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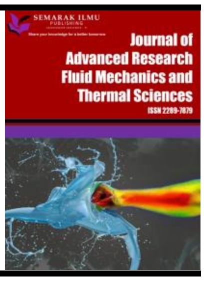


# Energy-Exergy Analysis of CI Engine Fueled with Moringa Oleifera Biodiesel at Different Loading Conditions

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**ABSTRACT**

This study aims to examine the impact of engine load (3, 6, 9, 12 kg) on the energy and exergetic performance of an internal combustion engine powered by diesel and Moringa biodiesel mixes. The trials were conducted on a common rail direct injection (CRDI) type single-cylinder diesel engine, using diesel fuel and mixes of Moringa biodiesel (MB10, MB20, and MB30) as the fuel. The experiment was conducted at a higher compression ratio (CR) of 18:1, a fuel injection pressure (IP) of 600 bar, an injection timing (IT) of 23ºbTDC, and a fixed engine speed of 1500 rpm. An energy and exergy analysis were conducted to estimate the energy and exergy rate of fuel, cooling water, and exhaust gases, unaccounted energy, energy and exergy efficiency, entropy generation, and sustainability index. The energy analysis showed that fuel inlet energy, energy of cooling water, exhaust gases, and energy efficiency rise with engine load, whereas unaccounted energy decrease. Exergy analysis showed that exergy rate of cooling water, exhaust gas, exergy efficiency, and SI increase with engine load, while fuel energy, destructed available energy, and entropy generation decrease. The highest energy and exergy efficiency reported for the diesel were 27.20 and 26.31% respectively while for biodiesel blend MB30 it was reported as 28.13 and 27.21% at full load condition. The highest entropy generation reported for the diesel was 0.022 kW/K at 50% loading condition and for biodiesel blend MB20 it was 0.020 kW/K at full loading condition. The highest SI reported for the diesel and biodiesel blend MB30 were 1.36 and 1.37 at full load condition. A study suggests that the energetic and exergetic performance of a VCR-CRDI type diesel engine is similar to that of diesel fuel when utilizing Moringa biodiesel, under various engine loading conditions.

## 1. Introduction

India's population increase, quick industrialization, higher GDP, and better living are all driving up its energy need on a constant basis. These days, conventional energy sources like coal and oil provide around 74% of India's overall energy consumption [1]. Regarding sustainable growth, this scenario appears more troublesome because traditional energy sources are running out and also

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add to the emission of dangerous pollutants. Concentrating on the efficient use of renewable energy sources and designing or modifying the current system to make the most of given energy are necessary.

Energy analysis method follows the conventional approach that centres on the first rule of thermodynamics, evaluating the extent to which energy is conserved inside the system. While it offers a general measure of effectiveness, it does not offer any information about the specific locations where energy is being lost. Exergy analysis extends beyond energy analysis by including the principles of the second law of thermodynamics. The purpose of this measurement is to assess the energy's level of excellence and pinpoint the specific locations and mechanisms where irreversibility takes place within the engine. This aids in identifying inefficiencies that may be overlooked by energy analysis alone.

Trans-esterification is a reaction that can be used to turn different types of feedstocks into biodiesel. These feed stocks include edible and non-edible vegetable oil, used cooking oil, used plastic oil, and animal fat [2-5]. Estimating fuel energy, power produced, losses through cooling water, exhaust, unexplained losses, and thermal efficiency of a bio-fueled engine is possible with the application of energy analysis. The exergy rate of fuel energy, cooling water, exhaust gas, destructed energy, and exergy efficiency of the engine can be measured using the exergy analysis [6-9].

Rath and Mohanta [10] undertook an experiment on a CI engine to assess the thermal and exergy efficiency of an engine running on the diesel and Karanja biodiesel blends K10 and K20. The experiment results show that K10 mix had the highest thermal and exergy efficiency than diesel at greater CR. K10 mix similarly exhibits the increase in BSFC at increasing CR. Based on energy and exergy studies, Kumar and Gautam [11] determined the ideal CR and IP for a VCR-type CI engine running on diesel and biodiesel made from tallow. The results of the experiment show that greatest energy and exergy were recorded for both diesel and tallow biodiesel at the CR of 17.5 and IP of 210 bar. Jain *et al.,* [12] investigated how injection timing affected the energy, exergy, and emission characteristics of a CI engine running on Mesua ferrea seed oil biodiesel. The results show that for the retarded IT of $20^0$ bTDC, the maximum energy and exergy efficiency and the lowest emission, with the exception of NOx. Furthermore, this delayed IT lowers the exergy destruction and offers the effective fuel conversion in CI engine. The performance, emission, energy, and exergy properties of a CI engine are examined by Das *et al.,* [13]. The thermal efficiency and BSFC are found to be improved by adding 20% V/V of WPO biodiesel to diesel. They further pointed out that while exergy efficiency decreases with increasing percentage amount of biodiesel in mixes with diesel, fuel exergy increases. The emission study findings show that when load increases, so does HC and NOx emissions. Krishnamoorthi and Malayalamurthi [14] looked into the impact of ternary furl mixes comprising DEE, Aegle marmelos biodiesel, and diesels. The thermal and emission performance of the fuel blend 60:30:10 is determined to be better than that of diesel at full load. The blend 60:30:10 was reported to have the maximum exergetic efficiency at the CR of 17.5 and full load condition, they added. They further claimed that an engine's thermal and emission performance increases with the number of holes in the fuel nozzle.

Yarlagadda and Ravuru [15] conducted an experiment to examine how plastic oil-based biodiesel and tire oil biodiesel impact the energy and exergy properties of a diesel engine. The experiment's results indicate that plastic oil-based biodiesel exhibits superior thermal efficiency and BSFC in comparison to tire oil biodiesel. The plastic oil biodiesel exhibits reduced heat losses, unquantified losses, and exergy degradation in comparison to tire-based biodiesel. In their study, Panigrahi [16] conducted an experiment on a compression ignition (CI) engine to examine the impact of Polanga biodiesel on the engine's energy and exergy efficiency. The energy analysis indicates that Polanga biodiesel has a higher heat loss energy compared to diesel, whereas the energy associated with exhaust loss is lower than diesel. The exergy analysis results indicate that the heat transfer exergy is greater for Polanga biodiesel compared to diesel. Additionally, the exergy destruction rate is lower for Polanga biodiesel due to its higher combustion efficiency. Odibi *et al.,* [17] conducted a study to examine the impact of waste cooking oil (WCO) biodiesel on the energy and exergetic performance of a six-cylinder, turbocharged diesel engine. According to their claim, oxygenated WCO biodiesel fuel has lower exhaust loss and higher thermal efficiency compared to diesel. The exergy analysis yields comparable trends to the energy analysis, indicating that WCO biodiesel exhibits lower accessible exhaust energy and higher exergy efficiency. López*et al.,* [18] conducted a study using a mixture of olive-pomace oil biodiesel and diesel to examine the exergy efficiency of a diesel engine. The experimental findings indicate that the utilization of biodiesel in a compression ignition (CI) engine result in a decrease in power output and an increase in fuel consumption. No notable disparity was seen in exergy efficiency when the engine was operated under full load conditions utilizing olive-pomace oil biodiesel. In this study, Azoumah *et al.,* [19] examine the impact of biodiesel blends derived from palm and cotton oil, as well as diesel, on the emissions and exergy performance of a two-cylinder compression ignition engine. It was discovered that running the engine at 60% to 70% of its maximum capacity resulted in the best emission and exergy performance for both biodiesel and diesel blends. M'hamed *et al.,*[20] experimentally investigate the feasibility and effects of using Diesel-ethanol and Diesel-methanol blends as alternative fuels in a Diesel engine. The performance of a four-stroke single-cylinder Diesel engine was tested using pure Diesel, Diesel-ethanol blends (D95E5, D90E10, and D85E15), and Diesel-methanol blends (D95M5, D90M10, and D85M15). The engine was operated at full load across a speed range of 700 to 3000 RPM. Among the fuel mixtures tested, D85E15 and D85M15 showed the greatest improvement in engine performance compared to pure Diesel and other blends. Notably, the lowest BSFC, which indicates better fuel efficiency, was observed with D95E5 and D95M5 blends. Nasir *et al.,* [21] examines the impact of incorporating diethyl ether (DE) and bael oil (BO) into commercial diesel fuel on the performance and emissions of a single-cylinder diesel engine. The goal is to optimize fuel quality in order to boost engine performance and minimize emissions. The cetane number of the fuel was assessed following the incorporation of 15% bael oil and 10% diethyl ether into the commercial diesel. Engine tests were performed by gradually raising the engine speeds, without any external resistance, throughout the range of 1000 to 2500 RPM, with increments of 250 RPM.

The literature review indicates a lack of research on the energy and exergy analysis of a diesel engine using Moringa oleifera biodiesel at a CR of 18:1, injection pressure (IP) of 600 bar, injection timing of 23$^{o}$bTDC, and under different engine loading conditions. This study aimed to investigate the effects of engine load and biodiesel blends on the energy and exergy characteristics, entropy generation, and sustainability index of a CRDI-VCR type diesel engine fueled by blends of Moringa oleifera biodiesel and diesel fuel. The engine was operated at a CR of 18:1, IP of 600 bar, and injection timing of 23$^{o}$bTDC, with a fixed speed of 1500 rpm. The engine load was varied at 3, 6, 9, and 12 kg, respectively. The fuel blends used in the experiment included pure diesel, MB10, MB20, and MB30.

## 2. Methodology

### *2.1 Biodiesel Production*

The single-step trans-esterification technique was employed to manufacture biodiesel from Moringa seed oil. The trans-esterification reaction was conducted using a magnetic stirrer that was equipped with a three-necked flask. The Moringa seed oil, together with methanol (in a molar ratio of 5.5:1) and a catalyst (KOH, 1% w/w of Moringa seed oil), was added to the flask. The reaction was conducted for 1 hour, with a stirring speed of 600 rpm and a temperature maintained between 60°C to 65°C. The liquid to sit undisturbed in a separating funnel for a period of 12 hours. The separated biodiesel was subjected to a water wash using mineral water heated to a temperature of 105ºC in order to eliminate any remaining methanol. The biodiesel was heated to eliminate any residual water content. The detailed process of Moringa biodiesel production is shown in Figure 1.

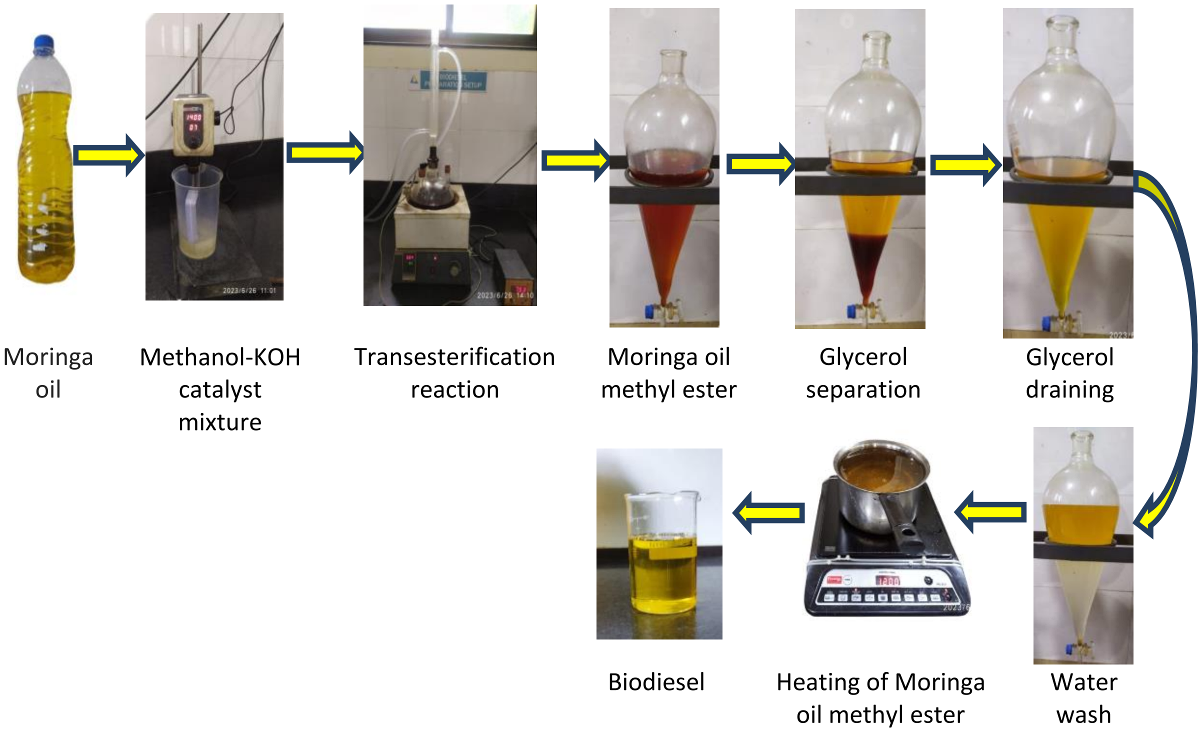



**Fig. 1.** Process of biodiesel production from Moringa oleifera oil

The experiment involved studying the physico-chemical characteristics of diesel, Moringa oleifera oil, and blends of Moringa oleifera biodiesel. As shown in Table 1, additionally, it demonstrates that the value of various attributes meets the predetermined threshold established by the ASTM standards.

**Table 1**
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 (0C) | 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 Experiment Setup*

The CRDI-VCR type diesel engine was utilized for the experiment. The engine shaft was connected to the eddy current type dynamometer and load cell. The comprehensive specifications were indicated in Table 2. The test setup was equipped with a crank angle decoder, piezo sensor, air flow transmitter, and differential pressure transmitter. These instruments were used to measure the crank angle, pressure in the engine cylinder, air flow rate, and fuel flow rate, respectively. The test configuration was equipped with RT- PT100-type temperature sensors to gauge the temperature of the cooling water as it passed through the engine block and calorimeter. Thermocouples of the k-Type are placed to gauge the temperature of the exhaust gas at both the inlet and exit points of the calorimeter. A calorimeter was equipped with an exhaust manifold to measure the amount of heat that is taken away by the flue gases. A panel box was included in the test setup to house the fuel tank, airflow transmitter, fuel flow transmitter, rotameter for fuel storage, and to measure the flow rates of air, fuel, and cooling water delivered to the engine, as well as the calorimeter. The "Enginesoft" software, which is based on lab-view, was used to analyze the performance of the engine and assess its parameters online. The actual image of the experiment setup used in the experiment work is shown in Figure 2.

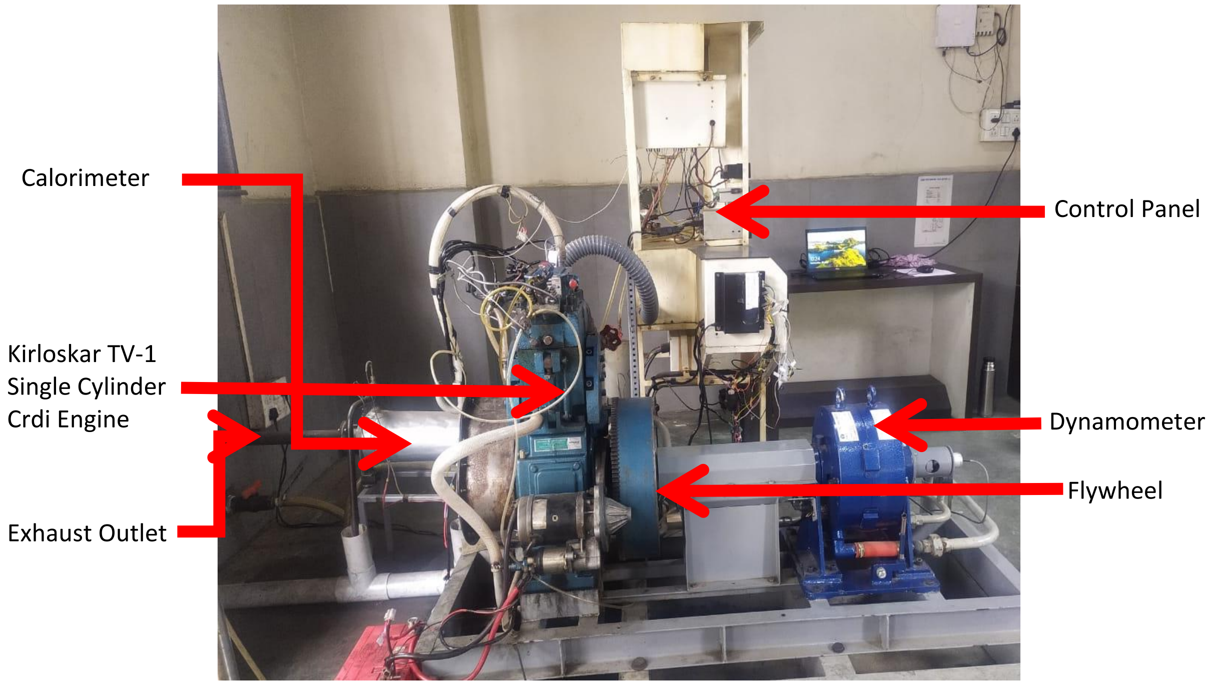



**Fig. 2.** Test setup

**Table 2**
Main specifications of test setup

| Test setup parts | Specifications |
|---|---|
| Test engine | Model: TV1, kirloskar make, mono cylinder and |
| Stroke length and bore Dia. | 110 mm and 87.5 mm |
| Cylinder volume and power output | 661 cc and 3.5 kW @ 1500 rpm |
| CR range | 12:1 to 18:1 |
| Dynamometer | Eddy current type, water cooled with loading unit |
| Propeller shaft | Universal joint type |
| Injector | Solenoid-driven type |
| Data acquisition system | NI USB-6210, 16-bit, 250kS/s |

### *2.3 Uncertainty Analysis*

The study estimates the total uncertainty value of the experimental data resulting from the measuring instruments. The instruments utilized in this experiment, along with their respective measurement ranges and accuracy values, are presented in Table 3. Error analysis is considered an essential approach for quantifying the amount of uncertainty that occurred during testing. The primary elements contributing to inaccuracies in experimentation were human error in measurement, inadequate maintenance of measuring equipment, and environmental influences. The current study utilized the back propagation approach to assess the level of uncertainty in experimentation. The uncertainty was determined by employing the formula shown below.

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)$^2$) = $((1.49)^2 + (1.49)^2 + (0.01)^2 + (2.38)^2)^{0.5} = \pm 3.18$ %

**Table 3**
Range and accuracy of measuring instruments

| Instruments | Range | Accuracy |
|---|---|---|
| K-Type thermocouple | 0-1200 °C | 0.1°C |
| Load cell | 0-50 kg | ± 0.125 kg |
| Rotameter | 40 to 400 LPH<br>25 to 250 LPH (Calorimeter) | ± 0.2% full flow |
| Differential pressure transducer | 1 to 100 kPa | ± 0.5% of span |
| Pressure transmitter | 0 to 25 mbar | ± 0.5% of span |
| Encoder | 5500 rpm | ± 0.25% |

### *2.4 Energy Analysis*

Energy analysis is a method employed to assess the efficiency of energy systems by measuring the energy inputs, outputs, and losses within a system. The concept is derived from the fundamental principle of thermodynamics, known as the first law, which asserts that energy is conserved and cannot be generated or annihilated, but can only undergo transformations. Energy analysis facilitates comprehension of energy distribution and utilization in a given process, allowing engineers to evaluate efficiency and pinpoint areas for enhancement.

The operation of an internal combustion engine involves a series of events, including the intake of air and fuel, the combustion process, the conversion of chemical energy in the fuel into mechanical energy, heat losses due to friction, radiation, cooling water, the surrounding environment, and the release of exhaust gas [22].

The evaluated diesel engine has been considered as a control volume for the purpose of conducting analysis. In order to simplify the computations; many assumptions were made regarding the control volume of the CI engine being tested and the application of the first and second laws of thermodynamics. These assumptions were

i. A state of equilibrium has been consistently maintained for the research engine under investigation.
ii. It has been established that the temperature and pressure of the reference environment are 27 °C and 1 atm, respectively.
iii. The combustion process' byproducts are in a state of chemical equilibrium.

iv. It is considered that the ideal combination occurs when the intake air to the control volume is combined with the outlet exhaust gases that are released from the control volume.
v. The kinetic and potential energy of the incoming and outgoing streams have not been considered.
vi. The stream's characteristics have remained constant across the control volume over time [22].

The mass balance and energy balance for the control volume in the steady-state condition can be expressed as per Eq. (1) and Eq. (2) when potential and kinetic energies are not taken into account

$$\sum\dot{m}_{inlet} = \sum\dot{m}_{outlet} \quad (1)$$

$$\dot{Q} - \dot{W} = \sum\dot{m}_{outlet}h_{outlet} - \sum\dot{m}_{inlet}h_{inlet} \quad (2)$$

where $\dot{m}_{inlet}$ and $\dot{m}_{outlet}$ is the mass flow rate for the fluid at the inlet and outlet of the control volume.$\dot{Q}$ represent the unit heat input at the inlet of the system and $\dot{W}$ represent the network developed by the system.

The network developed by the engine can be estimated using Eq. (3),

$$\dot{W} = \omega T \quad (3)$$

where $\omega$ is the angular velocity (rad/s) and T is is the torque developed by an engine (Nm). Further, The angular velocity can be estimated using following Eq. (4),

$$\omega = \frac{2\pi N}{60} \quad (4)$$

where N is the engine speed.

The energy at the inlet of the control volume can be estimated using Eq. (5),

$$E_{input} = m_{fuel}.\mathrm{LCV} \quad (5)$$

where $E_{input}$ is the energy at the inlet of the system, $m_{fuel}$ is the mass flow rate of the fuel supplied to the engine and LCV is the lower calorific value of the fuel.

The heat carried away by the exhaust gases can be estimated using Eq. (6),

$$Q_{exhaust} = (m_a + m_f)\, C_{pgas}\, (T_{exhaust} - T_{ambient}) \quad (6)$$

where, $m_a$ *and* $m_f$ represents the mass flow rate of the air and fuel respectively to an engine, $C_{pgas}$ is the specific heat constant for the exhaust gas while $T_{exhaust}$ and $T_{ambient}$ are the temperature of the exhaust gas leaving the engine and ambient temperature respectively.

The heat carried away by the cooling water from the engine can be calculated using Eq. (7),

$$Q_{CW} = m_{cw}\, C_{pw}\, (T_{cwoutlet} - T_{cwinlet}) \quad (7)$$

where, $m_{cw}$ represents the mass flow rate of the cooling water passing through engine cylinder, $C_{pw}$ is the specific heat constant for the cooling water while $T_{cwinlet}$ and $T_{cwoutlet}$ is the temperature of the cooling water at the entrance of the engine jacket and at the exit of the engine jacket.

The energy losses which cannot be figured out is calculated using Eq. (8),

$$Q_{unaccounted\ losses} = E_{input} - W - Q_{cw} - Q_{exhaust} \tag{8}$$

The energy efficiency of the system can be calculated using Eq. (9),

$$\eta = \frac{W}{E_{input}} \tag{9}$$

*2.5 Exergy Analysis*

Exergy analysis is a method of thermodynamic evaluation that is employed to measure the efficiency of energy conversion processes. The term "maximum useful work potential" refers to the highest amount of work that may be achieved by a system or process in comparison to a reference environment. This measurement considers both the quantity and quality of energy involved. Exergy analysis is a method that discovers and measures inefficiencies, allowing us to understand where and how energy is lost.

In the present experiment investigation available input energy converted into the useful work, exergy of destructed energy, exergy of cooling water and exhaust gas.

Availability of fuel supplied can be computed using Eq. (10),

$$A_{fuel} = \phi.E_{inlet} \tag{10}$$

where ϕ represent the chemical exergy factor and $E_{inlet}$ is the input energy of the system.

Availability of the fuel is always higher than the input energy as the value of the chemical exergy factor is always greater than one.

Exergy rate of the cooling water can be calculated using Eq. (11),

$$A_{cw} = Q_{cw} - m_{cw}*Cp_w*T_{atm}*\ln\left(\frac{T_{cwout}}{T_{cwin}}\right) \tag{11}$$

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

The available energy in the exhaust of an engine can be computed using Eq. (12),

$$A_{eg} = Q_{eg} + \{m_g*C_{pg}*T_{atm}*\ ln\left(\frac{T_{exhaust}}{T_{atm}}\right) - R_{exh}*\ln\left(\frac{P_{exhaust}}{P_{atm}}\right)\} \tag{12}$$

where, $Q_{eg}$= energy of 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 atmospheric pressure (bar).

The available energy that is destructed can be estimated using the following Eq. (13),

$$A_d = A_{in} - (A_s + A_{cw} + A_{exhaust}) \tag{13}$$

The formula for calculating exergetic efficiency is as per Eq. (14): braking power exergy divided by fuel exergy needed to control volume

$$\eta_{II} = \left(\frac{A_{SW}}{A_{fuel}}\right) \quad (14)$$

where, $A_{sw}$= Brake power exergy, $A_{fuel}$= fuel exergy at the inlet.

For the assessment of the performance of a system, the entropy generation rate is defined as ratio of the destructed available energy and temperature as expressed in Eq. (15).

$$Entropy\ generation = \left(\frac{A_d}{T_0}\right) \quad (15)$$

Exergy and sustainability are directly related. An engineering system's degree of sustainability is shown by the amount of thermodynamic irreversibility, which is calculated by exergy analysis and is strongly tied to resource depletion.The sustainability index can be expressed as per Eq. (16) and is a function of energy efficiency.

$$Sustainabilty\ index = \left(\frac{1}{1-\eta_{II}}\right) \quad (16)$$

## 3. Results and Discussion

The first law of thermodynamics applied to the system to perform the energy analysis of a system. The experiment was conducted on the CRDI-VCR type mono cylinder diesel engine fueled with the diesel and Moringa biodiesel to study the effect of engine load on the energy and exergy performance of an engine.

### *3.1 Energy Analysis*

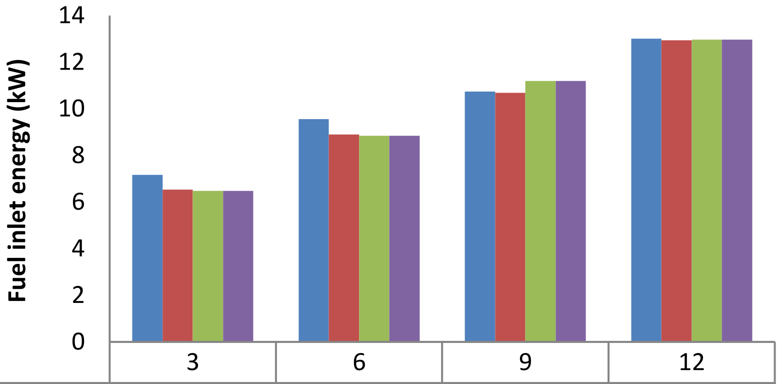
In the section of energy analysis different parameters such as fuel inlet energy, energy of cooling water and exhaust gases, unaccounted energy and energy efficiency were estimated for the VCR-CRDI type diesel engine fuelled with diesel and Moringa oleifera biodiesel blends at different loading condition.

#### *3.1.1 Fuel inlet energy*

Fuel inlet energy is a product of the lower calorific value of the fuel and mass flow rate of the fuel supplied to an engine.

Figure 3 illustrates the changes in fuel inlet energy for different fuel mixtures under varying load circumstances and a greater compression ratio of 18:1. The results indicated that the fuel inlet energy increased with the increase in load for every fuel blend tested. This is because the engine needs more gasoline to meet the increasing power requirements caused by a load [19]. The diesel and biodiesel blends MB10, MB20, and MB30 have recorded peak fuel energy values of 13.02 kW, 12.94 kW, 12.97 kW, and 12.97 kW, respectively, under full load conditions. The energy provided for the low load (25%) and full load (100%) for the diesel varied by 5.86 kW. However, for the biodiesel blends MB10, MB20, and MB20, the difference was 6.41, 6.49, and 6.49 kW respectively.

Additionally, it was constantly noted that the fuel inflow energy was lower when the engine was operated with biodiesel blends compared to diesel, independent of the loading circumstances. The possible reason for this is the higher cetane number and the presence of oxygen in biodiesel, which leads to a decrease in the time it, takes for ignition to occur and an enhancement in the efficiency of combustion [23].




| | 3 | 6 | 9 | 12 |
|---|---|---|---|---|
| CR-18-Diesel | 7.16 | 9.55 | 10.75 | 13.02 |
| CR-18-MB10 | 6.53 | 8.90 | 10.68 | 12.94 |
| CR-18-MB20 | 6.48 | 8.84 | 11.20 | 12.97 |
| CR-18-MB30 | 6.48 | 8.84 | 11.20 | 12.97 |

**Fig. 3.** Variation in fuel inlet energy with engine load

### *3.1.2 Cooling water energy*

The maintenance of the engine's optimal operating temperature is mostly reliant on the cooling system of the internal combustion engine. Internal combustion engines generate a substantial quantity of heat during the combustion process. Inadequate management of this heat can result in engine damage and decreased efficiency. The dissipation of this heat is crucial, and the cooling system, consisting of many components and fluids, is responsible for ensuring that the engine operates within a safe temperature range.

Figure 4 illustrates the changes in cooling water energy under various loading conditions and fuel mixtures. The results indicated that an increase in load resulted in a corresponding rise in the cooling water energy for all of the fuel mixes that were evaluated. The cause of this phenomenon may be attributed to the increased fuel consumption at higher engine load, which is essential for generating the desired power output. This results in an elevated production of heat within the engine cylinder and subsequent transfer of heat [24]. At full load circumstances, the highest energy observed in the cooling water for the diesel and biodiesel blends MB10, MB20, and MB30 were 4.09 kW, 3.84 kW, 3.56 kW and 4.12 kW, respectively. The maximum energy for the biodiesel blend MB30 was 4.12 kW. The difference in cooling water energy consumption between diesel operating at 100% and 25% loading circumstances was 3.21 kW. In comparison, the energy disparity for the biodiesel blends MB10, MB20, and MB30 was 2.63 kW, 1.97 kW, and 2.29 kW correspondingly.

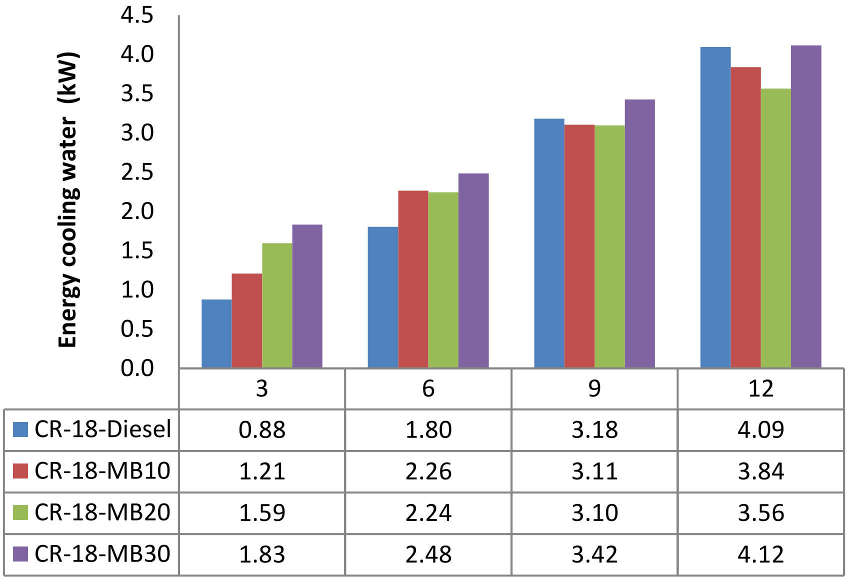
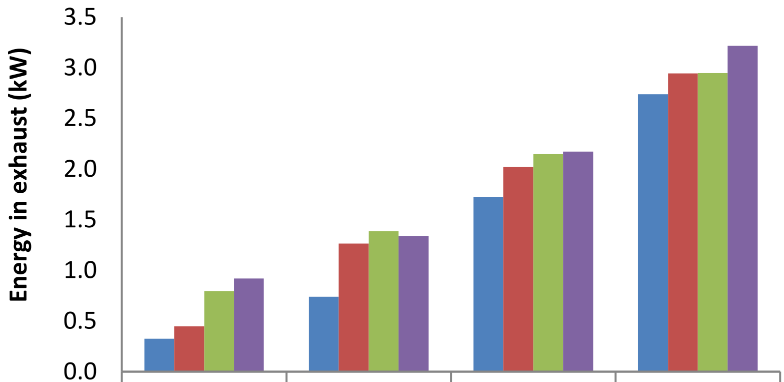



**Fig. 4.** Variation in energy of cooling water with engine load

### *3.1.3 Energy in exhaust*

The dissipation of energy from an engine's exhaust is the most significant form of energy loss compared to all other losses related with internal combustion engines. The energy expelled from the engine consists of 40% of the total energy input [25].

Figure 5 illustrates the changes in exhaust energy for various loading conditions and fuel mixtures. The experiment's findings suggest that an increase in engine load leads to a rise in exhaust energy. This is because the combustion efficiency directly affects the amount of exhaust energy. Increasing the engine load results in improved combustion efficiency due to increasing temperature and pressure within the cylinder [26]. The highest measured exhaust gas energy for the diesel and biodiesel MB10, MB20, and MB30 was 2.74 kW, 2.95 kW, 2.95 kW, and 3.22 kW, respectively, when the engine was operating at full load. The exhaust gas energy of the biodiesel blends was higher than that of diesel due to their elevated cetane number and oxygen concentration, leading to enhanced combustion.



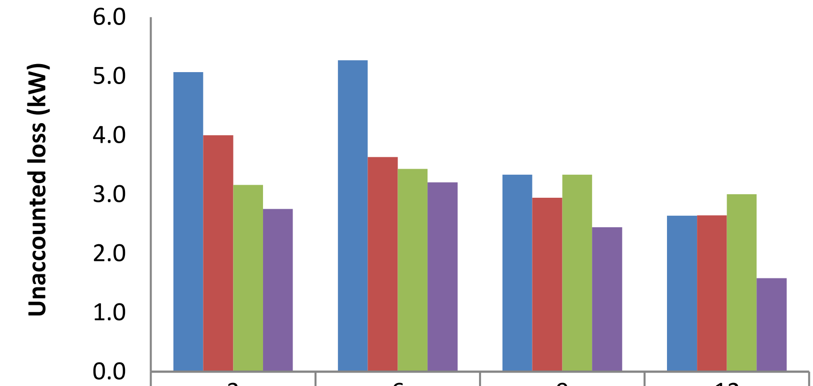

| | 3 | 6 | 9 | 12 |
|---|---|---|---|---|
| CR-18-Diesel | 0.33 | 0.74 | 1.73 | 2.74 |
| CR-18-MB10 | 0.45 | 1.27 | 2.02 | 2.94 |
| CR-18-MB20 | 0.80 | 1.39 | 2.15 | 2.95 |
| CR-18-MB30 | 0.92 | 1.34 | 2.17 | 3.22 |

**Fig. 5.** Variation in exhaust energy with engine load

### *3.1.4 Unaccounted energy*

The unaccounted losses in the diesel engine mostly pertain to friction, heat dissipation through radiation, and the irreversibility in the combustion reaction.

Figure 6 illustrates the changes in unaccounted energy losses for different fuel blends under varying engine load conditions. The experimental findings demonstrate that an increase in engine load significantly decreases the unaccounted losses. Augmenting the engine load results in elevated pressure and temperature within the engine cylinder. This greatly improves the efficiency of combustion and reduces the irreversibility associated with the combustion reaction. Elevated temperature inside the engine cylinder improves combustion efficiency by decreasing the time it takes for reactions to occur [27]. The diesel engine had an unaccounted loss of at least 2.64 kW when running at full loading condition. Out of all the biodiesel blends, the MB30 mixture exhibited the smallest unaccounted loss of 1.58 kW when operating at maximum capacity. It was observed that, under most operating situations; the unaccounted losses of biodiesel blends were smaller than those of diesel. The likely reason for these phenomena is the higher viscosity of biodiesel blends, which improves lubrication and reduces losses caused by friction.



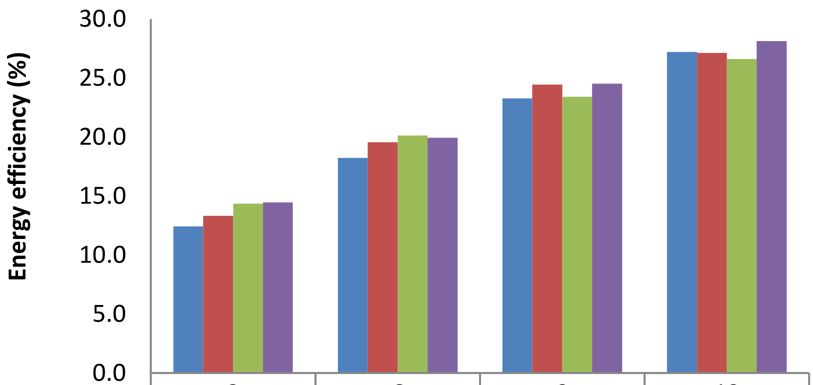

| | 3 | 6 | 9 | 12 |
|---|---|---|---|---|
| CR-18-Diesel | 5.07 | 5.27 | 3.34 | 2.64 |
| CR-18-MB10 | 4.00 | 3.63 | 2.95 | 2.65 |
| CR-18-MB20 | 3.16 | 3.43 | 3.33 | 3.00 |
| CR-18-MB30 | 2.76 | 3.21 | 2.44 | 1.58 |

**Fig. 6.** Variation in unaccounted loss with engine load

### *3.1.5 Energy efficiency*

Energy efficiency of any system is the ratio between the useful work developed by a system and the supplied energy.

Figure 7 illustrates the variations in energy efficiency for several fuel blends under different load conditions. Based on the information presented in Figure 7, it is evident that an increase in engine load leads to improved energy efficiency across all the fuel mixes that were evaluated. The observed phenomena can be explained by the correlation between energy efficiency and brake specific fuel consumption (BSFC), where BSFC decreases as engine load increases [19]. Moreover, it was shown that under full load conditions, the unidentified losses were reduced, leading to an increase in power generation. Under full load circumstances, the diesel and biodiesel mixes MB10, MB20, and MB30 obtained energy efficiencies of 27.20%, 27.13%, 26.61%, and 28.13% respectively. Among these blends, MB30 exhibited the highest efficiency of 28.13%.




| | 3 | 6 | 9 | 12 |
|---|---|---|---|---|
| CR-18-Diesel | 12.42 | 18.21 | 23.26 | 27.20 |
| CR-18-MB10 | 13.33 | 19.55 | 24.43 | 27.13 |
| CR-18-MB20 | 14.35 | 20.14 | 23.40 | 26.61 |
| CR-18-MB30 | 14.45 | 19.94 | 24.51 | 28.13 |

**Fig. 7.** Variation in energy efficiency with engine load

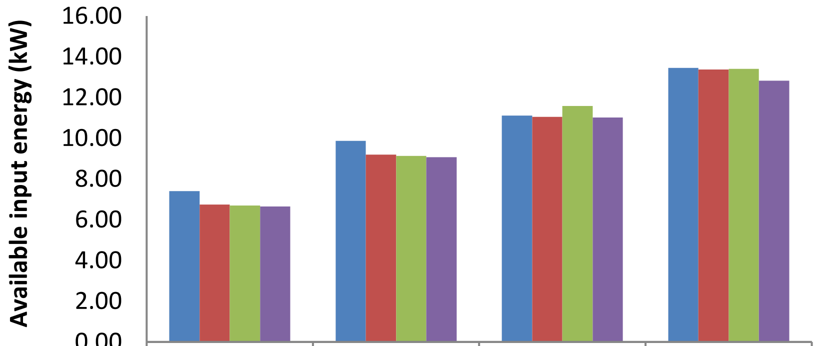
### *3.2 Exergy Analysis*

Exergy analysis was conducted to estimate the available input energy, available energy of the cooling water and exhaust gases, destructed available energy, exergy efficiency, entropy generation and SI of a VCR-CRDI type diesel engine fuelled with diesel and biodiesel blends of Moringa oleifera.

#### *3.2.1 Available input energy*

Available fuel energy represents the maximum amount of work can be developed form the combustion of fixed quantity of fuel.

Figure 8 illustrates the fluctuation in the amount of available input energy for various fuel blends under different loading conditions. The available input energy increases proportionally with the load growth, as a higher engine load necessitates the combustion of a greater quantity of fuel, as described in the fuel energy section [26]. The input energy available for biodiesel was less than that of diesel for the same unit power output. The improved combustion efficiency of biodiesel can be ascribed to its higher cetane number and greater oxygen content, resulting in a significant reduction in ignition delay. The highest available energy reported for the diesel was 13.46 kW at full load condition while biodiesel blends MB10, MB20, and MB30 offers highest available energy of 13.38, 13.40 and 12.83 kW at full load condition.



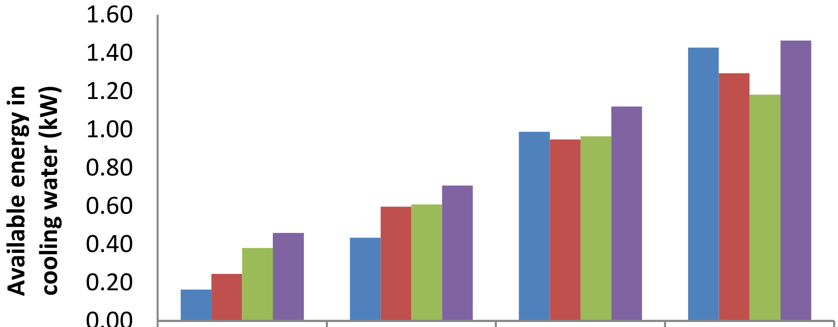

| | 3 | 6 | 9 | 12 |
|---|---|---|---|---|
| CR-18-Diesel | 7.41 | 9.88 | 11.11 | 13.46 |
| CR-18-MB10 | 6.75 | 9.20 | 11.04 | 13.38 |
| CR-18-MB20 | 6.70 | 9.14 | 11.58 | 13.40 |
| CR-18-MB30 | 6.65 | 9.07 | 11.01 | 12.83 |

**Fig. 8.** Variation in available energy with engine load

#### *3.2.2 Available energy in cooling water*

The exergy rate of cooling water in an internal combustion (IC) engine refers to the pace at which the cooling water carries away the potential for productive work. Evaluating the capacity to extract and utilize energy from the cooling system is crucial as it can significantly improve the overall efficiency of the engine.

Figure 9 illustrates the variation in the amount of available energy in the cooling water under various loading circumstances and fuel mixtures. The results indicate that an increase in engine load leads to an increase in the amount of energy available in the cooling water. The cooling water had the highest level of energy availability for all fuel mixes evaluated while operating at full load. This can be linked to the higher heat generation that took place at maximum loading circumstances, as a greater amount of fuel was combusted to fulfil the power need [24]. The cooling water demonstrated the highest exergy rate of 1.43 kW for the diesel fuel, while the MB30 blend of biodiesel exhibited a slightly higher exergy rate of 1.47 kW under full load conditions.



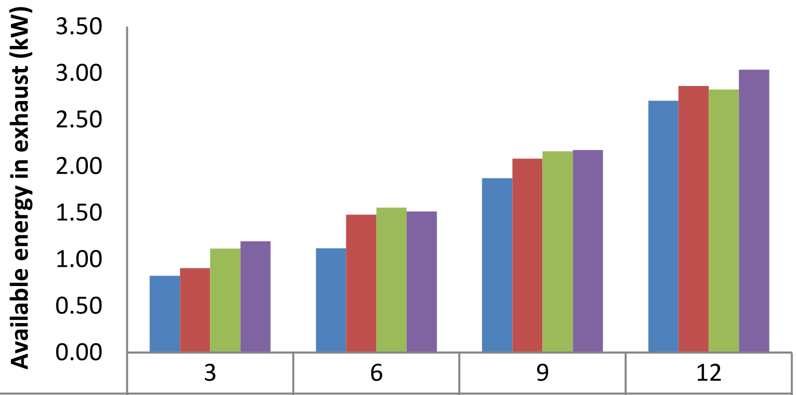

| | 3 | 6 | 9 | 12 |
|---|---|---|---|---|
| CR-18-Diesel | 0.16 | 0.44 | 0.99 | 1.43 |
| CR-18-MB10 | 0.25 | 0.60 | 0.95 | 1.30 |
| CR-18-MB20 | 0.38 | 0.61 | 0.97 | 1.18 |
| CR-18-MB30 | 0.46 | 0.71 | 1.12 | 1.47 |

**Fig. 9.** Variation in available energy of cooling water with engine load

### *3.2.3 Available energy in exhaust*

The exergy rate of exhaust gas in an internal combustion (IC) engine denotes the rate at which the exhaust gases are carrying away the potential for useful work. An exergy study of exhaust gases is crucial for enhancing the overall efficiency and sustainability of internal combustion engines. Engineers can enhance engine efficiency and environmental friendliness by quantifying and detecting exergy losses linked to exhaust gases. This enables the development of techniques to recover lost energy, minimize emissions, and maximize engine performance.

Figure 10 illustrates the fluctuation in the amount of energy present in the exhaust gas under various fuel mixtures and engine loads. The results demonstrate that an increase in engine load results in a corresponding increase in the amount of energy available in the exhaust gas for all of the fuel blends that were evaluated. The primary cause of this phenomenon is the increase in temperature and pressure within the engine cylinder, resulting from the more amount of fuel needed to achieve the desired power output. Furthermore, an additional factor that contributes to the improved effectiveness of combustion is the accelerated rate of combustion response witnessed as the engine load increases [27]. The maximum exergy rate observed for the exhaust gas in diesel and biodiesel mixes MB10, MB20, and MB30 were 2.70 kW, 2.86 kW, 2.82 kW, and 3.04 kW, respectively.



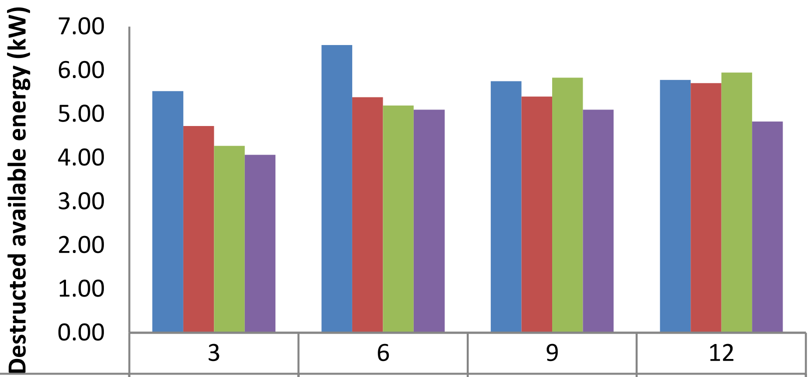

| | 3 | 6 | 9 | 12 |
|---|---|---|---|---|
| CR-18-Diesel | 0.83 | 1.12 | 1.87 | 2.70 |
| CR-18-MB10 | 0.91 | 1.48 | 2.08 | 2.86 |
| CR-18-MB20 | 1.12 | 1.56 | 2.16 | 2.82 |
| CR-18-MB30 | 1.20 | 1.52 | 2.18 | 3.04 |

**Fig. 10.** Variation in available energy of exhaust with engine load

### *3.2.4 Destructed available energy*

An exergy study of the destructed available energy is crucial for comprehending and reducing the inefficiencies in internal combustion engines. Engineers may achieve more efficiency, cost-effectiveness, and environmental friendliness in engine design by prioritizing the reduction of exergy destruction. This approach results in improved fuel economy, reduced emissions, and enhanced sustainability.

Figure 11 depicted the relationship between engine load and the fluctuation in available destructed energy. The rate of destructed usable energy rises proportionally to the engine load for all fuel mixtures, with the exception of diesel and biodiesel blend MB30. The increase in engine load leads to higher temperatures inside the engine cylinder and increased peak cylinder pressure. This, in turn, enhances combustion efficiency and accelerates heat transmission between the cylinder and the atmosphere [27]. The maximum destructed available energy recorded for the diesel engine was 6.58 kW under a 50% load situation. Among the biodiesel blends, MB20 exhibited the highest destructed available energy at full load, with a value of 5.95 kW.



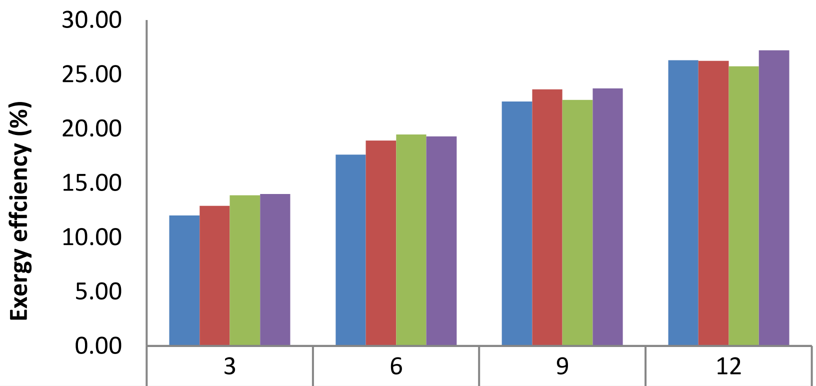

| | 3 | 6 | 9 | 12 |
|---|---|---|---|---|
| CR-18-Diesel | 5.53 | 6.58 | 5.75 | 5.78 |
| CR-18-MB10 | 4.73 | 5.38 | 5.40 | 5.71 |
| CR-18-MB20 | 4.27 | 5.19 | 5.83 | 5.95 |
| CR-18-MB30 | 4.07 | 5.10 | 5.10 | 4.83 |

**Fig. 11.** Variation in destructed available energy with engine load

### *3.2.5 Exergy efficiency*

Exergy efficiency, also referred to as second-law efficiency, quantifies the degree to which an internal combustion engine efficiently turns the available energy (exergy) into meaningful work.

Figure 12 illustrates the variation in exergy efficiency across several fuel blends under different loading conditions. The results indicate that the exergetic efficiency increases as the engine load increases for all the tested fuel blends. The diesel and biodiesel blend MB30 achieved exergy efficiencies of 26.31% and 27.21% respectively under full load conditions, which are the highest reported values. The increase in engine load results in higher power production and a decrease in brake specific fuel consumption (BSFC) at higher engine load conditions, with an improvement of 14.29 % [28]. For biodiesel blends MB10, MB20, and MB30, the improvements in exergy efficiency were 13.35 %, 11.86 %, and 13.23 %, respectively.



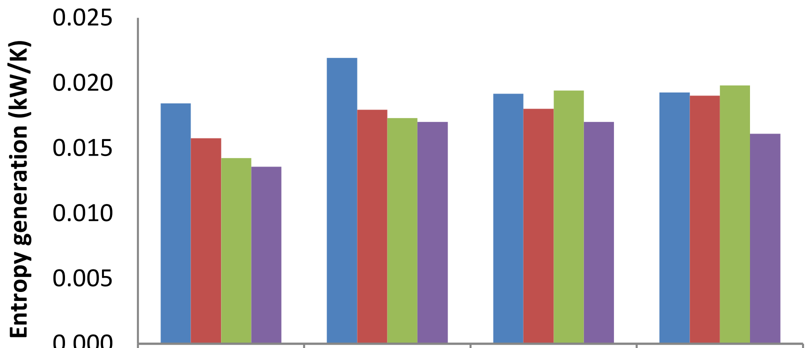

| | 3 | 6 | 9 | 12 |
|---|---|---|---|---|
| CR-18-Diesel | 12.02 | 17.62 | 22.50 | 26.31 |
| CR-18-MB10 | 12.89 | 18.91 | 23.63 | 26.24 |
| CR-18-MB20 | 13.88 | 19.48 | 22.63 | 25.74 |
| CR-18-MB30 | 13.98 | 19.28 | 23.70 | 27.21 |

**Fig. 12.** Variation in exergy efficiency with engine load

### *3.2.6 Entropy generation*

The creation of entropy is a crucial factor in assessing the thermal efficiency of equipment like heat pumps and engines. Moreover, the production of entropy is crucial for assessing the irreversibility in thermodynamic systems. The idea of entropy generation in an internal combustion (IC) engine refers to the inefficiencies that occur throughout the engine's thermodynamic operations. Gaining comprehension of and avoiding the production of disorder and randomness is crucial for enhancing the functioning of engines, optimizing the utilization of fuel, and mitigating the negative effects on the environment.

In this case, in Figure 13, the rise in loading was shown to be directly proportional to the increase in entropy production for all the tested blends except diesel and biodiesel blend MB30. The reason for this is entropy generation is directly proportional with the destructed available energy which increases with increase in engine load for all the fuel blends except diesel and MB30 [29]. The results indicate that the diesel fuel had the highest entropy generation of 0.022 kW/K at a 50% loading condition. Among the biodiesel blends, the MB20 blend had the highest entropy generation of 0.020 kW/K at full load.



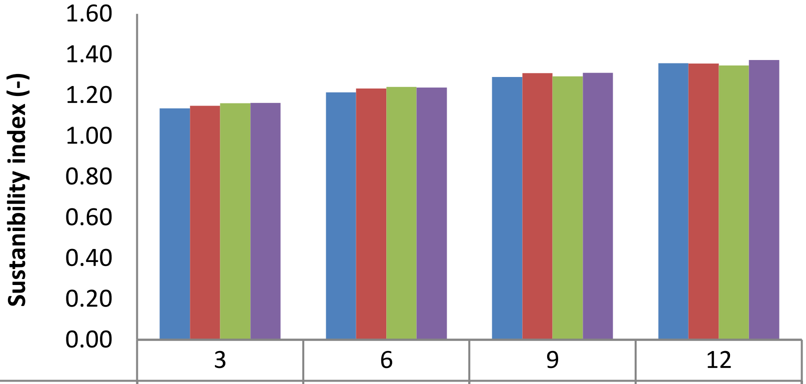

| | 3 | 6 | 9 | 12 |
|---|---|---|---|---|
| CR-18-Diesel | 0.018 | 0.022 | 0.019 | 0.019 |
| CR-18-MB10 | 0.016 | 0.018 | 0.018 | 0.019 |
| CR-18-MB20 | 0.014 | 0.017 | 0.019 | 0.020 |
| CR-18-MB30 | 0.014 | 0.017 | 0.017 | 0.016 |

**Fig. 13.** Variation in entropy generation with engine load

### *3.2.7 Sustainability index*

The sustainability index is crucial for determining sustainable alternatives to optimize systems. To assess the systems efficiently, the SI is employed, which is directly linked to exergy efficiency. There is a clear relationship between the engine loads and the SI results.The sustainability index of an IC engine is a vital metric that indicates the engine's total influence on the environment, usage of resources, and economic effectiveness. It functions as a crucial instrument for directing design enhancements, guaranteeing adherence to regulations, and fostering the enduring viability of engine technology [30].

Figure 14 illustrates the relationship between the sustainability index and engine load for various fuel blends. The data suggests that the SI of an engine increases proportionally with the rise in engine load. The reason for this is that the rise in SI of an engine is directly related to the exergy efficiency, which was found to increase with an increase in engine load [31,32]. The maximum SI values recorded for the diesel and biodiesel blends MB10, MB20, and MB30 were 1.36, 1.36, 1.35, and 1.37, respectively, under full load conditions.




| | 3 | 6 | 9 | 12 |
|---|---|---|---|---|
| CR-18-Diesel | 1.14 | 1.21 | 1.29 | 1.36 |
| CR-18-MB10 | 1.15 | 1.23 | 1.31 | 1.36 |
| CR-18-MB20 | 1.16 | 1.24 | 1.29 | 1.35 |
| CR-18-MB30 | 1.16 | 1.24 | 1.31 | 1.37 |

**Fig. 14.** Variation in sustainability index with engine load

## 4. Conclusion

The biodiesel derived from Moringa Oleifera oil underwent testing and demonstrated equivalent performance to conventional diesel fuel, as determined by the computed energetic and exergetic efficiency. The energy and exergy efficiency of the CI engine running on biodiesel and diesel fuel increased as the engine load increased.

At full load condition, the diesel engine when fuelled with diesel generated 4.09 kW and 2.74 kW of cooling water and exhaust energy, respectively. When operating at full engine load, the MB30 biodiesel blends exhibited higher values of 4.12 kW and 3.22 kW for cooling water and exhaust energy, respectively. The unaccounted energy decrease with increase in engine load and minimum unaccounted energy reported for the diesel and biodiesel blend MB30 were 2.64 and 1.58 kW at full load condition. The highest energy and exergy efficiency were seen for all the fuels evaluated under the full load scenario. The diesel and biodiesel blend MB30 had the maximum energy efficiency, with reported values of 27.20% and 28.13%, respectively.

Exhaust gas and cooling water exergy are improved in all tested gasoline mixes in proportion to the engine load. At full capacity, diesel fuel has the highest rates of cooling water and exhaust exergy, measuring 1.43 kW and 2.7 kW, respectively. Nevertheless, the biodiesel blend MB30 has the most elevated rates of cooling water and exhaust exergy, measuring 1.47 and 3.04 kW, respectively. The highest destructed available energy reported for the diesel was 6.58 kW at 50% loading condition and among biodiesel blends for MB20 it was 5.95 kW at full load condition. The exergy efficiency values for the diesel and biodiesel blends of MB30 were 26.31% and 27.21% respectively.

The formation of entropy increases as the engine load increases except with diesel and MB30. At a 50% load using diesel fuel, the engine exhibited a maximum entropy generation of 0.022 kW/K. However, when the engine was operated at full capacity with a biodiesel blend MB20, the maximum entropy generation recorded was 0.020 kW/K. Under full load conditions, the highest recorded SI values for the diesel and biodiesel blends in the MB30 were 1.36 and 1.37, respectively.

The energy efficiency and exergy efficiency of the CI engine, when using biodiesel as fuel, surpassed those of neat diesel fuel in all engine loading scenarios. This is due to improved combustion efficiency of the biodiesel compared to diesel fuel is attributed to its greater cetane number and oxygen content, which reduces the ignition delay and enhances efficiency.

Overall, the biodiesel produced from Moringa oil using the trans-esterification method shows potential as a substitute for diesel fuel. This is because the tested biodiesel exhibits comparable energetic and exergetic performance metrics to diesel fuel. Indeed, the aforementioned vegetable oil can be efficiently utilized as an alternative biodiesel fuel in a CI engine without necessitating any engine modifications. It is recommended to operate the engine under full load conditions, as the SI increases for all fuel blends tested as the engine load increases.

## Acknowledgement
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