption (BSFC) is an essential parameter for evaluating engine performance and efficiency, particularly in the automotive and aerospace industries. It helps engineers and designers evaluate the efficiency of an engine's conversion of fuel into useful work. It is important to compare different engines and identify opportunities for improvement and optimization.

Since BSFC is a critical parameter that reflects the efficiency of a combustion engine, it is essential to analyze adjustments to improve it regularly. As a result, engine efficiency will improve. Load, compression ratio, injection pressure, and fuel quality affect the brake-specific fuel consumption of a variable-compression-ratio diesel engine. Research suggests that a higher proportion of biodiesel in diesel blends is associated with increased fuel consumption. B80, marked by insufficient atomization, is the origin of this effect in all situations [49][50]. Certain academics propose addressing this difficulty by increasing the compression ratio, optimizing the load at maximum capacity, and increasing the injection pressure. The shortened ignition delay of biodiesel increases in-cylinder temperature during high compression ratio and full-load operation [51][52]. Increasing the compression ratio generally reduces BSFC by improving combustion efficiency and reducing ignition delay. The results of Ganesh S. Warkhade et al. [53] are summarized in CR 14-18. The BSFC for LB100 increases by the largest percentages at CR 14–18 and full load: 17.6%, 14.7%, and 8.8%, respectively, compared to the standard fuel PD. The improvement in LB10's brake-specific fuel consumption (BSFC) has been measured at 3-12%, while Jindal S and Salvi BL say 4-6% [54]. Lower compression ratios increase fuel consumption due to incomplete combustion and lower cylinder temperature.

3.4 Exhaust Gas Temperature (EGT)

Exhaust gas temperature (EGT) in diesel engines is crucial for optimizing engine performance and regulating emissions. Monitoring and regulating EGT emissions is essential for achieving optimal efficiency and complying with environmental regulations. Increased exhaust gas temperatures (EGT) can be advantageous for certain processes, including after-treatment systems that employ diesel particulate filters (DPF) and selective catalytic reduction (SCR) systems [15][55]. These systems necessitate a defined thermal threshold to purify and process exhaust gases, significantly diminishing harmful emissions. Excessively high exhaust temperatures can lead to overheating, potentially causing engine damage or reduced component lifespan.

Furthermore, EGT influences the engine's energy balance, thereby affecting the energy available for waste heat recovery systems, thereby improving overall engine efficiency [15]. Therefore, additional studies should focus on developing and improving exhaust systems to effectively regulate EGT. This will be essential for enhancing diesel engine performance, emissions, and thermal management. Exhaust gas temperature is strongly affected by compression ratio and fuel type. Higher compression ratios may improve combustion and reduce EGT by shortening combustion duration and improving fuel atomization.

3.5 Additional Performance Characteristics

Additional engine performance parameters, such as volumetric efficiency, mechanical efficiency, and brake power, are also affected by compression ratio and fuel characteristics. In general, increasing the compression ratio improves combustion stability and power output by enhancing fuel-air mixing and increasing in-cylinder temperature. However, excessively high compression ratios may increase residual gas effects and mechanical losses, slightly reducing volumetric efficiency under certain operating conditions [56][57]. No significant difference between diesel fuel and biodiesel blends in terms of volumetric efficiency was observed by Eknath et al. [58] at a compression ratios of 16 and 18, with variations within 1%. In the same manner, Venkateswara Rao et al. [41] reported that the reduction in the volumetric efficiency of blended fuels was about 0.9% lower than that of diesel under full load operation. The reduction was about 3.1%, with the increase in compression ratio from 14:1 to 20:1, due to a higher residual gas fraction in the clearance volume. Other factors that affect mechanical efficiency include compression ratio, engine loading, and fuel characteristics. Navaneetha Krishnan et al. [92] noted that the mechanical efficiency of the biodiesel blends increased with engine load, and at full load, the mechanical efficiency for the B40 and B10 blends was 93.77% and 87.62%, respectively. The higher the engine load and the better the combustion quality, the greater the brake power; however, if the biodiesel concentration is too high, brake power may decrease slightly due to the higher viscosity of diesel and the lower calorific value of biodiesel.

4. Combustion Characteristics

Combustion characteristics in VCR diesel engines are strongly influenced by compression ratio and fuel properties. Increasing the compression ratio generally increases in-cylinder pressure and heat release rate due to improved fuel atomization, enhanced air–fuel mixing, and higher in-cylinder temperature [56][59]. In a recent study by John et al. [59], it was shown that a higher compression ratio (16:1 to 19:1) in a hemp biodiesel-fuelled diesel engine has a significant impact on combustion behavior and thermal efficiency. At CR 19:1, the brake thermal efficiency for the HB30 blend was 29.47%, while the combustion duration and heat release rate were found to be lower than those at lower CRs. Higher compression ratios also reduce ignition delay due to elevated pressure and temperature inside the combustion chamber, leading to improved combustion efficiency and faster heat release [60][61]. An elevated compression ratio (CR) increases the chamber air intake temperature, facilitating premature combustion and reducing the ignition delay interval [60].

In contrast, lower compression ratios increase ignition delay and combustion duration because of slower fuel evaporation, incomplete combustion, and lower combustion temperatures. However, excessively high compression ratios may increase thermal stresses and lead to abnormal combustion behavior under certain operating conditions [62][63].

5. Emission Characteristics

Emission characteristics in VCR diesel engines are significantly influenced by compression ratio, combustion temperature, and fuel composition. In general, increasing the compression ratio improves combustion efficiency, leading to reductions in carbon monoxide (CO), hydrocarbons (HC), particulate matter (PM), and smoke emissions because of more complete combustion and improved air–fuel mixing [31][60]. In recent years, experimental work on sustainable biodiesel mixtures also showed that the compression ratio was the most important parameter for improving combustion quality and reducing fuel emissions, increasing it from 15 to 18. The R30D mix resulted in about 9.54% improved brake thermal efficiency at CR 18. At the same time, CO, HC, and soot emissions were significantly lower than in the lower-CR cases and in conventional diesel fuel. In general, the emissions of NOx increased at high engine loads, but due to the better combustion properties and oxygenated fuel behaviour the higher biodiesel content and CR 18 slightly decreased the formation of NOx [64]. Table 2 summarises recent emission-related studies on VCR diesel engines operating with different renewable and dual-fuel blends under various compression ratio conditions.

Table 2. Emission Characteristics of VCR Diesel Engines under Different Fuel Blends

Author(s)	Fuel Blend / Additive	Compression Ratio (CR)	Main Emission Findings	Key Outcome
Khan et al. [65]	Quaternary blends (diesel–biodiesel–alcohols)	Variable	Smoke ↓92.85%, CO_2 ↓27.9%, NOx ↓7.36%	Injection pressure and alcohol blending improved combustion
Vijayakumar et al. [66]	Mahua biodiesel blends	17–18	Lower emissions with higher CR	B20 at CR 18 showed optimum performance
Yeneneh et al. [67]	Biodiesel–ethanol ternary blends	18:1	Reduced CO, HC, and BSFC	Improved combustion and thermal efficiency
Akhtar et al. [68]	Hydrogen–diesel dual fuel	Variable	Lower NOx emissions at low engine speed	Brake power and torque improved by 17% and 16.5%, respectively
John et al. [69]	Hemp biodiesel blends (HB10–HB50)	16–19	Reduced CO, HC, and smoke emissions	HB30 at CR 19 achieved superior combustion behavior
Vasudeva et al. [70]	Rice bran biodiesel blends	15–18	Higher CR reduced CO and HC emissions	Cylinder pressure and combustion efficiency increased
Mahmood et al. [71]	Biodiesel blends	15.5–18.5	Higher CR increased NO formation and CO_2 emissions	Improved combustion efficiency at CR 18.5

Compression ratio optimization is a key factor in minimizing incompletely combusted emissions while maintaining good combustion quality under renewable and dual-fuel operating conditions, as shown in the comparative results in Table 2. At higher compression ratios, low emissions of CO, HC, smoke, and particulate matter are evident, but NOx emissions remain a significant problem due to higher combustion temperatures. Although it is clear that CO, HC, smoke, and particulate emissions have decreased, NOx emissions remain significant at higher compression ratios due to higher combustion temperatures. Higher compression ratios also enhance oxidation reactions and shorten ignition delay, which further reduces incomplete combustion products [72]. However, elevated compression ratios generally increase nitrogen oxide (NOx) emissions due to higher in-cylinder temperatures and peak combustion pressures [72][73]. Conversely, lower compression ratios reduce NOx formation by lowering combustion temperature, though they may increase CO, HC, and smoke emissions due to incomplete combustion [74][75]. The use of biodiesel, dual-fuel operation, and nanoparticle additives in VCR engines has shown considerable potential to improve emissions and support cleaner combustion across varying operating conditions [76][77].

6. Conclusion

Variable compression ratio (VCR) technology has proven to be a promising approach for improving performance, combustion, and exhaust emission characteristics of a diesel engine under different operating conditions. The reviewed studies indicate that increasing the compression ratio generally improves brake thermal efficiency, particularly as combustion quality improves due to better air-fuel mixing and higher in-cylinder pressure and temperature. Furthermore, it has been widely reported that blends of renewable fuels and biodiesel significantly reduced CO, HC, and smoke emissions when operated at optimized compression ratios. However, excessively high compression ratios can lead to higher nitrogen oxides (NOx) emissions due to higher combustion temperatures and increased thermal NOx formation.

The comparative analysis also showed that VCR technology efficiency depends heavily on the chosen implementation mechanism, fuel type, engine configuration, and operating conditions. Renewable-fuel-based VCR engines have the potential to achieve cleaner combustion and improve sustainability without significant engine modifications. In addition, combining advanced combustion methods, emission control technologies, and optimization techniques can improve the engine's overall performance and environmental compatibility.

Overall, VCR diesel engines represent a promising pathway for developing high-efficiency, low-emission IC engines. Intelligent control strategies, AI-driven optimization, hybrid renewable fuel applications, and long-term durability testing under real operating conditions should be the focus of future work.

Nomenclature

VCR	Variable compression ratio
BTE	Brake thermal efficiency
BSFC	Brake-specific fuel consumption
EGT	Exhaust gas temperature
CO	Carbon monoxide
HC	Hydrocarbons
NOx	Oxides of nitrogen
PM	Particulate matter
RCCI	Reactivity-controlled compression ignition
EGR	Exhaust gas recirculation
CR	Compression ratio
CI	Compression ignition
DI	Direct injection
HRR	Heat release rate
ID	Ignition delay
LPG	Liquefied petroleum gas
B20	20% biodiesel blend with diesel fuel

Reference

[1] K. S. Hasan, "Experimental Study on the Combustion of Gaseous Based Fuel (LPG) in a Tangential Swirl Burner of a Steam Boiler," Journal of Thermal Engineering, vol. 10, no. 5, pp. 1226–1240, 2024, doi: 10.14744/thermal.0000863.

[2] K. S. Hasan, "Study Operation of Steam Generation System Using Different Fuels," M.Sc. thesis, Al-Furat Al-Awsat Technical University, Al-Najaf, Iraq, 2020.

[3] A. A. Al-Jabiri, H. H. Balla, and M. S. Al-Zuhairy, "Using Renewable Alternative Fuels and Studying Their Impact on the Performance and Emissions of Compression Ignition Engines," Heat Transfer, vol. 53, no. 4, pp. 1975–1988, 2024.

[4] G. Xu et al., "Advances in Emission Control of Diesel Vehicles in China," Journal of Environmental Sciences, vol. 123, pp. 15–29, 2023.

[5] S. H. Hosseini, A. Taghizadeh-Alisaraei, B. Ghobadian, and A. Abbaszadeh-Mayvan, "Performance and Emission Characteristics of a CI Engine Fuelled with Carbon Nanotubes and Diesel-Biodiesel Blends," Renewable Energy, vol. 111, pp. 201–213, 2017.

[6] R. Karami, M. Hoseinpour, M. G. Rasul, N. M. S. Hassan, and M. M. K. Khan, "Exergy, Energy, and Emissions Analyses of Binary and Ternary Blends of Seed Waste Biodiesel of Tomato, Papaya, and Apricot in a Diesel Engine," Energy Conversion and Management: X, vol. 16, p. 100288, 2022.

[7] N. Ali and D. F. Maki, "Combustion Characteristics of CI Engine Fueled with WCO Biodiesel/Diesel Blends at Different Compression Ratios and EGR," Heat Transfer, vol. 52, no. 6, pp. 3953–3966, 2023.

[8] J. E et al., "Effect of Different Technologies on Combustion and Emissions of the Diesel Engine Fueled with Biodiesel: A Review," Renewable and Sustainable Energy Reviews, vol. 80, pp. 620–647, 2017, doi: 10.1016/j.rser.2017.05.250.

[9] P. Woś, K. Balawender, M. Jakubowski, A. Jaworski, P. Szymczuk, and A. Ustrzycki, "Application of Variable Compression Ratio (VCR) Technology in Heavy-Duty Diesel Engine," Numerical and Experimental Studies on Combustion Engines and Vehicles, pp. 1–17, 2020, doi: 10.5772/intechopen.93572.

[10] R. D. Reitz, "Directions in Internal Combustion Engine Research," Combustion and Flame, vol. 160, no. 1, pp. 1–8, 2013, doi: 10.1016/j.combustflame.2012.11.002.

[11] A. M. L. M. Wagemakers and C. A. J. Leermakers, "Review on the Effects of Dual-Fuel Operation, Using Diesel and Gaseous Fuels, on Emissions and Performance," SAE Technical Paper, 2012, doi: 10.4271/2012-01-0869.

[12] R. Stone, Introduction to Internal Combustion Engines. New York, NY, USA: Springer, 1999.

[13] M. Diezemann, C. Schramm, M. Brauer, and C. Severin, "Variable Compression Ratio in Diesel Engines," MTZ Worldwide, vol. 76, no. 7, pp. 26–31, 2015.

[14] R. D. Reitz et al., "IJER Editorial: The Future of the Internal Combustion Engine," International Journal of Engine Research, vol. 21, no. 1, pp. 3–10, 2020, doi: 10.1177/1468087419877990.

[15] F. Martinovic, L. Castoldi, and F. A. Deorsola, "Aftertreatment Technologies for Diesel Engines: An Overview of the Combined Systems," Catalysts, vol. 11, no. 6, p. 653, 2021.

[16] I. Sezer, "A Review Study on the Using of Diethyl Ether in Diesel Engines: Effects on Fuel Properties and Engine Performance," Energy Technology, vol. 6, no. 11, pp. 2084–2114, 2018.

[17] K. S. Hasan, W. A. Abd Al-Wahid, and H. H. S. Khwayyir, "Flashback and Combustion Stability in Swirl Burners," in IOP Conference Series: Materials Science and Engineering, IOP Publishing, 2020, p. 022045.

[18] X. Duan, M. C. Lai, M. Jansons, G. Guo, and J. Liu, "A Review of Controlling Strategies of the Ignition Timing and Combustion Phase in Homogeneous Charge Compression Ignition (HCCI) Engine," Fuel, vol. 285, 2021, doi: 10.1016/j.fuel.2020.119142.

[19] Z. Jia and I. Denbratt, "Experimental Investigation into the Combustion Characteristics of a Methanol-Diesel Heavy-Duty Engine Operated in RCCI Mode," Fuel, vol. 226, pp. 745–753, 2018, doi: 10.1016/j.fuel.2018.03.088.

[20] L. Eriksson and L. Nielsen, Modeling and Control of Engines and Drivelines. Hoboken, NJ, USA: John Wiley & Sons, 2014.

[21] J. Hirkude and A. S. Padalkar, "Experimental Investigation of the Effect of Compression Ratio on Performance and Emissions of CI Engine Operated with Waste Fried Oil Methyl Ester Blend," Fuel Processing Technology, vol. 128, pp. 367–375, 2014, doi: 10.1016/j.fuproc.2014.07.026.

[22] A. Boretti and J. Scalzo, "Exploring the Advantages of Variable Compression Ratio in Internal Combustion Engines by Using Engine Performance Simulations," SAE World Congress and Exhibition, 2011, doi: 10.4271/2011-01-0364.

[23] V. Hariram and R. Vagesh Shangar, "Influence of Compression Ratio on Combustion and Performance Characteristics of Direct Injection Compression Ignition Engine," Alexandria Engineering Journal, vol. 54, no. 4, pp. 807–814, 2015, doi: 10.1016/j.aej.2015.06.007.

[24] P. Woś, K. Balawender, M. Jakubowski, H. Kuszewski, K. Lejda, and A. Ustrzycki, "Design of Affordable Multi-Cylinder Variable Compression Ratio (VCR) Engine for Advanced Combustion Research Purposes," SAE Technical Paper, 2012.

[25] K. Subramani and M. Karuppusamy, "Performance, Combustion and Emission Characteristics of Variable Compression Ratio Engine Using Waste Cooking Oil Biodiesel with Added Nanoparticles and Diesel Blends," Environmental Science and Pollution Research, vol. 28, no. 45, pp. 63706–63722, 2021, doi: 10.1007/s11356-021-14768-8.

[26] M. Mohamed, Y. Feng, and X. Wang, "Investigating the Impact of Compression Ratio on Hydrogen Combustion and Emission: An Experimental Analysis," International Journal of Engine Research, vol. 27, no. 1, pp. 19–40, 2026, doi: 10.1177/14680874251341641.

[27] A. I. El-Seesy, A. K. Abdel-Rahman, M. Bady, and S. Ookawara, "Performance, Combustion, and Emission Characteristics of a Diesel Engine Fueled by Biodiesel-Diesel Mixtures with Multi-Walled Carbon Nanotubes Additives," Energy Conversion and Management, vol.

135, pp. 373–393, 2017, doi: 10.1016/j.enconman.2016.12.090.
[28] A. Sharma and S. Murugan, "Potential for Using a Tyre Pyrolysis Oil-Biodiesel Blend in a Diesel Engine at Different Compression Ratios," Energy Conversion and Management, vol. 93, pp. 289–297, 2015, doi: 10.1016/j.enconman.2015.01.023.
[29] O. A. Towoju, "Performance Optimization of Compression Ignition Engines: A Review," Engineering Perspectives, vol. 2, no. 2, pp. 21–27, 2022.
[30] C. Kumar, K. B. Rana, and B. Tripathi, "Effect of Diesel-Methanol-Nitromethane Blends Combustion on VCR Stationary CI Engine Performance and Exhaust Emissions," Environmental Science and Pollution Research, vol. 26, no. 7, pp. 6517–6531, 2019, doi: 10.1007/s11356-018-04058-1.
[31] T. Y. Kim, S. Lee, and K. Kang, "Performance and Emission Characteristics of a High-Compression-Ratio Diesel Engine Fueled with Wood Pyrolysis Oil-Butanol Blended Fuels," Energy, vol. 93, pp. 2241–2250, 2015, doi: 10.1016/j.energy.2015.10.119.
[32] S. Aravind, D. Barik, S. Praveenkumar, K. Tudu, and R. N. Dara, "Influence of Compression Ratio Variations on Hydrogen Combustion Dynamics in a Tri-Fuel Agricultural Diesel Engine Operating with Diesel, Algae Spirogyra Methyl Ester, and Di-tert-butyl Peroxide," International Journal of Hydrogen Energy, vol. 143, pp. 429–440, 2025, doi: 10.1016/j.ijhydene.2025.01.113.
[33] Y. Hou, J. Wang, J. Lei, and L. Chen, "Optimization Design of Combustion Chamber for a Non-Road Diesel Engine in High-Altitude Region," Case Studies in Thermal Engineering, vol. 68, p. 105943, 2025, doi: 10.1016/j.csite.2025.105943.
[34] P. Deb, D. Singh, M. Kumar, and A. Paul, "Effect of High Reactive Fuel Injection Advancement and Hydrogen-Biodiesel Premix Ratio on Combustion, Performance and Emission of a CI Engine under RCCI Mode," Fuel, vol. 382, p. 133710, 2025, doi: 10.1016/j.fuel.2024.133710.
[35] V. M. Domínguez, J. J. Hernández, Á. Ramos, and J. Rodríguez-Fernández, "Role of the Compression Ratio in Dual-Fuel Compression Ignition Combustion with Hydrogen and Methanol," Energy and Fuels, vol. 38, no. 19, pp. 19127–19136, 2024, doi: 10.1021/acs.energyfuels.4c02741.
[36] T. Ramesh, A. P. Sathiyagnanam, M. V. De Poures, and P. Murugan, "Combined Effect of Compression Ratio and Fuel Injection Pressure on CI Engine Equipped with CRDi System Using Prosopis juliflora Methyl Ester/Diesel Blends," International Journal of Chemical Engineering, vol. 2022, 2022, doi: 10.1155/2022/4617664.
[37] Y. Chen, J. Zhang, Z. Zhang, W. Zhong, Z. Zhao, and J. Hu, "Utilization of Renewable Biodiesel Blends with Different Proportions for the Improvements of Performance and Emission Characteristics of a Diesel Engine," Heliyon, vol. 9, no. 9, p. e19196, 2023, doi: 10.1016/j.heliyon.2023.e19196.
[38] K. Yeneneh and G. Sufe, "Enhancing Diesel Engine Performance and Emissions Using Alumina Nanoparticle-Blended Waste Plastic Oil Biodiesel: An Experimental and Predictive Approach," Industrial and Engineering Chemistry Research, vol. 64, no. 24, pp. 11681–11694, 2025, doi: 10.1021/acs.iecr.5c01296.
[39] J. B. Heywood, Internal Combustion Engine Fundamentals, 2nd ed. New York, NY, USA: McGraw-Hill Education, 2018.
[40] T. P. Muliyah, D. Aminatun, S. S. Nasution, T. Hastomo, and S. S. W. Sitepu, Diesel Engine Transient Operation Principles of Operation and Simulation Analysis, vol. 7, no. 2, 2020.
[41] V. R. P., "Compression Ratio Effect on Diesel Engine Working with Biodiesel-Diesel Blend as Fuel," vol. 5, no. 7, pp. 48–51, 2015.
[42] W. Li et al., "Investigations on Combustion System Optimization of a Heavy-Duty Natural Gas Engine," Fuel, vol. 331, p. 125621, 2023.
[43] S. Dev, H. Guo, and B. Liko, "A Study on the High Load Operation of a Natural Gas-Diesel Dual-Fuel Engine," Frontiers in Mechanical Engineering, vol. 6, p. 545416, 2020.
[44] S. Dev, H. Guo, S. Lafrance, and B. Liko, "An Experimental Study on the Effect of Exhaust Gas Recirculation on a Natural Gas-Diesel Dual-Fuel Engine," SAE Technical Paper, 2020.
[45] S. Tripathy, A. K. Sarangi, V. K. Patel, and S. Sreedhara, "The Effects of Intake Throttling with Hot and Cold EGR in a CNG/Diesel Dual-Fuel Engine," in Internal Combustion Engine Division Fall Technical Conference, American Society of Mechanical Engineers, 2023, p. V001T02A001.
[46] X. Meng, H. Tian, Y. Zhou, J. Tian, W. Long, and M. Bi, "Comparative Study of Pilot Fuel Property and Intake Air Boost on Combustion and Performance in the CNG Dual-Fuel Engine," Fuel, vol. 256, p. 116003, 2019.
[47] R. Silambarasan, R. Senthil, G. Pranesh, P. M. Samuel, and M. Manimaran, "Effect of Compression Ratio on Performance and Emission Characteristics of Biodiesel Blend Operated with VCR Engine," Journal of Chemical and Pharmaceutical Sciences, vol. 7, pp. 23–25, 2015.
[48] H. A. Patel and B. P. Patel, "Investigation on Performance and Emission Studies of Variable Compression Ratio Engine Using Neem Oil Biodiesel," Journal of Thermal Engineering, vol. 11, no. 6, pp. 1827–1844, 2025.
[49] K. A. Abed, M. S. Gad, A. K. El Morsi, M. M. Sayed, and S. A. Elyazeed, "Effect of Biodiesel Fuels on Diesel Engine Emissions," Egyptian Journal of Petroleum, vol. 28, no. 2, pp. 183–188, 2019.
[50] S. Thapa, N. Indrawan, and P. R. Bhoi, "An Overview on Fuel Properties and Prospects of Jatropha Biodiesel as Fuel for Engines," Environmental Technology and Innovation, vol. 9, pp. 210–219, 2018.
[51] Z. Zhang et al., "Effects of Low-Level Water Addition on Spray, Combustion and Emission Characteristics of a Medium-Speed Diesel Engine Fueled with Biodiesel Fuel," Fuel, vol. 239, pp. 245–262, 2019.
[52] S. K. Mahla, T. Goyal, D. Goyal, H. Sharma, A. Dhir, and G. Goga, "Optimization of Engine Operating Variables on Performance and Emissions Characteristics of Biogas Fuelled CI Engine by the Design of Experiments: Taguchi Approach," Environmental Progress and Sustainable Energy, vol. 41, no. 2, p. e13736, 2022.
[53] G. S. Warkhade and A. V. Babu, "Experimental Investigations on the Feasibility of Higher Blends of

Biodiesel in Variable Compression Ratio Diesel Engine," International Journal of Ambient Energy, vol. 41, no. 14, pp. 1617–1627, 2020.
[54] S. Jindal and B. L. Salvi, "Sustainability Aspects and Optimization of Linseed Biodiesel Blends for Compression Ignition Engine," Journal of Renewable and Sustainable Energy, vol. 4, no. 4, 2012.
[55] R. Feng, X. Hu, G. Li, Z. Sun, and B. Deng, "A Comparative Investigation between Particle Oxidation Catalyst (POC) and Diesel Particulate Filter (DPF) Coupling Aftertreatment System on Emission Reduction of a Non-Road Diesel Engine," Ecotoxicology and Environmental Safety, vol. 238, p. 113576, 2022.
[56] A. Sharma and S. Murugan, "Potential for Using a Tyre Pyrolysis Oil-Biodiesel Blend in a Diesel Engine at Different Compression Ratios," Energy Conversion and Management, vol. 93, pp. 289–297, 2015.
[57] K. Karunamurthy, A. A. Janvekar, P. L. Palaniappan, V. Adhitya, T. T. K. Lokeswar, and J. Harish, "Prediction of IC Engine Performance and Emission Parameters Using Machine Learning: A Review," Journal of Thermal Analysis and Calorimetry, vol. 148, no. 9, pp. 3155–3177, 2023.
[58] R. D. Eknath and J. S. Ramchandra, "Effect of Compression Ratio on Energy and Emission of VCR Diesel Engine Fueled with Dual Blends of Biodiesel," Journal of Engineering Science and Technology, vol. 9, no. 5, pp. 620–640, 2014.
[59] M. El-Kassaby and M. A. Nemit-Allah, "Studying the Effect of Compression Ratio on an Engine Fueled with Waste Oil Produced Biodiesel/Diesel Fuel," Alexandria Engineering Journal, vol. 52, no. 1, pp. 1–11, 2013.
[60] M. Suresh, C. P. Jawahar, and A. Richard, "A Review on Biodiesel Production, Combustion, Performance, and Emission Characteristics of Non-Edible Oils in Variable Compression Ratio Diesel Engine Using Biodiesel and Its Blends," Renewable and Sustainable Energy Reviews, vol. 92, pp. 38–49, 2018, doi: 10.1016/j.rser.2018.04.048.
[61] J. Senthil Kumar, B. R. Ramesh Bapu, S. Sivasaravanan, M. Prabhu, S. Muthu Kumar, and M. A. Abubacker, "Experimental Studies on Emission Reduction in a DI Diesel Engine by Using a Nano Catalyst Coated Catalytic Converter," International Journal of Ambient Energy, vol. 43, no. 1, pp. 1241–1247, 2022, doi: 10.1080/01430750.2019.1694584.
[62] S. K. Nayak, S. K. Nayak, P. C. Mishra, and S. Tripathy, "Influence of Compression Ratio on Combustion Characteristics of a VCR Engine Using Calophyllum inophyllum Biodiesel and Diesel Blends," Journal of Mechanical Science and Technology, vol. 29, pp. 4047–4052, 2015.
[63] K. Muralidharan and D. Vasudevan, "Applications of Artificial Neural Networks in Prediction of Performance, Emission and Combustion Characteristics of Variable Compression Ratio Engine Fuelled with Waste Cooking Oil Biodiesel," Journal of the Brazilian Society of Mechanical Sciences and Engineering, vol. 37, pp. 915–928, 2015.
[64] M. A. Fayad et al., "Assessment of Engine Performance and Characteristics of Soot and NOx Emissions in the VCR Engine Fuelled with Different Sustainable Fuel Blends," Terra Joule Journal, vol. 2, no. 1, p. 2, 2026.
[65] M. M. Khan, S. M. M. Hasnain, A. K. Kadian, R. P. Sharma, M. Abbas, and S. Pandey, "Reduction of Fossil Fuel Usage and Emissions of Diesel Engines by the Application of Quaternary Blends and Varied Fuel Injection Pressures," ACS Omega, vol. 9, no. 24, pp. 26388–26399, 2024, doi: 10.1021/acsomega.4c02541.
[66] S. J. D. Vijayakumar, S. Paulisingarayar, A. Anbarasu, K. Vetrivelkumar, and R. Silambarasan, "Impact of Compression Ratio and Effect of Biodiesel Blends in Performance, Combustion and Emission Characteristics of VCR DI Diesel Engine," Materials Today: Proceedings, vol. 37, pp. 967–974, 2021, doi: 10.1016/j.matpr.2020.06.182.
[67] K. Yeneneh, E. Wakshume, and B. N. Fetene, "Effect of Intake Air Preheating on Performance and Emissions of a Diesel Engine Using Diesel-Biodiesel-Ethanol Blends," ACS Omega, vol. 10, no. 33, pp. 37445–37461, 2025, doi: 10.1021/acsomega.5c03395.
[68] M. U. S. Akhtar, F. Asfand, M. I. Khan, R. Mishra, and A. D. Ball, "Performance and Emissions Characteristics of Hydrogen-Diesel Dual-Fuel Combustion for Heavy-Duty Engines," International Journal of Hydrogen Energy, vol. 143, pp. 454–467, 2025, doi: 10.1016/j.ijhydene.2025.01.246.
[69] C. B. John, G. J. J., and S. Baskar, "A Comprehensive Evaluation of the Impact of Compression Ratio on Performance, Combustion, and Emissions of Hemp Biodiesel-Fueled Direct Injection Diesel Engine," Fuel, vol. 405, p. 136627, 2026, doi: 10.1016/j.fuel.2025.136627.
[70] M. Vasudeva, S. Sharma, S. K. Mohapatra, and K. Kundu, "Performance and Exhaust Emission Characteristics of Variable Compression Ratio Diesel Engine Fuelled with Esters of Crude Rice Bran Oil," SpringerPlus, vol. 5, pp. 1–13, 2016.
[71] H. A. Mahmood, A. O. Al-Sulttani, H. A. Alrazen, and O. H. Attia, "The Impact of Different Compression Ratios on Emissions and Combustion Characteristics of a Biodiesel Engine," AIMS Energy, vol. 12, no. 5, pp. 924–945, 2024, doi: 10.3934/energy.2024043.
[72] B. J. Bora and U. K. Saha, "Optimisation of Injection Timing and Compression Ratio of a Raw Biogas Powered Dual Fuel Diesel Engine," Applied Thermal Engineering, vol. 92, pp. 111–121, 2016.
[73] R. Minamino, T. Kawabe, H. Omote, and S. Okada, "The Effect of Compression Ratio on Low Soot Emission from Small Non-Road Diesel Engines," SAE Technical Paper, 2013.
[74] R. Senthil, R. Silambarasan, and N. Ravichandiran, "Influence of Injection Timing and Compression Ratio on Performance, Emission and Combustion Characteristics of Annona Methyl Ester Operated Diesel Engine," Alexandria Engineering Journal, vol. 54, no. 3, pp. 295–302, 2015.
[75] A. Parlak, H. Yasar, and B. Sahin, "Performance and Exhaust Emission Characteristics of a Lower Compression Ratio LHR Diesel Engine," Energy Conversion and Management, vol. 44, no. 1, pp. 163–175, 2003.
[76] A. Sudalaimani, B. Rajendran, T. Jothi, and M. Mariappan, "Combustion, Emission, and Performance Characteristics of Hybrid Biofuel at Different

Compression Ratios," Chemical Industry and Chemical Engineering Quarterly, vol. 30, no. 3, pp. 207–221, 2024.
[77] G. P. K. Yadav, P. Muvvala, and R. M. Reddy, "Study of Performance, Emission Characteristics, and Parametric Optimization of Compression Ignition Engine Using Biofuels: A Review," Biofuels, vol. 15, no. 9, pp. 1215–1232, 2024.