Energy Science & Engineering

ORIGINAL ARTICLE OPEN ACCESS

Investigation of Bamboo Biodiesel Performance in Variable Compression Ratio Engines

Renjith Krishnan[1] | Kavitha Mol S[2] | Prabhu Paramasivam[3] | Abinet Gosaye Ayanie[4]

[1]Mechanical Engineer - Piping, Nasser Saeed Al Hajri & Partners Contracting Company L.L.C, Abu Dhabi, UAE | [2]Department of Mechanical Engineering, Government Polytechnic College, Kollam, Kerala, India | [3]Department of Research and Innovation, Saveetha School of Engineering, SIMATS, Chennai, Tamil Nadu, India | [4]Department of Mechanical Engineering, Adama Science and Technology University, Adama, Ethiopia

Correspondence: Renjith Krishnan (renjithkrishnan67@gmail.com) | Abinet Gosaye Ayanie (abinet.gosaye@astu.edu.et)

Received: 13 June 2025 | **Revised:** 31 July 2025 | **Accepted:** 5 August 2025

Funding: The authors received no specific funding for this work.

Keywords: bamboo | biodiesel | combustion analysis | emission test | engine performance

ABSTRACT

This study investigates the potential of bamboo-derived biodiesel as a sustainable alternative to conventional diesel fuel in compression ignition (CI) engines. Biodiesel produced from *Bambusa vulgaris* was evaluated in blends designated BV5, BV10, BV15, BV20, and BV25. The biodiesel was obtained through fast pyrolysis followed by transesterification, using a custom-fabricated 10-liter spherical reactor for bio-oil extraction. Engine performance, combustion behavior, and emission characteristics were analyzed on a variable compression ratio (VCR) engine operating at compression ratios of 17.5:1 and 18:1 under a 5.2 kW load at 1500 rpm. Among all tested blends, BV15 demonstrated superior suitability for CI engine applications without requiring modifications, fully meeting ASTM biodiesel standards. BV15 exhibited desirable physicochemical properties, strong performance, efficient combustion, and significant emission reductions, including CO by up to 64%, CO_2 by up to 81%, HC by up to 61%, and smoke opacity by over 55%, compared to diesel. These results underscore the potential of bamboo-derived biodiesel to reduce the environmental footprint of fossil diesel, offering a renewable, cleaner-burning alternative that supports global sustainability goals.

1 | Introduction

Biodiesel has emerged as a promising alternative to conventional diesel fuel, delivering comparable power and torque without requiring modifications to compression ignition (CI) engines. Its biodegradability, higher flash point, and substantially reduced environmental impact make biodiesel an attractive renewable substitute for fossil diesel [1]. However, biodiesel faces notable performance challenges, particularly in cold weather, where wax crystal formation at low temperatures can clog fuel lines and filters, impeding fuel flow within the system [2].

These limitations have prompted extensive research into producing biodiesel from renewable and waste organic sources, alongside the development of biodiesel-additive blends to optimize performance and emissions profiles. Advancements in engine technology, fuel formulations, and blending strategies are essential to enhance fuel performance while maintaining sustainability [2]. Comparative evaluations indicate that at low engine loads, both diesel and biodiesel fuels exhibit higher brake specific fuel consumption (BSFC), which progressively decreases with increasing load. Diesel, however, consistently shows lower BSFC than biodiesels derived from feedstocks such as jatropha, coconut, and rapeseed under varying

Abbreviations: BP, brake power, W; BSFC, brake specific fuel consumption, kg/kW-hr; BTE, brake thermal efficiency, %; BV10, *Bambusa vulgaris* biodiesel 10% and diesel 90% by mass; BV15, *Bambusa vulgaris* biodiesel 15% and diesel 85% by mass; BV20, *Bambusa vulgaris* biodiesel 20% and diesel 80% by mass; BV25, *Bambusa vulgaris* biodiesel 25% and diesel 75% by mass; BV5, *Bambusa vulgaris* biodiesel 5% and diesel 95% by mass; BVD, pure biodiesel of *Bambusa vulgaris*; CA, crank angle; CI, compression ignition; CR, compression ratio(s); D, diesel; HHV, higher heating value, MJ/kg; UC, uncertainty, %; VCR, variable compression ratio.

This is an open access article under the terms of the Creative Commons Attribution License, which permits use, distribution and reproduction in any medium, provided the original work is properly cited.

© 2025 The Author(s). *Energy Science & Engineering* published by Society of Chemical Industry and John Wiley & Sons Ltd.

load conditions [3]. Additionally, brake thermal efficiency (BTE) tends to peak around 80% load for all fuels before declining with further increases in load, with diesel maintaining superior BTE performance compared to biodiesels [4].

Studies have further demonstrated that blending biodiesel with diesel can improve BTE while reducing BSFC, though challenges related to higher viscosity, higher pour points, lower volatility, and reduced energy content remain, potentially affecting long-term engine operation and durability. Raman et al. [5] reported that rapeseed oil biodiesel and its blends achieved BTE comparable to diesel while maintaining acceptable performance in a direct-injection diesel engine. Tamilselvan et al. [6], in a comprehensive review, noted that biodiesel generally exhibits higher BSFC than diesel due to its lower energy content, yet still delivers satisfactory performance in CI engines. Azad and Rasul [7] showed that diesel engines fueled with grape seed and waste cooking biodiesel blends maintained comparable performance to conventional diesel while significantly reducing carbon monoxide (CO) and unburned hydrocarbons (HC), though with a slight increase in nitrogen oxide (NOx) emissions. Narayana et al. [8] found that increasing the compression ratio in a variable compression ratio (VCR) diesel engine improved BTE and reduced BSFC, thereby enhancing overall performance. Roy et al. [9] demonstrated that emulsified dual blends of castor–jatropha biodiesel enhanced combustion efficiency and led to reductions in CO and HC emissions, while maintaining engine performance comparable to conventional diesel. Similarly, Kaner-derived biodiesel has shown promise for efficient combustion and emission reduction, particularly when tested at varying compression ratios in CI engines (Yadav et al., 2017) [10]. Ma et al. (2021) [11] reported that diesel/biodiesel/alcohol blends significantly improved emission characteristics by lowering CO and particulate matter (PM) emissions. Goga et al. (2019) [12] highlighted that blending n-butanol with rice bran biodiesel not only enhanced engine performance but also resulted in notable reductions in NOx and smoke emissions. Shrivastava et al. (2019) [13] observed that biodiesel derived from roselle and karanja effectively reduced CO, HC, and smoke opacity, further supporting their potential as environmentally friendly fuels. Overall, these studies confirm that biodiesel and biodiesel–alcohol blends can be successfully utilized in CI engines without major modifications, offering emission benefits—particularly reductions in CO and HC—though often accompanied by a slight increase in NOx emissions.

Emission analyses have revealed that diesel engines emit pollutants including carbon monoxide (CO), carbon dioxide (CO_2), nitrogen oxides (NO_x), unburned hydrocarbons (HC), and sulfur dioxide (SO_2). Blending biodiesel and bioethanol has been shown to influence these emissions, where fuel properties and composition significantly affect CO and CO_2 emissions [14–17]. For example, higher oxygenated fuel blends can improve combustion and lower CO_2 output, while ethanol additions can reduce combustion temperatures due to their cooling effects, thereby helping to mitigate NO_x formation [16]. This study evaluates the impact of graphite nanoparticles on the combustion, performance, and emission characteristics of a diesel engine fueled with pyrolysis oil derived from waste plastics [18]. The research investigates how acetylene enrichment affects diesel engine operation when using a fuel mixture of microalgae biodiesel, waste plastic oil, and heptane [19]. Overall, biodiesel has demonstrated promising performance in CI engines with compression ratios ranging from 15:1 to 18.5:1, showing favorable engine behavior and emissions reduction at compression ratios of 17.5:1 and 18:1 [20–22].

From the detailed literature review, it is evident that biodiesel derived from renewable feedstocks holds significant promise for reducing environmental impacts and improving sustainability in compression ignition (CI) engine applications. While previous studies have widely investigated biodiesel derived from conventional feedstocks in compression ignition (CI) engines, the potential of bamboo-derived biodiesel has not been comprehensively explored, particularly in VCR engines under realistic load conditions. Bamboo (*Bambusa vulgaris*), with its rapid growth, renewability, and nonedible characteristics, presents a highly promising but underutilized biodiesel feedstock. This study uniquely addresses this study gap by producing bamboo-derived biodiesel through fast pyrolysis and transesterification, and systematically evaluating its physicochemical properties, engine performance, combustion behavior, and emissions at different compression ratios, thereby establishing its viability as a sustainable alternative fuel meeting ASTM standard. This study aims to systematically analyze the engine performance, combustion characteristics, and emission profiles of bamboo biodiesel blends (BV5, BV10, BV15, BV20, and BV25) in a VCR engine operated at compression ratios of 17.5:1 and 18:1 under a 5.2 kW load at 1500 rpm, and to identify the most suitable blend that meets ASTM biodiesel standards for use in unmodified CI engines.

2 | Materials and Methods

2.1 | Feedstock Selection and Collection

Five bamboo species were selected for this study: *Dendrocalamus asper*, *Pseudosasa japonica*, *Dendrocalamus giganteus*, *Bambusa vulgaris*, and *Sinarundinaria falcate*. The bamboo samples were collected from various regions across Kerala, India. The choice of these species was based on their abundance, growth characteristics, and suitability for thermochemical conversion processes Figure 1.

2.2 | Sample Preparation

Before extracting biofuels such as bio-oil and biodiesel, bamboo must be prepared in powdered form and properly dried. To characterize the bamboo, including proximate and ultimate analysis and determining its higher heating value (HHV), 5 g of the powdered sample are taken. Before drying, the bamboo is cut into smaller pieces and processed into powder. This cutting step is crucial because particle size significantly influences thermochemical reaction efficiency, reaction time, product yield, and product composition [23]. For optimal yield, the particle size should be between 0.71 mm and 3.56 mm [24, 25].

In this study, bamboo was processed into powder with particle sizes less than 2 mm, along with chips, using an angle grinder fitted with a toothed cutter (850 W, cutter wheel diameter: 100 mm, 11,000 rpm). Drying is essential to remove moisture and prepare the biomass for effective fuel generation. Various types of dryers can be used for biomass drying, with drying media including superheated steam, air, nitrogen, or flue gas from

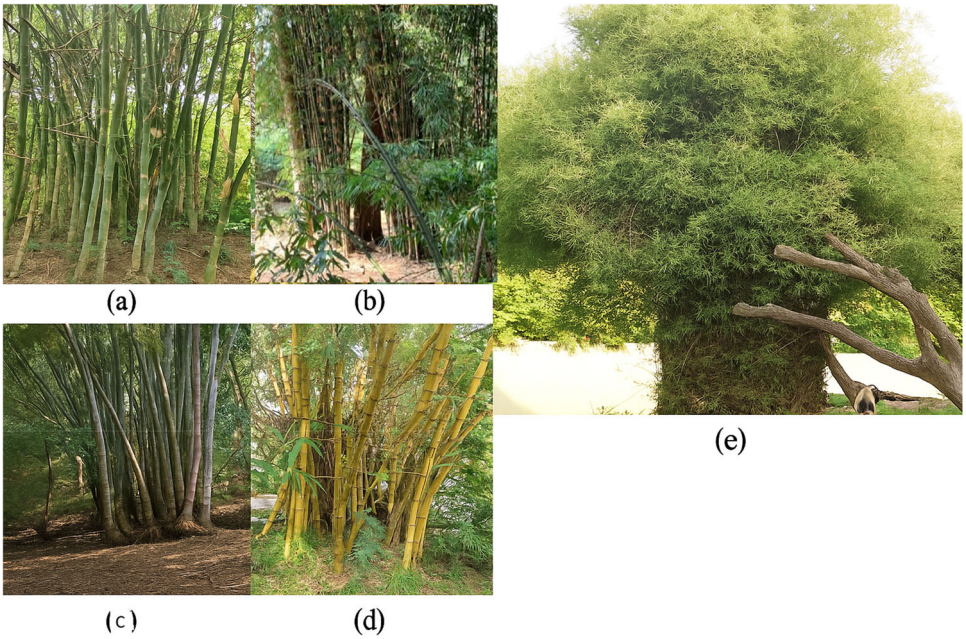


FIGURE 1 | (a) *Dendrocalamus asper*, (b) *Pseudosasa japonica*, (c) *Dendrocalamus giganteus*, (d) *Bambusa vulgaris*, and (e) Sinarundinaria falcate.

biomass residues [26, 27]. Typically, raw bamboo biomass has a moisture content of 40%–50%, which needs to be reduced to about 6%–8% [28]. If adequate sunlight is available, with atmospheric temperatures of at least 30°C, solar drying can be an effective method. In this study, bamboo samples were sun-dried for 7 days under varying temperatures ranging from 30°C to 38°C. Powder of *Bambusa vulgaris* (Particle size < 2 mm) is shown in Figure 2.



FIGURE 2 | Powder of *Bambusa vulgaris* (Particle size < 2 mm).

2.3 | Characterization of Bamboo Biomass

Characterization of bamboo was carried out to determine its proximate analysis, ultimate analysis, and HHV. The proximate analysis assesses physical properties such as moisture content (MC), ash content (AC), volatile matter (VM), and fixed carbon (FC), while the ultimate analysis provides the chemical composition, including carbon (C), hydrogen (H), nitrogen (N), oxygen (O), and sulfur (S) contents. Proximate analysis and HHV were determined following ASTM standards, and the ultimate analysis was performed using an elemental analyzer. It was observed that the bamboo contained no measurable nitrogen, as bamboo typically does not require nitrogen-rich soil for growth. The bamboos used for pyrolysis showed a moisture content ranging from 2.16% to 18.17% by mass, volatile matter between 60.15% and 78.46% by mass, ash content from 15.47% to 20.04% by mass, and fixed carbon content between 0.77% and 3.91% by mass. The carbon content ranged from 41.73% to 44.31% by mass, hydrogen content from 6.01% to 6.91% by mass, oxygen content between 49.12% and 51.29% by mass, and sulfur content from 0.07% to 0.56% by mass. The HHV of the bamboo samples was found to be in the range of 16.18–18.13 MJ/kg.

2.4 | Pyrolysis Process

Bamboo powder with a particle size below 2 mm was fed into a mild-steel pyrolysis reactor with a capacity of 10 L. The reactor was heated using an electric heater rated at 1200°C, and the internal temperature was continuously monitored via a thermocouple. The evolution of pyrolysis vapors began at approximately 165°C. These vapors were routed through a coil-type condenser and collected in a beaker as liquid condensate (bio-oil). Solid residues, consisting of char and ash, accumulated at the bottom of the reactor.

Following each pyrolysis cycle, the reactor walls were cleaned using ethyl alcohol or acetone to remove any tar or slag deposits, helping maintain consistent product yields and prolong reactor service life. Optionally, catalysts could be introduced into the feedstock before pyrolysis to enhance bio-oil yield and reduce slag formation.

2.5 | Transesterification of Bamboo Bio-Oil

The extracted bamboo bio-oil was converted into biodiesel through a transesterification process. Initially, methanol was mixed with potassium hydroxide (0.25% w/w) and heated until the KOH was completely dissolved. This methanolic catalyst

solution was then blended with the bamboo bio-oil at a mass ratio of 3:1. The mixture was continuously stirred and maintained at a temperature of 60°C–65 for 90 min to facilitate the reaction.

Upon completion, the reaction mixture was transferred to a separating funnel and allowed to cool at ambient conditions for 20 min. This enabled phase separation, with the denser glycerol settling at the bottom and the biodiesel forming the upper layer, which was then collected for further use.

2.6 | Biodiesel Characterization

The properties of both the bio-oil and the resulting biodiesel were characterized according to ASTM standards, including measurements of relative density, acid number, kinematic viscosity, cetane number, flash point, cloud point, pour point, ash content, carbon residue, and HHV. The pure bamboo biodiesels did not meet all ASTM standards, with the exception of the flash point. Among the tested bamboo species, biodiesel derived from *Bambusa vulgaris* showed the highest yield (75.3%) and physicochemical properties closest to ASTM requirements. Consequently, blends of *Bambusa vulgaris* biodiesel (BV5, BV10, BV15, BV20, BV25) with petroleum diesel were prepared and evaluated.

Of these blends, BV15 satisfied all ASTM biodiesel property standards. BV5 and BV10 only failed to meet the flash point requirement, while BV20 did not comply with cetane number and HHV specifications. Increasing the biodiesel proportion in the blends was observed to raise density, kinematic viscosity, and flash point, while slightly lowering the cetane number and HHV.

The provided information discusses the properties of different bamboo biodiesel (BV) and their blends, specifically focusing on how they meet various requirements for efficient biodiesel usage. The data is presented in Table 1, which highlights the key characteristics of these fuels. It appears that among the tested blends, BV15 is the only one that fully meets all the necessary criteria for effective biodiesel utilization. Here's a breakdown of the findings for each blend:

i. BV15: This blend complies with all the requirements for efficient biodiesel. This means it meets or exceeds the specified values for important properties, indicating its suitability for use as a biodiesel fuel.

ii. BV5 and BV10: These blends satisfy most of the typical property values expected from biodiesel but fall short in terms of flash point. While they may be suitable for many applications, the flash point deficiency could be a concern in certain contexts due to safety considerations.

iii. BV20: This blend satisfies most of the property values except for the cetane number and HHV. A lower cetane number might lead to less efficient combustion, and a lower HHV means less energy is available in the fuel. As a result, BV20 may not be as suitable for all applications as BV15.

The study involves the use of biodiesel extracted from *Bambusa vulgaris* and its various blends for testing in a VCR engine. These tests include evaluating engine performance, analyzing combustion, and assessing emissions. To provide a comprehensive view of the properties of these fuels, Table 1 [29] contains data on diesel, *Bambusa vulgaris* biodiesel, and its blends.

For reference and to ensure the reliability of the findings, this study applies ASTM (American Society for Testing and Materials) standards, as summarized in Table 2. These standards establish well-defined guidelines and specifications for fuel testing and characterization, ensuring that results are consistent and comparable with industry benchmarks.

The information presented in this section highlights the properties and suitability of various bamboo biodiesel blends for engine use, emphasizing compliance with performance criteria for efficient biodiesel operation. These data are valuable for researchers and engineers exploring bamboo biodiesel as an alternative fuel source and underscore the critical role of adhering to ASTM standards for accurate and reliable evaluations.

2.7 | Experimental Setup and Procedure

The experiment utilizes a Kirloskar TV1 VCR engine, shown in Figure 3 with its schematic diagram in Figure 4. This engine is particularly well-suited for the research, as it allows operation on both petrol and diesel fuels, providing a versatile platform for evaluating engine performance under various conditions.

TABLE 1 | Properties of diesel, biodiesel and biodiesel blends [29].

Fuel	Relative density, at 15°C, g/cm³	Acid number, mg KOH/g	Kinematic viscosity (at 40°C), mm²/s	Cetane number	Flash point, °C	Cloud point, °C	Pour point, °C	Ash content, %	Carbon residues, %	HHV, MJ/kg
BVD	0.945	0.5	5.43	41	104	4	−22	0.02	0.07	37.12
BV5	0.874	0.4	4.44	48	88	3	−22	0.01	0.03	44.18
BV10	0.884	0.4	4.58	48	91	2	−23	0.01	0.04	43.72
BV15	0.889	0.3	4.67	47	94	2	−25	0.01	0.04	42.44
BV20	0.896	0.2	4.82	45	97	2	−25	0.01	0.05	40.91
BV25	0.902	0.3	4.91	44	98	3	−25	0.01	0.05	39.63
Diesel	0.871	0.4	3.02	52	72	—	—	—	—	45.85

TABLE 2 | ASTM codes used for finding bio-oil/biodiesel properties.

Properties	ASTM codes	Standard values
Relative density, g/cm^3	D1298	0.86–0.90
Acid number, mg KOH/g	D 664	0.5 maximum
Kinematic viscosity (at 40°C), mm^2/s	D 445	1.9–6.0
Cetane number	D 613	47 minimum
Flash point, °C	D 93	93 minimum
Cloud point, °C	D 2500	3 maximum
Pour point, °C	D 2500	—
Ash content, %	D 482	0.01 maximum
Carbon residues, %	D 189	0.05 maximum
HHV, MJ/kg	D 2015-85	40 minimum

To enable effective operation and monitoring, several instruments and equipment are employed, with their specifications detailed in Table 3. The key components are described below:

- Rotary Encoder: The rotary encoder measures the engine's revolutions per minute (rpm), providing crucial data for evaluating performance across varying speeds and loads. This information supports real-time assessment of efficiency, power output, and other engine parameters.
- Thermocouple: Thermocouples are used to record temperatures at different points within the engine. These temperature measurements are essential for analyzing the engine's thermal behavior, including component and exhaust gas temperatures, thereby supporting evaluation of heat management and potential thermal stresses.
- Orifice System: The orifice system measures the flow rates of air and fuel. Accurate monitoring of these flow rates is critical for controlling the air–fuel mixture, which directly affects combustion efficiency, emissions, and overall engine performance.
- U-Tube Manometer: The U-tube manometer measures pressure variations within the engine. Pressure data, including air intake and exhaust backpressure, is fundamental to analyzing combustion processes and contributes to a comprehensive understanding of engine performance.

Additionally, Table 4 provides a checklist outlining the procedures and steps required to modify the operating modes of the VCR engine during the experiment. This checklist includes instructions for switching between fuel types (petrol and diesel), adjusting compression ratios, and controlling other relevant engine parameters.

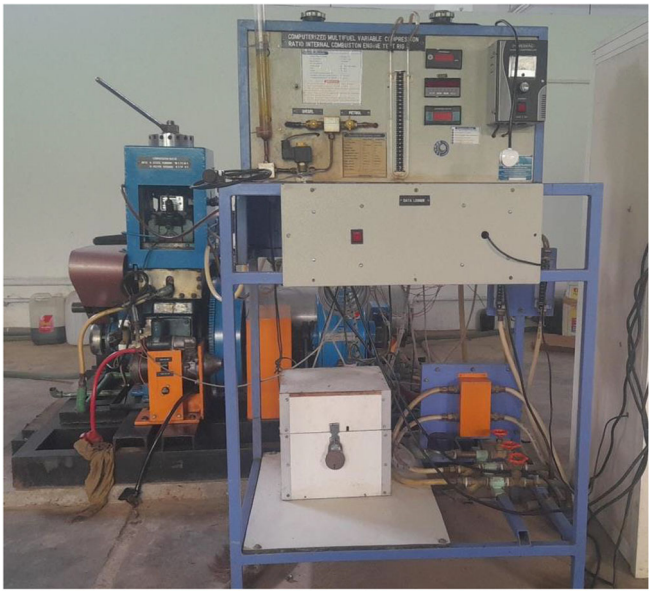


FIGURE 3 | Photographic perspective of the experimental set up.

Engine performance and emissions tests are conducted at compression ratios of 17.5:1 and 18:1. To minimize the influence of temperature on performance, lubricating oil and cooling water are used for thermal management. Fuel injection is employed to maintain a stable engine speed of 1500 rpm while ensuring the lubricating oil temperature is held at 60°C.

Before testing, the engine was operated at its rated speed of 1500 rpm under no-load conditions for approximately 30 min to achieve a steady-state condition. During testing, a load is applied using an eddy current dynamometer, and brake power (BP) is varied by adjusting this load. The load is progressively increased from 0% to 100% in 20% increments, resulting in corresponding changes in BP.

Before commencing the experiment, it is essential to start the exhaust gas analyzer (TESTO 340) and the smoke meter (TESTO 338) to allow the systems to stabilize. After completing the tests with diesel, the same experimental procedure is repeated using pure biodiesel derived from *Bambusa vulgaris* and its blends (BV5, BV10, BV15, BV20, and BV25).

All experiments were conducted four times to maximize accuracy and minimize potential errors, with the average of the measured values taken for analysis. The uncertainties associated with the instruments and devices used to determine the various parameters are summarized in Table 5. Furthermore, the overall uncertainty of the experimental measurements is calculated using the Root Sum Square method, as described in references [30–32].

$$
\begin{aligned}
\mathit{OverallUncertainty} &= \mathrm{Squarerootof}\{(\mathrm{UCofBFSC})^2 + (\mathrm{UCofBTE})^2 \\
&\quad + (\mathrm{UCofEGT})^2 + \mathrm{UCofCOemission})^2 \\
&\quad + (\mathrm{UCofCO_2emission})^2 + (\mathrm{UCofNO_xemission})^2 \\
&\quad + (\mathrm{UCofHCemission})^2 + (\mathrm{UCofsmoke})\} \\
&= \sqrt{(0.194)^2 + (0.438)^2 + (0.608)^2 + (1.325)^2 + (0.382)^2 + (0.253)^2 + (0.356)^2 + (0.219)^2} \\
&= \mathbf{1.943}
\end{aligned}
$$

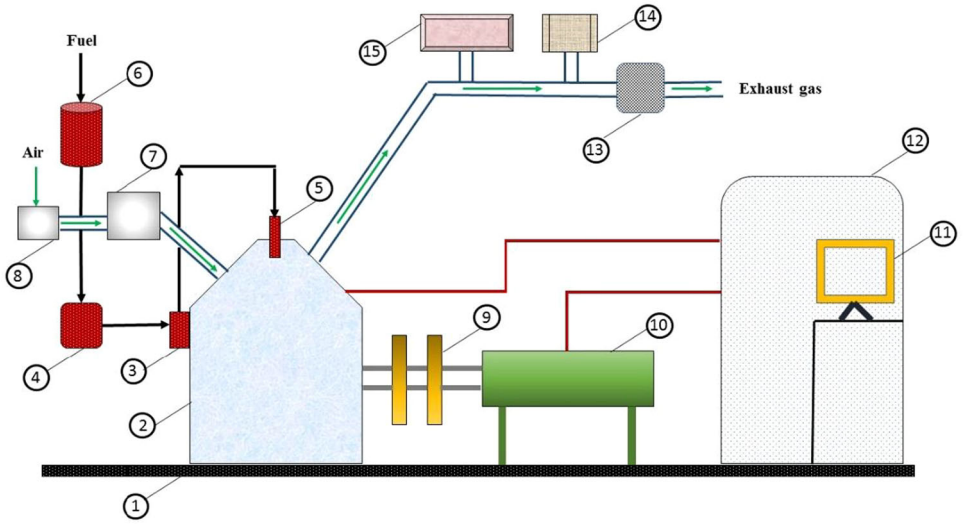


FIGURE 4 | Schematic diagram of VCR engine (diesel mode) setup used for engine performance test and emissions test: 1. Bed, 2. Kirloskar TV1 VCR engine, 3. Fuel pump, 4. Fuel filter, 5. Fuel injector, 6. Fuel tank, 7. Air stabilizing tank, 8. Air filter, 9. Coupling, 10. Eddy current dynamometer, 11. Monitor, 12. Data acquisition system, 13. Exhaust silencer, 14. Smoke analyzer, and 15. Gas analyzer.

TABLE 3 | Specifications of experimental set up.

Engine make and model	Kirloskar TV1
Output power	5.2 kW (7 hp)
Rated speed	1500 rpm
No. of cylinders	One. 4 strokes
Displacement	661 CC (0.661 litres)
Bore	87.5 mm
Stroke	110 mm
Normal compression ratio	17.5:1
Variable compression ratio (Diesel)	18:1 to 14:1
Variable compression ratio (Petrol)	9:1 to 6:1
Dynamometer	Type eddy current, water cooled with loading unit
Fuel tank capacity	6.5 liters

TABLE 4 | Checklist for changing modes of VCR engine.

Item	Diesel mode	Petrol mode
Inlet manifold	Pipe	Carburetor
Ignition	Fuel injector	Spark plug
Fuel pump	On	Off
Ignition switch	Off	On
Compression ratio	17.5	9
Maximum load	12 kg	12 kg
Speed regulation	Auto	Manual
Maximum speed	1500 rpm	1600 rpm
Coolant rate	145 cc/s	145 cc/s
Open valves	1,3,5	2,4,6
Close valves	2,4,6,7	1,3,5,7

3 | Results and Discussion

Experiments are carried out for BVD and its blends such as BV5, BV10, BV15, BV20, and BV25 at various loads 0%, 20%, 40%, 60%, 80%, and 100% to observe performance metrics such as BSFC and BTE, combustion analysis (on full load condition), exhaust gas temperature, and emission characteristics such as HC, CO, NO_X, and smoke density, which were later compared to diesel. Here, the experiments for this are done at a constant engine speed of 1500 rpm on compression ratios 17.5:1 and 18:1.

3.1 | Performance Test

3.1.1 | Brake Specific Fuel Consumption

The variation in BSFC for different fuels under varying load conditions, specifically Compression Ratios (CR) of 17.5:1 and 18:1, is graphically represented in Figure 5a,b, respectively. A noteworthy observation from these plots is that, regardless of the type of fuel, BSFC tends to be higher at a compression ratio of 17.5:1. Additionally, it is evident that for both compression ratios, the highest BSFC is consistently observed at a 20% load condition, while the lowest BSFC occurs at an 80% load condition. This pattern holds true for all fuels tested.

When specifically considering a compression ratio of 17.5:1, there is a substantial 62.5% reduction in BSFC for diesel when compared to *Bambusa vulgaris* biodiesel (BVD) at a 20% load condition. This reduction remains significant at full load conditions, with a 40% decrease in BSFC for diesel compared to BVD. Similarly, for a compression ratio of 18:1, a 61.2% reduction in BSFC is observed at a 20% load condition and a 37.7% reduction at full load condition for diesel compared to BVD. BSFC consistently decreases with an increase in load conditions up to 80%, at which point there is a slight upturn in BSFC observed at 100% load for both compression ratios.

TABLE 5 | Uncertainty values of various instruments/gadgets.

Instruments/Gadgets	Measuring range	Accuracy	UC (%)
U-tube manometer	0-250 mm	±1 mm	±1
Engine speed	300-4000 rpm	±10 rpm	±0.67
Burette	0–110 ml	±0.5 ml	±1.1
Dynamometer load	0–25 kg s	± 0.1 kgs	±1
Exhaust gas thermometer	−40°C–450°C	±1°C	± 1.2, T < 350°C ± 2.1, T > 350°C

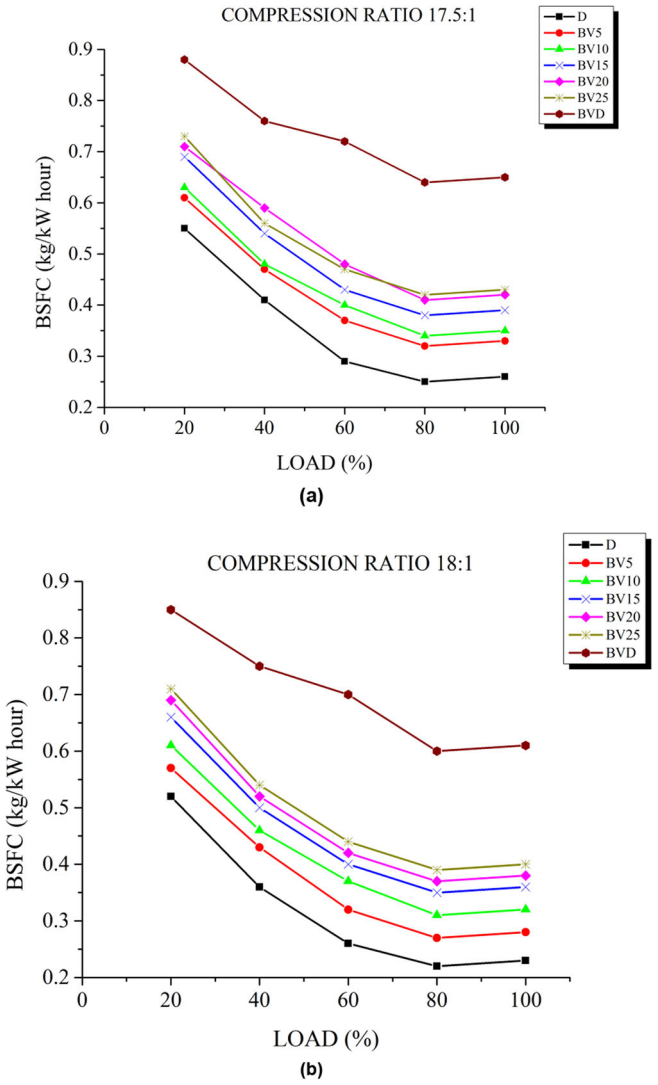


FIGURE 5 | Variation of BSFC with loads at (a) CR = 17.5:1, and (b) CR = 18:1.

In terms of the specific values, when considering both compression ratios and load conditions, the maximum BSFC is 0.88 kg/kW-h for BVD at a CR of 17.5:1, while the minimum BSFC is observed for diesel, at 0.23 kg/kW-h, at a CR of 18:1. Of particular interest is the performance of the blend BV5, which exhibits a BSFC closely aligned with diesel's BSFC compared to all other biodiesels for both compression ratios. This can be attributed to the fact that the HHV of BV5 (44.48 MJ/kg) is in close proximity to that of diesel (45.36 MJ/kg). Furthermore, it is noteworthy that at a compression ratio of 17.5:1, *Bambusa vulgaris* biodiesel has a BSFC that is 3.7 times higher than that of diesel, while at a compression ratio of 18:1, it is 3.4 times higher. Mathematically, BSFC can be calculated using equation number 1, which represents a model relating BSFC to the relevant parameters and helps quantitatively explain the observed differences across fuels and compression ratios

$$BSFC\ (kg/kW\text{-}hour) = \frac{Rate\ of\ fuel\ flow\ (in\ kg/hour)}{BP(in\ kW)} \tag{1}$$

$$\text{where, } BP\ (kW) = \frac{2 \times \pi \times N \times T}{60 \times 1000} \tag{2}$$

N = Rotation speed of engine in rpm

T = Engine torque in Nm

The observed trend in the study shows that, across all the fuels that were tested, the BSFC consistently decreased as the load on the engine increased. This pattern is consistent with the fundamental behavior of internal combustion engines and can be attributed to several underlying factors. One key factor contributing to this trend is the relationship between brake power and fuel consumption with varying load. As the engine load increases, the percentage increase in brake power generated by the engine becomes more significant than the increase in fuel consumption. In other words, the engine becomes more efficient in converting fuel into useful power as the load goes up. This efficiency gain offsets the additional fuel required to generate the extra power, resulting in a lower BSFC. Conversely, at low engine loads where there is relatively little fuel being injected into the engine, the heat generated during combustion is absorbed by a larger volume of air. This scenario results in a higher BSFC because the engine is less efficient in converting fuel into useful work under these conditions.

At high engine loads, a substantial amount of air and fuel are combusted, leading to a more efficient conversion of fuel into power. However, it's worth noting that at full load conditions, there is a slight increase in BSFC. This is due to the exceptionally high heat generation during full load operation, which can cause some of the energy to be lost as waste heat rather than being efficiently converted into mechanical work. This waste heat contributes to a small rise in BSFC. In practical terms, this trend implies that when an engine is operating at full load conditions, fuel consumption will be slightly higher

compared to operating at partial loads, despite the increased power output. However, overall, the engine demonstrates improved fuel efficiency with increasing load, as the gains in power output outweigh the additional fuel consumption. This observation is vital for understanding engine performance and optimizing fuel efficiency in various applications, including automotive and industrial settings.

3.1.2 | Brake Thermal Efficiency

BTE serves as a pivotal metric in the realm of internal combustion engines. It characterizes how effectively an engine transforms the energy contained within injected fuel into useful mechanical work. The expression of BTE hinges on both the fuel's lower heating value and the rate at which the fuel mass is consumed. The data presented in Figure 6a,b demonstrate how BTE varies between diesel and an alternative fuel, BVD, across different compression ratios (CR) and engine loads.

The comparison between diesel and BVD reveals that diesel outperforms BVD in terms of BTE, particularly at 80% engine load. This discrepancy emphasizes diesel's superior efficiency in converting fuel into power under these specific conditions. Furthermore, it is evident that the efficiency of BVD significantly diminishes as the engine load increases, with reductions of approximately 51.9% and 51.2% at 20% and 80% loads, respectively, at CR 17.5:1, and similar trends at CR 18:1. Comparatively, increasing the compression ratio from 17.5:1 to 18:1 results in higher BTE for all tested fuels, indicating that a higher compression ratio generally enhances the combustion process's efficiency. The discussion also briefly touches upon the fuel BV5, highlighting its BTE values as being more akin to diesel, thus presenting it as a potential alternative fuel source with comparable performance.

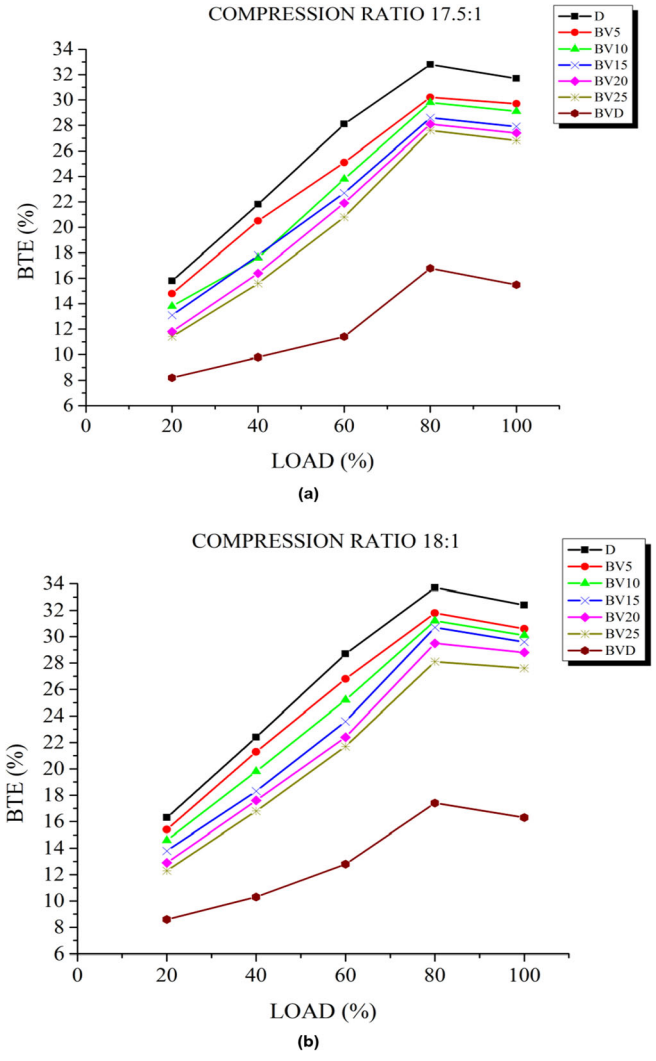


FIGURE 6 | Variation of BTE with loads at (a) CR = 17.5:1, and (b) CR = 18:1.

Furthermore, sensitivity of BTE to engine load is emphasized, with BTE generally increasing as engine load rises up to 80%. Beyond this point, a slight decrease in BTE is noted, attributed to heightened heat generation during full-load conditions, which can potentially impact engine performance adversely. Though Equation 3 is referred to as the means of calculating BTE, specific details regarding this equation are not provided within the text. In summation, BTE plays a pivotal role in evaluating engine efficiency, accounting for various factors like engine load, compression ratio, and fuel type, and has important implications for overall engine performance.

$$BTE\ (\%) = \frac{BP(in\ kW) \times 3600 \times 100}{Rate\ of\ fuel\ flow\ (in\ kg/hour) \times HHV\ (in\ kJ/kg)} \quad (3)$$

Brake specific fuel consumption (BSFC) and Brake thermal efficiency (BTE)

Superior performance of diesel in terms of BTE and BSFC can be attributed to its higher HHV (45.36 MJ/kg), which results in greater energy release per unit mass of fuel compared to biodiesel blends. Additionally, favorable volatility and lower viscosity of diesel enhances atomization and fuel–air mixing, leading to shorter ignition delays and a more prominent premixed combustion phase [1]. This results in a higher peak heat release rate and improved combustion efficiency. In contrast, biodiesel blends exhibit higher viscosity and lower volatility, leading to less effective atomization and longer ignition delay. These factors promote a greater proportion of mixing-controlled combustion, which spreads the heat release over a longer duration, reducing peak temperatures and thus BTE.

The oxygenated nature of biodiesel molecules also fosters leaner local mixtures that, while beneficial for soot reduction, can prolong combustion duration and lower thermal efficiency. Furthermore, the lower HHV of biodiesel requires higher mass flow rates to produce equivalent power, directly contributing to increased BSFC. Overall, diesel benefits from its thermophysical and chemical properties—including higher HHV, shorter ignition delay, and higher heat release rates—leading to faster, more complete, and more efficient combustion compared to biodiesel blends [1]. Diesel fuel inherently possesses a HHV (45.36 MJ/kg) compared to the bamboo biodiesel and its blends, which translates to more energy available per unit mass of fuel. In addition, diesel has superior volatility and lower viscosity, which promotes better atomization and finer fuel spray formation during injection. This facilitates more uniform air–fuel

mixing, shortening the ignition delay period and leading to a more controlled and complete combustion process.

A shorter ignition delay means that diesel combustion is characterized by an earlier start of combustion and a higher heat release rate during the premixed combustion phase, thus improving combustion efficiency. Biodiesel, by contrast, generally exhibits higher viscosity and lower volatility, which increases spray penetration length but reduces atomization quality, leading to a comparatively longer ignition delay and lower premixed burn fraction. As a result, the heat release rate becomes lower and more distributed during the mixing-controlled phase, reducing peak combustion temperatures and BTE.

Moreover, the oxygenated nature of biodiesel molecules promotes leaner local mixtures, which although beneficial for reducing soot, can extend combustion duration, further lowering BTE. The higher BSFC observed for biodiesel and its blends is directly linked to their lower HHV, requiring more mass of fuel to generate the same power output as diesel. In summary, diesel outperforms biodiesel blends in terms of BTE and BSFC due to its higher HHV, superior volatility, shorter ignition delay, and higher heat release rate, leading to more efficient and rapid combustion.

3.2 | Combustion Analysis

3.2.1 | Variation of Cylinder Pressure Wwith Crank Angle at Compression Ratios 18:1 and 17.5:1 on Full Load Condition

Cylinder pressure data is a crucial parameter in analyzing power production and emissions in internal combustion engines. This data provides valuable insights into the combustion process and serves as a basis for calculating key thermodynamic parameters. By examining in-cylinder pressure, one can estimate the heat release from combustion and calculate the mean cylinder temperature using principles such as the universal gas law and the first law of thermodynamics.

In compression ignition engines, the initial combustion fuel fraction strongly influences peak cylinder pressure. Cylinder pressure essentially represents the fuel's ability to combine with air within the combustion chamber, a fundamental aspect of engine operation. Figure 7a,b presents the variation of in-cylinder pressure with crank angle (CA) at different compression ratios (CR) under full-load conditions, offering significant insights into engine behavior.

At a crank angle of 10°CA, there is a substantial decrease in in-cylinder pressure for BVD (an alternative fuel) compared to diesel, with reductions of 72.1% and 72.2% observed at CR 17.5:1 and 18:1, respectively. This significant difference suggests that BVD combustion behaves differently from diesel, potentially due to variations in ignition delay, fuel reactivity, and atomization characteristics. Specifically, BVD's longer ignition delay may be attributed to its lower cetane number, which indicates a reduced tendency for autoignition, along with its higher viscosity, which can negatively affect spray atomization and air–

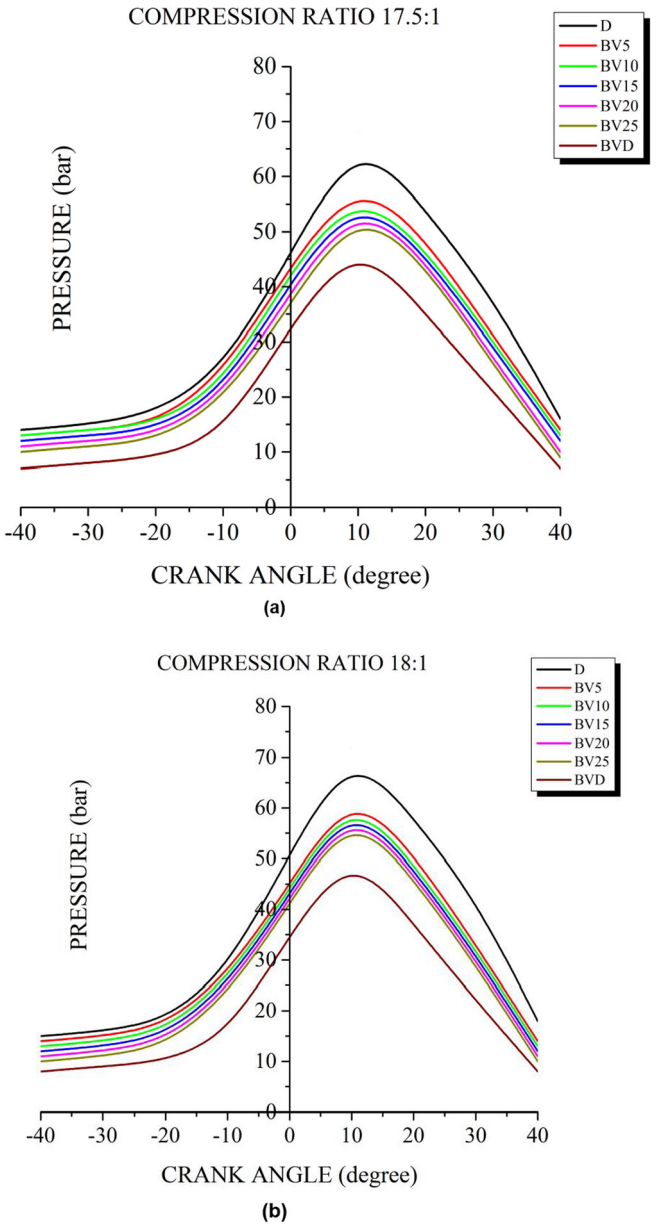


FIGURE 7 | Variation of cylinder pressure with crank angle at (a) CR = 17.5:1, and (b) CR = 18:1.

fuel mixing. These factors collectively influence the in-cylinder pressure development during the initial combustion phase.

As the crank angle advances to 40°CA, the gap between BVD and diesel narrows, with a decrease of 43.8% and 44.4% in in-cylinder pressure at CR 17.5:1 and 18:1, respectively. This suggests that the combustion process of BVD progresses and partially catches up with that of diesel as the crank angle advances. For all tested fuels at both compression ratios, the maximum in-cylinder pressure occurs around 10°CA, while the minimum is observed at 40°CA. Such cyclic variation in pressure is characteristic of internal combustion engines due to the distinct phases of combustion.

Comparing the two compression ratios, it is evident that in-cylinder pressure is higher at CR 18:1 than at CR 17.5:1. For diesel, the peak in-cylinder pressure reaches 72 bar at CR 18:1,

compared to 68 bar at CR 17.5:1. In contrast, BVD records a peak pressure of 8 bar at CR 18:1 and 7 bar at CR 17.5:1. This indicates that higher compression ratios generally lead to higher peak cylinder pressures, influencing both engine performance and efficiency.

3.2.2 | Variation of Heat Release With Crank Angle at Compression Ratios of 18:1 and 17.5:1 on Full Load Condition

The analysis of heat release rate, as depicted in Figure 8a,b, provides further valuable insights into the combustion characteristics of diesel and biodiesel (BVD) under full-load conditions for compression ratios of 17.5:1 and 18:1. Understanding heat release is essential for optimizing engine performance and emissions.

The heat release profiles for all fuels exhibit a common trend: initially, at the start of combustion, there is a negative heat release due to the ignition delay interrupting vaporization. As the combustion process initiates, the heat release becomes positive, which is typical for compression ignition engines where the ignition delay precedes the main combustion event.

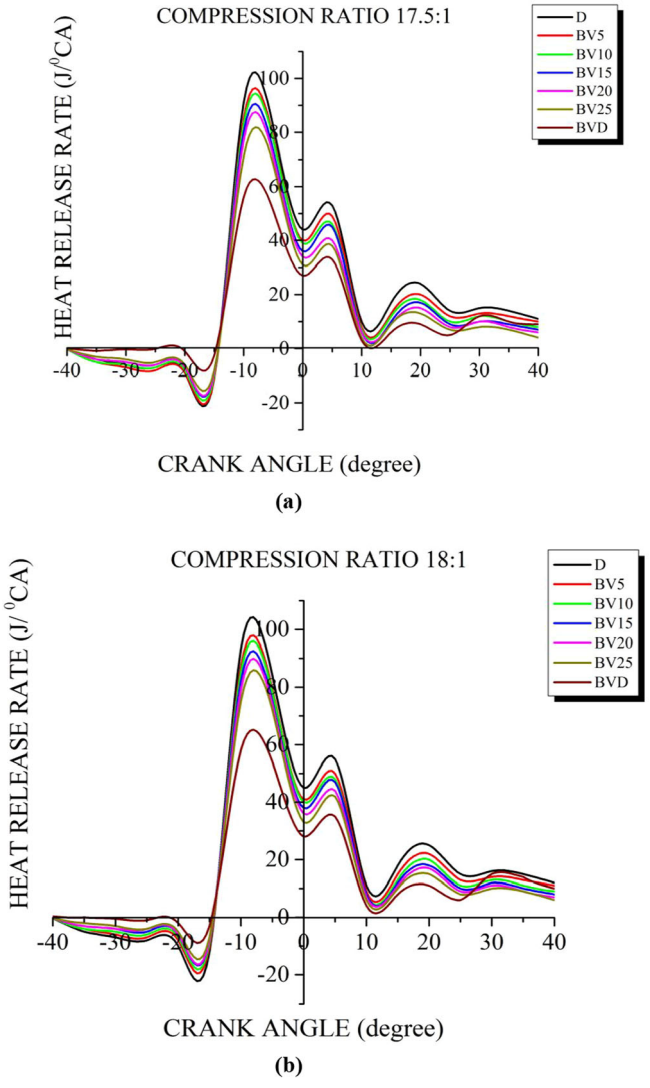


FIGURE 8 | Variation of heat release with crank angle at (a) CR = 17.5:1, and (b) CR = 18:1.

The maximum heat release for all fuels occurs within a narrow crank angle window, specifically between 5°CA and 10°CA before top dead center (BTDC), for both compression ratios. This indicates that the bulk of combustion energy is released over a very short time. Among the fuels examined, diesel demonstrates the highest heat release rates, with values of 108 J/°CA at CR 18:1 and 102 J/°CA at CR 17.5:1. Following diesel, BV5 (a blend) showed heat release rates of 98 J/°CA at CR 18:1 and 96 J/°CA at CR 17.5:1. BVD, in contrast, exhibits considerably lower heat release rates, measuring 66 J/°CA at CR 18:1 and 61 J/°CA at CR 17.5:1.

These differences can be attributed to fuel volatility, atomization behavior, and cetane number. Diesel, with its higher cetane number, superior volatility, and better atomization characteristics, promotes more rapid ignition and efficient premixed combustion, resulting in higher heat release rates compared to BVD and its blends.

The comparison between BVD and diesel at specific crank angles further highlights these differences. For example, at −10°CA, BVD shows a reduction in heat release rate of 61.5% and 62.4% compared to diesel at CR 17.5:1 and 18:1, respectively. At −40°CA, the difference is even more pronounced, with reductions of 58.8% and 85.7%, respectively. Again, these results are influenced by BVD's lower cetane number, poorer atomization, and lower reactivity, which collectively extend the ignition delay and limit the initial heat release.

3.2.3 | Ignition Delay

Ignition delay duration, a critical parameter in internal combustion engines, represents the time gap between the start of fuel injection and the onset of combustion. It is influenced by both physical and chemical factors. The physical delay is determined by atomization, fuel–air mixing, and vaporization processes. Efficient atomization and thorough mixing help reduce the physical delay by ensuring a homogeneous fuel–air mixture within the combustion chamber. The chemical delay, meanwhile, stems from the preflame chemical reactions in the fuel–air mixture and is strongly linked to the fuel's cetane number and overall chemical reactivity. Fuels with higher cetane numbers exhibit superior autoignition qualities and hence shorter chemical delays. Higher brake power, associated with increased engine loads, leads to shorter ignition delays because elevated loads raise the in-cylinder gas temperature and pressure, accelerating chemical reaction rates and reducing ignition delay. The variation of ignition delay with loads at CR = 17.5:1, and CR = 18:1 are shown at Figure 9a,b respectively.

In comparison to diesel, biodiesels and their blends often display longer ignition delays due to their higher viscosity and surface tension, which hinder spray atomization and evaporation, extending the physical delay. Their distinct molecular structure and generally lower volatility may also contribute to longer chemical delays. However, in many cases, biodiesel fuels possess higher cetane numbers than conventional diesel, which offsets these

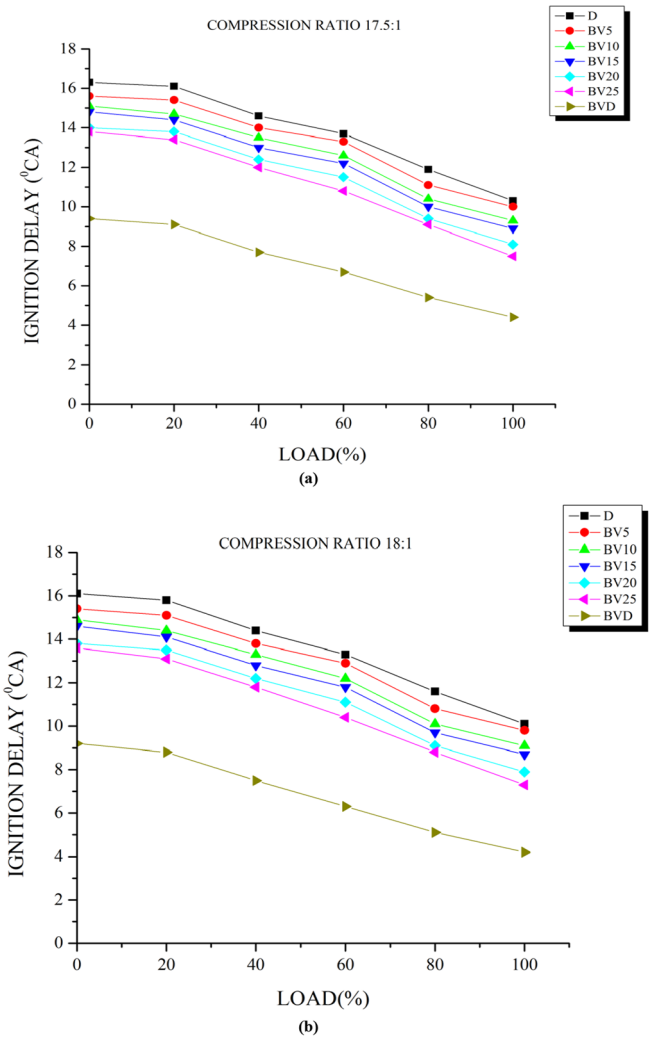


FIGURE 9 | Variation of ignition delay with loads at (a) CR = 17.5:1, and (b) CR = 18:1.

disadvantages by improving their chemical reactivity and facilitating earlier ignition. As a result, biodiesel (BVD) and its blends can sometimes demonstrate shorter overall ignition delays compared to diesel at both compression ratios. This suggests that the high cetane number and favorable chemical reactivity of BVD compensate for its physical atomization limitations.

The compression ratio also plays a decisive role: CR 18:1 yields a shorter ignition delay compared to CR 17.5:1 due to higher peak temperatures and pressures, which promote rapid ignition reactions. Overall, ignition delay is governed by a combination of cetane number (affecting chemical reactivity), atomization quality (affecting physical delay), and in-cylinder thermodynamic conditions. Diesel fuel inherently possesses a higher HHV (45.36 MJ/kg) compared to the bamboo biodiesel and its blends, which translates to more energy available per unit mass of fuel. In addition, diesel has superior volatility and lower viscosity, which promotes better atomization and finer fuel spray formation during injection.

This facilitates more uniform air–fuel mixing, shortening the ignition delay period and leading to a more controlled and complete combustion process.

A shorter ignition delay means that diesel combustion is characterized by an earlier start of combustion and a higher heat release rate during the premixed combustion phase, thus improving combustion efficiency. Biodiesel, by contrast, generally exhibits higher viscosity and lower volatility, which increases spray penetration length but reduces atomization quality, leading to a comparatively longer ignition delay and lower premixed burn fraction. As a result, the heat release rate becomes lower and more distributed during the mixing-controlled phase, reducing peak combustion temperatures and BTE.

Moreover, the oxygenated nature of biodiesel molecules promotes leaner local mixtures, which although beneficial for reducing soot, can extend combustion duration, further lowering BTE. The higher BSFC observed for biodiesel and its blends is directly linked to their lower HHV, requiring more mass of fuel to generate the same power output as diesel. In summary, diesel outperforms biodiesel blends in terms of BTE and BSFC due to its higher HHV, superior volatility, shorter ignition delay, and higher heat release rate, leading to more efficient and rapid combustion.

3.2.4 | Exhaust Gas Temperature

Exhaust gas temperature is a critical parameter in assessing the efficiency of an internal combustion engine. It provides valuable insights into whether the heat energy derived from the fuel is being effectively utilized to produce work within the engine. A high exhaust gas temperature can signify heat losses in the exhaust system or excessive thermal energy being expelled, indicating suboptimal conversion of heat energy into useful work. Conversely, a lower exhaust temperature suggests that the engine is operating more efficiently and is not thermally overburdened.

In the context of using biodiesel fuels, despite requiring more fuel to maintain the same power output as diesel, engines tend to exhibit lower exhaust temperatures. This indicates that biodiesel fuels are effectively harnessing the heat energy from combustion, resulting in improved thermal efficiency. The reduced exhaust temperature suggests that less energy is being wasted as heat in the exhaust system, and more of it is being converted into mechanical work. Comparing biodiesel (BVD) to diesel, there is a significant reduction in exhaust gas temperature, specifically a decrease of 54.4% and 54.2% at both CR 17.5:1 and 18:1 under zero load conditions, and a decrease of 57.8% and 57.4% at CR 17.5:1 and 18:1 under full load conditions. This substantial reduction highlights the superior thermal efficiency of BVD, which is able to maintain lower exhaust temperatures even when subjected to full engine load. Diesel, on the other hand, exhibits higher exhaust gas temperatures (345°C at CR 18:1°C and 325°C at CR 17.5:1), indicating that a significant amount of heat energy is being lost in the form of hot exhaust gases.

Additionally, the blend BV5 shows exhaust gas temperatures that are closer to those of diesel, suggesting a more comparable thermal performance. Figure 10a,b illustrates that as the blending ratio of biodiesel in the fuel increases, the exhaust gas

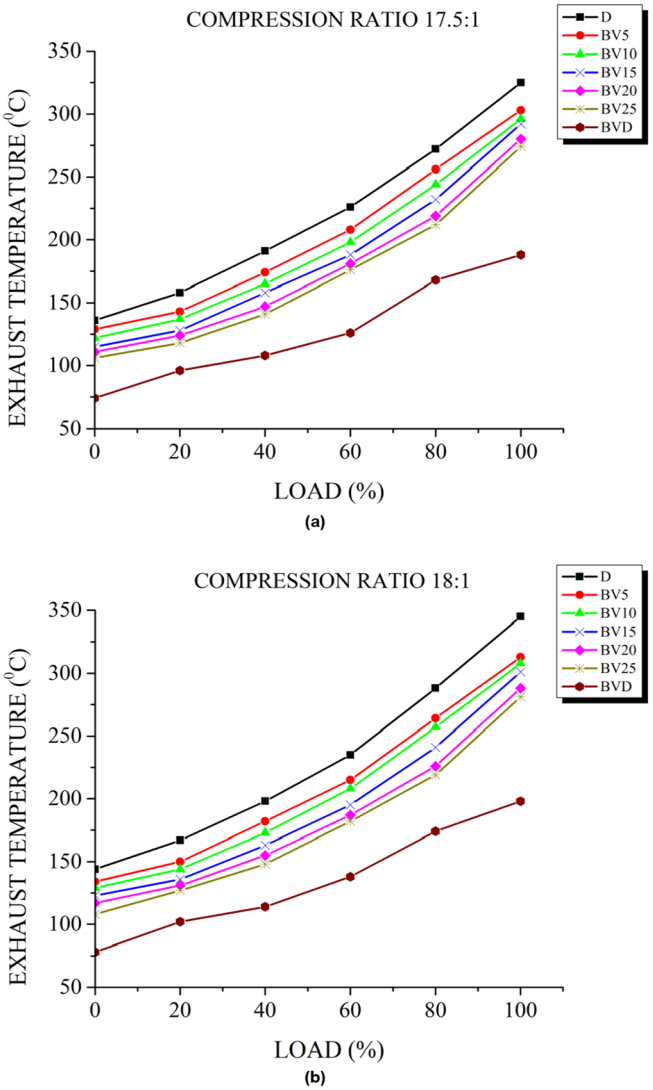


FIGURE 10 | Exhaust gas temperature on different loads at (a) CR 17.5:1, and (b) CR 18:1.

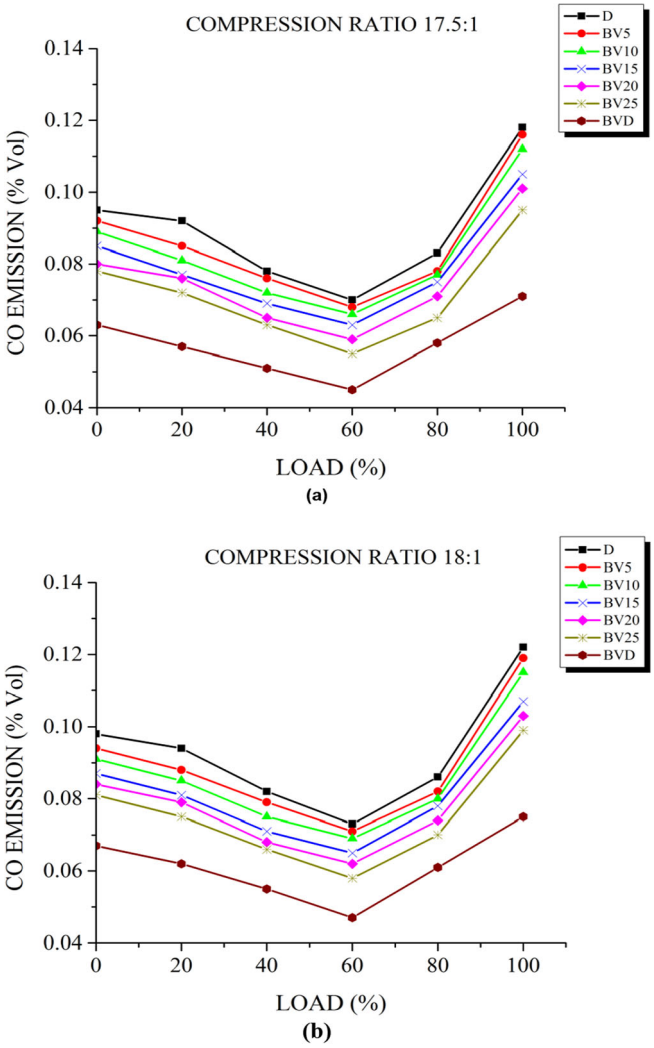


FIGURE 11 | CO emission on different loads at (a) CR = 17.5:1, and (b) CR = 18:1.

temperature tends to decrease. Furthermore, pure biodiesel (BVD) consistently demonstrates the lowest exhaust gas temperatures across all load conditions, reaffirming its superior thermal efficiency. The relationship between the heat release rate and exhaust gas temperature is notable. As the heat release rate increases, the exhaust gas temperature also rises. This correlation indicates that a higher rate of energy release during combustion leads to higher exhaust temperatures. However, diesel, despite having a HHV compared to biodiesels, exhibits higher exhaust temperatures. This suggests that diesel generates more heat at the end of the compression stroke but may not efficiently convert this heat into useful work.

3.3 | Emission Characteristics

Emission characteristics play a critical role in evaluating the environmental and health impacts of internal combustion engines. Pollutants such as carbon monoxide (CO), carbon dioxide (CO2), nitrogen oxides (NOx), unburned hydrocarbons (HC), and smoke opacity are of particular concern due to their contributions to air pollution, climate change, and harmful health effects. CO is a product of incomplete combustion and can impair air quality and human health. CO2 is a major greenhouse gas contributing to global warming. NOx compounds promote smog formation and respiratory issues, while unburned hydrocarbons can react to form secondary pollutants like ozone. Smoke emissions indicate incomplete combustion and contribute to particulate pollution. In this study, these emissions were systematically measured using a gas analyzer and smoke meter connected before the exhaust silencer of the experimental setup, providing a comprehensive assessment of the fuels' environmental performance under different compression ratios and load conditions. Here the emissions such as CO, CO2, NOx, HC, and smoke of all fuels used here are investigated by using a gas analyzer and a smoke meter connected before an exhaust silencer of the experimental set up.

3.3.1 | CO Emission of Fuels at CR 18:1 and 17.5:1

This study observed that for both compression ratios (CR), the highest CO emissions occur at full engine load, while the lowest emissions are recorded at 60% engine load, as indicated in Figure 11a,b. This pattern is consistent with typical engine behavior,

as higher loads often lead to richer air-fuel mixtures and increased CO production. When comparing different fuels, diesel exhibits the highest CO emissions, with values of 0.122% at CR 18:1% and 0.188% at CR 17.5:1. Following diesel, the blend BV5 registers higher CO emissions. In contrast, pure biodiesel (BVD) demonstrates the lowest CO emissions, with values of 0.047% at CR 18:1% and 0.045% at CR 17.5:1. This marked difference in CO emissions is primarily attributed to the combustion characteristics of the fuels.

Biodiesel, such as BVD, tends to have lower CO emissions compared to diesel due to its complete oxidation process during combustion. Biodiesel has a higher oxygen content and better oxygen availability, leading to more thorough and cleaner combustion. In contrast, diesel combustion may result in incomplete oxidation, leading to the formation of CO. The reduction in CO emissions when using BVD compared to diesel is significant. At 60% engine load conditions on both CR 17.5:1 and 18:1, there is approximately a 64.3% and 64.4% decrease in CO emissions, respectively. At full load conditions, the decrease in CO emissions for BVD compared to diesel is approximately 60.2% and 61.5% for both CR. These findings underscore the environmental benefits of using biodiesel as a cleaner-burning alternative to diesel.

Furthermore, Figure 11a,b illustrates that CO emissions tend to be higher for all fuels at CR 18:1 compared to CR 17.5:1. This trend is consistent with the combustion characteristics associated with different compression ratios. Higher compression ratios often lead to higher combustion temperatures and pressures, which can influence the formation of pollutants like CO. Therefore, selecting an appropriate compression ratio is essential for achieving desired emission levels.

3.3.2 | CO_2 Emission of Fuels at CR 18:1 and 17.5:1

From the data presented in Figure 12a,b, it is evident that diesel fuel results in higher CO_2 emissions compared to biodiesel and biodiesel blends. Additionally, the highest CO_2 emissions are observed under full load conditions for all fuels. This correlation between engine load and CO_2 emissions is a typical observation in internal combustion engines. As engine load increases, more fuel is combusted to produce the required power output, leading to higher CO_2 emissions. One contributing factor to higher CO_2 emissions in diesel combustion is the formation of incomplete oxidation products. During high load conditions, excessive crankcase vapor can create incorrect positive crankcase ventilation, leading to the contamination of engine oil. This contamination can result in incomplete oxidation of fuel, contributing to elevated CO_2 emissions.

In contrast, biodiesel fuels, such as pure biodiesel (BVD), tend to exhibit lower CO_2 emissions due to the more complete oxidation process that occurs during combustion. Biodiesel's higher oxygen content and better oxygen availability promote thorough combustion, leading to reduced CO_2 emissions. Biodiesel's cleaner-burning characteristics make it an environmentally favorable alternative to diesel. The blend BV5 shows a unique behavior, with higher CO_2 emissions at 100% load conditions, specifically 9.9% at CR 18:1% and 8.8% at CR 17.5:1, as indicated in Figure 12. This behavior could be attributed to the specific composition and properties of the blend, which may affect the combustion process differently than pure biodiesel or diesel.

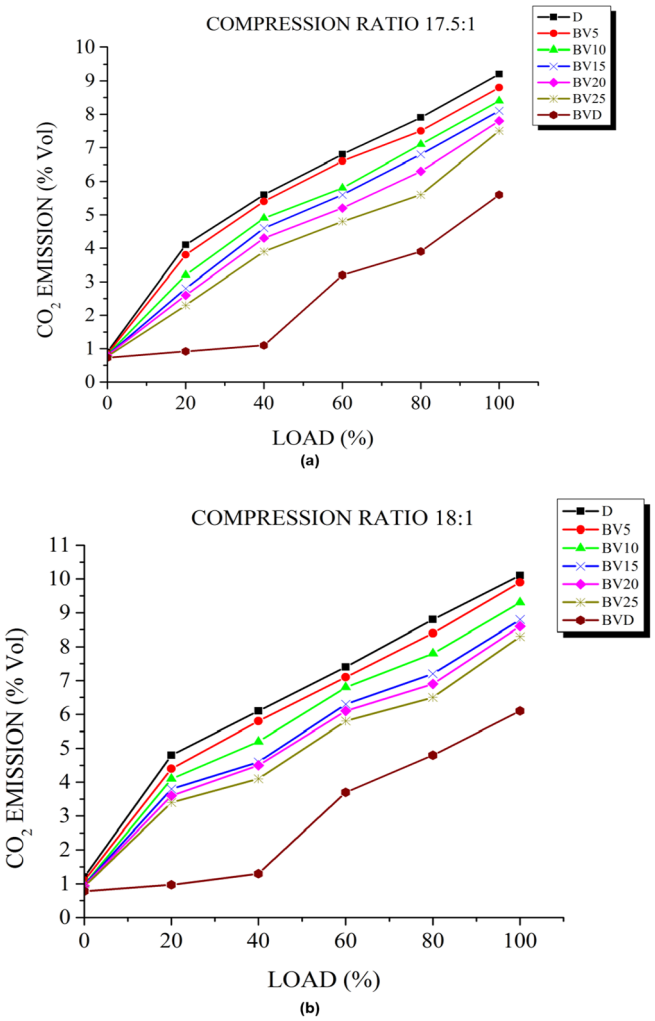


FIGURE 12 | CO_2 emission on different loads at (a) CR = 17.5:1, and (b) CR = 18:1.

Furthermore, the choice of compression ratio (CR) also influences CO_2 emissions. CR 17.5:1 results in lower CO_2emissions compared to CR 18:1. This difference is attributed to the combustion characteristics associated with different compression ratios. Lower compression ratios generally lead to lower combustion temperatures and pressures, which can influence the formation of CO_2. Quantitatively, the percentage decrease in CO_2 emissions of BVD compared to diesel is significant, highlighting the environmental advantages of using biodiesel. At CR 17.5:1 and 18:1 under zero load conditions, the decrease in CO_2 emissions for BVD compared to diesel is 81.1% and 65%, respectively. Under full load conditions, this decrease remains substantial, with a percentage decrease of 60.9% at CR 17.5:1% and 60.4% at CR 18:1. These Figures 12a,b emphasize the potential for biodiesel to significantly reduce CO_2 emissions and mitigate environmental impacts compared to diesel.

3.3.3 | NO_X Emission of Fuels at CR 18:1 and 17.5:1

Figure 13a,b illustrates that biodiesel, particularly pure biodiesel (BVD), tends to produce higher NO_x emissions compared to diesel fuel. This increase in NO_x emissions is attributed to the higher oxygen content present in biodiesel. Biodiesel fuels typically contain more oxygen atoms in their molecular structure, which can

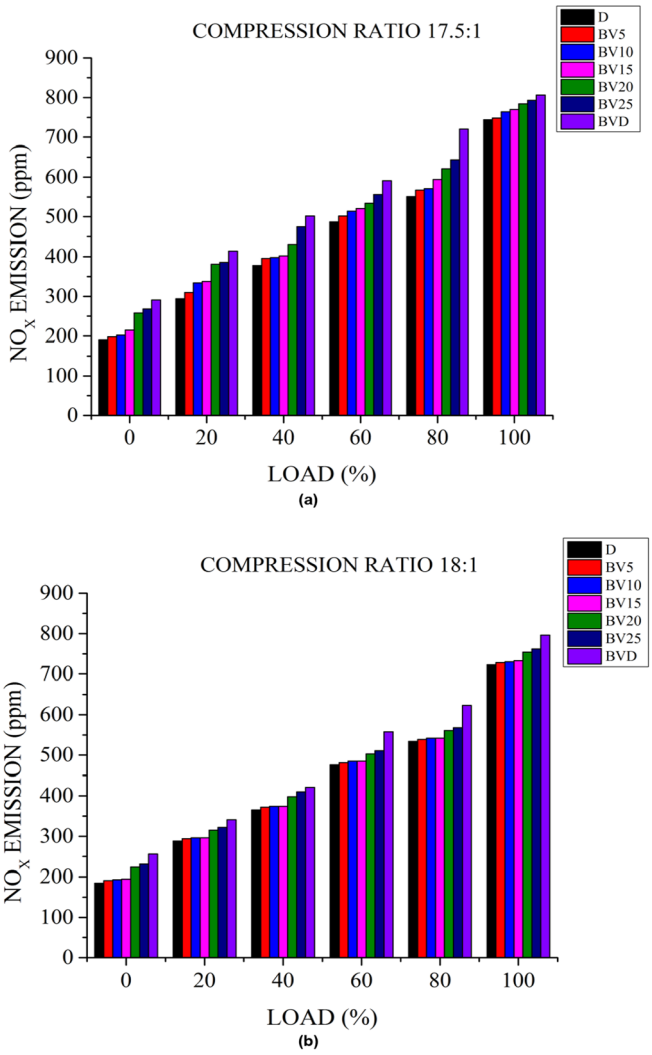


FIGURE 13 | NO_X emission on different loads at (a) CR = 17.5:1, and (b) CR = 18:1.

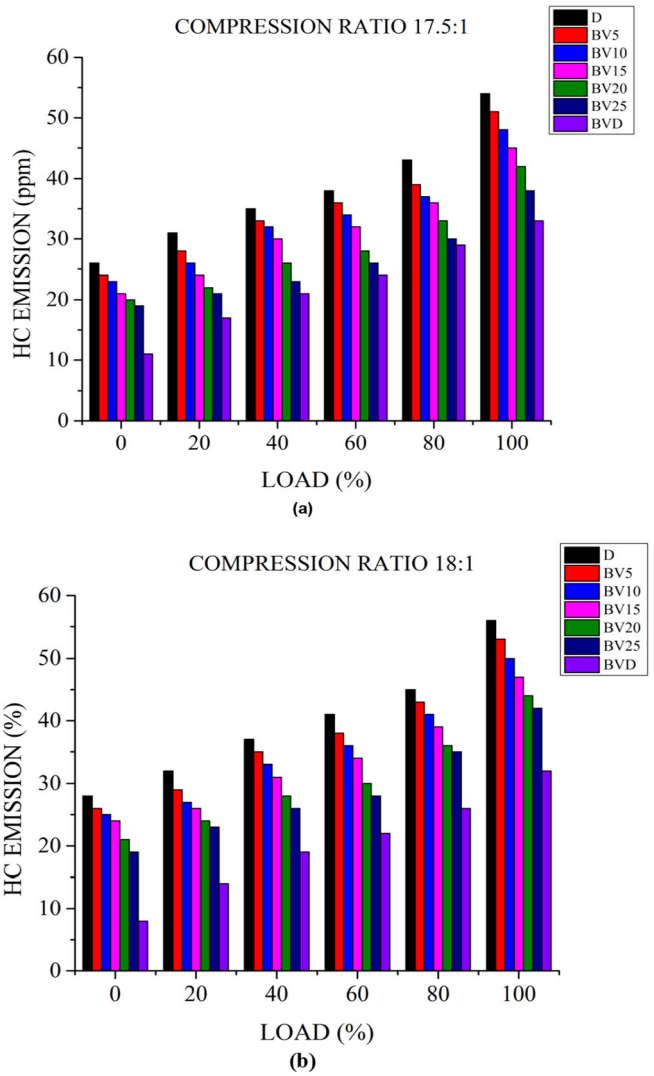


FIGURE 14 | HC emission on different loads at (a) CR = 17.5:1, and (b) CR = 18:1.

lead to increased NO_x formation during combustion. Among the biodiesel fuels studied, the blend BV5 exhibits lower NO_x emissions compared to pure biodiesel (BVD) in all load conditions and across different compression ratios (CR). This finding suggests that the presence of diesel in the blend may have a mitigating effect on NO_x emissions, bringing them closer to diesel levels.

As engine load increases, NO_x emissions tend to rise. This trend is linked to higher cylinder combustion temperatures and increased adiabatic flame temperatures at elevated engine loads. Higher temperatures promote greater NO_x formation during the combustion process. The key factor contributing to higher NO_x emissions in biodiesel combustion is the excess oxygen available in biodiesel molecules. After combustion, this excess oxygen has a tendency to react with nitrogen present in the air to form NO_x gases, leading to higher NO_x emissions.

Comparatively, diesel fuel exhibits lower NO_x emissions than biodiesel due to its lower oxygen content. Diesel fuel has a reduced potential for excess oxygen to react with nitrogen, resulting in fewer NO_x emissions. Quantitatively, the increase in NO_x emissions when using BVD compared to diesel is substantial. At CR 17.5:1 and 18:1 under zero load conditions, there is an increase of 65.3% and 72.3% in NOx emissions for BVD, respectively. Under full load conditions, the increase in NO_x emissions for BVD compared to diesel is even more pronounced, with a percentage increase of 90.3% at CR 17.5:1% and 90.8% at CR 18:1. These Figure 13a,b highlight the significant impact of biodiesel's higher oxygen content on NOx emissions.

Consistent with previous research findings, all types of biodiesel combustion produce higher NO_x emissions compared to diesel. Additionally, NO_x emissions tend to be higher at compression ratio (CR) 17.5:1 compared to CR 18:1. This trend aligns with the higher combustion temperatures associated with lower CR, which can promote greater NO_x formation [33, 34].

3.3.4 | HC Emission of Fuels at CR 18:1 and 17.5:1

Figure 14a,b depicts that unburned HC emissions are higher in diesel fuel compared to biodiesel, and these emissions are more pronounced at full load conditions for both compression ratios (CR). This pattern is consistent with typical engine behavior, as higher loads can result in richer air-fuel mixtures, increasing

the likelihood of incomplete combustion and elevated HC emissions. Specifically, diesel fuel exhibits HC emissions of 56 ppm at CR 18:1 and 54 ppm at CR 17.5:1 under 100% load conditions. As the blending ratio of biodiesel in the fuel increases, HC emissions tend to decrease. Notably, pure biodiesel (BVD) consistently demonstrates the lowest HC emissions, measuring 33 ppm at CR 18:1 and 31 ppm at CR 17.5:1 under full load conditions. The trend of decreasing HC emissions with increasing blending ratios is likely due to the improved combustion characteristics of biodiesel. Biodiesel typically contains more oxygen atoms, which enhance combustion efficiency and reduce the formation of unburned hydrocarbons.

Moreover, the choice of compression ratio (CR) also influences HC emissions, with higher CR leading to higher HC emissions. This trend is associated with higher combustion temperatures and pressures at elevated CR, which can promote the formation of HC emissions. Comparatively, when evaluating the reduction in HC emissions, biodiesel, including BVD, demonstrates a significant advantage over diesel. At zero load conditions on CR 17.5:1 and 18:1, there is a decrease of 42.3% and 28.6% in HC emissions compared to diesel, respectively. Under full load conditions, the decrease in HC emissions for BVD compared to diesel is even more substantial, with a reduction of 61.1% and 57.1% at both CR.

3.3.5 | Smoke Opacity of Fuels at CR 18:1 and 17.5:1

Figure 15a,b reveal that smoke opacity increases significantly for all fuels, including diesel, after reaching an engine load of 80% on both compression ratios (CR). This observation aligns with common engine behavior, as higher engine loads often lead to increased fuel consumption, resulting in a richer air-fuel mixture. A richer mixture can promote incomplete combustion, leading to higher levels of smoke emissions. The increase in smoke emissions with higher engine load is attributed to the altered combustion dynamics, which can lead to less efficient fuel-air mixing and combustion. Consequently, higher smoke opacity values are recorded under these conditions. One noteworthy finding is that all biodiesel fuels, including pure biodiesel (BVD), exhibit lower smoke emissions compared to diesel. This reduction in smoke opacity is primarily attributed to the chemical composition of biodiesel, which includes higher oxygen molecules and lower carbon content compared to diesel oil. These characteristics improve combustion efficiency, resulting in cleaner and more complete combustion.

Furthermore, the choice of compression ratio (CR) influences smoke opacity, with higher CR resulting in slightly higher smoke emissions. This trend is associated with the increased combustion temperatures and pressures associated with higher CR, which can influence the formation of particulate matter and smoke. Interestingly, the magnitude of the increase in smoke opacity between CR 18:1 and CR 17.5:1 is relatively small, suggesting that compression ratio choice does not significantly impact smoke emissions compared to other factors, such as engine load and fuel type. The maximum smoke opacity is typically observed for diesel fuel, consistent with its well-known characteristics for producing higher smoke emissions.

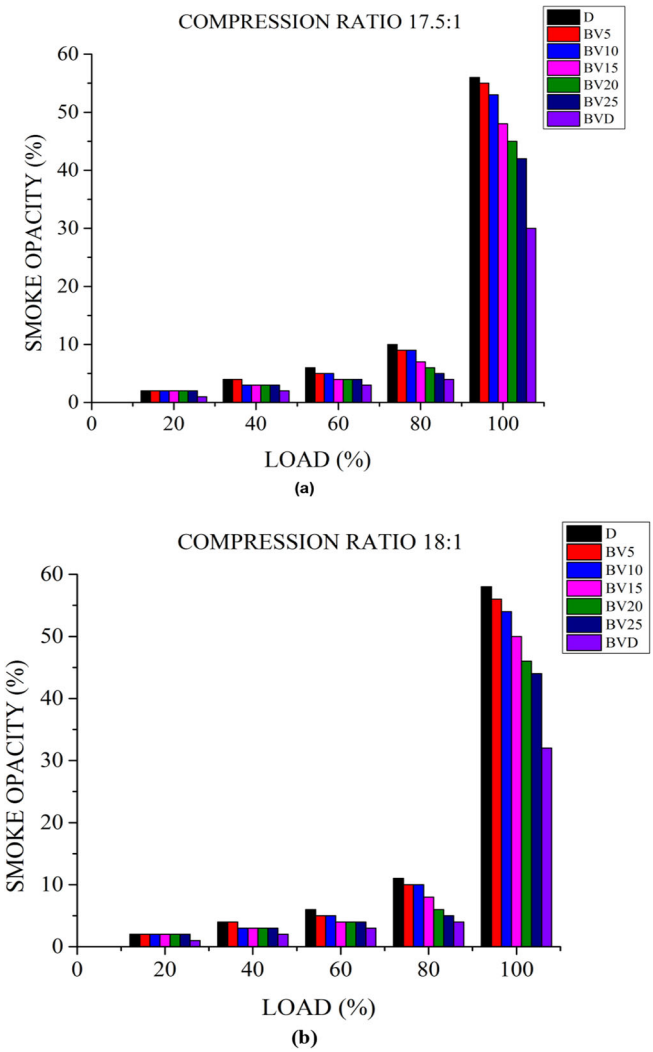


FIGURE 15 | Smoke opacity on different loads at (a) CR = 17.5:1, and (b) CR = 18:1.

As the blending ratio of biodiesel in the fuel increases, there is a notable reduction in smoke opacity. Pure biodiesel (BVD) consistently demonstrates the lowest smoke opacity values across all load conditions and CR.

Quantitatively, the decrease in smoke opacity when using BVD compared to diesel is substantial. Under full load conditions at both CR 17.5:1 and 18:1, there is a decrease of 53.6% and 55.2% in smoke opacity compared to diesel, respectively. In contrast, under zero load conditions for both CR, all fuels exhibited zero smoke opacity, indicating complete combustion and efficient combustion processes. The comparative analysis of various biodiesel blends—BV5, BV10, BV15, BV20, and BV25—with diesel and pure biodiesel (BVD) reveals important insights into their performance, combustion behavior, and emission characteristics. Each blend presents distinct advantages and limitations, which are critical when evaluating their practical viability as alternative fuels.

BV5 closely mirrors diesel in terms of performance, making it a potential substitute. However, it exhibits higher emissions of carbon monoxide (CO), carbon dioxide (CO_2), unburned hydrocarbons (HC), and smoke compared to other blends, which

raises environmental and health concerns despite its favorable performance metrics.

BV10 offers improved emission performance over BV5, with noticeable reductions in CO, CO_2, HC, and smoke. However, it shows an unusually low flash point, falling below the recommended safety threshold for biodiesel. This could increase the risk of accidental ignition during storage and handling, limiting its safe applicability.

BV15 stands out as the most balanced and efficient blend among those tested. It excels in fuel properties, combustion efficiency, and emissions across both tested compression ratios. BV15 meets key biodiesel quality standards, positioning it as a strong candidate for sustainable diesel replacement.

In contrast, **BV20** and **BV25** failed to meet several standard fuel property requirements. Their deviations from ideal biodiesel characteristics may negatively impact handling, storage, and engine performance, thereby reducing their suitability for widespread use.

4 | Conclusion

This study demonstrates the potential of *Bambusa vulgaris* biodiesel (BVD) and its blends as alternative fuels in compression ignition engines. Among the tested blends, BV15 offered the best balance of performance, combustion efficiency, and emission characteristics at both 17.5:1 and 18:1 compression ratios. While diesel fuel continues to show superior brake thermal efficiency and lower BSFC, BVD blends contribute significantly to reductions in harmful emissions such as CO, CO_2, HC, and smoke opacity. However, they also result in increased NO_x emissions.

The results confirm that BVD blends can be utilized in existing diesel engines without modification, promoting sustainability through reduced environmental impact and the use of a renewable feedstock. Future research should focus on optimizing engine parameters to reduce NOx emissions, evaluating long-term engine wear, and assessing the lifecycle emissions and economic viability of large-scale bamboo biodiesel production.

5 | Scope for Future Work

The current study was limited by the operational run time of the VCR engine, which ranged from 1 to 2 h. Future investigations should focus on extended-duration engine testing to evaluate the long-term performance, combustion stability, and emission characteristics of bamboo biodiesel and its blends. Additionally, a comprehensive tribological analysis of engine components can provide insights into wear behavior and lubrication performance when using biodiesel.

Given the elevated NOx emissions observed due to the high oxygen content in bamboo biodiesel, future work should explore effective emission control strategies. One promising approach is Selective Catalytic Reduction (SCR), which converts NO_x into nitrogen and water using a catalyst and a reducing agent such as ammonia. Investigating the application of SCR systems, including the use of lean NO_x catalysts and NO_x absorber catalysts, can help in mitigating NO_x emissions. These catalytic systems may also contribute to further reductions in CO and HC emissions. Exploring and optimizing such after-treatment technologies will enhance the environmental sustainability of bamboo biodiesel as a viable alternative fuel.

Author Contributions

Renjith Krishnan: writing – conceptualization, data curation, formal analysis, investigation, methodology, supervision. **Kavitha Mol S:** original draft, validation, supervision. **Prabhu Paramasivam:** software, writing – review and editing, supervision. **Abinet Gosaye Ayanie:** writing – review and editing, supervision, methodology.

Acknowledgements

The authors thank their respective institutions for their extended support throughout the research work.

Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The data used to support the findings of this study are included in the article. Should further data or information be required, these are available from the corresponding author upon request.

References

1. G. Knothe, "Biodiesel and Renewable Diesel: A Comparison," *Progress in Energy and Combustion Science* 36, no. 3 (2010): 364–373, https://doi.org/10.1016/j.pecs.2009.11.004.

2. A. E. Atabani, A. S. Silitonga, I. A. Badruddin, T. M. I. Mahlia, H. H. Masjuki, and S. Mekhilef, "A Comprehensive Review on Biodiesel as an Alternative Energy Resource and Its Characteristics," *Renewable and Sustainable Energy Reviews* 16, no. 4 (2012): 2070–2093, https://doi.org/10.1016/j.rser.2012.01.003.

3. S. Sivalakshmi and T. Balusamy, "Performance and Emission Characteristics of a CI Engine Fuelled With Biodiesel (Methyl Ester of Sesame Oil) and Its Blends With Diesel," *Renew Energy* 36, no. 5 (2011): 1314–1320, https://doi.org/10.1016/j.renene.2010.10.004.

4. N. Lakshmaiya, T. Raja, and D. Yuvarajan, "Sustainable High-Strength Composites: Hybrid Bamboo and Cellulose Reinforced Polyester for Automotive Engineering," *Journal of Bio- and Tribo-Corrosion* 11 (2025): 85, https://doi.org/10.1007/s40735-025-01011-x.

5. L. A. Raman, B. Deepanraj, S. Rajakumar, and V. Sivasubramanian, "Experimental Investigation on Performance, Combustion and Emission Analysis of a Direct Injection Diesel Engine Fuelled With Rapeseed Oil Biodiesel," *Fuel* 246 (2019): 69–74, https://doi.org/10.1016/j.fuel.2019.02.106.

6. P. Tamilselvan, N. Nallusamy, and S. Rajkumar, "A Comprehensive Review on Performance, Combustion and Emission Characteristics of Biodiesel Fuelled Diesel Engines," *Renewable and Sustainable Energy Reviews* 79 (2017): 1134–1159, https://doi.org/10.1016/j.rser.2017.05.176.

7. K. Azad and M. Rasul, "Performance and Combustion Analysis of Diesel Engine Fueled With Grape Seed and Waste Cooking Biodiesel," *Energy Procedia* 160 (2019): 340–347, https://doi.org/10.1016/j.egypro.2019.02.166.

8. K. S. Narayana, V. Kumar Padala, T. V. H. Rao, and S. V. U. Swararao, "Variable Compression Ratio Diesel Engine Performance Analysis," *International Journal of Engineering Trends and Technology* 28 (2015): 6–12, https://doi.org/10.14445/22315381/IJETT-V28P202.

9. A. Roy, Y. Dabhi, H. Brahmbhatt, and S. K. Chourasia, "Effect of Emulsified Fuel Based on Dual Blend of Castor–Jatropha Biodiesel on CI Engine Performance and Emissions," *Alexandria Engineering Journal* 60 (2021): 1981–1990, https://doi.org/10.1016/j.aej.2020.12.003.

10. A. K. Yadav, M. E. Khan, and A. Pal, "Kaner Biodiesel Production Through Hybrid Reactor and Its Performance Testing on a CI Engine at Different Compression Ratios," *Egyptian Journal of Petroleum* 26 (2017): 525–532, https://doi.org/10.1016/j.ejpe.2016.07.006.

11. Q. Ma, Q. Zhang, J. Liang, and C. Yang, "The Performance and Emissions Characteristics of Diesel/Biodiesel/Alcohol Blends in a Diesel Engine," *Energy Reports* 7 (2021): 1016–1024, https://doi.org/10.1016/j.egyr.2021.02.027.

12. G. Goga, B. S. Chauhan, S. K. Mahla, and H. M. Cho, "Performance and Emission Characteristics of Diesel Engine Fueled With Rice Bran Biodiesel and n-Butanol," *Energy Reports* 5 (2019): 78–83, https://doi.org/10.1016/j.egyr.2018.12.002.

13. P. Shrivastava, T. N. Verma, and A. Pugazhendhi, "An Experimental Evaluation of Engine Performance and Emisssion Characteristics of CI Engine Operated With Roselle and Karanja Biodiesel," *Fuel* 254 (2019): 115652, https://doi.org/10.1016/j.fuel.2019.115652.

14. S. H. Park, J. Cha, and C. S. Lee, "Impact of Biodiesel In Bioethanol Blended Diesel on the Engine Performance and Emissions Characteristics in Compression Ignition Engine," *Applied Energy* 99 (2012): 334–343, https://doi.org/10.1016/j.apenergy.2012.05.050.

15. K. Nanthagopal, B. Ashok, B. Saravanan, D. Patel, B. Sudarshan, and R. Aaditya Ramasamy, "An Assessment on the Effects of 1-Pentanol and 1-butanol as Additives With *Calophyllum inophyllum* Biodiesel," *Energy Conversion and Management* 158 (2018): 70–80, https://doi.org/10.1016/j.enconman.2017.12.048.

16. W. Tutak, A. Jamrozik, M. Pyrc, and M. Sobiepański, "Investigation on Combustion Process and Emissions Characteristic in Direct Injection Diesel Engine Powered by Wet Ethanol Using Blend Mode," *Fuel Processing Technology* 149 (2016): 86–95, https://doi.org/10.1016/j.fuproc.2016.04.009.

17. K. Cheenkachorn and B. Fungtammasan, "An Investigation of Diesel-Ethanol-Biodiesel Blends for Diesel Engine: Part 1. Emulsion Stability and Fuel Properties," *Energy Sources Part A: Recovery, Utilization, and Environmental Effects* 32, no. 7 (2010): 637–644, https://doi.org/10.1080/15567030903059608.

18. P. Sambandam, N. Punitha, K. Vijetha, et al., "Effect of Graphite Nanoadditives on the Behavior of a Diesel Engine Fueled With Pyrolysis Fuel Recovered From Used Plastics," *ACS Omega* 9, no. 38 (2024): 39584–39595, https://doi.org/10.1021/acsomega.4c03715.

19. V. Sakthimurugan, D. Yuvarajan, S. Ganesan, V. J. Upadhye, A. Gill, and N. kailiappan, "Investigation on Influence of Acetylene Enrichment in Diesel Engines Operating With Microalgae–Waste Plastic Oil–Heptane Fuel Mixture," *Energy Science & Engineering* 13, no. 6 (2025): 3107–3122, https://doi.org/10.1002/ese3.70089.

20. A. Uyumaz, B. Aydoğan, E. Yılmaz, et al., "Experimental Investigation on the Combustion, Performance and Exhaust Emission Characteristics of Poppy Oil Biodiesel–Diesel Dual Fuel Combustion in a CI Engine," *Fuel* 280 (2020): 118588, https://doi.org/10.1016/j.fuel.2020.118588.

21. A. Jain, B. J. Bora, R. Kumar, et al. "Conversion of Water Hyacinth Biomass to Biofuel With TiO_2 Nanoparticle Bblending: Exergy and Statistical Analysis," *Case Studies in Thermal Engineering* 67 (2025): 105771, https://doi.org/10.1016/j.csite.2025.105771.

22. V. Ganesan, J. S. Chohan, K. Gengappan, et al. "Mechanical and Structural Characterization of Curauá Fiber, Sugarcane Biochar, and Poly (Lactic Acid) Hybrid Green Composites for Sustainable Biomass Utilization," *Sugar Tech* (2025), https://doi.org/10.1007/s12355-025-01628-9.

23. R. Zanzi, K. Sjöström, and E. Björnbom, "Rapid Pyrolysis of Agricultural Residues at High Temperature," *Biomass and Bioenergy* 23, no. 5 (2002): 357–366, https://doi.org/10.1016/S0961-9534(02)00061-2.

24. P. Weerachanchai, C. Tangsathitkulchai, and M. Tangsathitkulchai, "Characterization of Products From Slow Pyrolysis of Palm Kernel Cake and Cassava Pulp Residue," *Korean Journal of Chemical Engineering* 28, no. 1 (2011): 2262–2274, https://doi.org/10.1007/s11814-011-0116-3.

25. D. Wüst, C. R. Correa, D. Jung, et al, "Understanding the Influence of Biomass Particle Size and Reaction Medium on the Formation Pathways of Hydrochar," *Biomass Convers Biorefinery* 10 (2019): 1357–1380, https://doi.org/10.1007/s13399-019-00488-0.

26. M. Ståhl, K. Granström, J. Berghel, and R. Renström, "Industrial Processes for Biomass Drying and Their Effects on the Quality Properties of Wood Pellets," *Biomass and Bioenergy* 27, no. 6 (2004): 621–628, https://doi.org/10.1016/j.biombioe.2003.08.019.

27. N. Fernando, M. Narayana, and W. A. M. K. P. Wickramaarachchi, "The Effects of Air Velocity, Temperature and Particle Size on Low-Temperature Bed Drying of Wood Chips," *Biomass Conversion and Biorefinery* 8, no. 2 (2018): 211–223, https://doi.org/10.1007/s13399-017-0257-7.

28. C. Di Blasi, E. G. Hernandez, and A. Santoro, "Radiative Pyrolysis of Single Moist Wood Particles," *Industrial & Engineering Chemistry Research* 39, no. 3 (2000): 873–882, https://doi.org/10.1021/ie990720i.

29. R. Krishnan, L. Hauchhum, R. Gupta, and G. Gopan, "Production and Characterisation of Biodiesel Extracted From Indian Bamboos," *International Journal of Oil, Gas and Coal Technology* 31 (2022): 316–329, https://doi.org/10.1504/IJOGCT.2022.126358.

30. T. Wang, G. Zhou, J. Wang, and T. Chen, "Statistical Characteristics and Probabilistic Analysis of Uncertain Settlement of Subgrade in Permafrost Regions," *Cold Regions Science and Technology* 175 (2020): 103079, https://doi.org/10.1016/j.coldregions.2020.103079.

31. J. Cui, Z. H. Zhao, J. W. Liu, P. X. Hu, R. N. Zhou, and G. X. Ren, "Uncertainty Analysis of Mechanical Dynamics by Combining Response Surface Method With Signal Decomposition Technique," *Mechanical Systems and Signal Processing* 158 (2021): 107570, https://doi.org/10.1016/j.ymssp.2020.107570.

32. M. V. Kulikova and G. Y. Kulikov, "The J-Orthogonal Square-Root MATLAB-Based Continuous-Discrete Unscented Kalman Filtering Method," *IFAC-PapersOnLine* 53, no. 2 (2020): 4967–4972, https://doi.org/10.1016/j.ifacol.2020.12.1083.

33. K. A. Abed, A. K. El Morsi, M. M. Sayed, A. A. E. Shaib, and M. S. Gad, "Effect of Waste Cooking-Oil Biodiesel on Performance and Exhaust Emissions of a Diesel Engine," *Egyptian Journal of Petroleum* 27, no. 4 (2018): 985–989, https://doi.org/10.1016/j.ejpe.2018.02.008.

34. M. S. Gad, R. El-Araby, K. A. Abed, N. N. El-Ibiari, A. K. El Morsi, and G. I. El-Diwani, "Performance and Emissions Characteristics of C.I. Engine Fueled With Palm Oil/Palm Oil Methyl Ester Blended With Diesel Fuel," *Egyptian Journal of Petroleum* 27, no. 2 (2018): 215–219, https://doi.org/10.1016/j.ejpe.2017.05.009.