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Energy–Exergy Performance Mapping of a Diesel Engine Powered by Hydrogen-Assisted Algal Bio-Oil Hybrid Fuel

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Nomenclature

BP - Brake power kW

IP - Indicated power kW

FP - Friction power kW

BMEP - Brake mean effective pressure bar

IMEP - Indicated mean effective pressure bar

BSFC - Brake specific fuel consumption kg/kWh

ISFC - Indicated specific fuel consumption kg/kWh

EGT - Exhaust gas temperature ◦C

DAQ - Data Acquisition system –

ECU - Electronic control unit –

EGR - Exhaust gas Recirculation system

D100 - Pure diesel

B20 - 20 % algae biodiesel

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Abstract

An experimental study was conducted to measure the energy and exergy characteristics of a four-stroke single-cylinder CRDI-VCR diesel engine on the microalgae-derived biodiesel blends and hydrogen-assisted biodiesel blends. The experiment entailed the use of traditional diesel (D100), standard diesel and microalgae bio-diesel put together (B20) and hydrogen-enriched bio-diesel put together (B20). The intake under full-load mode was used to run fifty experimental runs with pulse-width adjustment of 0 to 75% and the fuel-out of the intake variable to ten different fuel configurations. The results revealed that step-by-step increments, in the content of hydrogen, were having notable positive contributions in engine operating characteristics. An increase in supply of more hydrogen increased the combustion energy and this increased the brake thermal efficiency (BTE) and reduced the brake specific fuel consumption (BSFC) significantly. The optimal test fuel was simply the B20 with 75% hydrogen that had the highest BTE thus, attaining a peak of approximately 15% higher than a normal diesel fuel and at the same time reduced the BSFC by approximately 17%. The thermodynamic efficiency also improved greatly with the exergy analysis. This increased the exergy efficiency by a considerable margin, and also cut the exergy destruction by 18% resulting in the sustainability index value of 1.4 to 1.5. The benefits of hydrogen-assisted biodiesel combustion on the environment were also proved by measurements of emissions. The optimized fuel mixture led to a cut of carbon monoxide (CO) and incomplete hydrocarbon (HC) emissions by more or less 21% and 26% respectively and 14-18% cut of nitrogen oxide think tank, although the combustion temperatures were relatively high. Through the interaction of the variable compression ratio (VCR) mechanism and the programmable electronic control unit (ECU), the engine speed and injector parameters could be accurately optimized, and thereby provided an opportunity to engage in a variety of additional dynamic optimization of the combustion conditions. In general, the results suggest that hydrogen-enriched microalgae biodiesel could prove to be an effective alternative fuel with a compression-ignition engine, with better thermodynamic performances and lower emissions of pollutants.

Keywords: Energy analysis, Exergy analysis, Hydrogen, Algae oil

1. Introduction

The high pace of energy consumption in the global arena as well as the necessity to diminish climate change and reliance on exhaustible fossil fuels has speedily heightened the understanding of sustainable and environmentally safe substitute sources of energy. Traditional petroleum sources are still a critical source of greenhouse emissions and give out toxic gases like nitrogen oxides and particulate matter that project a serious environmental and health danger [1]. This has seen the future fuels such as biodiesel and hydrogen attracting increasing attention as the alternative to the reduction of the carbon footprint of the transportation and the energy industry. Among renewable fuels formed on the basis of microalgae, biodiesel made of microalgae has had some attention due to its carbon-free, and sustainability qualities [2]. The microalgae are extremely productive, photosynthetic organisms, which have the capability of storing large fraction of lipids, which can be made into biodiesel by transesterifying. Their ability to multiply in wastewater and their ability to trap high carbon dioxide atoms and manufacture a big output of fatty acids (usually 30-80%) is also a valuable source of renewable fuel [3]. Notwithstanding these strengths, large scale commercialization has eluded the potential due to the comparatively high costs of production, extraction methods that are energy consuming and other bio-diesel feed stocks. The biodiesel extraction is getting more and more through the new ways of extraction namely ultrasonic-assisted extraction and supercritical fluid processing hence necessitating the new advancement in technology to be refined economically viable. The development of bio-diesel has been paralleled to the development of hydrogen that has emerged as an efficient clean carrier of energy [4]. Hydrogen combustion produces water vapor that is the greatest by-product, thereby eliminating carbon dioxide and particulate emissions. It is also very energetic and propagates more on flame hence meaning that Hydrogen can be well used in high efficiency combustion non-renewable power generation. The high cost of producing green hydrogen, namely, electrolysis, and the problem of storage and transportation infrastructure are, however, hindrances to the widespread adoption. Bio-hydrogen also can provide an option of synergy in confronting the individual ineffective nature of the two classes of fuel [5]. The hydrogen combustion rate may be used to boost an increased proportion of burning biodiesel to offset the comparatively low heating quality of biodiesel and reduced pyrophoric compounds such as hydrocarbons. Conversely, the increased cetane number and superior lubricating properties of biodiesel can stabilize the combustion in the hydrogen assisted engines that result in the consequent effects of enhancing the reliability of the functioning of the engine [6]. Consequently, dual-fuel engine systems, in which hydrogen

is used as an additional fuel, have shown high potential in enhancing engine performance as well as falling the level of pollutant emissions. Previous investigations have reported encouraging outcomes for hydrogen-assisted combustion in compression-ignition engines [7]. For instance, studies have shown that replacing conventional fuels with hydrogen can significantly reduce carbon emissions while improving combustion efficiency due to faster flame propagation. Similarly, experimental analyses of microalgae-based biodiesel blends have demonstrated improvements in BTE along with reductions in fuel consumption and exhaust energy losses. Energy and exergy calculations made on various biodiesel feedstocks have shown that the content of oxygen and thermal stability may vary and affect thermodynamic efficiency and exergy destruction [8]. These results demonstrate the need to increase the combustion parameters, including hydrogen enhancement, to reduce irreversibilities and improve the overall engine performance. Hydrogen supplementation studies performed experimentally have also found gains in brake thermal efficiency as well as decreases in specific fuel consumption, but high combustion temperatures can sometimes raise nitrogen oxide emissions. Experiments with a variety of biodiesel feedstocks (soybean, algae, and dimethyl ether mixes) have revealed that fuel made with algae feedstocks frequently offers better combustion properties due to high cetane number [9]. Hydrogen-diesel Dual-fuel systems have also shown significant improvements in thermal efficiency and decreases in brake-specific energy consumption especially under full load. Nevertheless, the high hydrogen flow rates may contribute to the abnormal combustion processes, including pre-ignition or backfire, so there is the risk that the tendency towards supplying hydrogen should be optimized carefully [10]. The act of keeping the hydrogen levels low will provide steady engine performance without compromising the ability to have increased combustion. All in all, the available literature proves the fact that the use of both hydrogen and biodiesel has the potential to enhance the functionality of the engine to a considerable degree. Based on these results, the current study conducts a comprehensive experimental assessment of several biodiesel-hydrogen mixtures of fuels [11]. Along with the analysis of performance and emission, the more thorough thermodynamic analysis (together with exergy destruction, exergy efficiency, and sustainability index calculations) is performed to give a more in-depth picture of the energetic behavior of the dual-fuel system. Outside of the internal combustion engine studies, some progress in the optimization of thermodynamic cycles have been made, including organic Rankine cycle systems to recover low-temperature waste heat, which has shown to potentially make the use of energy more efficient [12]. All these developments underscore the need to combine high-level thermodynamic technologies with alternative fuel technologies to attain

better energy performance. Research work on higher order combustion regimes and two-fuel engine designs has also revealed that a controlled addition of hydrogen can affect the ignition delay, combustion period and stability of the cycle, whereas too high levels of hydrogen can cause unwanted combustion characteristics [13]. The current study will help develop the hybrid fuel systems that can enhance sustainability, reduce emissions, and boost the energy security by investigating the complementary nature of microalgae biodiesel and hydrogen. The results of this study can be beneficial to the engineers, researchers, and policymakers who want to pursue viable solutions to carbon-neutral and environmental-friendly energy systems.

2. Methodology

2.1 Experimental setup

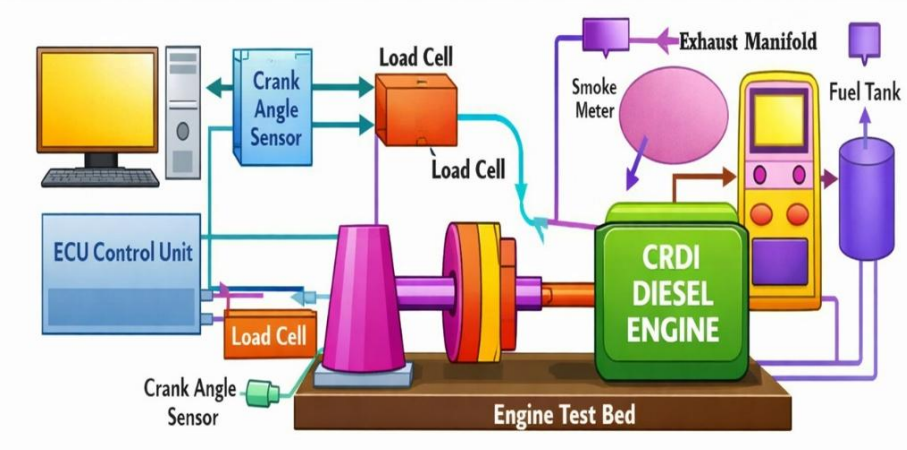


Fig. 1. Engine test setup

The experimental was conducted in a compression-ignition (CI) single-cylinder engine that was specially modified to permit the introduction of hydrogen into the intake system the overall experiment apparatus shown in Figure 1. The test engine was also connected to an eddy current dynamometer in order to simulate under different operating conditions and make accurate evaluation of the engine performance since it allowed a controlled and accurate application of load and a good assessment of the performance characteristics [14]. The intake of hydrogen was made through the solenoid-activated injection system in the intake manifold. A pulse-width modulation (PWM) control strategy controlled the flow of hydrogen and enabled the quick change of the gas flow at a precision of milliseconds to obtain the required hydrogen concentration of the intake airstream. The technical specifications of the engine are beamed out in Table 1 and the physicochemical properties of the fuels in Table 2.

Table 1 . Engine specifications.	
Parameter	**Value/Description**
Stroke/Stroke length	110 mm
Cylinder/Bore	87.5 mm
Cooling type	Liquid cooling
Injector/Nozzle Count	1/3
Nozzle diameter	0.25 mm
Compression ratio (used)	17.5
Range of CR	12:1–18:1
Engine speed	1500 rpm
Injection pressure	220 bar
Injection timing	22.5° bTDC
Initial pressure	1 bar
Initial temperature	300 K
Inlet valve opens	4.5° bTDC
Inlet valve closes	35.5° aBDC
Outlet valve opens	35.5° bBDC
Outlet valve closes	4.5° aTDC

Table 2. Fuel Properties					
Fuel Type	**Flash Point (°C)**	**Cetane Rating**	**Lower Heating Value (kJ/kg)**	**Density (kg/m^3)**	**Viscosity (mm^2/s)**
D100	98	56	43,550	855	4.8
B20	108	58	42,530	875	5.0
Hydrogen	–	–	1,19,920	0.09	0.0138 at 0 °C

2.2 Blend preparation

2.2.1 Diesel–Hydrogen (D100 + H_2):

The experiments used conventional diesel fuel (D100) as a reference fuel. The intake system was then supplied with a controlled and gradually increased flow of hydrogen gas (45%and 75%) to investigate the effect of the enrichment of the hydrogen on the engine operation.

2.2.2 Biodiesel Blend–Hydrogen (B20 + H_2):

A blended fuel which was composed of 20 % microalgae-derived biodiesel and 80 % petroleum diesel (B20) was prepared and utilized as the primary liquid fuel. The performance, combustion and emission biodiesel mixture, was then tested by introducing hydrogen into the intake manifold at the same incremental flow durations.

2.2.3 Diesel–Biodiesel–Hydrogen Ternary Blend:

Along with the single fuel mixtures, a ternary fuel mixture with diesel, microalgae biodiesel, and hydrogen was also tested. Hydrogen was added in this instance at sequentially increasing flow periods to test. The experimental assessment began by the engine working with conventional diesel fuel to set the performance conditions as a baseline. The engine load was incrementally stepped to reflect both of the part-load and full-load operating regimes.

3. Experimental setup

In the current experimental study, hydrogen was added in the engine intake compartment with the controlled flow rates, i.e. at the proportions of 45%and 75%. The other engine operating parameters remained constant to be in a position to have stable and repeatable experimental conditions. This was regulated with special hydrogen control system that regulated the supply of gas in real time and allowed delivery of hydrogen to be accurate and consistent throughout the test period. The engine load and hydrogen flow rate were measured in each of the test conditions; the main performance indicators of the engine and exhaust emissions characteristics were measured with the help of the properly calibrated diagnostic instruments. The data obtained was well tabulated and ready to be subjected to further post-process and analysis. After conducting the experiments using conventional diesel fuel, the identical process was repeated using the assistance of B20 biodiesel mixture which was acquired through the assistance of microalgae. The same predetermined intervals of flow were imposed again on hydrogen supplementation to give the same comparison between the different fuel settings. To make the experimental findings more powerful and more stable, a number of trials was made on each of the operating conditions and mean values were used in the general analysis. The experimental results which were gathered were analyzed further to do energy and exergy analysis, sustainability indicators analysis and determine the impact of hydrogen enrichment on engine efficiency and environmental performance. This experimental system proposed technique was capable of a critical examination of the thermodynamic activity and emission characteristics of hydrogen-assisted combustion in compression ignition engines. The results are applicable in the feasibility and feasibility of hydrogen-biodiesel dual fuel plans in the renewable power systems.

4. Results and Discussion

4.1 Thermodynamic Interpretation of the Engine Cycle

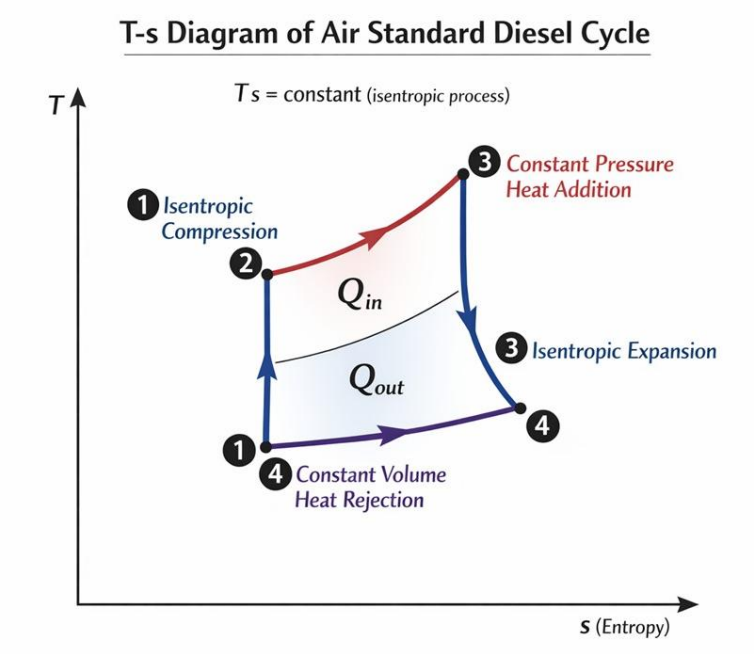


Fig. 2. T-s diagram for the air standard Diesel cycle.

The thermodynamic behavior of the compression ignition engine examined in this study can be represented using a temperature–entropy (T–s) diagram, as depicted in Figure. 2. During the compression phase, the working fluid is assumed to undergo an adiabatic and reversible compression process, moving from state 1 to state 2 until ignition begins. The combustion stage is then modeled as a constant-pressure heat addition process occurring between states 2 and 3. Following combustion, the expansion phase (power stroke) takes place, which is approximated as an isentropic expansion process from state 3 to state 4. In this stage, mechanical work is produced as the high-pressure gases expand within the cylinder. The final stage of the cycle corresponds to heat rejection, which occurs at nearly constant volume between states 4 and 1, thereby completing the thermodynamic cycle of the engine.

4.2 Brake Specific Fuel Consumption

Figure 3. shows the change in the brake specific fuel consumption (BSFC) with engine load under various fuel blends of conventional diesel fuel (D100), microalgae-derived biodiesel blend (B20), and hydrogen-enriched B20 blends. Investigated levels of hydrogen enrichment relate to pulse width values between about 47% and 75%. BSFC is observed to be on a downward trend with respect to engine load in all the fuel combinations studied [15]. The increase in fuel consumption is normally at lower load especially at 25 % load, and the fuel efficiency improves with increase in the load. This is typical of compression ignition engines

whereby incomplete combustion under low load conditions comes about due to comparatively low in-cylinder temperature and pressure. In this case, a greater amount of fuel is necessary as a result of which the same amount of useful power output will be produced. The higher the engine load, the more favorable the combustion conditions (high cylinder temperatures and pressures) and the better the fuel is used and the lower the BSFC. In a comparison of the fuels, the B20 biodiesel blend tends to have a little more fuel consumption as compared to pure diesel in the same circumstances. This is because the heating value of biodiesel was relatively low and the viscosity was high and this could interfere with the atomization of fuels and their ability to burn. Adding hydrogen to the B20 biodiesel mixture is very effective in enhancing the fuel use properties. Among the conditions tested, the most desirable BSFC performance is exhibited by the hydrogen levels of enrichment of 47%. These findings indicate that moderate supplementation of hydrogen will offer a good compromise between increased efficiency in combustion and engine stability [16]. The improvement in fuel efficiency can be explained by the combustion properties of hydrogen. Hydrogen has large flame propagation velocity and low ignition energy that facilitate faster oxidation of the fuel air mixture and lead to a further full combustion. This effect can be linked with differences in formation of mixtures or the higher probability of abnormal combustion processes like pre-ignition. When pure diesel fuel is further added to the hydrogen, BSFC also decreases; however, this is more significant when combined with the B20 biodiesel mixture. This implies that there is a greater synergistic interaction between hydrogen and bio-diesel fuels, which positively affects the combustion properties and the overall engine performance [17].

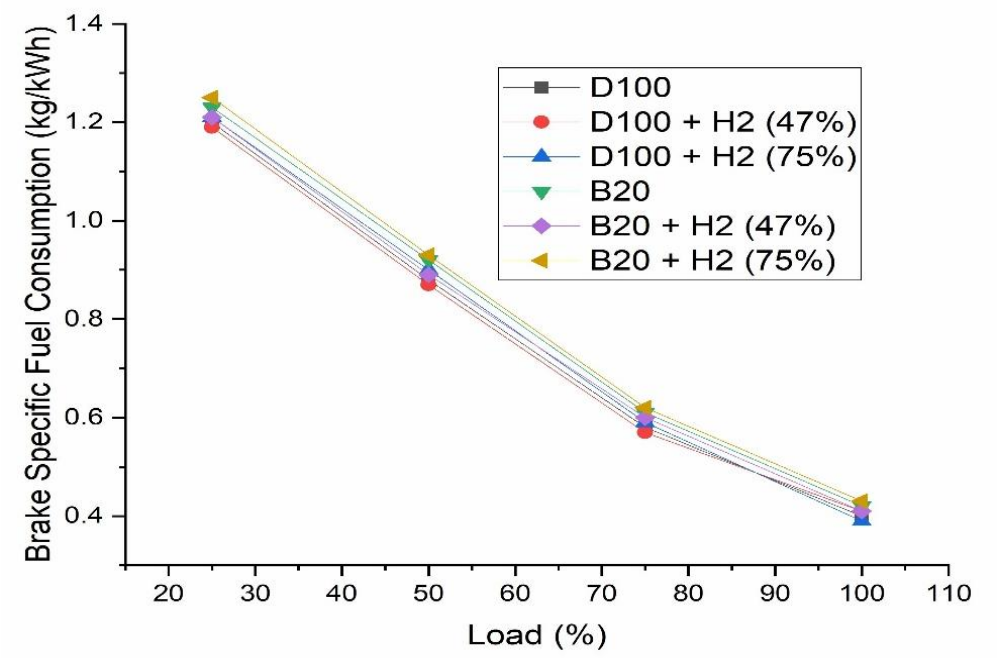


Fig. 3. Variation of Brake Specific Fuel Consumption

4.3 Brake Thermal Efficiency (BTE)

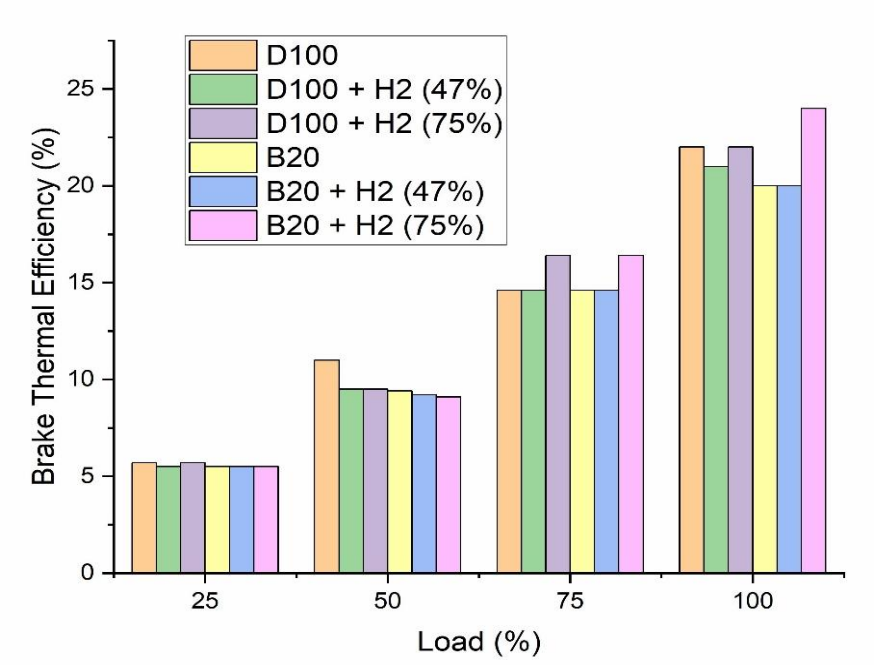


Fig. 4. Variation in Brake Thermal Efficiency

Figure 4. shows the change in brake thermal efficiency (BTE) at various engine loads 25%, 50%, 75%, and full load of various fuel content, such as conventional diesel (D100), microalgae-derived biodiesel blend (B20), and hydrogen-enriched biodiesel blend (B20) and hydrogen pulse-width level of BTE with all the studied fuels rises with engine load. This is common in compression ignition engines, as loads that are high provide a higher in-cylinder pressure and temperature, which provide a better environment to undergo fuel combustion and energy conversion [18]. The conversion of chemical energy to useful mechanical work is therefore more efficient as the engine load is increased. The BTE values across all fuel combinations are relatively low at low load conditions (25%) and have only slight differences. This has been explained by the fact that they would not burn completely due to the lack of adequate cylinder pressure and temperature to allow the efficient oxidation of the fuel-air mixture. When the load is increased to about 50, all fuels show a moderate improvement in BTE. In these circumstances, pure diesel (D100) and the hydrogen-enhanced B20 blend with a 47% of hydrogen supplementation prove a little bit better than the rest of the tested fuels [19]. An increase in BTE is more apparent in the higher load conditions, at 75% and full load. Hydrogen enriched B20 blends are better in these operating regimes than pure diesel and the standard B20 biodiesel fuel. In particular, when the hydrogen concentration in the B20 mixture is increased to approximately 47% the B20 mixture has the best thermal performance at full-

load conditions, which demonstrates that moderate hydrogen enrichment can boost the combustion properties of biodiesel-based fuels to a considerable extent. The enhancement of BTE is explicable by the natural combustion nature of hydrogen. High flame propagation velocity and very low ignition energy requirement are the features of hydrogen that contribute to quick ignition and better flame development in the combustion chamber. The properties also lead to further complete oxidation of the fuel-air mixture, which permits a larger fraction of the thermal energy released to be converted into mechanical work and minimizes heat losses at the same time [20]. The highest possible hydrogen enrichment level of the D100 fuel (75) has the highest value of the BTE at full load but the progressively smaller value of the percentage change in the enrichment level at very high hydrogen concentrations. This decrease in efficacy could be attributed to other factors like flame quenching or the development of excessively lean mixtures of combustion in the event of excessive hydrogen concentration.

4.4 Sustainability Analysis

The sustainability index (SI) is used as a measure to conceptualize the thermodynamic performance of the engine system through a connection between exergy efficiency and exergy destruction. An increase in the SI values indicates more efficient use of the provided energy and reduced irrevocable losses in the process of energy conversion [21]. The fuel mix that is studied shows that the B20 biodiesel blend with 75% of hydrogen has the most sustainability index when full-load is applied to the operating conditions.

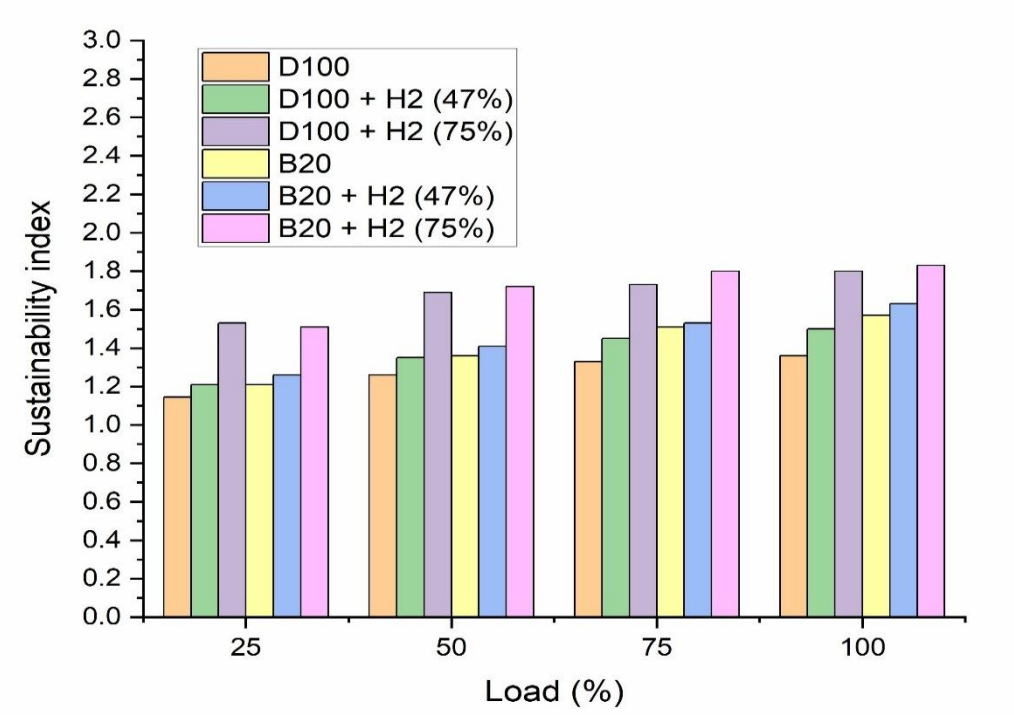


Fig. 5. Variation of Sustainability index

This finding suggests the fuel has better combustion characteristics, less thermodynamic losses, and better energy conversion than other fuels that were also tested. Overall, there is an increase in SI values with engine load in all fuel configurations. The reason behind this trend is that increased loads result in increased in-cylinder temperature and pressure which encourage complete combustion and enhance the use of the available energy. On the other hand, the traditional diesel fuel (D100) demonstrates relatively low SI values under most operating conditions. This reduced sustainability performance of diesel may be explained by higher thermodynamic losses, especially by the losses of exhaust energy and internal irreversibilities produced in the course of combustion process. The introduction of hydrogen plays a major role in improving the sustainability properties of the engine system [22]. Hydrogen has desirable combustion characteristics such as high flame speed and clean burning characteristics, which make it generate less entropy and exergy efficiency. Also, the oxygenated character of the B20 bio diesel blend enhances better oxidation of the fuel-air mixture leading to an overall better quality of combustion. Using hydrogen enrichment and biodiesel blending simultaneously hence generates a synergistic enhancement in thermodynamic performance. Consequently, B20 fuel arrangements with hydrogen assistance have better sustainability features, especially at higher loads of the engine [23]. According to Figure. 5, the largest SI value is registered in the B20 blend with 75% of hydrogen at full-load conditions, which means the best energy use with minimum exergy loss. Conversely, the pure diesel operation is associated with the lowest sustainability index because of increased thermal losses in the form of exhaust gases and higher irreversibility in the combustion process. These losses are largely alleviated by the addition of hydrogen that improves the efficiency of combustion and lowers the entropy generation due to incomplete combustion.

4.5 Heat Loss

Figure 6 shows the change of heat loss through the engine walls at various engine loads with the combinations of fuel tested. The findings show that the wall heat losses are less as the engine load rises. This decrease is more evident when it comes to hydrogen assisted fuel blends. In case of low engine load conditions, conventional diesel fuel (D100) experiences the highest heat loss of about 18%. Conversely, B20 biodiesel mix with 75% of hydrogen has the lowest wall heat loss, which varies between about 11 to 12 % at full-load operating [24]. The decrease in thermal losses to higher loads is largely due to the increase in combustion efficiency. Under a condition of higher load of the engine, the process of combustion is more intense because of the rise in temperature and pressure within the cylinder. This causes the fuel-air mixture to be

oxidized faster and produces a short combustion period. Consequently, the duration of exposure of heat transfer between hot combustion gases and the cylinder walls is minimized, which decreases the total heat dissipation. This is also enhanced when the hydrogen enrichment is done due to its good combustion characteristics. Flame propagation and low ignition energy are the defining characteristics of hydrogen that determines the acceleration of the combustion process and minimized the amount of time required to transfer the heat to the other engine parts. As a result, the possibilities of conductive heat loss through the engine walls are reduced [25]. The microalgae-derived B20 biodiesel mixture also has a rather high cetane number, which is associated with better ignition properties and more stable combustion behavior. This enhances the quality of ignition to curb the occurrence of uneven flame formation and minimizes the thermal inefficiency normally caused due to incomplete combustion.

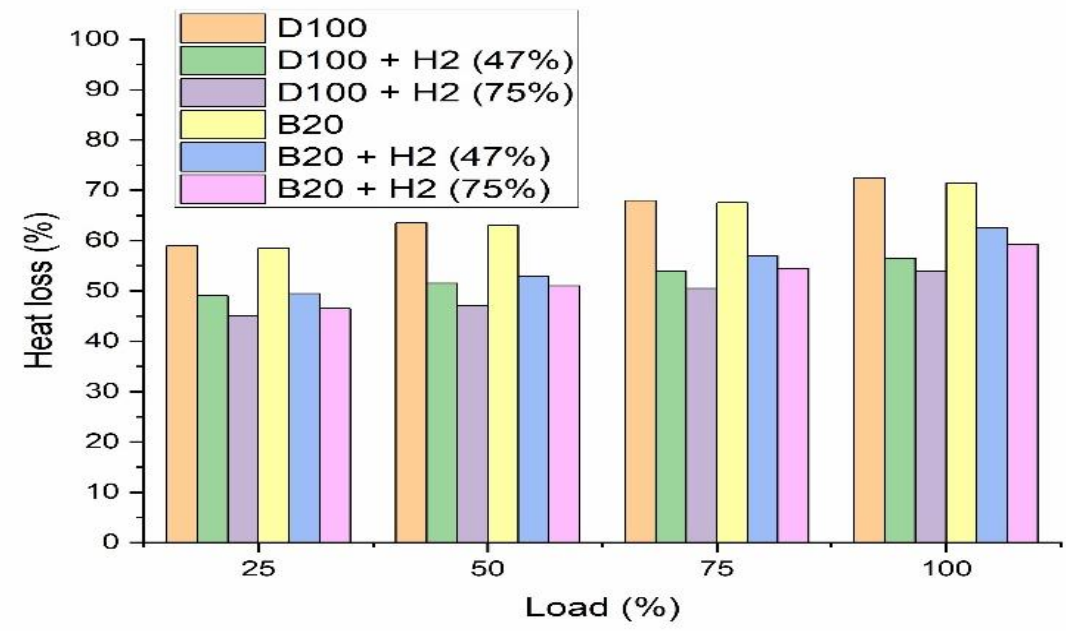


Fig. 6. Variation of heat loss

4.6 Exhaust Loss

Figure 7 shows how the energy losses that are taken away by the exhaust gases vary with the engine load conditions in the fuel combinations under study. The findings indicate that energy losses associated with the exhaust decrease slowly as the engine load increases. At reduced load conditions, pure diesel fuel (D100) has relatively higher exhaust energy losses, which go as high as 25%. Conversely, the B20 biodiesel blend to which hydrogen has been added in the proportion of 75% of the total exhibits a much lower exhaust loss at full-load operation of about 18 %. Such reduction implies that a higher percentage of chemical energy

in the fuel is used up to useful mechanical output and that more energy is not wasted in exhaust stream [26]. The addition of hydrogen plays an important role in improving the overall energy utilization of the engine. Hydrogen has desirable combustion properties such as a high rate of flame propagation and high reaction kinetics which makes it easier to combust. These properties enhance better mixing of the air fuel charge and balanced combustion process. In addition, the B20 microalgae-derived biodiesel mixture also adds to better combustion characteristics because of the oxygenating molecular structure [27]. The oxygen content of biodiesel also induces a greater oxidation degree of the fuel-air mixture, and, therefore, less partially burnt products are formed and the amount of thermal energy released with the exhaust gases is also reduced. The concomitant effect of the enrichment of hydrogen and the addition of biodiesel then brings about a synergistic effect on combustion efficiency. Consequently, the level of exhaust energy losses can be significantly minimized using hydrogen-assisted biodiesel blends. Comparatively, in traditional diesel combustion, a higher fraction of the energy is usually exhausted due to comparatively slower and incomplete oxidation reactions.

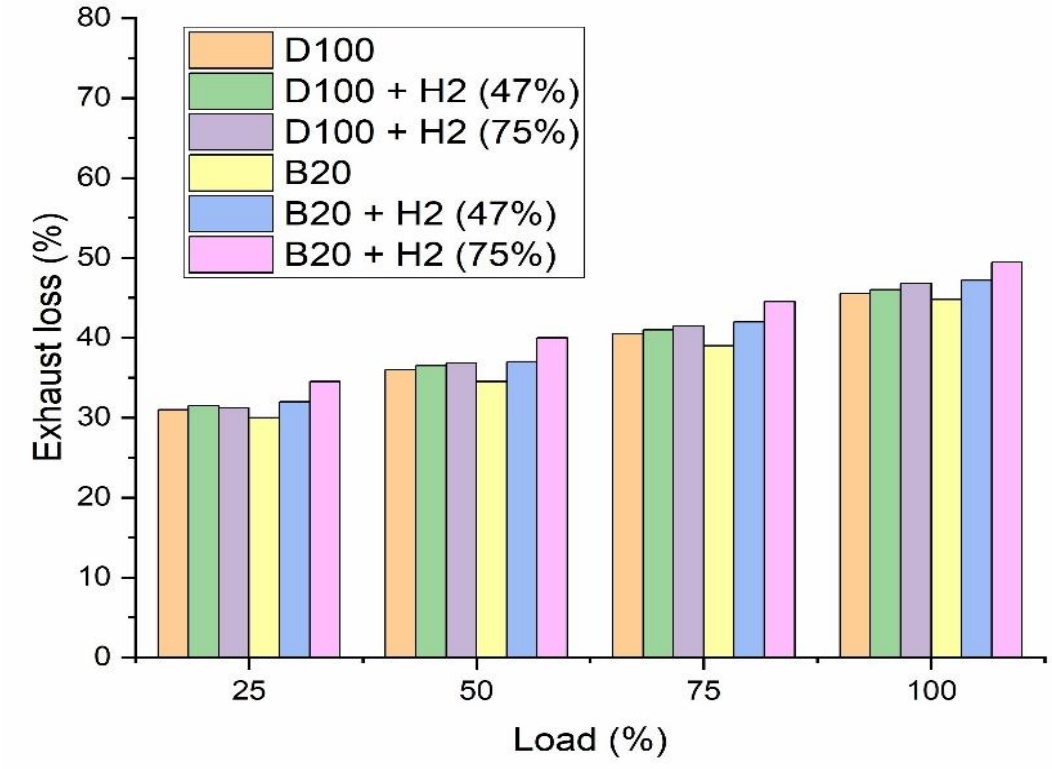


Fig. 7. Variation of exhaust loss

4.7 Input Exergy

Input exergy is the total chemical energy input in the engine due to fuel and is an essential parameter in the assessment of the thermodynamic performance of the system. The input exergy rises with the engine load as illustrated in Figure 8. This is due to the fact that the

load conditions are high and they require increased fuel consumption to meet the equally increased engine torque and power output [28]. The highest input exergy value of about 70 kW is observed in the combinations of fuels of B20 biodiesel and 75% of hydrogen and diesel fuel that is added with an equivalent amount of hydrogen. This growth is not unexpected as an increase in engine output will demand more energy to get the combustion process going and to support the necessary mechanical output. The addition of hydrogen is important in augmenting the input exergy of the fuel mixture. Hydrogen promotes the overall energy content supplied to the engine due to its high calorific value and the desirable combustion properties [29]. By combining hydrogen with microalgae-derived B20 biodiesel, which has intrinsic oxygen that helps in efficient oxidation of fuels during combustion, the effect is increased. Furthermore, the duration of time to inject the hydrogen is increased to about 75% which injects more hydrogen in the combustion chamber. The consequence of this is an increase of the fuel air mixture energy density. As a result, the possible work output of the engine which is the available exergy also increases.

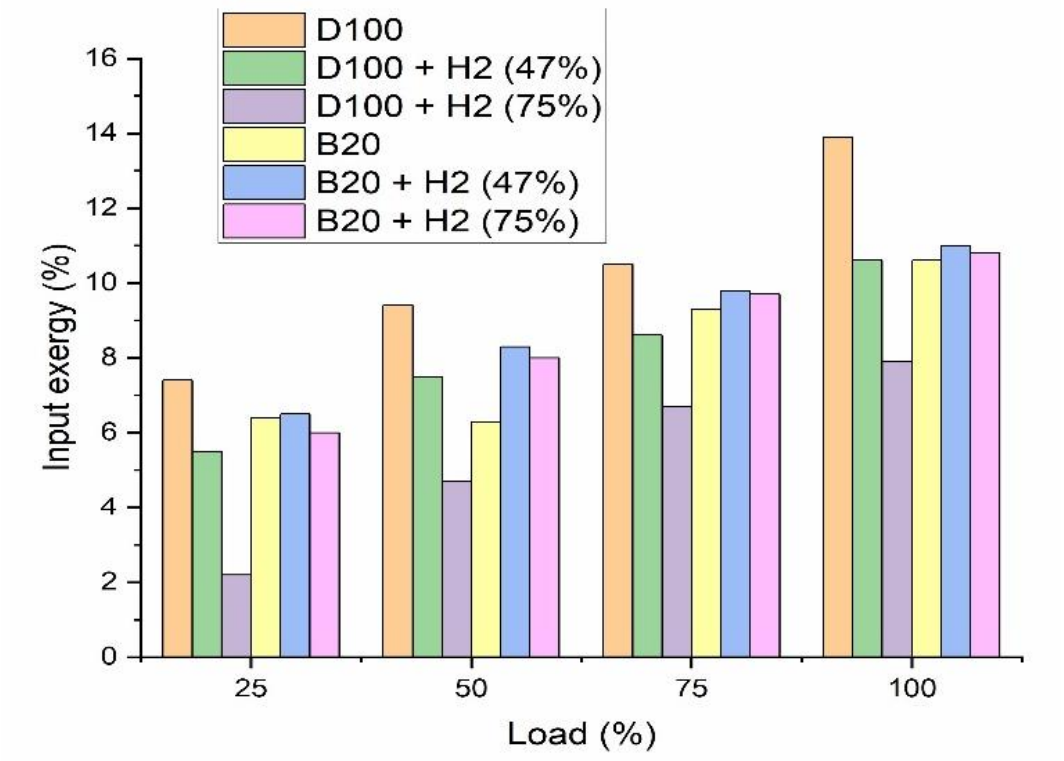


Fig. 8. Variation of input exergy

4.8 Exergy at the shaft

Figure 9. shows how the exergy of the shaft, or useful mechanical energy generated by the engine, varies in the various fuel combinations under consideration in this paper. The findings show that all the tested fuels have a consistent increase in shaft exergy with engine

load. Among the studied fuel combinations, the B20 biodiesel mixture enriched by 75% of hydrogen shows the greatest shaft exergy output of around 2100 kW at full-load operation. Comparatively, traditional diesel fuel (D100) produces relatively lower values of shaft exergy, usually between 18 and 20 kW. These findings indicate that the hydrogen-assisted biodiesel blends allow a more effective conversion of the given fuel energy into the mechanical work [30]. The positive combustion properties of hydrogen can explain the increase in shaft exergy. The hydrogen has a large flame propagation rate and diffusivity which increases the fuel air mixture mixing rate and helps in a faster and a better combustion rate. These characteristics enhance the rate of pressure rise during expansion process which enhances the mechanical work output during the power stroke. Moreover, the microalgae-based B20 biodiesel mixture also has a positive effect on the behavior of combustion as it contains oxygen and rather high cetane number. The features enhance quality in ignition and assist in stabilizing combustion during the engine operating cycle. Hydrogen enrichment plus biodiesel blending has a combined effect in that way it increases the thermodynamic efficiency of the engine by increasing the conversion of chemical energy into useful mechanical output [31]. The peak shaft exergy value of the B20 + H_2 (75) configuration proves that this fuel mix offers the most efficient consumption of the supplied energy under the conditions of the experiment.

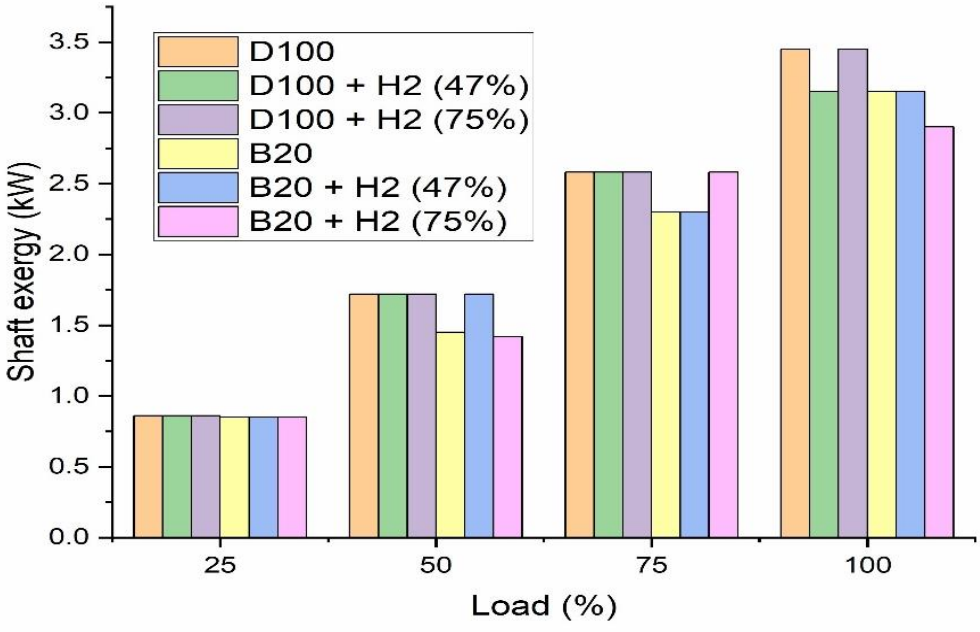


Fig. 9. Variation of shaft exergy.

4.9 Exergy Potential in Combustion

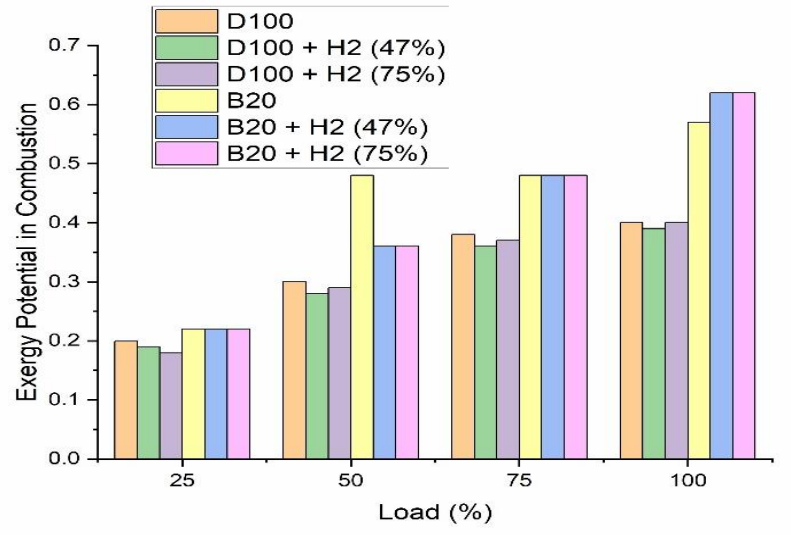


Fig. 10. Variation of EPC

Figure 10 shows the change in the Exergy potential in Combustion (EPC) which shows the fraction of the exergy supplied to the fuel that can be theoretically utilized in the combustion reaction and converted into useful energy. The findings illustrate that EPC rises slowly with the rise in the engine load in all the fuel mixes that were examined. Hydrogen assisted fuels have the maximum EPC values, especially when it comes to the B20 biodiesel fuel with the hydrogen concentration of 75%. The tendency towards the increase of EPC when the engine loads are higher can be explained by the fact that the amount of fuel injected and the intake air that is needed to maintain the higher power output are greater [32]. With such conditions, the energy density inside the combustion chamber is increased and a higher proportion of the provided chemical energy can be effectively used during the combustion process. Enrichment of hydrogen will greatly enhance EPC owing to its good nature of combustion. Hydrogen reacts rapidly and the flame propagation speed is high and that favour quick ignition and efficient oxidation of the fuel. These properties enhance the rate of the fraction of fuel energy participating in the thermodynamic cycle. Moreover, the biodiesel mixture prepared using the microalgae is more efficient in combustion due to the oxygenated molecular structure of the mix. Oxygen content in the biodiesel structure enhances better oxidation of the fuel-air mixture, promotes better pre-flame reactions, and decreases activation energy needed to initiate combustion. The blending of hydrogen enrichment and biodiesel, therefore, enhances the combustion properties of the mixture [33]. This synergistic action increases the stability and efficiency of the overall combustion process, that is the ability of the supplied energy to be transformed into useful work is a greater fraction.

4.10 Exhaust gas exergy

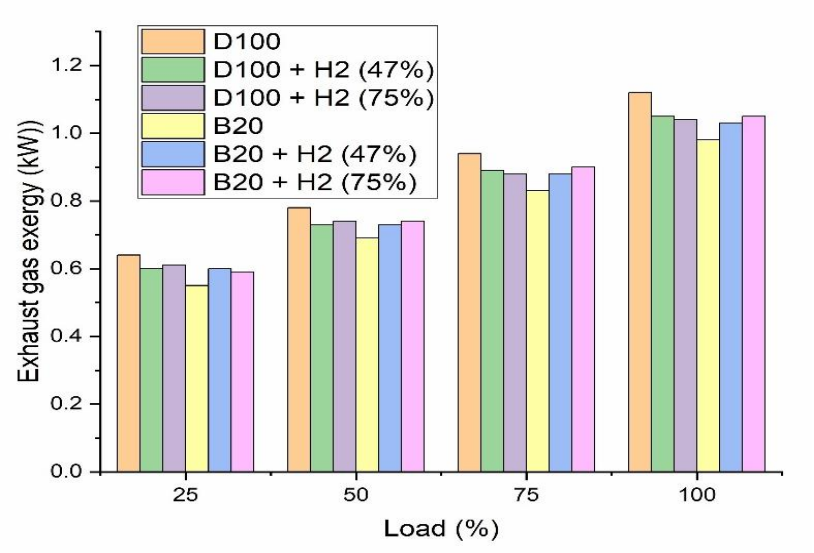


Fig. 11. Variation of exhaust gas exergy

Figure 11. shows that the exergy of exhaust gases rises with engine load and it is more pronounced in the case of hydrogen-enriched fuel blends. A higher proportion of chemical energy exits the engine via the exhaust at lower working rates due to the presence of un-combusted and partially oxidized products in the exhaust stream. This results in the exhaust gases having more thermal and chemical exergy [34]. The combustion process is more efficient when the engine is operated at higher loads, as the conditions in the cylinder are better in terms of temperature and pressure. This is especially the case with hydrogen-assisted fuel mixtures, where even faster and more complete combustion of the fuel means that the remaining energy carried away by the exhaust gases is significantly reduced. Conversely, the case with conventional diesel fuel is that it is more likely to have a relatively higher exhaust exergy throughout the working range. This is mostly associated with its slower combustion properties and relatively higher fuel blends which creates a higher quantity of unused thermal energy exiting the system. The B20 + H_2 (75) blend has the lowest exhaust exergy loss per full-load work, with a higher fraction of the chemical energy provided by the fuel being used in the engine. One of the reasons behind this improvement is hydrogen because of its great diffusivity and quick combustion properties, which enhances mixing and even spread of the flames. Besides this, the oxygenated nature of microalgae-derived B20 biodiesel is favourable in enhancing the full oxidation of combustion intermediates like carbon monoxide and unburned hydrocarbons.

4.11 Cooling Water Exergy

Figure 12. shows the exergy loss variation with engine cooling water of varying operating conditions. Its findings indicate that exergy loss to the cooling system reduces with the increase in engine load, and the effect is more pronounced in the case of hydrogen-assisted fuel mixtures. With low engine loads, a greater percentage of the discharged thermal energy is dumped to the cooling system [35]. This is because under such conditions, the combustion process is slower and less efficient and therefore the flame takes longer time to develop and the heat to be transferred to the cylinder walls by the combustion gases. Consequently, there is an increased conduction of thermal energy through the engine walls, and dissipation of the thermal energy through the cooling water. The higher the engine load, the faster and more complete will be the combustion process. This reduces the time that the heat is transferred between the combustion gases of high temperature and the engine components. This means that the level of thermal energy discarded with the help of the cooling system reduces. This is being particularly observed in the case of the B20 biodiesel mix with a hydrogen content of 75%. The high rate of combustion of hydrogen, along with the increased in-cylinder temperatures that the combustion process generates, concentrates the heat release in the combustion chamber [22]. This restricts the conduction of thermal energy to the cooling jackets and the loss of exergy. Conversely, the traditional diesel fuel normally has more cooling-water exergy losses, particularly during part-load operation. This action may be explained by the fact that there are more delayed time to ignite, and a longer combustion period, which results in more time to share heat with the engine walls. The fuel mixes that have been tested (B20 + H_2) exhibit the least cooling-water exergy loss at high engine loads with the B20 + H_2 (75) fuel mix showing the lowest loss. This shows that a greater proportion of the emitted energy is stored in the combustion process and transformed into work. The fast combustion character of hydrogen reduces the heat transfer duration whereas the presence of oxygen in the composition of B20 biodiesel blend facilitates good and stable combustion.

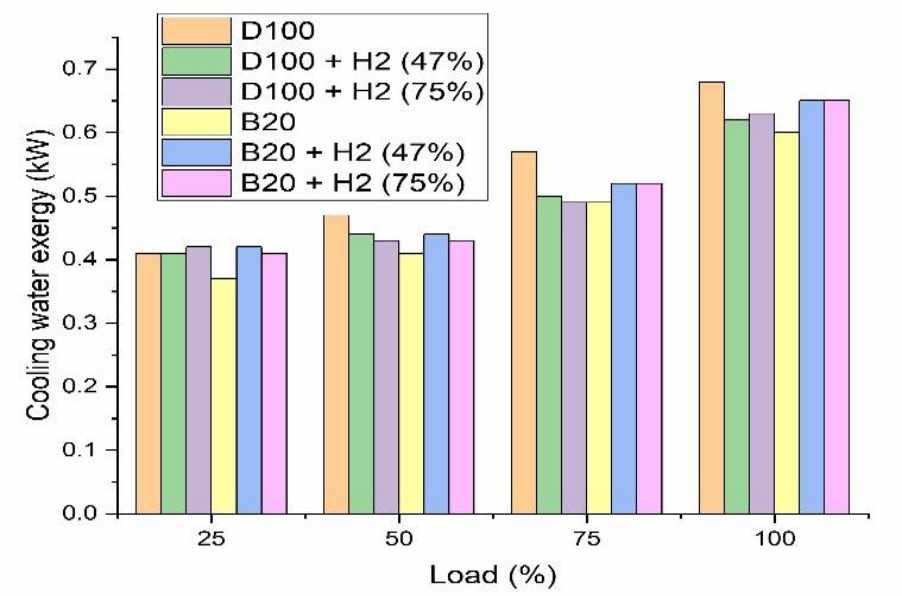


Fig. 12. Variation of cooling water exergy

4.12 Exergy Destruction

Figure 13. shows how the exergy destruction varies with engine load using the various fuel configurations such as traditional diesel fuel (D100), microalgae-derived B20 bio-diesel and hydrogen-enhanced mixtures of both diesel and B20. Exergy destruction is the energy supplied that cannot be transformed to useful work because of irreversible processes that are involved in combustion and energy conversion [9]. Thus, it is a valuable parameter that can be used in measuring the thermodynamic efficiency of an engine system. The findings indicate that exergy destruction is higher when engine loads rise when in 0% and full-load conditions regardless of the type of fuel used. This is expected behavior since increasing loads on the engine lead to increased fuel input and energy release, which increases the rate of entropy generation and system irreversibilities in the combustion process. Nevertheless, there is a wide range in the rate of exergy destruction basing on the fuel type. In traditional diesel fuel (D100) and diesel-hydrogen blends, exergy destruction increases at a higher rate as the load increases, to over 8.5 kW at full-load operation. The trend represents the comparatively greater thermodynamic losses to the conventional diesel combustion, despite the presence of hydrogen supplementation [36]. These losses can be due to inefficient timing of combustion and constraints in the formation of mixtures associated with the nature of ignition of diesel fuel. Contrastingly, hydrogen-enriched B20 bio-diesel blends have relatively lower exergy destruction under most engine loads especially when they are above 50% of the rated capacity. The blends that have been tested to exhibit significantly lower thermodynamic losses are B20

with 47% of hydrogen. These findings show better combustion and reduced entropy production when biodiesel fuels are mixed with hydrogen. It is interesting to note that the B20 + 47% (H_2) configuration has a relatively constant and less exergy destruction profile across the load range indicating increased thermodynamic stability and improved energy conversion. This is possible due to the positive combustion characteristics of hydrogen such as the high diffusivity of hydrogen and the high rate of flame propagation. These features enhance more homogenous mixing of fuels and air as well as boosts the combustion process in biodiesel-based fuel blends [21]. Hydrogen enrichment, therefore, counteracts various constraints that are usually related with biodiesel burning, including slower reaction rates and oxidation incompleteness. This is because the overall product of hydrogen supplementation and blending of bio-diesel results in increased combustion efficiency and less thermodynamic irreversibility in the engine system.

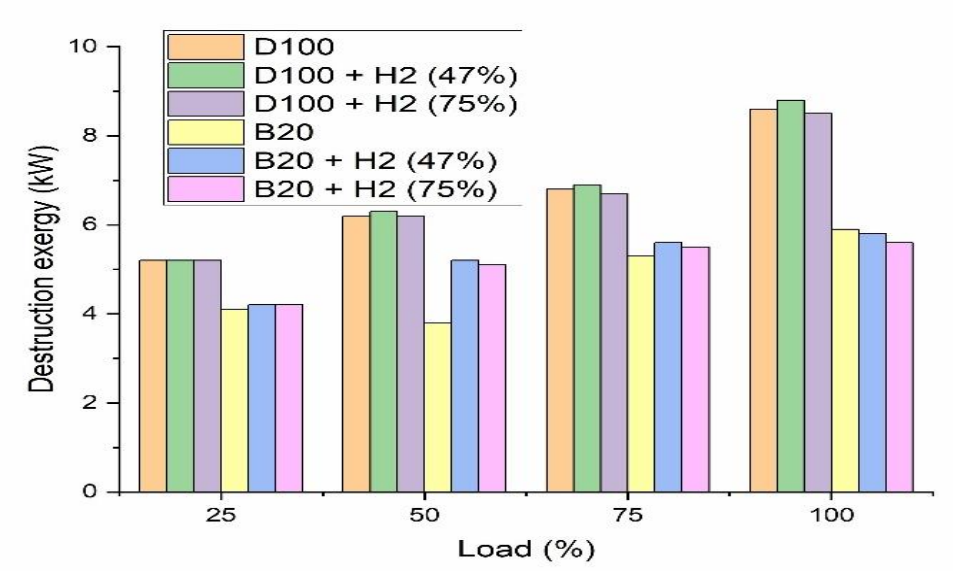


Fig. 13. Variation of destruction exergy

4.13 Exergy Efficiency

Figure 14. shows the change in exergy efficiency with the engine load of various fuel options, such as conventional diesel (D100), microalgae-based B20 biodiesel, and hydrogen-based blends of the two fuels. Exergy efficiency is a useful parameter to determine the extent to which the chemical energy provided by the fuel is converted to useful mechanical energy and the thermodynamic irreversibilities in the system have been taken into consideration.

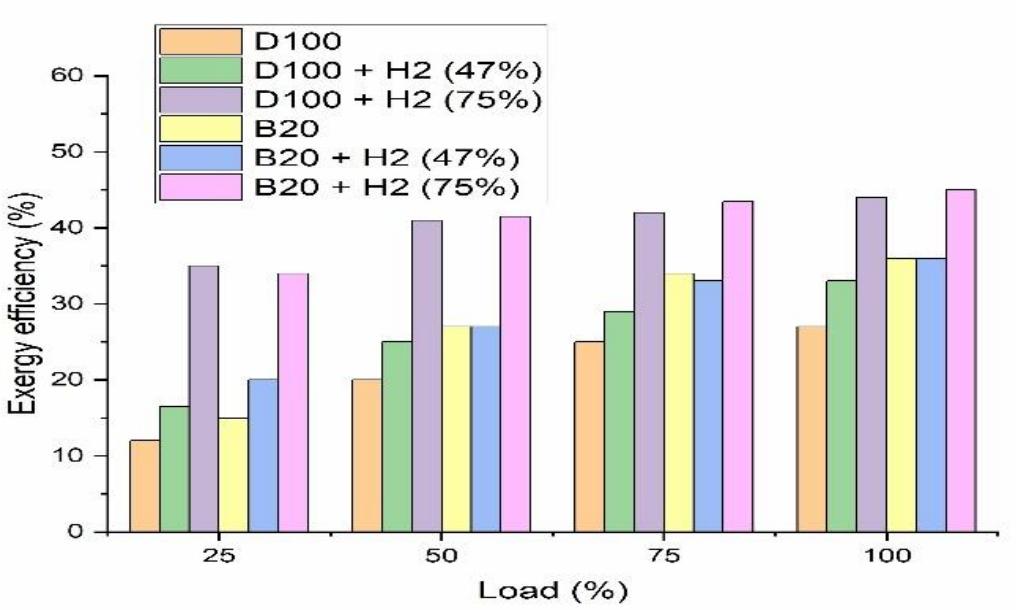


Fig. 14. Variation of destruction exergy

Exergy efficiency is higher when the engine load is higher in all combinations of fuel tried. This is usually the case with compression ignition engines since the increased load conditions encourage more stabilized combustion, higher in-cylinder temperature, and lower relative heat losses than at low load operation [37]. The B20 biodiesel mix enriched by 75% of hydrogen is the fuel with the highest exergy efficiency, with values of about 4600 % at full-load conditions. This is significantly high as compared to the pure diesel fuel and the unmodified B20 biodiesel blend. The finding throws light on the positive relationship between hydrogen enrichment and biodiesel fuels in enhancing the overall thermodynamic performance. The enhancement of the exergy efficiency is, to a great extent, explained by the favourable combustion properties of hydrogen. Hydrogen has high energy density, high flame propagation speed, and high diffusivity, which increase the speed and completeness of fuel-air mixture, thereby increasing the rate of combustion. These properties make it possible to transform a greater proportion of the chemical energy in the fuel to useful work. Moreover, the oxygenated composition of B20 biodiesel blend facilitates a better oxidation of the fuel-air mixture especially in the cases where hydrogen is found in the combustion chamber [29]. The product of this is enhanced quality of combustion and minimized thermodynamic losses. Pure diesel fuel and the B20 biodiesel blend with hydrogen tend to have lower exergy efficiency in most operating conditions, in comparison. The only difference in performance of the biodiesel fuels can be attributed to the high viscosity and low volatility that might have bad effects on the fuels atomization and combustion characteristics. Hydrogen introduction also enhances exergy efficiency of diesel and biodiesel fuels greatly. D100 with 75% of hydrogen and

intermediate B20 + hydrogen blends have uniform improvements with the increase of the hydrogen fraction. On the whole, the outcomes indicate that hydrogen enrichment is a significant factor that can be used to improve thermodynamic efficiency, especially with the B20 biodiesel blend.

4.14 Parameter optimization

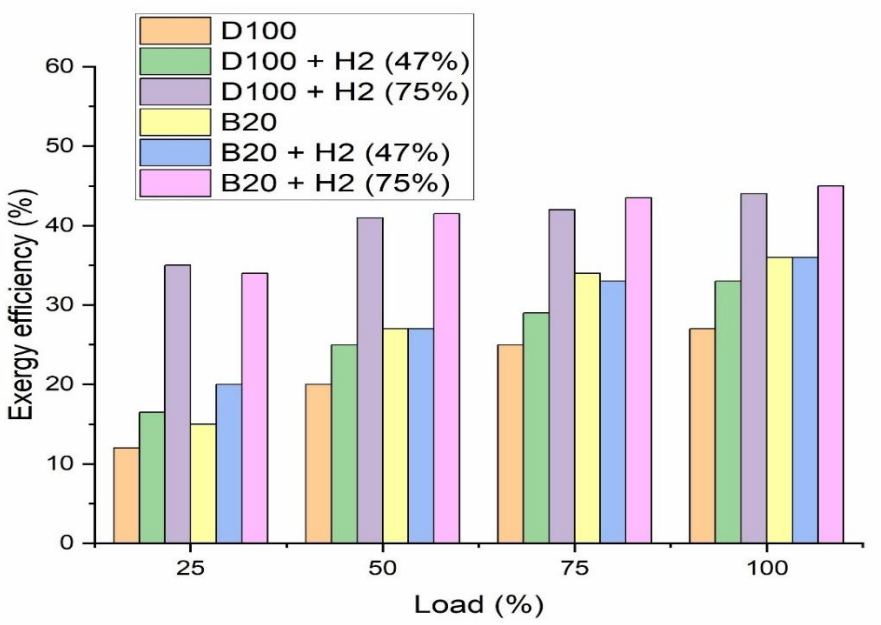


Fig. 15. Variation of exergy efficiency

The experimental data reveal that the best pulse width of hydrogen induction. The Variation of exergy efficiency as shown in Figure 15. A decrease in the hydrogen supply beyond this range causes the thermal efficiency improvement to either stabilize or start to decrease. This could be explained by the presence of undesirable combustion processes, such as knocking propensity and incomplete combustion, which adversely affect the overall engine performance. The biodiesel blend of B20 microalgae with hydrogen at a pulse width of approximately 60% gave the most desirable balance of fuel efficiency and reduction of emission among the fuel configurations that were tested [22]. This condition of operation is thus the most appropriate mode of operation of a dual fuel engine in a sustainable manner. The exergy destruction evaluation also showed that the main point of occurrence of thermodynamic irreversibilities in the engine system is in the combustion chamber. The main causes of such losses are non-ideal combustion processes and entropy production when converting energy. The further development of the engine design, therefore, needs to be aimed at improving the homogeneity of the combustion process, which might contribute to the reduction of energy losses, minimization of irreversibilities, and, therefore, the overall efficiency of the system.

4.15 Unburnt Hydrocarbons (HC)

Figure 16. shows how the emissions of the hydrocarbon (HC) varies with the load of the engine when using different fuel combinations, namely pure diesel (D100), microalgae-based B20 biodiesel, and the corresponding hydrogen-enriched mixtures. Hydrocarbon emissions are primarily due to the insufficiency of the combustion of the fuel-air mixture, and their concentration depends on a variety of parameters, including the properties of the fuel, the temperature in the in-cylinder, and engine conditions [37]. The experimental data shows that both traditional diesel and hydrogen-assisted diesel fuels tend to be less emitting of HCs at lower engine loads. The D100 fuel enriched with 75% of hydrogen has one of the lowest HC emission rates, indicating the favourable effect of hydrogen on the completeness of combustion. This decrease can be explained by the good combustion characteristics of hydrogen such as high flame propagation rate and high flammability range that allow enhanced ignition stability and efficient oxidation of the fuel-air mixture. Conversely, the B20 biodiesel blend and some of its hydrogen-enriched versions are found to have rather higher HC emissions especially at medium and high engine loads. Out of these fuel mixes, the B20 blend with about 47% hydrogen gives the maximum HC emissions, and the maximum emissions are recorded at 50-75 engine load. This observation indicates that too much enrichment in biodiesel blends with hydrogen might negatively influence the combustion stability or cause flame killing effects [8]. These conditions can occur as a result of low in-cylinder temperatures or the lack of mixing of the fuel-air mixture. It is also possible that the comparatively greater viscosity and oxygenated molecular structure of the B20 bio-diesel can encourage the development of localized areas of fuel concentration in the combustion chamber. These areas are able to inhibit full oxidation of the fuel hence increasing the emission of hydrocarbons. Interestingly, as moderate enrichment of hydrogen, specifically, the B20 blend, which is enriched with about 45% of hydrogen, the B20 blend has lower HC emission than other hydrogen-based B20 blends. The observation indicates the existence of the ideal hydrogen concentration that maximizes the efficiency of combustion and reduces the amount of unburned hydrocarbons.

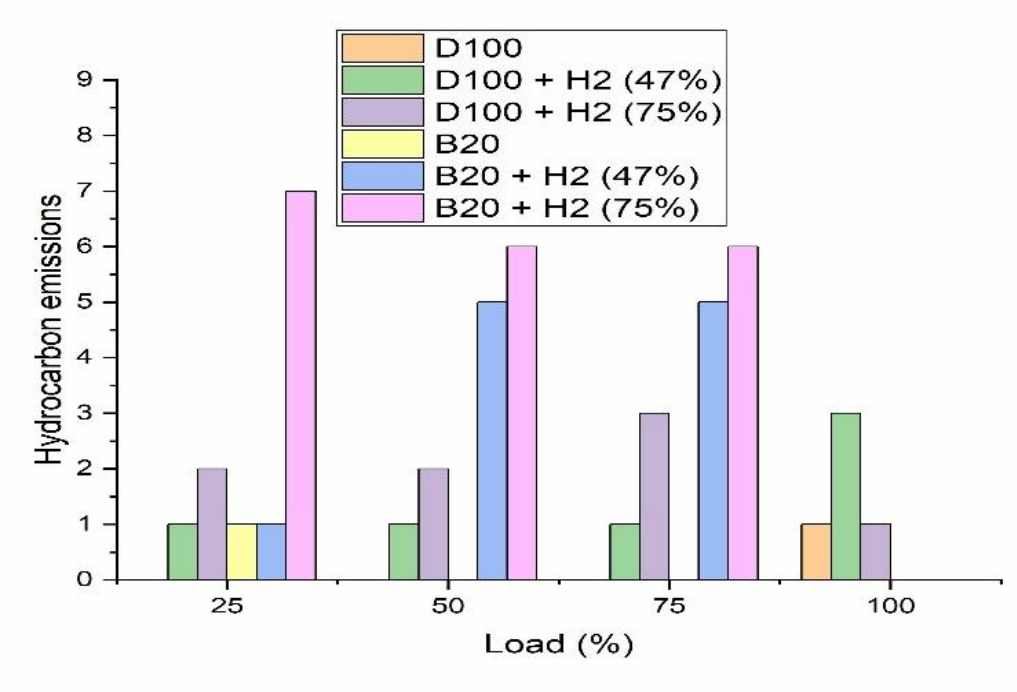


Fig. 16. Variation of Hydrocarbon

4.16 Carbon Dioxide (CO_2)

Figure 17. shows how carbon dioxide (CO_2) changes with the engine load under various fuel blends, such as the standard diesel (D100), microalgae-based B20 biodiesel, and the corresponding blends with hydrogen. Generally, CO_2 emission rises with the rise in engine load since the high load conditions necessitate high consumption of fuel in order to satisfy the rise in power demand. The B20 biodiesel blend and hydrogen-assisted versions of the blend, especially B20 with 47% and 75% of hydrogen content, yield relatively higher CO_2 emissions, particularly at moderate and high engine loads [38]. This is explained by the fact that the combustion qualities of the oxygenated biodiesel fuels have been enhanced. Inherent oxygen in the biodiesel molecular structure facilitates easier oxidation of carbon in the combustion process thus more CO_2 is formed. Conversely, an increase of the hydrogen enrichment level, e.g. D100 + 75% (H_2) and B20 + 75% (H_2) blends, leads to a significant reduction in CO_2 emissions. This decrease is largely caused by the fact that carbon-based fuel is partially replaced with hydrogen that does not include carbon atoms and thus does not directly add to the formation of CO_2 during combustion. These findings suggest that the overall carbon intensity of the combustion process can be effectively reduced by increasing the hydrogen fraction in the fuel mixture, and thus reduce CO_2 emissions [11]. Biodiesel fuels, though having a seemingly inherent higher CO_2 emission due to the oxygenated structure, are greatly

suppressed in their emissions by hydrogen supplementation, especially with increased enrichment.

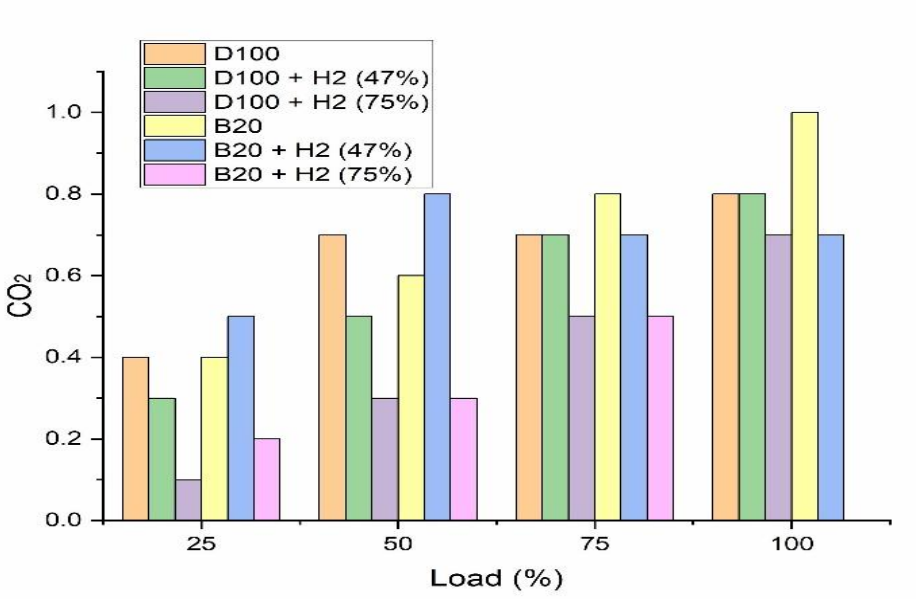


Fig. 17. CO_2 emissions

4.17 Oxides of Nitrogen (NOx)

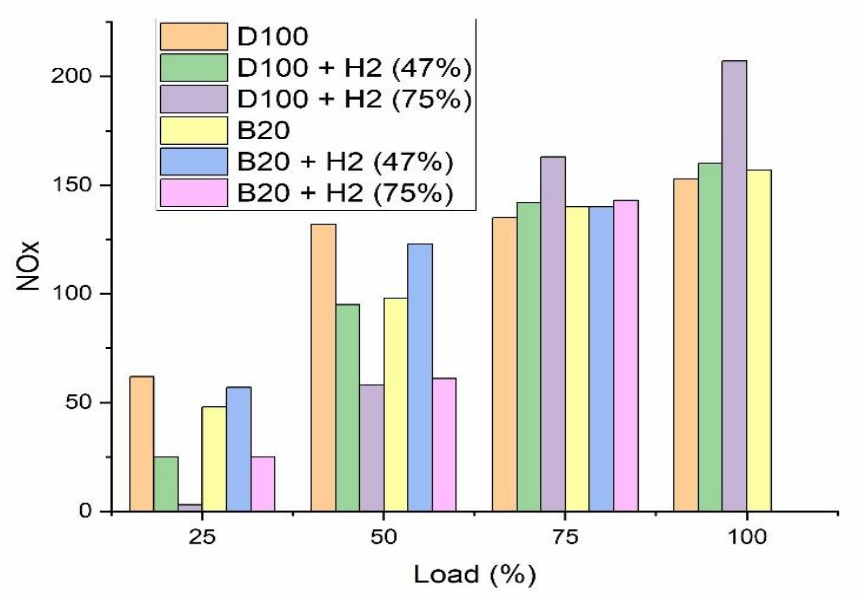


Fig. 18. NOx emissions

The difference between the emissions of nitrogen oxide (NOx) as a function of engine load with respect to the fuel composition with various fuel types (conventional diesel (D100), microalgae-derived B20 biodiesel), and with their respective hydrogen-enriched mixtures is illustrated in Figure 18. Generally, all the tested fuels show a rising pattern of NOx emissions with an increase in engine load. The increase in this trend is primarily due to the high temperatures of combustion and fuel consumption that arise when the load condition is high.

Pure diesel and the biodiesel blend of B20 have comparatively higher NOx emissions [27]. Specifically, the B20 blend has been shown to generate a little higher level of NOx compared to the use of conventional diesel during full loads. This tendency can be linked to the oxygenated molecular structure of biodiesel that facilitates better combustion reactions and increased local flame temperatures and, as a result, the development of nitrogen oxides. The addition of hydrogen to the fuel mixture leads to a significant decrease in the emission of NOx. A modest reduction in NOx formation is exhibited at lower levels of hydrogen enrichment at most engine load conditions. The decrease in NOx emissions with increasing hydrogen fraction is becoming more pronounced, especially in the medium and high loads [38]. The B20 biodiesel blend with the addition of 75% of hydrogen exhibits the greatest reduction in NOx emissions and it has the lowest level of emissions over the entire range of engine loads. This observation implies that the production of nitrogen oxides can be effectively countered by increasing the level of hydrogen enrichment in biodiesel-diesel blends. The decrease in the emissions of NOx can be explained by the enhanced nature of the combustion of hydrogen and the absence of carbon. Hydrogen facilitates better oxidation of the fuel, and it can adjust the combustion process in such a manner that restricts the excessive peak temperatures. Consequently, the production of the thermal NOx is inhibited without compromising the combustion performance.

4.18 Energy analysis

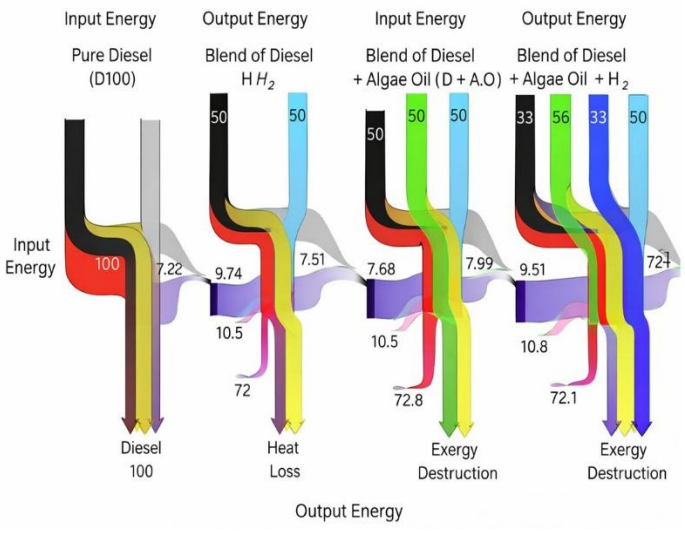


Fig. 19. Energy Sankey diagram for all blends

Figure19. shows a Sankey diagram that was used to determine the distribution of energy of four different fuel combinations (pure diesel D100), diesel mixed 47% hydrogen, microalgae

biodiesel blend (B20), and B20 mixed 75%hydrogen. The diagrams are a visual interpretation of the way in which the input fuel energy is distributed into favorable mechanical output and heat losses, exhaust energy losses and the relevant performance indices like brake specific fuel consumption (BSFC) and brake thermal efficiency (BTE). The system shows a BTE of 11 with a relatively high heat loss of 55 units to operate on pure diesel (D100) with a relatively large inefficiency in converting heat to energy during the combustion process [11]. A slight change in performance is recorded when hydrogen is added to the diesel at a concentration of 47%. This results in a slight rise in the BTE to approximately 11% and an increment in the useful energy output to approximately 100.5 units, though there is still a lot of heat and exhaust energy loss. The B20 biodiesel mixture is more efficient than pure diesel with a BTE of approximately 15% and no heat losses and less exhaust losses. These advancements illustrate the positive combustion features that are associated with the biodiesel fuels [39]. The B20+75% of hydrogen mixture has the most desirable energy distribution and offers the best brake thermal efficiency which is around 16.45% and a useful energy production of about 100 units with minimum heat and exhaust loss. This finding is a strong indication that hydrogen-enriched biodiesel blends greatly improve the total energy consumption since they can increase the efficiency of the combustion process and minimize the thermodynamic engine system losses.

4.19 Exergy Analysis

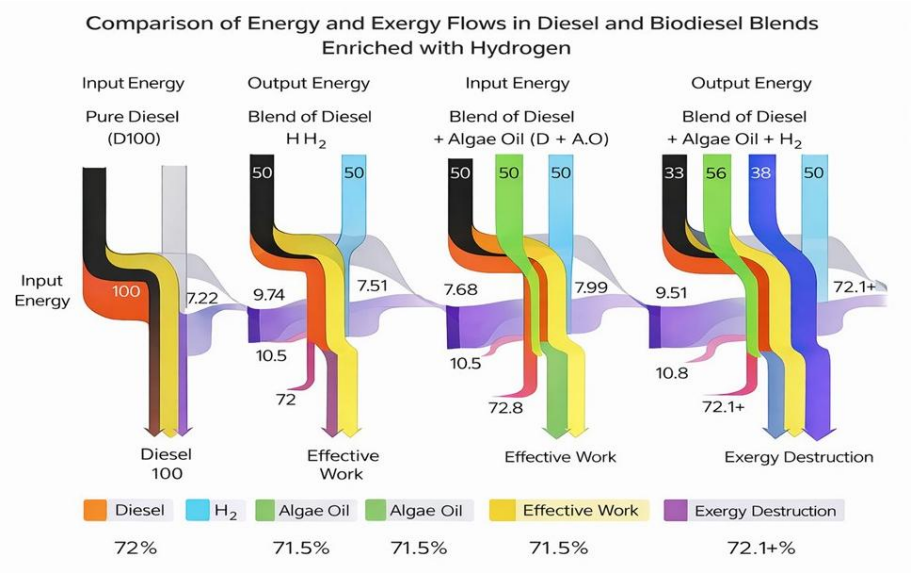


Figure 20. illustrates the exergy Sankey diagram that was employed to determine the thermodynamic performance of various fuel structures, such as the conventional diesel (D100), diesel augmented with 47% of hydrogen, the B20 biodiesel blend, and B20 fortified with 75%of hydrogen. The diagram shows how the input exergy is acted on in useful mechanical production, exergy destruction, losses associated with cooling and other unexplained thermal

losses, which helps in shedding light to the overall efficiency of each fuel setup. In the case of the baseline diesel and the D100 blend with hydrogen added at 47% exergy efficiency is almost the same that is only 26%. The general result of this is in such cases, 8 units of exergy are lost to exergy destruction and some 63 units of exergy are lost to unaccounted heat losses [40]. This finding indicates that a comparatively low percentage of hydrogen addition on diesel content has no significant impact on improving exergy use since significant thermodynamic irreversibilities and energy losses are still in the system. A significant increase in the thermodynamic performance is realized when the fuel is replaced with the B20 biodiesel blend. The exergy efficiency goes up to about 31% and the exergy destruction is reduced to about 5 units. Furthermore, the losses associated with heat that is not accounted are minimised to about 62 units [25]. These advancements can be credited to the desirable combustion properties of biodiesel, specifically its natural level of oxygen content, which enhances the more complete oxidation of the fuel, and decreases the entropy formation upon combustion. The greatest thermodynamic performance enhancement is seen with B20 blend that has 75%of hydrogen. In such a situation, the exergy efficiency level would rise significantly to about 45%. Meanwhile, exergy destruction is lowered down to about 5 units and the non-traceable heat losses are further narrowed to about 48 units. These findings show that there is a high synergistic effect of the use of hydrogen and biodiesel fuels [19]. The enrichment of hydrogen increases combustion rates and the degree of fuel air intermixing whereas the oxygenated character of biodiesel contributes towards efficient oxidation of the fuel mixture. This leads to the minimization of thermodynamic irreversibilities and an even greater portion of chemical energy supplied being turned into useful mechanical work.

5. Conclusions

This paper was an experimental study on the energy and exergy performance of compression ignition (CI) engine using various fuel blends such as conventional diesel (D100) and microalgae-derived biodiesel blend (B20) and their respective hydrogen-enriched counterparts. The findings indicate that the thermodynamic and sustainability performance of the engine system with integration of hydrogen and biodiesel blends with diesel is considerably enhanced. The most promising overall-performance of the fuel mixes tested included the B20 biodiesel blend enriched with 75 batteries of hydrogen. This fuel mix had a peak brake thermal efficiency (BTE) of about 16% and an exergy efficiency of about 45% with the lowest exergy destruction of about 5.12 kW. Moreover, this mixture had less heat and exhaust energy emissions than other fuels considered. This high performance witnessed on hydrogen-assisted biodiesel blends can be explained by the complementary nature of combustion of the hydrogen

and biodiesel fuels. Hydrogen is said to be rapidly propagating flame with high diffusivity which hastens the combustion process, and enhances mixing of fuels and air. In the meantime, biodiesel already has oxygen built into the molecular structure, thus enhancing further oxidation of the fuel during combustion. The net effect of the properties is faster and more efficient combustion which translates to higher energy conversion efficiency. These observations are additionally reinforced by emission analysis. Decreases in carbon monoxide (CO) and unburned hydrocarbon (HC) emissions were significant in the biodiesel-hydrogen fuel blends and were reduced by about 21% and 26% respectively. Nitrogen oxides (NO_2) increased by a modest percentage of approximately 18 %, and this can be explained by the fact that with higher combustion temperatures there are better oxidation reactions leading to higher oxidation levels. However, the rise in the percentage of hydrogen in the fuel blend helped to decrease the total carbon sources of emissions. All in all, the findings support the claim that integration of biodiesel and hydrogen offers significant benefits regarding engine performance, emission properties and thermodynamic effect. The dual-fuel biodiesel-hydrogen system exhibits greater fuel economy, a greater stability in the combustion process, and a lower exergy destruction especially at the higher engine loads compared to the conventional diesel operation. These results demonstrate the potential of hydrogen-assisted biodiesel fuels as one of the promising directions to cleaner and more sustainable energy scales of the transport system in the future.

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Data Availability Statement

The datasets generated and/or analyzed during the current study are available from the corresponding author on reasonable request.