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EFFECT OF DIESEL BIODIESEL AND OXYGENATED ADDITIVE BLENDS ON ENGINE PERFORMANCE FROM EXERGY PERSPECTIVE

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Agricultural machinery relies heavily on diesel, creating a need for cleaner and more sustainable fuel options. This study investigates the blends of diesel with a small proportion of biodiesel, combined with varying amounts of ethanol and ethylene glycol, to evaluate their effects on fuel characteristics and engine efficiency. Fuel properties were assessed according to ASTM standards, and performance was analysed using exergy principles. Results indicate that ethanol tends to reduce density and viscosity, while ethylene glycol has the opposite effect. Biodiesel slightly lowers efficiency under light loads but improves performance under moderate to high loads. Certain blends exhibit minimal energy losses and demonstrate enhanced efficiency at higher engine demands. These findings suggest that carefully formulated biofuel blends can support more sustainable and energy-efficient operation of agricultural machinery.

Keywords: biodiesel; diesel engine; fuel additive; oxygenated additives; diesel; sustainable agriculture; data analysis; data science, applied mathematics; applied data science

Agricultural machinery depends heavily on diesel, which contributes to greenhouse gas emissions and air pollution. To support sustainable farming, cleaner fuel alternatives are needed that maintain efficiency while reducing environmental impact. Using alternative fuels such as biodiesel reduces emissions, with the exception of nitrogen oxides (Liu et al., 2023). In diesel engines, biodiesel lowers UHC, CO_2, CO, polycyclic aromatic hydrocarbons, and suspended particles (Ogunkunle and Ahmed 2021). Its contribution of CO_2 during combustion is limited (Ogunkunle and Ahmed, 2021). Replacing diesel with biodiesel can cut CO_2 emissions by 77–104 $g \cdot MJ^{-1}$. The reduction in pollutants becomes more pronounced as the share of biodiesel increases, with the strongest effect observed in 100% biodiesel. To further enhance performance and reduce emissions, oxygenated additives have been widely studied. Common examples include methanol, ethanol, glycerol-based compounds, and triacetin (Duraisamy et al., 2020; Shrivastava et al., 2021; Cakmak and Ozcan, 2022; Mukhopadhyay et al., 2022; Yilmaz and Davis, 2022). Their oxygen content promotes more complete combustion and helps reduce emissions (Vijayashree and Ganesan, 2018). However, these additives also lower the calorific value of the fuel, which can reduce engine power. This loss of energy density often leads to higher fuel consumption and an increase in specific fuel consumption (Rakopoulos et al., 2010; Chang et al., 2013). Engine performance is usually measured through parameters such as power, thermal efficiency, fuel use, and gas emissions. Yet, these alone do not capture the full picture. According to the second law of thermodynamics, exergy analysis provides a more accurate measure of efficiency changes and losses in internal combustion engines. Recent research has examined various additives for their effects on both performance and exergy. For example, Kumar et al. (2017) showed that iron nanoparticles in a four-stroke single-cylinder engine with 20% biodiesel reduced fuel consumption and lowered CO and HC emissions. Ashok et al. (2017) reported that adding zinc oxide and ethanox improved available work (exergy) by about 5% but also raised NO_x emissions under full load. Nanthagopal et al. (2017) found that zinc oxide and titanium dioxide nanoparticles improved engine exergy by 5–17% and reduced CO and HC emissions. Similarly, Bär et al. (2018) demonstrated that antioxidant additives improved biodiesel stability and reduced exergy degradation. Gharehghani (2020) reported that nanoparticles at different concentrations could increase both first-law and exergy efficiency in biodiesel-diesel-water blends. It is important to note, however, that several studies report higher energetic and exergetic efficiency for pure diesel compared to biodiesel blends. This apparent contradiction highlights the trade-off between efficiency and sustainability. While diesel may outperform biodiesel blends in strict energy terms, biodiesel and oxygenated blends contribute substantially to emission reduction, renewable energy use, and sustainable agriculture by valorising waste oils and bio-based feedstocks.

Our study addresses this balance by testing biodiesel in combination with ethanol and ethylene glycol. The results indicate that the triple blend can reduce exergy destruction and improve engine efficiency compared to biodiesel or diesel alone. This does not dismiss the higher baseline efficiency of pure diesel but shows that optimised blends can close part of the gap while offering major sustainability benefits. The present research therefore aims to assess diesel engine performance with biodiesel, ethanol, and ethylene glycol from an exergy perspective. The methodology includes biodiesel production, measurement of its properties, preparation of blends, and engine tests at 1500 rpm under full load. Performance and emission data are analysed through exergy science. To our knowledge, the combined use of these three oxygenated components has not been previously studied. By linking performance analysis with sustainability outcomes, this work contributes to advancing cleaner fuel technologies while supporting more sustainable agricultural and energy systems.

Material and methods

The study was carried out in four main stages to evaluate the performance of biodiesel–diesel blends with ethanol and ethylene glycol additives. First, biodiesel was produced from waste edible oil through the transesterification process using methanol and a suitable catalyst to achieve high purity. Its thermophysical properties, including density, viscosity, and calorific value, were measured according to ASTM standards (Nadkarni, 2007). The fuel blends were then prepared by mixing 5% biodiesel in diesel with varying amounts of ethanol and ethylene glycol to study the effects of these oxygenated additives. The blends were tested on a single-cylinder diesel engine under different load conditions. Engine performance, including power output and efficiency, was recorded, and exergy analysis was performed to assess energy utilisation and identify losses. This approach allowed direct comparison among pure diesel, B5, and the oxygenated blends, revealing how the combination of ethanol and ethylene glycol can reduce exergy destruction and improve overall engine efficiency. The results provide practical guidance for developing more sustainable and energy-efficient fuels for agricultural machinery.

Biodiesel production

Waste cooking oil is passed through a paper strainer to produce biodiesel. Its temperature is raised to 60 °C by heating. Then, alcohol is added at a molar ratio of alcohol to oil of 6 : 1. Sodium hydroxide equal to 0.5% of the oil weight is added to the alcohol. Furthermore, the temperature of this mixture is raised to about 60 °C so that the catalyst is dissolved more effectively. The alcohol and catalyst solution is added to the oil. The mixture is stirred at a constant speed for 30 minutes. At the same time, the temperature of the solution is increased to 65 °C. After the completion of the process, the obtained solution is placed under laboratory conditions, i.e., 25 °C and 101.3 kPa. As a result, glycerine, which is formed during the reaction, is collected at the bottom of the container because of its higher density. Thus, it is separated from the main reaction phase during cooling. After glycerine separation, the remaining phase is neutralised with hydrochloric acid. The acidity of the solution is adjusted to 7. Therefore, the acidity of biodiesel fuel after the neutralisation stage is maintained between 6 and 7.

Fuel sample preparation

Different mixtures of fuel samples containing diesel fuel and biodiesel were prepared at one level of 5% by volume, ethanol at three levels of 2, 4, and 6 volume fractions, and ethylene glycol at three levels of 2%, 4%, and 6% by volume. These samples were shown with the symbol BXEYEtZ, where B stands for biodiesel, E stands for ethanol, and Et stands for ethylene glycol. X, Y, and Z indices represent the volume percentage of each additive in diesel fuel, respectively. Pure diesel fuel was also used as control fuel.

Fuel properties measurement

In this study, the density of fuel samples was measured according to the ASTM D4052 standard (Nadkarni, 2007) which uses a DA-130N digital density meter with accuracy of $\pm 1 \times 10^{-3}$ $g \cdot cm^{-3}$. Next, a Parr model bomb calorimeter was used, according to the ASTM D240 standard (Nadkarni, 2007), to measure the calorific value of the fuel samples (accuracy of $\pm 1 \times 10^{-2}$ $MJ \cdot kg^{-1}$). According to the ASTM D5773 standard (Nadkarni, 2007), the cloud point is determined by observing the transparency of the fuel that is cooled under controlled conditions, i.e., accuracy of $\pm 1 \times 10^{-1}$ °C. The sample was poured into a glass cylinder, and to create homogeneous conditions in the fuel, its temperature was brought to 40 °C using an oven. Then, the sample was taken out of the oven, and after equalising with the environment, it was placed in the cooling device. Reducing the temperature of the control sample, and as soon as the first crystal and waxy particles were seen at the bottom of the container, the temperature of the sample was recorded as the cloud point. The kinematic viscosity of fuel samples was measured using a Brookfield DV-II Prime viscometer equipped with a UAL adapter according to the ASTM D445 standard with accuracy of $\pm 1 \times 10^{-3}$ $mm^2 \cdot s^{-1}$ (Nadkarni, 2007). This adapter allows for measuring the kinematic viscosity of samples ranging from 1 to cP 10. This adapter was connected to a hot water bath with a temperature of 40 °C to create a standard temperature for measuring the kinematic viscosity of biodiesel fuel. From each fuel sample, 16 cc is poured into the desired place in the device and by rotating the spindle inside the solution, its kinematic viscosity is shown on the device's display screen. Flash point temperature is one of the criteria for measuring the tendency of a sample to form a flammable compound with air under controlled laboratory conditions. This test was also done using the open cup method, according to ASTM D93 standard (Nadkarni, 2007), with accuracy of $\pm 1 \times 10^{-1}$ °C.

Engine test

Power data, fuel consumption, and thermal efficiency are required to conduct experimental tests to investigate the effect of the fuel sample containing biodiesel containing oxygen additives on the exergy produced by the diesel engine. The engine was a vertical, four-stroke, single-cylinder engine produced by Kirloskar Oil Engines Ltd., India. The engine's maximum power was 7.4 kW at 1500 rpm, with a displacement volume of 0.948 L. The compression ratio was 17.5 with a maximum pressure of 6.21 bar at 1500 rpm. These tests were performed based on the engine's short-term test and the standard ECE R-49 (Nadkarni, 2007). These tests consider 25%, 50%, 75%, and 100% loads. Then, by changing the fuel samples, the engine's performance parameters are measured and recorded at a constant rotational speed (at 1500 rpm). To do the engine test, the engine was first started with diesel fuel and ran for a quarter of an hour at full load to warm up. Then, the engine was turned off, and the fuel tank was emptied. In the next step, the mixture of biodiesel with diesel fuel was poured into the fuel compartment of the diesel engine, and the diesel engine was restarted. Each engine test was repeated three times under the same operating conditions, and the average values were reported in the manuscript. After completing the tests and collecting the data related to each set, the analysis was done to compare the engine's performance and pollution parameters using a mixture of fuels and pure diesel fuel with the help of Excel software.

Exergy calculation

The following relations were used to calculate exergy. Based on this, the values related to input exergy, exergy output from exhaust, shaft exergy, and destroyed exergy were calculated. Then, they were compared for different fuel samples at loads of 25%, 50%, 75%, and 100%. In this comparison, diesel fuel was considered as control fuel. Table 1 presents the formulation of exergy calculations in different stages.

Results and discussion

Thermophysical properties of fuel samples

The first part of the results presentation presents the values related to the thermophysical properties of the fuel samples. These values were obtained using the standards and methods given in the Material and Methods section. Table 2 presents the values of kinematic viscosity, density, flash point, cloud point, and fuel calorific value as fuel samples' main properties.

As presented in Table 2, adding biodiesel, ethylene glycol, and ethanol has reduced the calorific value of the fuel. This can be due to the low calorific value of biodiesel, ethylene glycol, and ethanol compared to diesel fuel. On the other hand, adding ethanol to B5 decreased the density and kinematic viscosity of the samples, and adding ethylene glycol increased the density and kinematic viscosity of the fuel samples. This feature of the fuel sample can affect the combustion behaviour of the fuel sample. This claim has also been reported by Lin et al. (2006) and Sivaramakrishnan and Ravikumar (2012). The addition of ethanol has decreased the ignition temperature and cloud point temperature. On the other hand, the addition of ethylene glycol shows the same behaviour as ethanol to the fuel sample at the temperature of cloud point and flash point. As known, adding ethanol and ethylene glycol has reduced the calorific value of fuel compared to diesel and B5 fuel. One of the main reasons is the high oxygen content in ethanol and ethylene glycol. This claim has been confirmed by Aydın and Öğüt (2017) and Venu and Madhavan (2016, 2017).

Exergy analysis results

The first part of this section presents the results related to input exergy, which includes exergy carried by fuel and air. Figure 1 presents the results related to the input exergy of different fuels for engine loads of 25% (a), 50% (b), 75% (c), and 100% (d). Figure 1 presents the variation of input exergy with different fuel blends under four engine load conditions (25%, 50%, 75%, and 100%). The input exergy includes the exergy of fuel and air entering the engine. At low loads (25%), the 5% biodiesel blend slightly reduces input exergy

Table 1 A summary of exergy analysis relationships

System	Exergy analysis
Intake air (kW)	$\dot{E}x_a = \dot{Q}_a - \dot{m}_a C_{p,a} T_0 Ln\frac{T_1}{T_0} + R_a Ln\frac{P_1}{P_0}$
Intake fuels (kW)	$\dot{E}x_f = \dot{m}_f \left[x\phi_F LHV_D + (1-x)\phi_{NG} LHV_{NG} \right]$
Shaft work (kW)	$\dot{E}x_{sh} = \dot{W}_{sh}$
Exhaust gas (kW)	$\dot{E}x_{ex} = \dot{Q}_{ex} - \dot{m}_{ex} C_{p,ex} T_0 Ln\frac{T_3}{T_0} + R_a Ln\frac{P_3}{P_0}$
Heat transfer to the coolant (kW)	$\dot{E}x_c = \dot{Q}_c + \dot{m}_w T_0 C_w Ln\frac{T_{w,out}}{T_{w,in}}$
Heat transfer to the ambient (kW)	$\dot{E}x_{em} = \dot{Q}_{em}\left(1 - \frac{T_0}{T_s}\right)$
Destruction (irreversibility) (kW)	$\dot{E}x_{des} = \dot{E}x_{ex} + \dot{E}x_{sh} + \dot{E}x_w + \dot{E}x_{em} - \dot{E}x_a - \dot{E}x_f$

Table 2 Thermophysical properties of fuel samples

Fuel samples	Viscosity (mm^2·s^{-1})	Density (g·cm^{-3})	Flash point	Cloud point	Calorific value (MJ·kg^{-1})
D100	2.790	0.865	86.0	0.0	43.00
B5	2.845	0.871	87.0	0.1	42.70
B5E3	2.842	0.870	86.5	-1.0	42.69
B5E5	2.840	0.868	86.0	-2.0	42.68
B5E7	2.837	0.867	85.5	-2.0	42.67
B5Et3	2.845	0.872	87.0	0.0	42.68
B5Et5	2.845	0.873	87.5	-1.0	42.66
B5Et7	2.846	0.875	88.5	-1.0	42.64
B5E3Et3	2.843	0.870	86.5	-2.0	42.67
B5E5Et3	2.840	0.871	86.0	-3.0	42.66
B5E7Et3	2.837	0.872	86.0	-3.0	42.66
B5E3Et5	2.843	0.872	87.0	-4.0	42.65
B5E5Et5	2.840	0.872	87.0	-3.0	42.65
B5E7Et5	2.837	0.873	86.5	-4.0	42.64
B5E3Et7	2.843	0.873	88.0	-3.0	42.64
B5E5Et7	2.840	0.873	87.5	-4.0	42.63
B5E7Et7	2.838	0.874	87.5	-5.0	42.62

as compared to diesel, primarily by virtue of biodiesel's lower calorific value. On the contrary, at 50–100% loads, B5 affords us with higher input exergy than diesel due to the compensatory effect of increased fuel consumption at high loads for the loss of energy density.

Adding biodiesel by 5% (B5) at 25% load has decreased the input exergy, and at 50–100% engine loads, it has

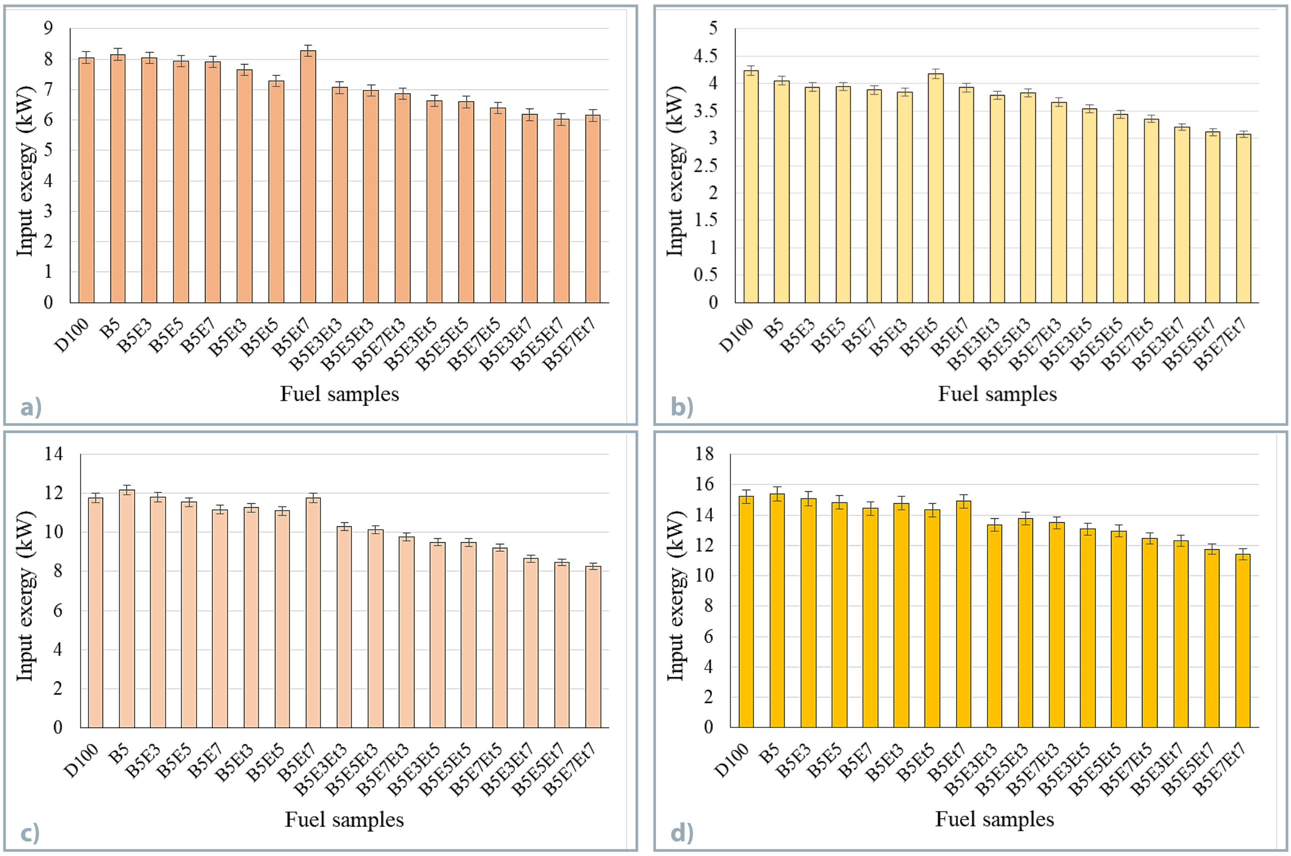

Fig. 1 Input exergy: a) 25% load; b) 50% load; c) 75% load; and d) 100% engine load

increased the input exergy. On the other hand, the presence of oxygen additives reduces the amount of input exergy. This can be due to the decrease in the calorific value of the fuel and changes in the air-fuel ratio with the change like combustion. On the other hand, it can be seen that increasing the load from 25% to 100% has successfully increased the amount of input exergy from 25% to 75%, respectively. As increasing the load causes an increase in fuel consumption demand, the input exergy increases. When oxygenated substances (ethanol and ethylene glycol) are introduced into the combustion system, the input exergy undergoes a further reduction with respect to all loads. This reduction is, in fact, tightly linked with the lower heating values of the oxygenates vis-à-vis diesel. Ethanol, having a lesser density and calorific values, brings about a much noticeable reduction in the input exergy, whereas ethylene glycol delivers a somewhat similar effect but to a lower degree. Thereby, the combined blends (biodiesel + ethanol + ethylene glycol) also seem to follow this trend, confirming that oxygenated additives dilute the fuel mixture energy-wise.

Figure 1 indicates that while biodiesel alone can enhance input exergy under higher loads, the use of oxygenated additives (ethanol and ethylene glycol) reduces the input exergy because of their lower heating value. This highlights a key trade-off: oxygenated additives improve combustion and emissions, but they decrease the energy content supplied to the engine.

Figure 2 presents the results related to the exergy output from the exhaust for different fuel samples at engine loads of 25% (a), 50% (b), 75% (c) and 100% (d).

According to Fig. 2, it can be considered that the increase of engine load increases the exhaust exergy across all fuel samples. This is expected, since higher loads require greater fuel input, which inevitably leads to more energy release and higher exhaust flow. The effect of additives is also clear. Going by the exhaust exergy, the maximum values occur with pure diesel and B5, and by raising the percentage of ethanol and ethylene glycol, this decreases. Such a reduction is in consonance with the lower calorific value of oxygenated additives, which decreases the total input energy and consequentially reduces the portion taken away in the exhaust. Or, in other words, oxygenated blends lose less exergy through their exhaust gases, meaning more of the energy available remains within the system. As presented in Fig. 2, increasing the amount of additives reduces the exergy output from the exhaust and increasing the load also increases the exergy output from the exhaust. One of the reasons for this is the reduction of input exergy by increasing the amount of additives. Another reason for this is the increase in the efficiency of the entire sample of fuels containing oxygen additives. This observation was also presented by Farhadi et al. (2017) for oxygenated additives. For further investigations on this claim, the exergy values related to the shaft (practical work) and the lost exergy values (destroyed and irreversible) should be checked. According to Fig. 2, there is a sudden increase in energy in B5Et7 samples. It can be due to several reasons. But the probable reason with high certainty could be due to the chemical formulation of the fuel in terms of its oxygen content, which has driven combustion towards reduced shaft energy and

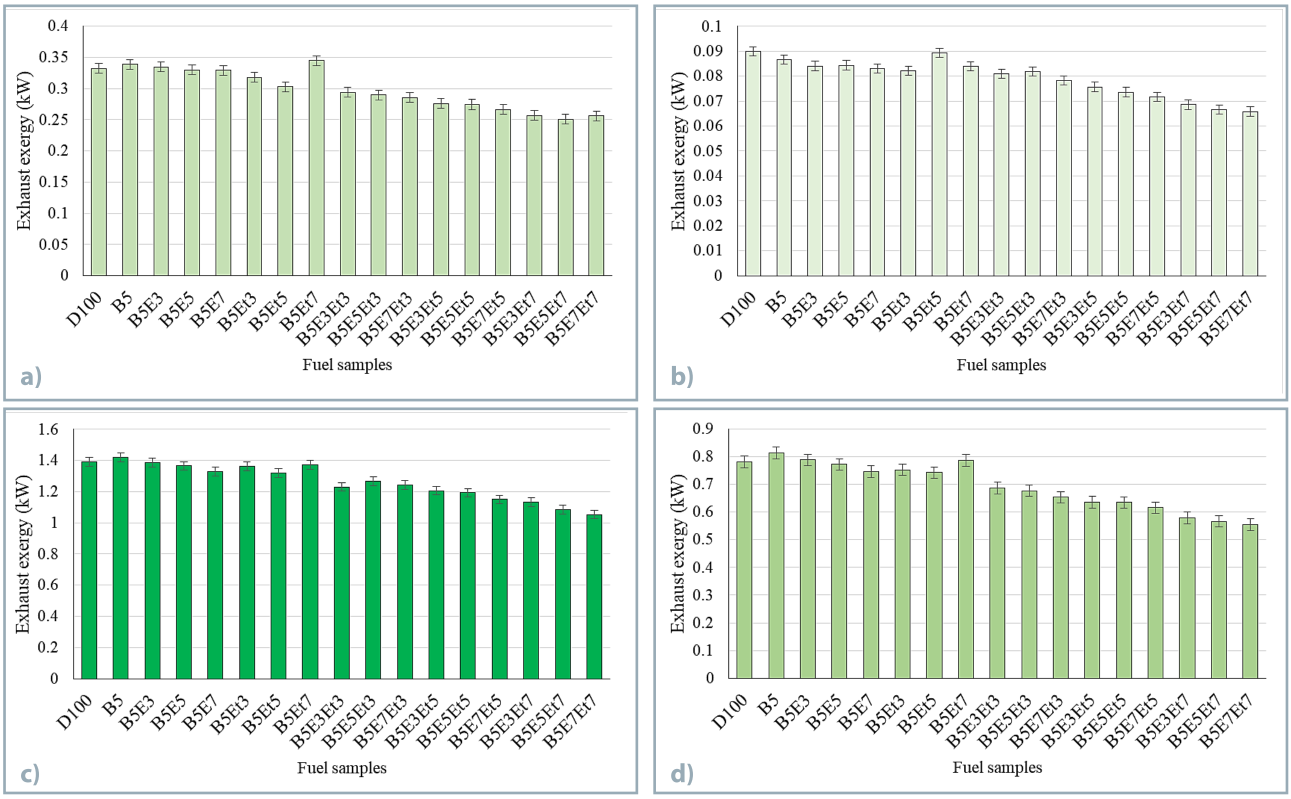

Fig. 2 Results related to output exergy from exhaust: a) 25% load; b) 50% load; c) 75% load; and d) 100% engine load

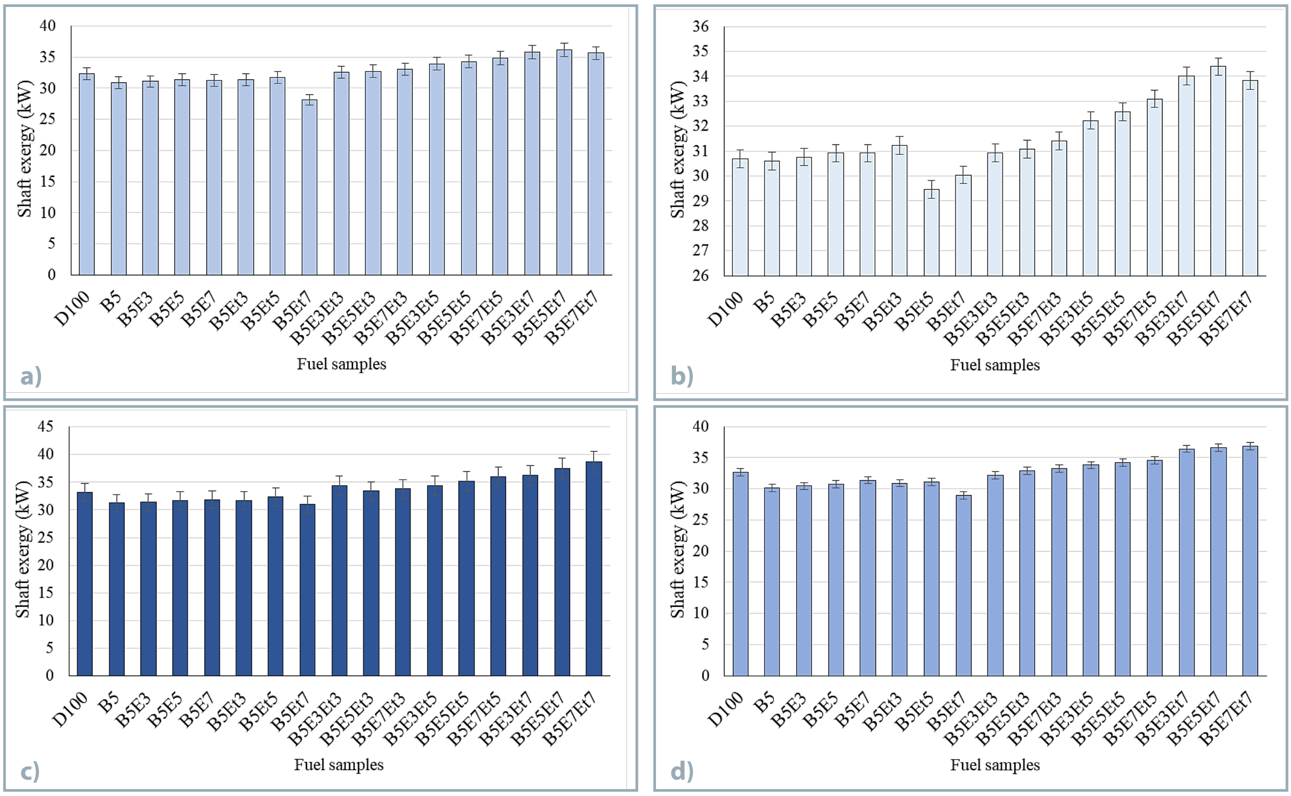

Fig. 3 Results related to output shaft exergy: a) 25% load; b) 50% load; c) 75% load; and d) 100% engine load

exergy content (Fig. 3) and increased exergy destruction (Fig. 4). Figures 3 and 4 present the values of shaft exergy and its percentage relative to input exergy, respectively.

As evident from Fig. 3, adding ethanol has reduced the shaft exergy more than ethylene glycol. This can be due to the oxygen content of these two additives relative to each other. According to Fig. 3, it appears that the blends containing ethanol (i.e., B5E3, B5E5, B5E7) generally exhibit less shaft exergy than the ethylene glycol containing counterparts (i.e., B5Et3, B5Et5, B5Et7). This is because of ethanol's low energy density, which reduces the burning value of the fuel mixture more significantly, compared to ethylene glycol. Meanwhile, ethylene glycol causes a slight increase in density and viscosity of the fuel, which seems to stabilise the combustion and actualise the conversion of the found input exergy to shaft work. According to Fig. 3, it can be said that compared to input exergy, the presence of additives has increased the ratio of shaft exergy to input exergy. In other words, additives have caused more input exergy to be converted into practical work. One of the main reasons is the oxygen content of these additives, which can improve the combustion process and provide more useful work to the user. This claim was also presented by Coughlin and Hoxie (2017) and Kumar et al. (2017). From Fig. 3, the effect of ethanol and ethylene glycol is entirely different, one of the reasons for the difference in thermophysical properties of fuel samples. When ethanol and ethylene glycol are used together, the combined blends (e.g., B5E3Et3, B5E3Et5) achieve a better balance, showing higher shaft exergy compared to the individual additive cases. This indicates a synergistic effect of the two oxygenated additives: ethanol enhances fuel atomisation and combustion speed, while ethylene glycol improves combustion stability, leading to more effective conversion of energy into mechanical work. In terms of ratios, the results show that the presence of additives increases the fraction of shaft exergy relative to the input exergy, particularly at higher loads. For instance, at 100% load, the additives improved the shaft exergy ratio by nearly 19% compared to pure diesel. This demonstrates that although additives reduce the absolute input exergy, they enable more efficient utilisation of the available energy, enhancing overall engine performance. The final step in exergy analysis is checking the destroyed exergy values. This amount of exergy is the useful work that is out of reach. Based on this, it is possible to directly observe how much each fuel sample has destroyed useful work compared to the control fuel. Based on the results, additives increased the ratio of shaft exergy to input exergy by 10%, 13%, 17%, and 19% for the loads of 25%, 50%, 75%, and 100%, respectively. Figure 4 presents the destroyed exergy values for the samples of fuels. By increasing load, this trend becomes more pronounced due to the nearly complete destruction of exhaust gases, which share the additional oxygen provided by the additives for the efficient oxidation of the fuel molecules. It is to be noted that combined blends, for instance, B5E3Et3 and B5E3Et5, exhibit the least values of exergy destruction, thereby confirming the benefits of a synergistic effect between ethanol and ethylene glycol. Apart from an enhancement of combustion due to the additives, these results highlight the fact that the additives tend to cut down the input exergy by virtue of their lower heating value but at the same time will help in reducing exergy loss and so improve engine thermodynamic performance. Figure 5

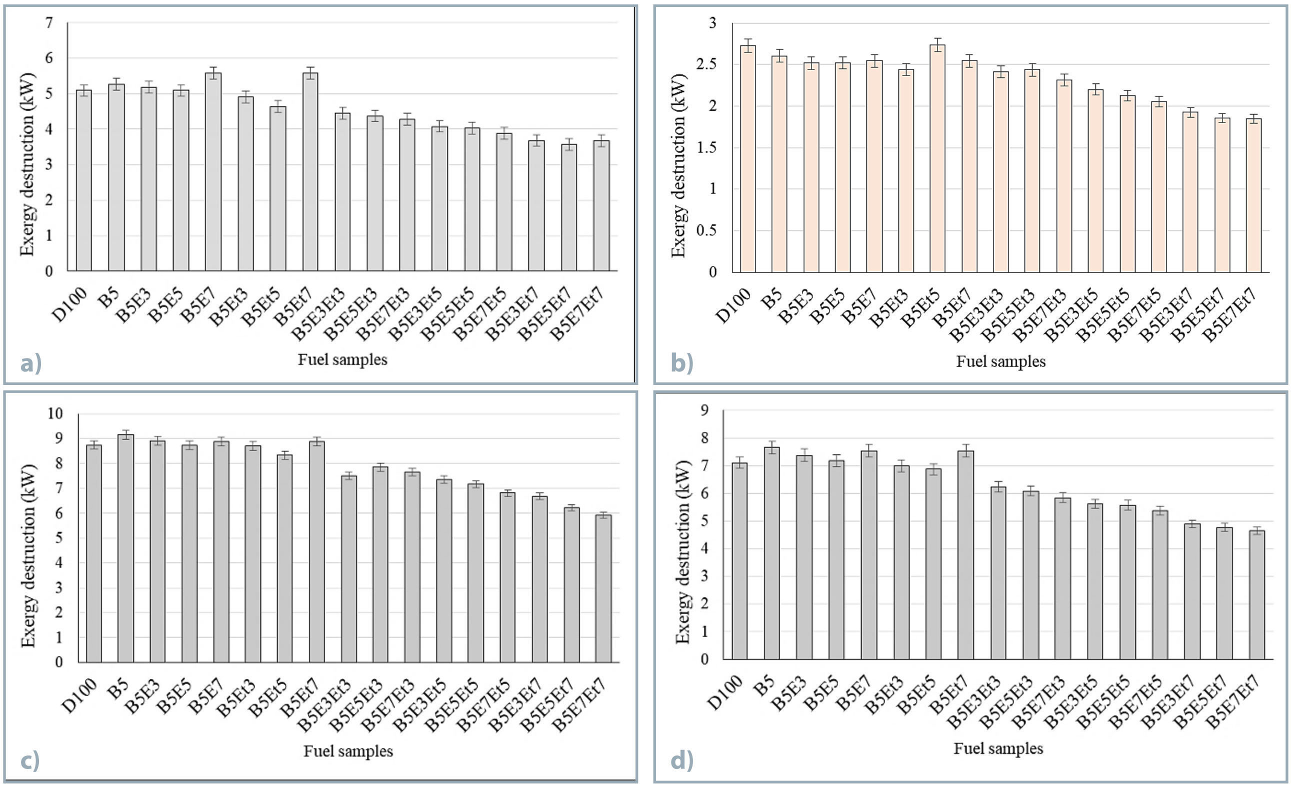

Fig. 4 Results related to exergy destruction: a) 25% load; b) 50% load; c) 75% load; and d) 100% engine load

shows the percentage of destroyed exergy compared to input exergy.

Figure 4 shows that the destroyed exergy values decrease with additives. The percentage of destroyed exergy can be checked for further investigation compared to the input exergy. The destroyed exergy has been plotted for various fuel blends in Fig. 4 under varying engine loads. The results strongly point to the lessening of exergy destruction due to the addition of oxygenated additives, which include ethanol, ethylene glycol, and most importantly, a blend of the two, with respect to pure diesel and B5 blends. This shows that more of the presently available energy is increasingly converted into work rather than becoming lost in irreversibility.

According to Fig. 5, it can be seen that the presence of additives has reduced the percentage of destroyed exergy compared to the input exergy from about 5% to 41% for the loads of 25% to 100 %, respectively. This reduction has been the highest in the combination of additives (on average, about 29% for loads from 25% to 100%). This process shows that the mutual effect of additives increases the useful work in diesel engines compared to diesel fuel in a way that can show the effectiveness of the oxygen additive in improving the combustion process. On the other hand, the increase in engine load has reduced the destroyed exergy, and more useful work has been produced. One of the reasons is the increase in pressure inside the combustion chamber, followed by the rise in the temperature inside the combustion chamber and an increase in engine efficiency. This claim was presented by (Ghazanfari et al., 2017). The best fuel type is the combined addition of biodiesel, ethanol, and ethylene glycol additives. In this study, the samples of B5E3Et3, B5E3Et5, and B5E3Et7 fuels can be considered as fuels with lower exergy destruction percentages (approximately 54%, 53%, and 52%, respectively) for 100% operating load. Based on observations, the best operating load of the engine is close to the maximum engine load. Kumar et al. (2018) declared the engine's best operating load.

Also, Najafi et al. (2018) conducted a study to optimise the engine's performance conditions and announced the engine's best performance load at 90% load. As it is known, diesel engines perform better at loads close to full load than at partial load operating conditions. The results show that although biodiesel, ethanol, and ethylene glycol individually influence the engine performance and exergy behaviour, their conjoint use results in a more favourable balance between energy efficiency and exergy destruction. From the findings, enhanced oxygen content leads to improved combustion completeness which diminishes irreversibilities and increases the portion of input exergy converted to shaft work. The fuel heating value decreases due to oxygen presence, which may elevate fuel consumption. Therefore, blends with oxygenated additives exhibit lower energy density, yet they display lesser exergy destruction than traditional fuels. The current investigation's observations resonate with earlier investigations (Venu and Madhavan, 2016; Aydın and Ogut, 2017; Kumar et al., 2017). This gives the current work its novelty. This study is recognised as one of the leading works that address a diesel blend that contains biodiesel, ethanol, and ethylene glycol, which is assessed through a systematic exergy evaluation. The blend composition is examined under controlled thermodynamic conditions. Past studies focus on single additives or binary blends. However, the combined influence

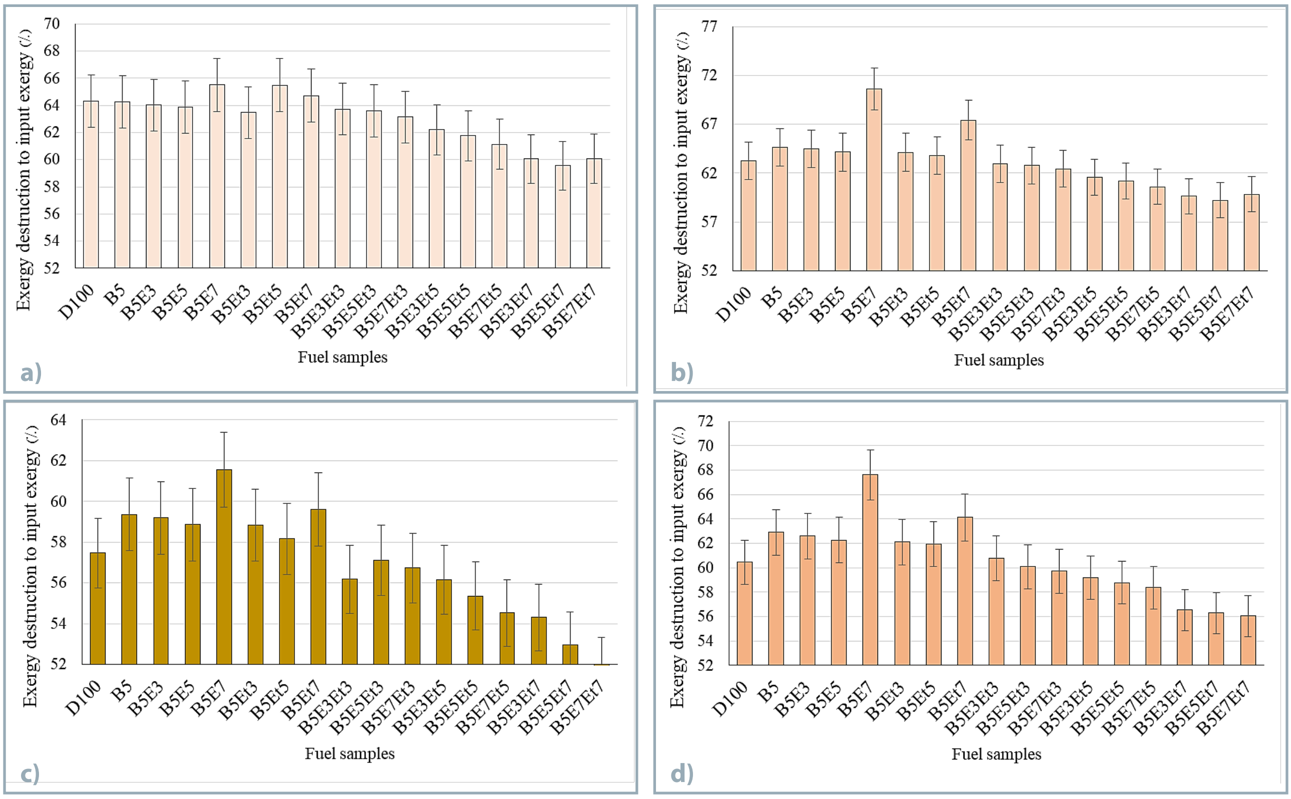

Fig. 5 Ratio of exergy destruction to useful work: a) 25% load; b) 50% load; c) 75% load; and d) 100% engine load

of three oxygenated components is rarely addressed. In this work, a triple oxygenated blend is evaluated, which is shown to serve a synergistic role. As a result, exergy destruction is reduced. In addition, conversion into shaft work is improved. Cleaner engine operation is also enabled, in which we aim to even improve on that considering the importance of reducing air pollutants (Penenko et al., 2019). Higher efficiency at elevated engine loads is achieved. Therefore, improved energy utilisation is supported. This contribution offers extended insight into the design of multi-additive fuel optimisation strategies beyond the well-known biodiesel diesel mixtures. Moreover, guidance for advanced fuel formulation is provided, which supports improved thermal performance and emission control. Furthermore, future research is directed toward the use of secure machine learning to model the process (Mubarakova et al., 2022).

Conclusion

This study investigated the effects of ethanol and ethylene glycol as oxygenated additives in biodiesel-diesel blends on engine performance using exergy analysis. The additives modified fuel properties, with ethanol reducing density and viscosity and ethylene glycol increasing them, creating contrasting effects on combustion. While the blends showed a slight decrease in calorific value compared to pure diesel, exergy analysis revealed improved utilisation efficiency, particularly under medium to high engine loads. At low loads, biodiesel slightly reduced input exergy, but at higher loads, the combined presence of ethanol and ethylene glycol enhanced performance, reduced exergy destruction, and increased useful work output. Overall, blends containing both additives demonstrated the highest efficiency, which highlights their potential as cleaner and more energy-efficient alternatives to conventional diesel, which supports sustainable operation of agricultural machinery.

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