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Energy and exergy analysis of a single-cylinder diesel engine fueled with biodiesel derived from waste oil

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ABSTRACT

Biodiesel, as a renewable and environmentally friendly alternative to conventional diesel fuel, has gained significant attention due to its potential to reduce greenhouse gas emissions and mitigate the depletion of fossil fuel reserves. In this study, statistical analysis was employed to evaluate the performance of a diesel engine using different biodiesel fuels, engine load, and engine speed, along with their interactions in terms of exergy efficiency. The first and second laws of thermodynamics were applied to analyze the energy and exergy of a direct injection, four-stroke, single-cylinder, air-cooled diesel engine. Biodiesel fuel was prepared from waste cooking oil, and factorial experiments were conducted with a completely randomized design at engine speeds of 1800-2200 rpm, with five levels of biodiesel fuel blend. Diesel and biodiesel fuel blends, with biodiesel content ranging from 0% (B0) to 20% (B20), were tested under 50% and 100% engine loads to apply the first and second laws of thermodynamics. The interaction of independent parameters on energy and exergy parameters for the controllable volume of the diesel engine was investigated using data obtained from the experiments. The results showed that engine speed and biodiesel fuel composition significantly affected exergy efficiency at the 1% level. Additionally, triple interactions of independent variables were significant only for engine cooling exergy (heat loss exergy) and not for other dependent variables. Similar trends were observed for energy efficiency.

1. Introduction

The increasing demand for fossil fuels, coupled with the depletion of fossil fuel reserves and the growing environmental pollution caused by these fuels, has driven researchers to seek alternative, environmentally friendly fuels derived from plant and animal sources (Najafi, 2018). These alternative fuels are less polluting than fossil fuels and can be obtained from agricultural residues and food waste for internal combustion engines (Mahapatra et al., 2021). Due to environmental concerns and economic considerations, renewable fuels for compression combustion engines have gained significant attention. Biodiesel, produced from biodegradable sources such as vegetable or animal oils and fats, has emerged as a promising alternative fuel for diesel engines. The energy density of biodiesel depends on the oil or fat content of the raw materials used. While biodiesel's calorific value is slightly lower (about 9%) than that of petroleum-based diesel, it offers advantages over pure diesel, including purity, recyclability, non-toxicity, biodegradability, and reduced sulfur content. In addition to these benefits, biodiesel has positive social and environmental impacts, such as job creation, reduced heat emissions, and improved physical properties (Hájek et al., 2021).

The continued reliance on fossil fuels in industry, science, and the environment, coupled with the challenges of managing waste cooking oil (WCO), has underscored the importance of exploring sustainable alternatives. Utilizing WCO for the production of combustion engine fuels addresses both these issues. The use of vegetable oil and its derivatives is a logical solution for diesel engines (Demirbas, 2008). However, the direct use of vegetable oil in these engines is impractical due to its high viscosity, the presence of acidic compounds, and its poor cold-flow properties (Dwivedi and Sharma, 2014). To address these issues, the oil must be modified to improve its fuel properties. Biodiesel fuels, composed of long-chain alkyl esters of fatty acids, are derived from fatty raw materials. Alternative energy sources such as fatty acid methyl esters (biodiesel) possess properties similar to crude oil, making them suitable for use in compression combustion engines without requiring engine modifications. The utilization of vegetable oil as a common fuel and its potential as an economical waste management solution has also been proposed (Hassan and Kalam, 2013). Improving the combustion process and optimizing the thermodynamic performance of internal combustion engines, including diesel engines, as well as the utilization of renewable fuels such as biodiesel, remain significant areas of research interest. While the first law of thermodynamics has been widely used to study engine performance parameters, recent research indicates its limitations in providing a comprehensive understanding of energy conversion systems. The first law alone cannot determine the quality of energy and often fails to elucidate the underlying causes of performance degradation.

To address these limitations, the second law of thermodynamics has emerged as a valuable tool for analyzing

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energy systems. By considering both the quantity and quality of energy, the second law enables the identification of irreversibility and losses within various processes. This deeper understanding facilitates the optimization of engine performance (Sciubba, 2021). While the first law provides a fundamental understanding of energy conservation, it lacks the ability to quantify the degradation of system efficiency. To overcome this limitation, exergy analysis, based on the second law of thermodynamics, offers a more comprehensive approach. Exergy represents the maximum useful work potential of a system at a given state. By comparing exergy to actual work output, irreversibility, and potential losses can be quantified. It is worth noting that exergy analysis is typically conducted at the system level or within simulations of industrial sites. In other studies, it guides policymakers and process designers, informing process design decisions based on insights and observations. However, researchers in industries also significantly influence industrial performance at the site level by identifying opportunities for improvement and fine-tuning operations (Michalakakis and Cullen, 2022).

Another study utilized the first and second laws of thermodynamics to analyze the quantity and quality of energy in a four-cylinder diesel engine using diesel and biodiesel fuels. Accurate measurements of fuel, air, and water flow rates, as well as engine load and total temperature, were obtained. The energy balance and exergy rate of the engine were determined, and various performance parameters, including energy and exergy efficiency, were calculated and compared for biodiesel fuel. The results showed that biodiesel fuel exhibited similar exergy performance to diesel fuel (Sekmen and Yılbaşı, 2011). Researchers examined the engine performance curve at full load and various rotational speeds using biodiesel fuel and its blends with diesel fuel. The results indicated a 5.6% reduction in maximum engine power and a 7% increase in fuel consumption when using biodiesel fuel. Consequently, according to the second law of thermodynamics, employing biodiesel fuel and its blends did not significantly impact exergy efficiency or exergy cost (Lopez et al., 2014). A study investigating the impact of different biodiesel fuel blends on diesel engine performance, based on energy and exergy analysis, revealed that the optimal point for energy efficiency occurs at 82.9% of the final load. In terms of energy efficiency, the B20 fuel blend demonstrated the best performance. However, considering exergy efficiency, the B40 fuel blend exhibited superior performance due to lower exergy destruction (Khoobbakht et al., 2016). A further study compared the combustion and exergy characteristics of B5, B20, B50, and B100 fuels with diesel fuel. The findings revealed a reduction in maximum in-cylinder pressure by 37%, 0.57%, 1.25%, and 3.42%, respectively, due to decreased heat release. Irreversibility values decreased by 1.12%, 1.92%, 6.1%, and 10.34% with increasing biodiesel content. As biodiesel content increased from 0% to 100%, the heat value decreased by 6%. Ultimately, B20 fuel was identified as the optimal biodiesel blend in terms of exergy performance (Bahoosh et al., 2017). Another study examines the performance characteristics of biodiesel derived from waste cooking oil when used in a four-stroke direct injection diesel engine under various load conditions. Additionally, this research indicates that biodiesel fuel produced from waste kitchen oil can serve as a replacement for diesel, contributing to air pollution control, promoting the collection and recycling of waste for biodiesel production, and reducing reliance on fossil fuel resources, thereby potentially accelerating the country's economic growth (Gupta et al., 2023).

Given the importance of energy and exergy in diesel engines, numerous studies have been carried out to develop suitable models for a more accurate representation of this critical process. So far, this study employs a thermodynamic approach combined with statistical techniques to analyze and predict the performance of a single-cylinder diesel engine. The primary focus is on identifying optimal operating parameters by examining the interaction effects of three key variables: biodiesel fuel compositions, crankshaft rotational speed, and engine load. These factors were systematically evaluated to understand their influence on energy and exergy equations, which are critical for assessing the engine’s efficiency and overall performance. Additionally, the study explores how these interactions impact the efficiency of various engine components, providing insights into the system’s thermodynamic behavior. By integrating statistical methods, the research aims to uncover patterns and relationships that can guide the optimization of engine operations, particularly when using biodiesel fuels. This approach not only enhances the understanding of engine dynamics but also contributes to the development of more sustainable and efficient energy systems.

2. Materials and Methods

Energy and exergy analyses were performed on a four-stroke, single-cylinder, air-cooled, direct-injection diesel engine fueled with various blends of biodiesel derived from waste cooking oil. The first and second laws of thermodynamics were applied to analyze and evaluate engine performance under different operating conditions. A randomized complete block design was employed at engine speeds of 1800, 1900, 2000, 2100, and 2200 rpm. Biodiesel fuel blends were mixed in proportions ranging from 0% to 20% by volume with pure diesel fuel. The engine was tested under two load conditions: 50% and 100%. The experimental data were analyzed to investigate the dynamic relationship and interactions between energy and exergy within the engine's controllable volume.

2.1. Biodiesel production

The optimal method and conditions for synthesizing biodiesel from WCO via transesterification are crucial for analyzing sustainable energy in thermodynamic systems. Studies on pre-purified WCO have also gained attention, as biodiesel derived from WCO is increasingly recognized as a suitable alternative for sustainable fuels in environmental contexts. Biodiesel fuel was produced using the transesterification method, the most widely used commercial process for industrial biodiesel production (Mostafaei et al., 2013). In this process, triglycerides are sequentially converted to diglycerides and monoglycerides, ultimately yielding glycerol (Royon et al., 2007). Waste cooking oil was collected from the kitchen facilities of Tarbiat Modares University, and served as the raw material for biodiesel production.

To prepare the oil for transesterification, it was initially purified by passing it through filters and multi-layered mesh fabrics to remove excess particles. Subsequently, the oil was heat-treated in a tank to eliminate water content through settling and evaporation. Initial test results indicated that the acid value of the waste oil was within the range of 50-60 mgKOH/g (specifically 55 mgKOH/g), and the moisture content was 0.18%, making transesterification a suitable method for biodiesel production (Gerpen et al., 2004). For the transesterification reaction, a molar ratio of 6:1 methanol to oil was employed, and potassium hydroxide (KOH) served as a catalyst. The resulting methoxide mixture was then added to the waste oil. The reaction mixture was stirred at 3 rps in a reactor to facilitate biodiesel formation (Figure 1). After the reaction, the obtained biodiesel was washed with distilled water to remove residual impurities and by-products, yielding usable biodiesel suitable for combustion in a diesel engine.

After three washing steps, the clear biodiesel fuel produced from waste cooking oil was ready for injection into the fuel system of a single-cylinder diesel engine. The statistical population, encompassing diesel and biodiesel fuel mixtures, engine load, and engine rotational speed, was considered for experimental design. The range of diesel fuel mixtures was varied from 0% (pure diesel) to 20% (biodiesel), with intermediate percentages included to establish reference points. Based on repeated experiments conducted at different rotational speeds and loads, 3000 ml of pure diesel was accurately measured for each biodiesel percentage, starting from B0. Similarly, 150 ml, 300 ml, 450 ml, and 600 ml of biodiesel were prepared for B5, B10, B15, and B20 fuels, respectively. The fuel mixtures are stirred using an ultrasonic homogenizer. The resulting biodiesel fuels are shown in Figure 2.

2.2. Engine specifications and tested accessories

Also, given that most research in this field focuses on 50% and 100% loads (Xue et al., 2020), the motor loads (dynamically adjustable loads) were selected within this range. The rotational speed was chosen between 1800 and 2200 rpm, which aligns with the performance range of the single-cylinder diesel engine. Pure diesel fuel (B0) and a 20% biodiesel blend (B20) were used without any major modifications to the Italian-made 510 LD3 single-cylinder air-cooled diesel engine. The technical specifications of the engine used are presented in Table 1.

An eddy current dynamometer (model D400) was used to measure engine torque and power under various conditions (Figure 3). The SPSS 20 was used to investigate the main, two-way, and three-way interactions of independent variables on dependent variables, aiming to predict and improve performance variables, energy equations, exergy equations, and exhaust emissions.

Figure 1. Reactor used in this research

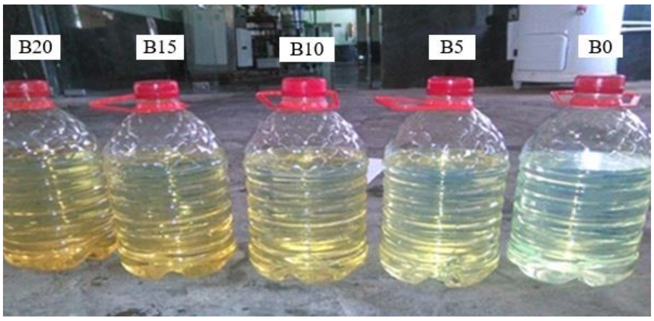

Figure 2. Preparation of biodiesel fuel mixture

Table 1. Specifications of 3LD 510 single-cylinder air-cooled diesel engine

Variable	Value
Factory Manufactured	Italian Company Lombardini
Number of Cylinders	1
Displacement Volume	10 cm^3
Piston Course	90 mm
Piston Diameter	85 mm
Cooling System	Air
Maximum Power at 3000 rpm	9 kW (12.2 hp)
Maximum Torque at 1800 rpm	33 Nm
Density Ratio	17.5:1

Figure 3. Performing engine performance tests with a dynamometer

To evaluate exergy efficiency, experiments were conducted at rotational speeds ranging from 1800 to 2200 rpm, with increments of 100 rpm at five levels. The engine rotational speed was controlled and adjusted at both 50% and 100% load. Based on thermodynamic principles, exergy efficiency was calculated for various engine components. To reduce experimental time and costs, a completely randomized factorial design was implemented using SPSS with 20 replications. Considering that linoleic acid, which constitutes 53% of biodiesel fuel, is the primary acid produced (Ghobadian and Khatamifar, 2005), Eq. (1) was used to model the combustion of biodiesel fuel.

$$C_{18}H_{32}O_2 + 25(O_2 + 3.76N_2) \rightarrow 18CO_2 + 16H_2O + 94N_2 \quad (1)$$

To investigate and analyze energy and exergy, the diesel engine was tested under steady-state conditions within a controlled volume. The sequence of events analyzed included: combustion of the air-fuel mixture, conversion of chemical energy into mechanical work, heat loss to the cooling air, and heat and exhaust gas losses at a specific engine speed.

If a control volume is considered around the engine (Figure 4) to calculate the energy balance, Eq. (2) is the general equation for the steady-state energy balance, according to the first law of thermodynamics.

$$\dot{Q} + \sum \dot{m}_{in} + h_{in} = \dot{W} + \sum \dot{m}_{out} + h_{out} \quad (2)$$

This equation accounts for the net heat input rate at the system boundaries and the engine operating rate, assuming to be faster than the instantaneous state of the system (Tat, 2011). This time interval encompasses both the energy transfer to the cylinder inlet and the energy transfer from the cylinder outlet.

The algorithm shown in Figure 5 was used to calculate the exergy of the various engine components and the overall exergy efficiency. To measure pollution levels, exhaust gases were transferred to the AVL DiTEST Gas 1000 emission meter. A computer is connected to the measurement instrument and records the percentage of pollutants for each fuel mixture. Error for the measurement instrument was for CO (±2% of reading or ±0.02%), CO_2 (±1% of reading or ±0.1%, HC (±3% of reading or ±10 ppm), NOx (±4% of reading or ±10 ppm), and O_2 (±1% of reading or ±0.1%), whichever greater.

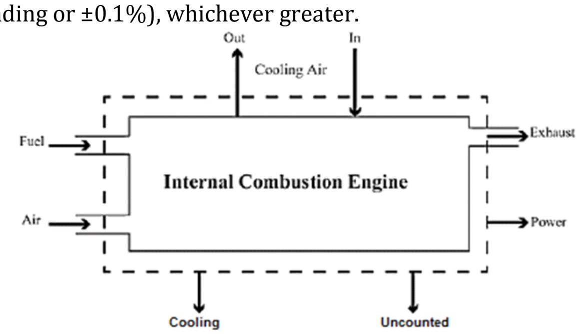

Figure 4. Control volume in engine energy analysis

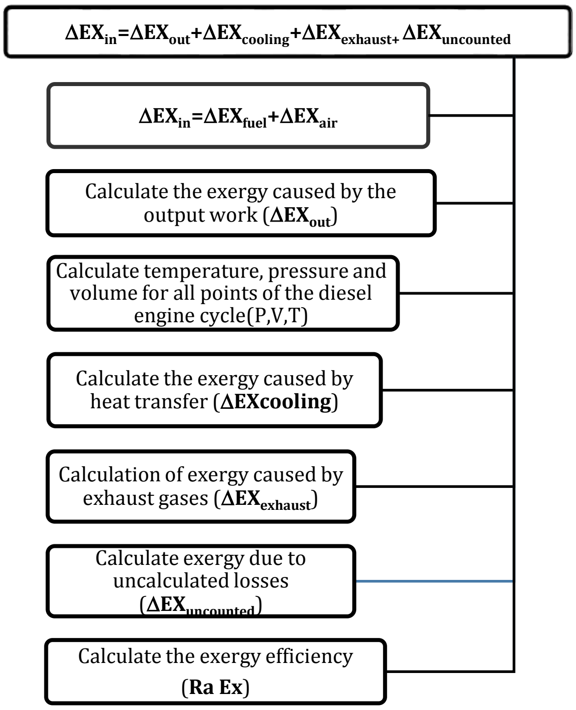

Figure 5. Exergy calculation model (X represents work)

3. Results and Discussion

Table 2 presents the results of analysis of variance of the effect of independent variables (load, rotational speed, and type of fuel composition) on the dependent variables (power, torque, specific fuel consumption, inlet exergy, cooling exergy, exhaust exergy, unspecified exergy, and exergy efficiency).

Figure 6 illustrates the statistically significant influence of engine speed on exergy efficiency (at the 1% significance level) for the B20 biodiesel blend under full load (100%) conditions. Exergy efficiency decreased from 18.86% to 16.937% as the engine speed increased from 1800 to 2200 rpm, a 7.5% reduction. Due to the higher consumption of diesel engine fuel exergy compared to fuel energy, the exergy efficiency was consistently lower than the energy efficiency, varying from 6.9% to 6.1%. These findings are consistent with the findings of other researchers (Canakci and Hosoz, 2006), who utilized biodiesel fuel derived from soybean oil and yellow oil and concluded that exergy efficiency was inferior to energy efficiency. Consequently, the second law of thermodynamics provides a more accurate measure of heating system performance than the first law. In terms of engine operating conditions, higher exergy efficiency is generally more desirable.

Figure 7 illustrates the effect of fuel type on the dynamic variations in exergy efficiency observed at an engine speed of 2200 rpm under full-load operating conditions. The results indicate that fuel type significantly influences exergy efficiency at the 1% level, with B20 exhibiting the highest impact and B0 having the lowest. In group a, the difference in exergy efficiency between B0 and B5 fuels is minimal, at 0.5%. In group b, B10 and B15 fuels exhibit a 1.5% decrease in exergy efficiency. These findings suggest that there is no significant difference in exergy efficiency between B5 and B0 or between B10 and B15 fuels. Moreover, B20 fuel demonstrates the highest energy efficiency at 21.773% in group c. One possible reason for the increased exergy efficiency of biodiesel fuel is its oxygen content. The additional 10-11% oxygen content in biodiesel fuel enhances combustion quality, leading to more complete combustion. This result contradicts the researchers' findings (Iortyer and Bwonsi, 2017), who used palm kernel oil as a biodiesel fuel source for a diesel engine. Their study revealed that pure diesel fuel (B0) exhibited higher efficiency than pure biodiesel (B100) derived from palm kernel oil, possibly due to differences in the properties of the oils used for biodiesel production.

Figure 8 highlights the significant interaction effects (at the 1% level) of engine speed and biodiesel fuel compositions on exergy efficiency. However, the results for exergy destruction and other performance parameters, such as power and emissions, were not reported as the focus was primarily on exergy efficiency under varying fuel compositions and operating conditions. The lowest and highest energy efficiency values were observed at 2100 rpm with B0 fuel (16.092%) and 1800 rpm with B20 fuel (21.97%), respectively. Generally, for B5, B10, B15, and B20 fuels, exergy efficiency decreases with increasing engine speed due to reduced volumetric efficiency caused by shorter cylinder filling time at higher speeds. Conversely, with sufficient oxygen availability, biodiesel fuel's increased composition leads to enhanced oxidation of unburned hydrocarbons within the cylinder and exhaust system at higher engine speeds, as the gas temperature rises significantly during the combustion and exhaust processes (Baskar and Senthilkumar, 2016). The graph reveals that the average exergy efficiency for B0 and B20 fuels is 16.96% and 20.32%, respectively. This finding is consistent with the results reported by Gavhane et al. (2020), who noted that the higher energy content of biodiesel fuel, compared to pure diesel (B0), contributes to improved exergy efficiency. In their research on a single-cylinder diesel engine using rapeseed oil-derived biodiesel, they found that although biodiesel has greater density and viscosity than diesel, its lower calorific value negatively impacts combustion efficiency and exergy performance (Gavhane et al., 2020).

Table 2 revealed that the three-way interaction of rotational speed, biodiesel fuel type, and engine load significantly affected only cooling exergy (heat loss exergy) at the 1% level, with a group size of 25. The highest cooling exergy was observed at 100% load, 2200 rpm, and with B0 fuel. Conversely, the lowest cooling exergy was found at 100% load, 1800 rpm, and with B15 fuel, with a 67.83% reduction. Regarding the behavior of other forms of exergy, such as exhaust or destruction exergy, these were not significantly influenced under the tested conditions, which is why they were not discussed in detail. Also, results of the research by Gnanamani et al. (2022) demonstrated that at the optimal engine speed of 2500 rpm, incorporating 5% cottonseed oil into diesel fuel resulted in a 6.58% increase in engine cooling exergy compared to diesel fuel at the same speed. Based on these findings, it was concluded that adding more than 5% biodiesel was not an effective approach for optimizing engine performance. The experimental findings from this research can provide valuable insights for optimizing diesel engine operation based on the principles of the second law of thermodynamics.

Table 2. Analysis of variance of the effects of independent variables on study variables

Independent Variable	DF	Power	Torque	Sfc	EX in	EX cool	EX exhaust	EX un	Ra EX (%)
load	1	935.24**	957.47**	94.14**	836.62**	6.81**	172.58**	799.90**	121.55**
rpm	4	7.41**	1.51ns	32.88**	16.17**	370.15**	12.54**	17.06**	32.08
bio	4	17.16**	17.97**	59.39**	1.45ns	311.56**	0.57ns	1.94ns	85.28**
load*rpm	10	0.06ns	0.82ns	1.84**	0.11ns	7.87**	0.20ns	0.13ns	7.33**
load* biodisel	9	110.62**	134.15**	22.27**	1.13ns	21.39**	18.53**	1.40ns	26.46**
rpm* biodisel	24	0.49ns	0.49ns	1.40ns	0.45	9.09**	0.085ns	0.47ns	10.11**
load*rpm*biodisel	49	0.30ns	0.27ns	0.80ns	0.26ns	89.47**	0.49ns	0.27ns	0.75ns

**: at the level of 1% significant ns: not significant

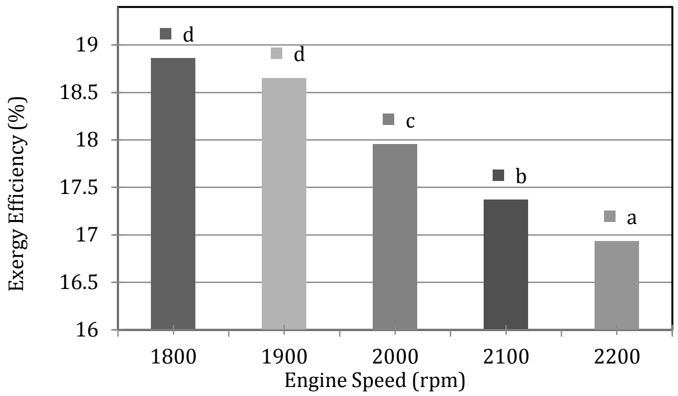

Figure 6. The main effects of motor rotational speed on exergy efficiency

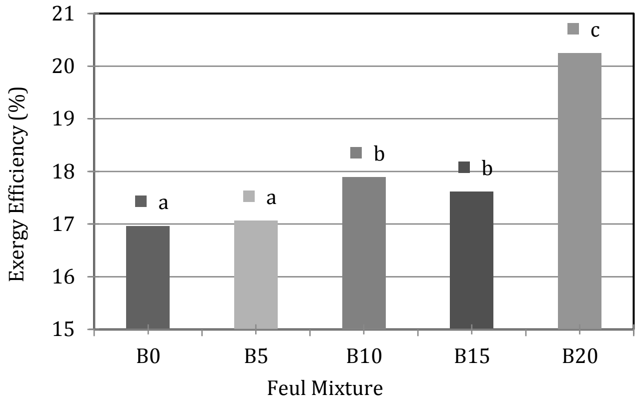

Figure 7. The main effect of biodiesel fuel on exergy efficiency

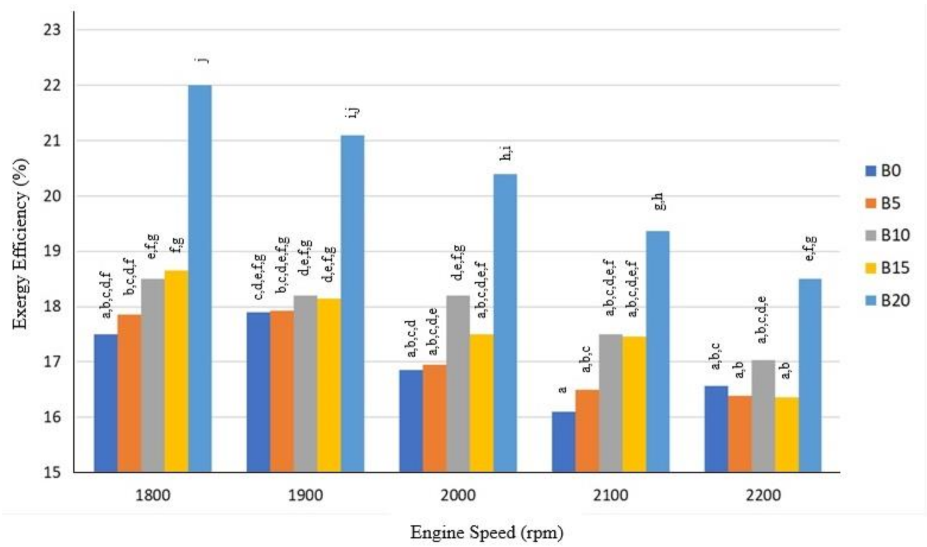

Figure 8. Dual effect of engine speed and different biodiesel fuel combinations on exergy efficiency at 100% engine load

Similar to the exergy equations, the main, two-way, and three-way interactions of the independent variables on the dependent parameters of the energy equations were also analyzed. The three-way interaction was significant only for cooling energy at the 1% level. Load had a significant impact on the independent variables at the 1% level. Engine speed significantly influenced all dependent parameters except torque. Biodiesel fuel composition significantly affected most dependent variables, except for input energy, exhaust losses, and unaccounted losses, at the 1% level. Tables and figures related to energy analysis were omitted in this section due to their methodological overlap with the exergy.

4. Conclusion

The objective of this study was to investigate how individual operational parameters, including rotational speed, load, and biodiesel composition, and their interactions influence dependent performance metrics, energy, and exergy efficiency. The statistical analysis revealed that engine load exerts a statistically significant influence (at the 1% level) on the operational parameters, underscoring its critical role in system performance. Rotational speed was similarly impactful, driving changes across all dependent variables except torque, which remained unaffected These findings emphasize the importance of optimizing load and speed settings while selecting biodiesel blends to enhance thermodynamic performance, while also acknowledging the stability of certain parameters (e.g., input energy) across fuel types under the tested conditions. Despite production limitations, biodiesel fuels have the potential to enhance combustion efficiency in compression ignition engines. While challenges persist, the commercial and widespread adoption of biodiesel fuels in combustion engines holds promise, especially in the context of global efforts to reduce fossil fuel consumption.

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