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Research Article

Thermodynamic Analysis of CRDI-VCR Type Diesel Engine Fueled with Moringa Oleifera Biodiesel

Vasant Patel [a] *, **Vyomesh Buch** [b]

[a] *Faculty of Engineering and Technology, Parul University, Vadodara, 391760, India*

[b] *Parul Institute of Technology, Parul University, Vadodara, 391760, India*

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ABSTRACT

The purpose of the present study is to examine the impact of Compression Ratio (CR) on energy and exergy efficiency of a Variable Compression Ratio (VCR) and Common Rail Direct Injection (CRDI) type diesel engine powered by a blend of diesel and biodiesel from Moringa oleifera. Experiments are performed at four distinct CRs of 15:1, 16:1, 17:1, and 18:1 at 100% loading condition with a fixed engine speed of 1500 rpm, Injection Timing (IT) of 23°before top dead center (bTDC), and Injection Pressure (IP) of 600 bar. Analysis was done on the energy and exergy potential of the fuel input, cooling water, exhaust gas, first and second law efficiency, entropy generation, and Sustainability Index (SI). The energy analysis results show that for all tested fuel blends, an increase in CR results in a decrease in fuel inlet energy, exhaust gas energy, and unaccounted losses, as well as an increase in cooling water energy and energy efficiency. The highest energy efficiency reported for the diesel and biodiesel blend MB30 was 27.20% and 28.13%, respectively, at a higher CR of 18:1. The maximum cooling water energy reported for diesel and biodiesel blend MB30 was 4.09 kW and 4.36 kW, respectively, at a higher CR of 18:1. The reported minimum energy of the exhaust gases for the diesel was 2.74 kW and for biodiesel blends MB10, and MB20 it was reported as 2.95 kW for both blends at a higher CR of 18:1. Across all tested fuel blends, the fuel exergy rate, exergy rate of exhaust gas, and destructed energy decrease as CR increases which results in improvements in entropy generation, SI, and exergy efficiency. The highest exergy efficiency reported for the diesel and biodiesel blend MB30 was 26.31% and 27.21%, respectively, at a higher CR of 18:1. The maximum SI reported for the diesel and biodiesel blend MB30 was 1.36 and 1.37respectively at a higher CR of 18:1. The minimum entropy generation reported for diesel and biodiesel blend MB30 was 0.019kW/K and 0.016 kW/K at higher CR of 18:1.An investigation of the thermodynamics of methyl esters of Moringa oleifera oil mixed with diesel in a VCR-CRDI type engine shows that the combination consists of CR 18:1 and fuel blend MB30 at full load condition offers better performance.

1. Introduction

Diesel engines exerted a substantial influence on the energy and power industries. Diesel engines provide power effectively and dependably at a cheap cost, with minimum requirements. Diesel engines are utilized in several industries, including pumping, construction, transportation, power generation, maritime, and defense sectors. In India, most agricultural machinery relies on diesel fuel for

* **Corresponding author.**
E-mail address: *vasant_073@yahoo.co.in*

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both mobile and fixed functions. Diesel engines are mostly preferred for their capacity to function with little to no modification required for the utilization of alternative fuels like biodiesel and biogas. It is essential to regulate diesel engine emissions adequately to meet regulatory standards [1, 2]. Biodiesels, sourced from both consumable and non-consumable oils, have significant potential as renewable resources. They can substantially reduce emissions when utilized under authorized operational settings. The energy and exergy analysis proved to be an effective and attractive approach for enhancing the performance of internal combustion engines. Internal combustion engines are often analyzed using the first law of thermodynamics and mass-energy balance principles, which just identify heat energy transfer or losses, failing to recognize energy degradation resulting from irreversible losses or their specific locations. An exergy-based analysis can provide detailed insights into irreversibility and identify the specific areas of losses. "Exergy" is the quantification of the maximum work that can be extracted when a system attains equilibrium with its environment.

Kavitha et al. [3] investigated the impact of engine load on energy and exergy efficiency using ternary fuel blends of diesel, ethanol, and jatropha biodiesel in a single-cylinder, CRDI-VCR type engine. Their results indicated that the fuel blend D95J3.75E1.25 resulted in the lowest unaccounted losses and entropy generation, whereas the blend D98J1.5E0.5 achieved the highest second law efficiency among all tested fuels. Similarly, Golmohammad Khoobbakht et al. [4] explored the energy and exergy performance of a multi-cylinder diesel engine using diesel, ethanol, and biodiesel blends at varying loads and speeds. They found that increasing the biodiesel and ethanol content, along with operating parameters such as load and speed, enhanced the second law efficiency of an engine. The blend D80B14E06, tested at 1900 rpm and 94% load, yielded a maximum energy efficiency of 36.92%. BengiGozmenSanli et al. [5] compared the energy and exergetic performance of a diesel engine fueled with conventional diesel and methyl esters of hazelnut and canola. They observed that the highest thermal and energy efficiencies for all fuels occurred at 1800 rpm. The least amount of exergy destruction was also noted at this speed, with values of 45.45% for diesel, 47.36% for hazelnut biodiesel, and 47.41% for canola biodiesel. Moreover, the rate of entropy generation was minimized at 1800 rpm for all tested fuels.

Murat Kadir et al. [6] studied the energy and exergy efficiencies of a diesel engine at different injection pressures. The engine was powered by a combination of diesel fuel and biodiesel derived from a mixture of recycled cooking oil and canola oil. The diesel-powered engine had superior energy and exergy efficiencies while operating at the initial injection pressure of 190 bar. Conversely, the biodiesel-powered engine exhibited the highest energy and exergy efficiencies when operating at an injection pressure of 210 bar. Enhanced efficiency can be achieved with biodiesel, especially when utilizing elevated injection pressures. S. Murugapoopathi et. al. [7] performed theoretical energy and exergy evaluations on a VCR type engine that was powered with a rubber seed methyl ester and diesel. The objective is to determine the most favorable engine configurations by considering the compression ratio and biodiesel mixtures. The research indicates that the optimal outcome is achieved when using a compression ratio of 20:1 in conjunction with biodiesel blends containing 20% and 40% biodiesel by volume at 80% load.

Nabnit Panigrahi et al. [8] evaluated diesel engine performance using diesel and simarouba biodiesel. The result of energy analysis shows that diesel converts 37.23% of input energy into usable capacity, while the SB20 blend achieves 37.79%. The exergetic efficiency was 34.8% for diesel and 35% for simarouba biodiesel. Selcuk Sarıkoc et al. [9] investigated the effects of biodiesel and butanol properties on the energy and exergy efficiencies, as well as the sustainability, of a single-cylinder, naturally aspirated, water-cooled diesel engine. The investigation demonstrated that biodiesel when compared to Euro diesel, had superior energy and exergetic efficiency, as well as a higher sustainability index. This was achieved by utilizing different combinations of diesel, biodiesel, and butanol. Blends with lower ratios of butanol demonstrated comparable performance and sustainability measures to Euro diesel. However, these metrics deteriorated as the butanol ratios increased. Murat Kadir Yesilyurt [10] conducts research on a single-cylinder, direct-injection type CI engine that runs on Peanut oil biodiesel and conventional diesel fuel. The engine is tested at different loads (ranging from 25% to 100%) while keeping a constant speed of 1500 rpm. Both diesel fuel and biodiesel demonstrated the highest levels of energy efficiency and exergy efficiency and the lowest levels of exergy destruction under full load conditions.

In a study conducted by Sedigheh Karami et al. [11], nano-particles of cerium oxide were added to a diesel and biodiesel blend in varying amounts. The researchers discovered that increasing the concentration of these nano-particles in the blend enhanced the thermal performance of an engine and exergy efficiency.

In their study, Karagoz et al. [12] examined the impact of incorporating nano-particles on the exergetic performance and sustainability of the engine. They discovered that the addition of aluminum oxide nano-particles to diesel and biodiesel resulted in enhanced exergy performance and sustainability index.

The cited research indicates that several operational parameters, such as engine speed, load, compression ratio, injection pressure, and fuel characteristics, influence the energy and exergy performance of an engine. Current literature demonstrates that research primarily focuses on examining the impact of engine speeds and loads on the energy and exergy performance of internal combustion engines. A lack of study exists about the effects of compression ratio, injection pressure, and injection time on the energy and exergy performance of an engine. An experimental study on the VCR-CRDI type diesel engine is essential to evaluate the impact of compression ratio on the engine's energy and exergy efficiency.

The primary objective of this experimental study is to provide insight into the impact of CR on entropy production, exergy efficiency, sustainability index, and energy efficiency. The experiment was conducted on a CRDI-VCR type, single-cylinder diesel engine utilizing a blend of pure diesel and biodiesel mixtures sourced from Moringa oleifera (MB10, MB20, and MB30). The experimental investigation was conducted at four distinct compression ratios: 15:1, 16:1, 17:1, and 18:1, under a 100% loading situation, with a constant engine speed of 1500 rpm, an injection timing of 23° before the top dead center, and an injection pressure of 600 bar.

2. Material and Methods

2.1. Biodiesel Production from Moringaoleifera Oil

Tamil Nadu, Karnataka, Kerala, and Andhra Pradesh are the main growing regions for Moringa in southern India, with Andhra Pradesh being the leading producer. Moringa oleifera seeds contain oil, approximately 35% of its weight[13]. Moringa oleifera biodiesel is produced from the Moringa oil using the single-step trans-esterification process. The mixing of catalyst KOH (1% w/w of Moringa oil) and methanol (methanol to Moringa oil molar ratio: 5.5:1) is carried out using a laboratory stirrer at a stirring speed of 1400 rpm for 15 minutes. The methanol solution of potassium hydroxide with Moringa oleifera oil was poured into three neck flask of the magnetic stirrer to carry out the trans-esterification reaction. The reaction occurs at a temperature of 60°C-65°C for the duration of 60 minutes at a stirring speed of 600 rpm. After the trans-esterification reaction is complete, the resulting mixture, which contains both biodiesel and glycerin, is poured into a separation funnel to settle down for 12 hours to separate the biodiesel from the glycerin[14]. After the separation, biodiesel was washed with warm water. This washing process is done to remove any remaining glycerin, catalyst residue, or impurities from the biodiesel. After washing, the methyl ester may still contain some water, and to remove it, the methyl ester is heated up to 105°C. Water vaporizes at this temperature, leaving behind pure biodiesel. The process of biodiesel preparation from the Moringa oil is shown in Fig. 1.

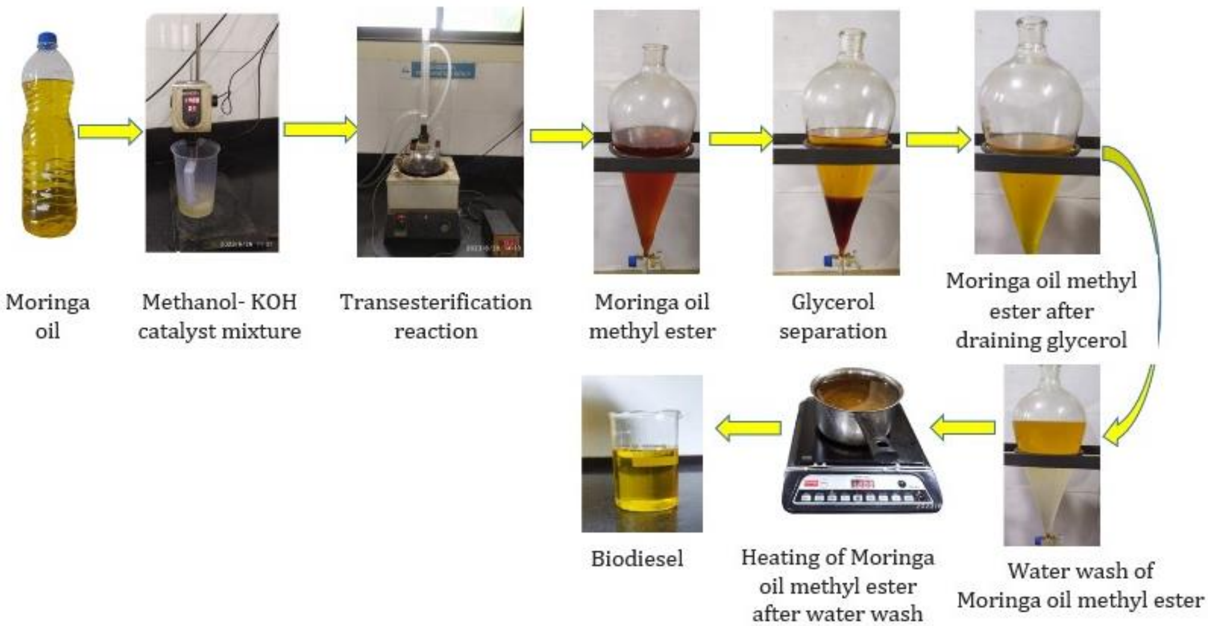


Fig. 1. Process of biodiesel production from Moringa oleifera oil

The physio-chemical properties of the diesel, Moringa oleifera oil, and Moring oleifera biodiesel blends used in the experimental work shown in Table 1. It also shows that the value of different properties fulfills the limit set by the ASTM standards.

Table 1. Physio-Chemical properties of fuel blends

Property	ASTM Standard	Diesel	MB100	MB10	MB20	MB30	Limits as per ASTM Standard
Acid Value (mg of KOH/gm of oil)	D 6751	0.03	0.41	0.06	0.09	0.15	Max 0.5
FFA (%)	---	0.02	0.21	0.03	0.05	0.08	----
Calorific Value (kJ/kg)	D 4809	42987	40005	42731	42433	42134	----
Flash Point (^oC)	D 93-58 T	53	135	62	70	78	Min 1300C
Density (kg/m^3)	D 287	816	874	829	834	838	870-890
Kinematic Viscosity @ 40°C (cSt)	D 445	2.09	4.03	2.31	2.50	2.70	1.9-6
Dynamic Viscosity @ 40°C (cP)	D 445	1.73	3.52	1.93	2.1	2.28	----

2.2. Experimental Setup

The CRDI-VCR type, single-cylinder, 4-stroke diesel engine installed at Apex Innovations Ltd., Sangli, Maharashtra, was used to perform the experiment. The experiment measurements were started once the engine and other measuring instruments installed achieved the steady state condition. Fig. 2 illustrates the schematic layout of the experiment setup. The setup is provided with a separate control panel with two fuel tanks and an air-tank, along with the transmitter for detecting the fuel and air flow.

The cooling water flow to the engine and calorimeter is measured by rotameters. The setup is equipped with the lab-view based “Enginesoft” software package used for online performance assessment and to collect, monitor, and analyze the experiment data. “Enginesoft” is used to estimate various parameters of performance tests such as the efficiency of an engine, consumption of fuel and air, heat release, and power developed by an engine.

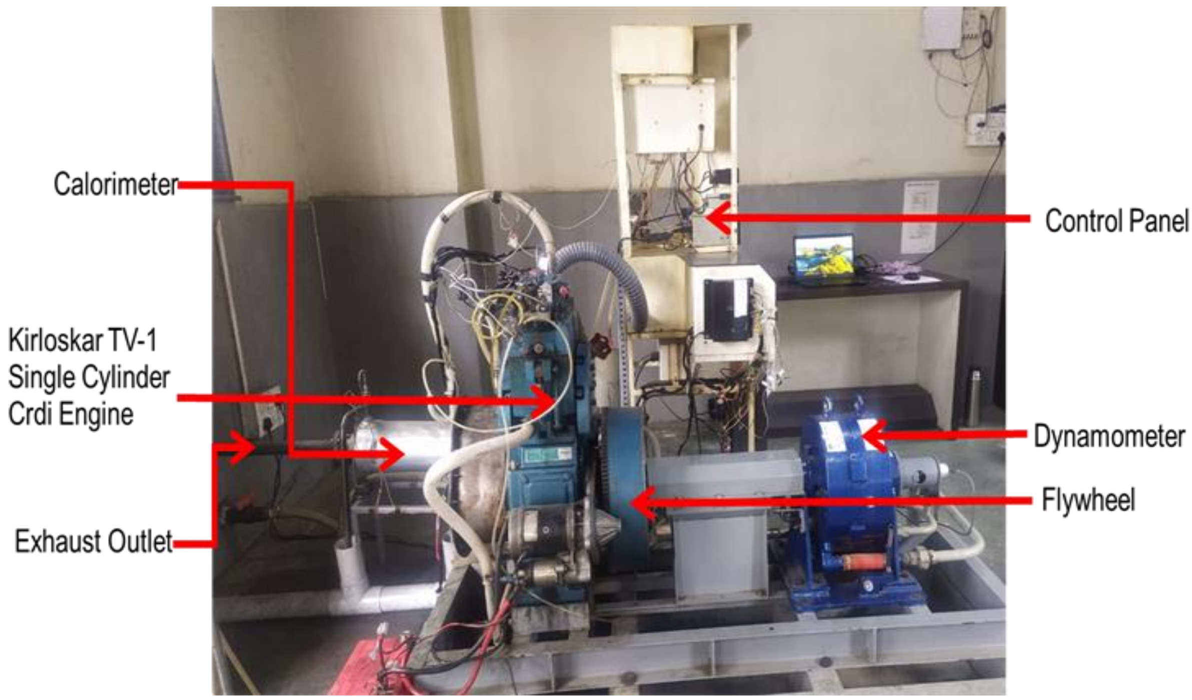


Fig. 2. Schematic layout of the experiment setup

The primary specification of an engine is shown in Table 2.

Table 2. Specification of the engine

Engine Parameters	Specification
Engine manufacturer and model	Kirloskar, TV1
Engine type	VCR-CRDI type CI engine
No of cylinder and stroke	1-cylinder and 4-stroke
Engine cooling system	Water-cooled engine
Stroke length (mm)	110
Bore diameter (mm)	87.5
CR	12:1 to 18:1
Dynamometer	Eddy current type
Rated power output (kW)	3.5

The analyses of emissions from the engine were conducted right after the combustion chamber to monitor changes subsequent to the combustion process. AVL made a five-gas analyzer (Model-Digas444N) used to measure exhaust emissions.

2.3. Uncertainty Analysis

The experiments must be carried out in conditions that are known in order to determine the error of the measurement apparatus. To estimate the overall measurement uncertainty, it is necessary to determine the sources of measurement error and the magnitude of each of them [15]. There are two kinds of errors in measuring apparatus: bias and precision. The errors that remain constant throughout the experiment are referred to as bias errors, which can only be removed through calibration. Many experimental study results are dependent on multiple independent parameters, making them difficult to quantify directly. In this situation, the total result's cumulative uncertainty needs to be calculated[16].

Uncertainty of experiment= Square root of ((uncertainty of energy efficiency)^2+ (uncertainty of exergy efficiency) ^{2} + (uncertainty of heat loss)^2 +(uncertainty of exhaust loss)^2)= $((1.49)^2 + (1.49)^2 + (0.01)^2 + (2.38)^2)^{0.5} = \pm 3.18$ %

3. Estimating Engine Performance

Energy efficiency and balance were examined using the first law of thermodynamics. The entire engine was modeled as a steady-state open system with a control volume for calculations involving energy and exergy. Exhaust gases, mechanical work, and heat loss left the control volume as fuel and air mixture entered.

The following assumptions were made to simplify the calculation procedure.

- The combustion exhaust gases and air were considered perfect gas mixtures.
- The system was open; the reference state was specified as T_0 = 27°C and P_0 = 1 atm.
- The kinetic and potential energy on the fluid streams entering and exiting were neglected.

An engine receives energy in the form of its fuel's heat value. Only a small percentage of this energy is converted into purposeful work, with the rest being wasted or put to better use. The two main sources of heat that are unusable for work are the heat carried away by exhaust gases and the cooling medium.

3.1. Energy Analysis

The energy input in internal combustion engines plays a crucial role in enhancing fuel efficiency, minimizing emissions, and optimizing engine performance across diverse applications. The energy supplied to the engine is the product of the mass flow rate of the fuel and the lower heating value of the fuel, which can be expressed as;

$$E_{inlet}=m_{fuel}*LHV_{fuel} \quad (1)$$

where E_{inlet}= energy supplied (kW), m_{fuel}=fuel's mass flow rate (kg/s), LHV_{fuel}= lower heating value of the fuel (kJ/kg).

Brake power represents the exact power output attainable at the engine's crankshaft that can be utilized to carry out productive work. , which can be expressed as;

$$BP= 2\pi NT/60000 \quad (2)$$

where N= crankshaft RPM, T= resisting torque (Nm).

The energy of the cooling water in an internal combustion engine is essential for ensuring optimal engine performance, durability, and safety. The energy associated with cooling water pertains to the heat energy extracted from the engine by the cooling system, which is typically water-based. The following formula can be used to estimate the amount of heat removed by the engine jacket cooling water:

$$Q_{cw}=m_{cw}*C_{pw}*(T_{cwout} - T_{cwin}) \quad (3)$$

where Q_{cw}=cooling water heat loss (kW), m_{cw} =cooling water's mass flow rate (kg/s), C_{pw}= specific heat of cooling water (kJ/kg -K), $T_{cwin}$and T_{cwout}= cooling water temperature at the entry and exit of engine jacket (K).

The calculation of exhaust gas energy in an internal combustion engine is essential for comprehending engine performance, efficiency, and opportunities for energy recovery. Exhaust gas energy denotes the segment of energy derived from fuel combustion that is expelled by the exhaust gases as heat. The calculation of this energy carries important consequences for the design, optimization, and environmental effects of engines. The following formula was used to quantify the energy lost with the exhaust gases Qexhaust:

$$Q_{exhaust}=m_g*C_{pg}*(T_{exh}-T_{atm}) \tag{4}$$

where $Q_{exhaust}$=heat dissipated by exhaust gases (kW), C_{pg}= specific heat of exhaust gas (kJ/kg-K), m_g= mass flow rate of exhaust gases (kg/s), T_{exh} and T_{atm}=temperature of the exhaust gases and atmosphere (K).

3.2. Exergy Analysis

Thermal systems undergo exergy analysis to determine the order of exergy losses and destructions in the system components and operations. This process increases the utilization of energy sources. Fuel supply availability (Ain) is translated into coolant water availability (Acw), exhaust gas availability (Aex), shaft availability (As), and destroyed availability (Ad). These formulas are used to calculate these parameters.

The fuel exergy rate refers to the amount of available energy from the fuel that can theoretically be converted into useful work. The exergy rate of the fuel energy (inlet availability) of the engine (Ain) is equal to:

$$A_{in}= \phi* \text{Einlet} \tag{5}$$

where ϕ= chemical exergy factor, E_{inlet}= energy supplied to the engine (kW).

The shaft availability (A_s) is to be considered the same as the brake power developed by the engine.

The exergy rate of cooling water in an IC engine refers to the quantity of energy within the cooling water that can theoretically be transformed into useful work instead of simply being lost as waste heat. The exergy rate of the cooling water is expressed as:

$$A_{cw}= Q_{cw}-m_{cw}*C_{pcw}*T_{atm}*\ln\left(\frac{T_{cwout}}{T_{cwin}}\right) \tag{6}$$

where Q_{cw}=cooling water heat loss (kW), m_{cw} =cooling water's mass flow rate (kg/s), C_{pcw}= specific heat of cooling water (kJ/kg -K), T_{cwin} and T_{cwout}= cooling water temperature at the inlet and exit of engine jacket (K), T_{atm}=ambient temperature (K).

The examination and enhancement of the exhaust gas exergy rate, professionals can create engines that exhibit greater efficiency, environmental sustainability, and economic viability, leading to decreased energy waste and emissions while improving overall performance. The exergy rate of the exhaust gas can be estimated as,

$$A_{exhaust}=Q_{exhaust}+\{m_g*C_{pg}*T_{atm}*\ln\left(\frac{T_{exhaust}}{T_{atm}}\right) -R_{exh}*\ln\left(\frac{P_{exhaust}}{P_{atm}}\right)\} \tag{7}$$

where $A_{exhaust}$=exergy rate of the exhaust gases, $Q_{exhaust}$= heat carried away by the exhaust gases (kW), C_{pg}= specific heat of exhaust gas (kJ/kg-K), m_g= mass flow rate of exhaust gases (kg/s), T_{exh} and T_{atm}= temperature of the exhaust gases and atmosphere (K), $P_{exhaust}$ and P_{atm}= pressure of the exhaust gas at the exit and atmosphere (bar).

Exergy destruction arises from the irreversibility that is intrinsic to actual processes, including inefficiencies in combustion, friction, heat transfer, and mixing. The presence of these irreversibility results in a diminished capacity to execute beneficial work. Assessing the lost available energy is crucial for pinpointing the areas and extent of energy loss from the fuel, which may lead to strategies to minimize inefficiencies and enhance the overall performance of the engine. The rate of the energy distruction is expressed as,

$$A_d= A_{in}- (A_s+A_{cw}+A_{exhaust}) \tag{8}$$

In comparison to first law efficiency, exergetic efficiency provides a more precise assessment of the system's performance by addressing the issue of "how much of the fuel exergy is converted into power." The exergetic efficiency can be computed as follows, where it is defined as the brake power exergy divided by the fuel exergy required to control the volume.,

$$\eta_{II}=\left(\frac{A_{sw}}{A_{in}}\right) \tag{9}$$

where A_{sw}= brake power exergy, A_{in}= fuel exergy at the inlet.

Entropy generation arises from irreversible processes, including friction, heat transfer, and chemical reactions (such as combustion) occurring within the engine. The aforementioned processes diminish the engine's capacity to transform energy into productive work. High entropy generation signifies that a considerable amount of the fuel's energy is dissipated in ways that are irretrievable, including waste heat. The entropy generation rate, used to evaluate system performance, is defined as the ratio of the destroyed available energy to the temperature, as given in the equation.

$$\text{Entropy generation} = \left(\frac{A_d}{T_0}\right) \quad (10)$$

The sustainability index acts as a thorough measure that assesses the enduring environmental and economic feasibility of IC engines, promoting the advancement of engines that are cleaner, more efficient, and in harmony with worldwide sustainability initiatives. The sustainability index can be mathematically represented by the equation above and is dependent on the level of energy efficiency.

$$\text{Sustainabilty index} = \left(\frac{1}{1-\eta_{II}}\right) \quad (11)$$

4. Result and Discussion

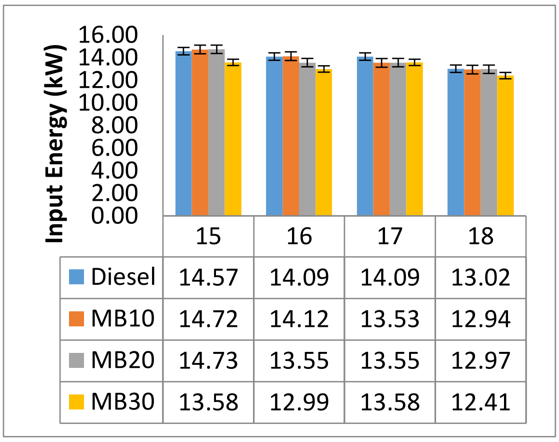
For the various fuel blends of diesel and Moringa oleifera biodiesel, the effect of the CR on the energy and exergy performance of a diesel engine has been examined. In the energy analysis section, the effects of CR and fuel blends were investigated for a range of parameters, such as fuel input energy, cooling water, exhaust energy, unaccounted losses, and energy efficiency. Similar to this, the effects of CR and fuel blends were investigated for the exergy rate of fuel, cooling water, and exhaust energy, exergy efficiency, entropy generation, and sustainably index in the exergy analysis section.

4.1. Energy Analysis

Based on the first law of thermodynamics, energy analysis of internal combustion engines has been used to measure the different amounts of chemical energy in the fuel that are converted to work, heat, or lost to the environment during the exhaust process. The x-axis of all the graphs in the energy and exergy analysis section represents the compression ratio.

4.1.1. Energy Input

The mass flow rate and LHV of the fuel fed to the engine multiply to produce the energy supplied to the engine. [17].



	15	16	17	18
Diesel	14.57	14.09	14.09	13.02
MB10	14.72	14.12	13.53	12.94
MB20	14.73	13.55	13.55	12.97
MB30	13.58	12.99	13.58	12.41

Fig. 3. Variation in input energy for different fuel bends at different CR

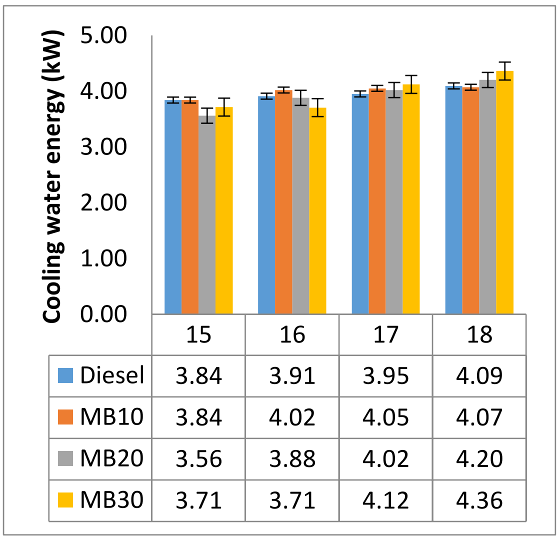
Fig. 3 shows the change in input energy with the CRs for the different fuel blends at full load conditions. The results demonstrate that an increase in CR results in a reduction of energy consumption across all fuel mixtures. For a compression ratio of 18:1, fuel blends diesel, MB10, MB20, and MB30 require minimal energy inputs of 13.02, 12.94, 12.97, and 12.41 kW, respectively.

This results from the positive association between CR and BTE, whereby a rise in CR corresponds with an increase in BTE. Consequently, the amount of fuel used to produce a specific level of power output is decreased. Additionally, the increased pressure and temperature in the combustion chamber resulting from a higher compression ratio accelerates fuel evaporation and promotes more complete combustion [23].

Furthermore, the results demonstrate that biodiesel blends with higher compression ratios (17:1 and 18:1) require less energy input than diesel. The energy intake for biodiesel blends MB10, MB20, and MB30 decreased by 0.6%, 0.4%, and 4.68%, respectively, in comparison to diesel fuel at a compression ratio of 18:1. Correspondingly, at a compression ratio of 17:1, the energy input diminished by 3.97%, 3.83%, and 3.61%, respectively. This is due to the fact that biodiesel contains inherent oxygen and possesses a higher cetane number, which reduces ignition time and improves combustion efficiency at elevated compression ratios [18].

4.1.2. Cooling Water Energy

The four-stroke diesel engine is equipped with a cooling system to achieve the best performance of an engine. The engine needs to release heat to run smoothly. Traditionally, liquid coolant is used in radiators to remove heat [19].



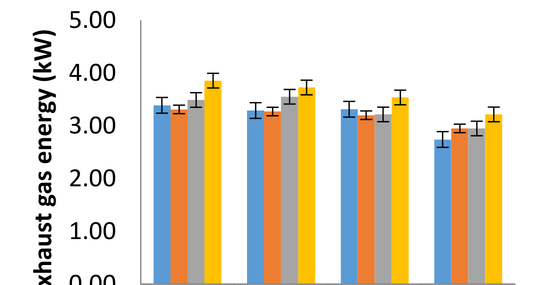
	15	16	17	18
Diesel	3.84	3.91	3.95	4.09
MB10	3.84	4.02	4.05	4.07
MB20	3.56	3.88	4.02	4.20
MB30	3.71	3.71	4.12	4.36

Fig. 4. Variation in cooling water energy for different fuel bends at different CR

Fig. 4 demonstrates the change in the energy carried by the cooling water for each fuel mix evaluated at different CRs. The results suggest that the engine cooling water removes more energy as the CR rises. The cooling water energy of the diesel fuel increased by 6.11% when the CR was increased from 15:1 to 18:1. At a CR of 18:1, the cooling water energy of biodiesel blends MB10, MB20, and MB30 raised by 5.65%, 5.23%, and 14.90%, respectively, compared to a CR of 15:1. This is due to the production of higher cylinder temperature and pressure because of improved combustion efficiency. Consequently, this leads to an increased amount of energy that must be dissipated by the cooling water in order to avoid excessive heat buildup [20]. Under full load circumstances, the highest cooling water energy recorded for the fuel blends diesel, MB10, MB20, and MB30 is 4.09, 4.07, 4.20, and 4.36 kW, respectively, at a higher CR of 18:1.

4.1.3. *Exhaust Gas Energy*

In a diesel engine, approximately 40% of the fuel energy is lost through exhaust heat. The efficiency of a fuel's heat energy utilization can be determined by measuring the temperature of its exhaust gases. Heat loss in the exhaust pipe or an increase in exhaust temperature reduces the amount of fuel's heat energy that is converted to work [21].



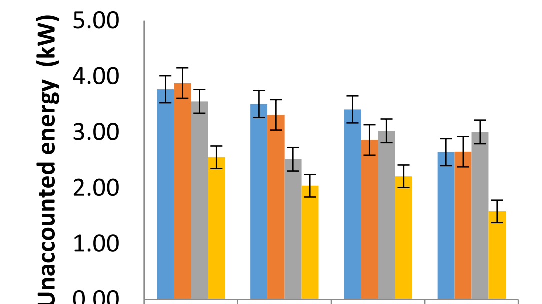
	15	16	17	18
Diesel	3.39	3.29	3.31	2.74
MB10	3.31	3.27	3.20	2.95
MB20	3.49	3.55	3.22	2.95
MB30	3.86	3.73	3.54	3.22

Fig. 5. Variation in exhaust gas energy for different fuel bends at different CR

Fig. 5 illustrates that exhaust gas energy diminishes as the CR increases for all tested fuel mixes. The lowest exhaust gas energy for all fuel mixtures is recorded with a compression ratio of 18:1. The energy of exhaust gas for diesel diminished by 23.72% when the compression ratio increased from 15:1 to 18:1. Utilizing a higher compression ratio of 18:1 results in a decrease in exhaust gas energy for biodiesel blends MB10, MB20, and MB30 by 10.87%, 18.3%, and 19.87%, respectively, as compared to a lower compression ratio of 15:1.The minimum energy levels of the exhaust gas for the diesel and biodiesel blends MB10, MB20, and MB30 are 2.74 kW, 2.95 kW, 2.95 kW, and 3.22 kW, respectively. This may be ascribed to the increased compression ratio, which diminishes the ignition delay and combustion duration, leading to efficient combustion of fuel within the cylinder, hence reducing the combustion of unburned fuel particles in the last phases of the combustion reaction [22].

4.1.4. *Unaccounted Energy*

The term "unaccounted heat energy" refers to the difference between the total heat equivalent of the cooling water heat, exhaust gas heat, brake power, and the supplied amount of heat [23].



	15	16	17	18
Diesel	3.77	3.50	3.41	2.64
MB10	3.88	3.31	2.86	2.65
MB20	3.55	2.51	3.02	3.00
MB30	2.55	2.04	2.21	1.58

Fig. 6. Variation in unaccounted energy for different fuel bends at different CR

The alteration in unaccounted energy among different fuel mixtures at compression ratios of 15:1, 16:1, 17:1, and 18:1 is shown in Fig. 6. The experimental results reveal that an increase in the CR led to a reduction in the amount of unaccounted energy across all fuel mixes. The minimum unaccounted energy for the diesel and Moringa oleifera biodiesel blends MB10, MB20, and MB30 was 2.64, 2.65, 2.51, and 1.58 kW, respectively, at a higher compression ratio of 18:1. This is due to the fact that at higher compression ratios, combustion irreversibility decreases because of the reduction in ignition delay observed with increased temperature and pressure inside the cylinder. Additionally, as outlined in the input energy section (4.1.1), it is evident that a higher CR improves brake thermal efficiency (BTE), thereby decreasing the energy needed to produce a unit of power output [22].

4.1.5. Energy Efficiency

Energy efficiency is determined by dividing the work rate by the fuel energy input rate, a crucial parameter for understanding engine performance.

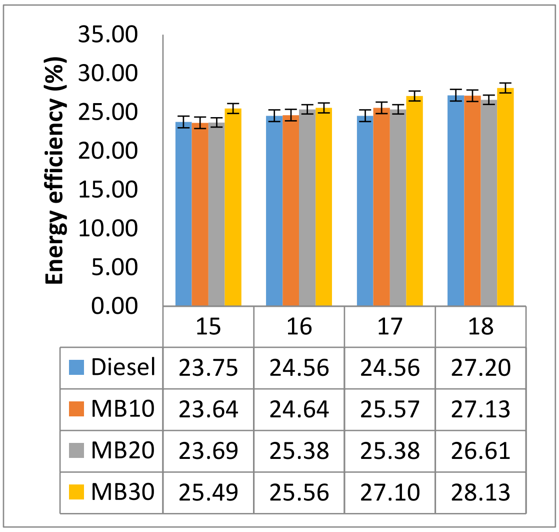


Fig. 7. Variation in energy efficiency for different fuel bends at different CR

Fig. 7 demonstrates the impact of compression ratio on the energy efficiency of an engine running on diesel and different blends of Moringa oleifera biodiesel MB10, MB20, and MB30. The results of the experiment demonstrate that a rise in CR led to improved energy efficiency for all tested fuel combinations. The highest energy efficiencies achieved by the diesel and biodiesel mix MB10, MB20, and MB30 were 27.20%, 27.13%, 26.61%, and 28.13%, respectively, at a higher compression ratio of 18:1. This is due to the fact that a greater compression ratio squeezes the air-fuel combination tighter, resulting in more efficient combustion, which enables the engine to produce more work from the same quantity of fuel [24]. The biodiesel mix MB30 demonstrates the highest energy efficiency among all tested fuels, showing an approximate enhancement of 3.42% relative to diesel at higher CR of 18:1. This is related to the MB30 fuel blend's greater cetane number and intrinsic oxygen concentration, which lower ignition delays and increase combustion efficiency [24].

4.2. Exergy Analysis

4.2.1. Available Input Energy

Fuel exergy rate is also termed as available input energy. The result of the engine's energy supply and the chemical exergy factor is fuel exergy [7]. Fuel exergy is greater than input energy since the chemical exergy factor has a value greater than one.

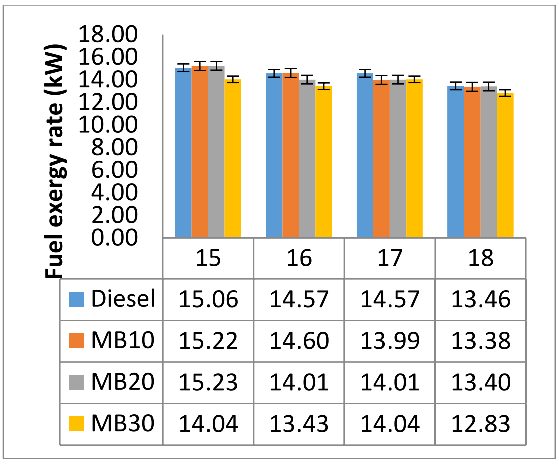


Fig. 8. Variation in fuel exergy rate for different fuel bends at different CR

Fig. 8 demonstrates that an increase in the CR correlates with a reduction in fuel exergy across all fuel mixtures. This phenomenon occurs due to an elevated BTE at increased CR, resulting in a decreased fuel requirement for a specific power output [20]. The fuel blends diesel, MB10, MB20, and MB30 exhibited minimum fuel exergy values of 13.46, 13.38, 13.40, and 12.83 kW, respectively, when evaluated at a compression ratio of 18:1. Additionally, the fuel exergy rate of the biodiesel mix is consistently lower than that of diesel for all compression ratios. The reason for this may be that Moringa oleifera biodiesel has a higher cetane number and inherent oxygen. This characteristic reduces the ignition delay and enhances combustion efficiency. As a result, reduced energy is required to produce a given power output. The biodiesel blend MB30 exhibits the lowest fuel exergy, recorded at 12.83 kW. This value is 4.68% lower than that of diesel [18].

4.2.2. Exergy Rate of Cooling Water

The variation in exergy rate of the cooling water for each tested fuel blends at various CRs is displayed in Fig. 9.

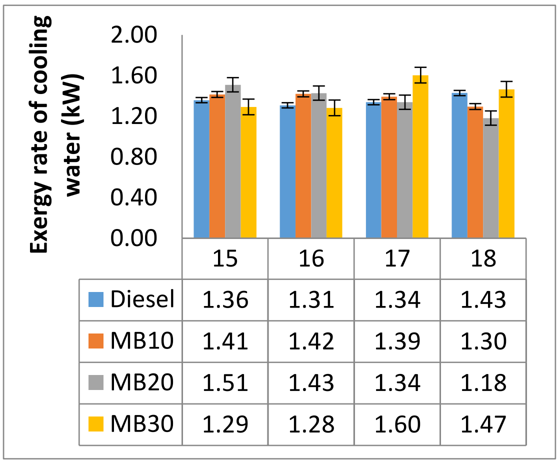


Fig. 9. Variation in exergy rate of cooling water for different fuel bends at different CR

The results suggest that when the CR increases, a marginal drop in available energy in the cooling water is observed for fuel blends MB10 and MB20; however, for diesel and fuel mix MB30, there is an initial decline followed by an increase. The minimal exergy rate of cooling water for diesel was recorded at 1.31 kW with a compression ratio (CR) of 16:1, while the biodiesel blend MB20 exhibited the lowest exergy rate of cooling water at 1.18 kW with a CR of 18:1. An elevated compression ratio enhances combustion efficiency, generating higher combustion temperatures. The elevated temperature enhances the total energy present in the system. Consequently, a greater amount of heat is transported from the engine to the cooling water, augmenting the energy available in the cooling water.

4.2.3. *Exergy Rate of Exhaust Gas*

The variation in the exhaust gas's exergy rate for various diesel and Moringaoleifera biodiesel fuel blends at various CRs of 15:1, 16:1, 17:1, and 18:1 is depicted in Fig. 10.

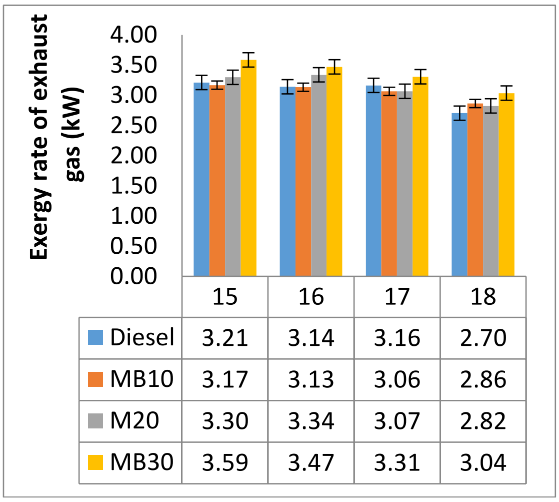


Fig. 10. Variation in exergy rate of exhaust gas for different fuel bends at different CR

The findings indicate that an increase in CR results in a reduction of the exergy rate of the exhaust gas, irrespective of the fuel mixes used. The energy available in the exhaust gases of the diesel engine decreased by 15.88% as the compression ratio increased from 15:1 to 18:1. The biodiesel blends MB10, MB20, and MB30 demonstrate reductions in exergy rate of exhaust gas by 9.77%, 14.54%, and 15.32%, respectively, as the compression ratio is elevated from 15:1 to 18:1. The reduced ignition lag at higher compression ratios allows for complete combustion of fuel combinations before the exhaust valve opens, resulting in a decrease in the exergy rate of the exhaust gas [25]. Biodiesel exhibits higher density and lower volatility than diesel, resulting in delayed combustion and an increased exergy rate in the exhaust gas [26]. The minimum exergy rates of exhaust gas for Diesel, MB10, MB20, and MB30 are reported as 2.7, 2.86, 2.82, and 3.04 kW, respectively, with a compression ratio of 18:1.

4.2.4. *Exergy Rate of Destructed Energy*

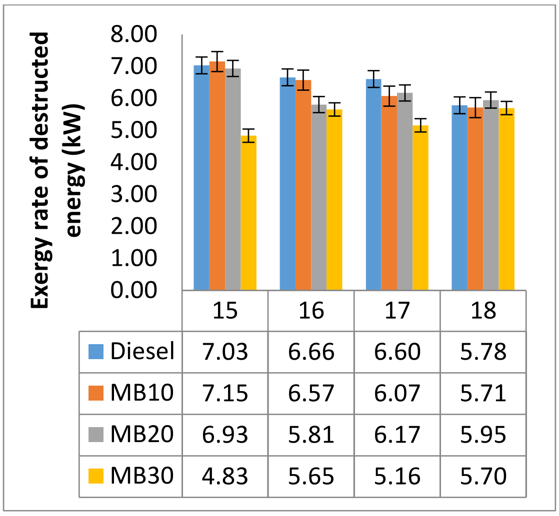


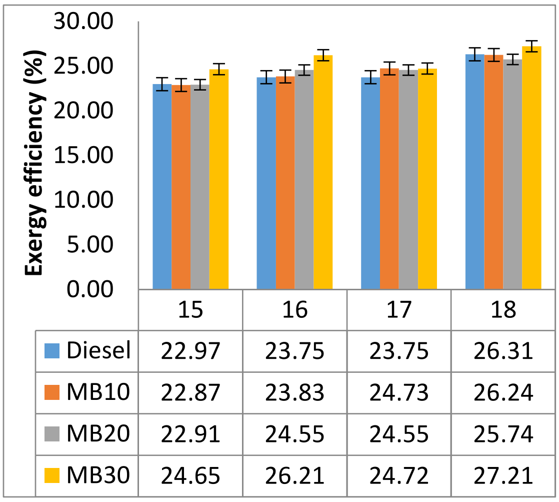
Fig. 11. Variation in exergy rate of destructed energy for different fuel bends at different CR

Fig. 11 illustrates the exergy rate of the destroyed energy for various fuel mixtures under different compression ratios and full load conditions. The findings demonstrate that the exergy rate of destructed energy decreases as the CR increases across all examined fuel blends. The primary factor contributing to the reduction in the exergy rate of the destroyed energy is the elevated compression ratio, which enhances combustion efficiency. This leads to decreased fuel consumption and irreversibility [10]. The minimum exergy rates for the destructed energy of the diesel fuel and biodiesel blends MB10, MB20, and MB30 are 5.78, 5.71, 5.95, and 5.70 kW, respectively, at a compression ratio of 18:1.

4.2.5. *Exergy Efficiency*

Exergy efficiency is described as the ratio of a system's real thermal efficiency to a system's idealized or reversible version for heat engines. The higher value of exergy efficiency indicates the higher sustainability of the system due to fewer energy losses and irreversibility.

Fig. 12 illustrates the variation in exergy efficiency across various fuel mixes at different compression ratios (CR). The findings demonstrate a direct correlation between the increase in CR and the rise in exergy efficiency across all evaluated fuel mixes. This phenomenon results from the rise in CR, which causes a reduction in fuel consumption per unit of power production. This results from improved combustion efficiency and decreased irreversibility, leading to a more effective utilization of fuel exergy [7]. The fuel mixtures of diesel and biodiesel blend MB10, MB20, and MB30 attained maximum exergy efficiencies of 26.31%, 26.24%, 25.74%, and 27.21%, respectively, when functioning at a compression ratio of 18:1.

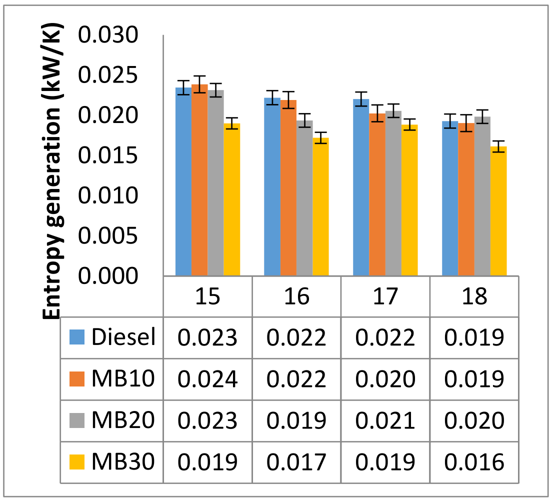


	15	16	17	18
Diesel	22.97	23.75	23.75	26.31
MB10	22.87	23.83	24.73	26.24
MB20	22.91	24.55	24.55	25.74
MB30	24.65	26.21	24.72	27.21

Fig. 12. Variation in exergy efficiency for different fuel bends at different CR

4.2.6. Entropy Generation

All fuel blends at varying CR and full load conditions exhibit variations in entropy generation, as seen in Fig. 13.



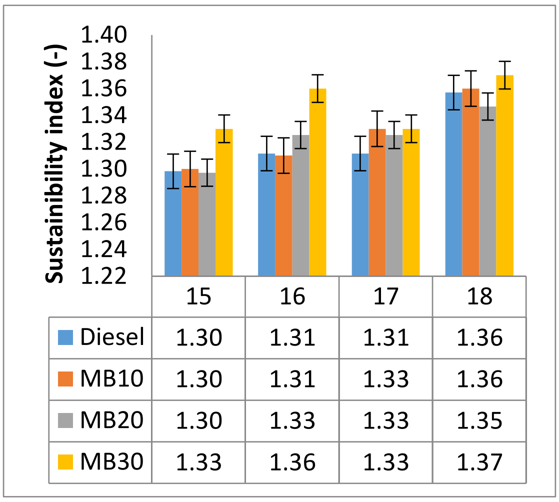
	15	16	17	18
Diesel	0.023	0.022	0.022	0.019
MB10	0.024	0.022	0.020	0.019
MB20	0.023	0.019	0.021	0.020
MB30	0.019	0.017	0.019	0.016

Fig. 13. Variation in entropy generation for different fuel bends at different CR

The findings indicate that an increase in the CR results in a reduction of entropy generation. This results primarily from decreased fuel consumption per unit of power generated, enhanced combustion efficiency, minimized heat loss and lowered irreversibility [23]. The entropy generation for diesel is between 0.023 and 0.019 kW/K, whereas for biodiesel blends, it ranges from 0.024 to 0.016 kW/K. The diesel engine showed a minimum entropy generation of 0.019 kW/K when operated with diesel at a higher compression ratio of 18:1, while the biodiesel blend MB30 exhibited a minimum entropy generation of 0.016 kW/K at the same compression ratio of 18:1.

4.2.7. Sustainability Index

The energy efficiency of the engine determines its sustainability index, and as energy efficiency rises, so does the system's sustainability. The SI with CR change for each tested fuel blend under full load conditions is shown in the Fig. 14.



	15	16	17	18
Diesel	1.30	1.31	1.31	1.36
MB10	1.30	1.31	1.33	1.36
MB20	1.30	1.33	1.33	1.35
MB30	1.33	1.36	1.33	1.37

Fig. 14. Variation in the sustainability index of exhaust gas for different fuel bends at different CR

Fig. 14 illustrates the variation in the SI of an engine with CR for each fuel blend tested under full load conditions. The SI of an engine increases with an increase in CR for all tested fuel blends. This is due to the fact that the SI of an engine is directly proportional to exergy efficiency, which increases with an increase in compression ratio [26]. The reported SI for diesel ranges from 1.30 to 1.36, whereas for biodiesel blends, the SI varies from 1.30 to 1.37. The highest SI recorded for diesel was 1.36, whereas the biodiesel blend MB30 exhibited the highest SI of 1.37, approximately 0.73% greater than that of diesel.

5. Conclusions

The current study examined the thermodynamics of a CRDI-VCR type diesel engine running on blends of diesel and biodiesel from Moringaoleifera (MB10, MB20, and MB30) under full load conditions. The CR was varied between 15:1 and 18:1. The biodiesel blends of Moringaoleifera MB10, MB20, and MB30 exhibited similar trends of energy and energy efficiency when compared to diesel.

At a higher CR of 18:1, the minimum energy input for the diesel and biodiesel blends for the

MB30 blends was reported as 13.02 and 12.41 kW, respectively. The minimum fuel exergy rate reported for the diesel and MB30 biodiesel blends among biodiesel blends was 13.46 kW and 12.83 kW, respectively.

The minimum exhaust gas energy and exergy rate of exhaust gas were reported at a higher CR of 18:1 for all the fuel blends. Diesel offers minimum exhaust gas energy and exergy rate of exhaust gas of 2.74 and 2.7 kW respectively while among the biodiesel blends MB20 offers minimum exhaust gas energy and exergy rate of exhaust gas as 2.95 and 2.82 kW respectively.

For the diesel and biodiesel blend MB30, the lowest unaccounted energy and the exergy rate of destroyed energy were recorded at a higher CR of 18:1.The minimum unaccounted energy reported for diesel and biodiesel blend MB30 was 2.64 and 1.58 kW while the minimum exergy rate of destructed energy reported for diesel and biodiesel MB30 was 5.78 and 5.7 kW.

The highest cooling water energy and exergy rate of cooling water for diesel reported at higher CR of 18:1 which was 4.09 and 1.43 kW while for the biodiesel blend MB30 it was 4.36 and 1.47 kW respectively.

For both the fuel blend—diesel and biodiesel—the highest energy and energy efficiencies were noted at the higher CR of 18:1. At a higher CR of 18:1, the highest energy efficiencies recorded were 27.20 % for the diesel and 28.13 % for the biodiesel blend MB30 while the highest exergy efficiencies reported for both diesel and biodiesel blend MB30 were 26.31% and 27.21 % respectively.

The highest SI and lower entropy generation reported for the diesel was 1.36 and 0.019 kW/K at higher CR of 18:1 while for the biodiesel blend MB30 highest SI and lower entropy generation reported was 1.37 and 0.016 kW/K at higher CR of 18:1.

The highest energy efficiency, exergy efficiency, and SI were reported for all the tested fuel blends at a higher CR of 18:1; hence, it is advisable to operate the engine at a higher CR. The engine fueled by the MoringaOleifera biodiesel mix MB30 exhibited superior energy efficiency, exergy efficiency, and SI values compared to the engine fueled by diesel. This is due to the biodiesel's elevated cetane number, which lowers ignition delay, and its inherent oxygen content, which enhances combustion efficiency. Moringaoleifera biodiesel has great potential as an alternative fuel for diesel engines.

The authors highly suggest that more study to be conducted in order to examine the impacts of different engine loads in a multi-cylinder diesel engine. Furthermore, it is recommended to do additional study to explore the thermo-economic, enviro-economic, and exergy-economic aspects of diesel-biodiesel fuel mixes in a diesel engine.

Nomenclature

CRDI	Common rail direct injection
VCR	Variable compression ratio
CR	Compression ratio
IT	Injection timing
IP	Injection pressure
bTDC	Before top dead centre
MB10	Blend with 90% diesel and 10% MoringaOleifera biodiesel by volume
MB20	Blend with 80% diesel and 20% MoringaOleifera biodiesel by volume
MB30	Blend with 70% diesel and 30% MoringaOleifera biodiesel by volume
ICE	Internal combustion engine
D95J3.75E1.25	Blend with 95% diesel, 3.75% jatropha biodiesel, and 1.25 % ethanol by volume
D98J1.5E0.5	Blend with 98% diesel, 1.5% jatropha biodiesel, and 0.5 % ethanol by volume
D80B14E06	Blend with 80% diesel, 14% jatropha biodiesel, and 06 % ethanol by volume
DI	Direct Injection
SI	Sustainability index

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Conflicts of Interest

The author declares that there is no conflict of interest regarding the publication of this article.

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