INTERNATIONAL JOURNAL OF AUTOMOTIVE SCIENCE AND TECHNOLOGY

2025, VOL. 9, NO: 1, 121-135 www.ijastech.org e-ISSN: 2587-0963

Eco-Friendly Nano-Additives: Energy, Exergy, and Environmental Impacts in Motor Vehicle Emission Control

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Research Article

Abstract

This study investigates the performance and emission behavior of borax decahydrate nanoparticles when blended with biodiesel and commercial diesel fuels in diesel engines. Experimental tests were conducted at five different engine power levels: 1 kW, 2 kW, 3 kW, 4 kW, and 5 kW-to evaluate the impacts of these fuel blends on engine performance, emissions, energy efficiency, exergy, and exergoenvironmental parameters. The data collected demonstrated a general trend where higher engine power output led to increased heat generation. Among the tested blends, the D40W50P1 fuel achieved efficiencies of 15.236%, 15.466%, 18.290%, 25.606%, and 24.258% at the respective power levels, highlighting the positive effect of borax nanoparticle addition on engine performance. The inclusion of borax nanoparticles particularly improved the performance of diesel/waste cooking oil blends. The results also revealed that the D50W50 fuel blend performed optimally at 2 kW, whereas the D40W50P3 blend showed a notable improvement, achieving an efficiency increase of 12.10%. Furthermore, sustainability index values were consistently above 1, indicating a favorable environmental and energetic balance for all tested fuel blends. The lowest recorded sustainability index was 1.123, observed for the D50W50 blend. In terms of exergoenvironmental analysis, the D40W50P2 fuel blend demonstrated carbon dioxide (CO_2) emissions of 311.69 kg/month at 1 kW and 786.34 kg/month at 5 kW. These results highlight the potential of borax nanoparticle additives to not only improve fuel efficiency and engine performance but also contribute to reducing environmental emissions. The results indicate that boron additives can enhance engine performance and energy efficiency while reducing CO_2 emissions. Additionally, the improvement in the sustainability index reveals the potential of boron-based fuels from both environmental and economic perspectives. These findings serve as an important reference for future research and industrial applications related to alternative fuel additives.

Keywords: Borax decahydrate; Energy; Exergy; Environmental; Waste frying oil

History
Received 23.12.2024
Revised 04.02.2025
Accepted 18.02.2025

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To cite this paper: Özer, S., Arslan, A., Doğan, B., Tuncer, E., Arslan, Ö. Eco-Friendly Nano-Additives: Energy, Exergy, and Environmental Impacts in Motor Vehicle Emission Control. International Journal of Automotive Science and Technology. 2025; 9 (1): 121-135. http://dx.doi.org/10.30939/ijastech..1605832

1. Introduction

In recent years, the growing demand for energy and advancements in technology have led to a significant in-crease in energy consumption. As a result, researchers and industry professionals are continuously seeking alternative and more efficient methods of energy utilization. A prominent area of focus has been the transportation sector, where the energy required to power internal combustion engines primarily comes from fossil fuels. Although these fuels dominate the energy landscape, concerns about their environmental impacts have prompted significant efforts to explore cleaner and more sustainable energy sources [1-4].

Diesel engines are widely used across various applications due to their high energy efficiency, robustness, and ability to operate under diverse conditions [5]. These engines are favored for their durability, reliability, and cost-effectiveness, making them prevalent in industries, transportation, and power generation. However, diesel engine emissions, such as carbon monoxide (CO), carbon dioxide (CO_2), nitrogen oxides (NOx), and particulate matter, pose serious environmental and health risks. This has led to the implementation of stricter emission regulations worldwide [6-8]. With rising fuel prices and the depletion of fossil fuel reserves projected to last fewer than 50 years the need for alternative fuels has become more urgent than ever. Biodiesel has emerged as a promising alternative, offering performance comparable to conventional diesel while being renewable and environmentally friendly [10-11].

Biodiesel can be derived from various sources, including vegetable oils, animal fats, and waste cooking oil. Among these, waste cooking oil biodiesel holds promise as it not only recycles waste materials but also reduces environmental pollution. Utilizing waste oils helps minimize waste disposal issues and provides an economical and sustainable energy option. This dual benefit of waste recycling and energy production makes biodiesel from waste cooking oil a critical component in achieving sustainability goals.

Several studies have examined the effects of blending waste cooking oil biodiesel with conventional diesel fuel. For instance, Şanlı [12] investigated the influence of waste cooking oil-diesel blends on engine performance, injection, combustion, and emissions. The study revealed that higher concentrations of waste cooking oil in the blend, coupled with increasing engine loads, resulted in reduced performance and deteriorating emission characteristics. Similarly, Pugazhvadivu and Jeyachandran [13] demonstrated that preheating waste cooking oil to 135°C improved engine efficiency, reduced carbon monoxide (CO) emissions, and decreased smoke opacity, suggesting that waste oil can serve as a short-term diesel substitute.

Ulusoy et al. [14] conducted performance and emission tests using biodiesel derived from waste cooking oil in a Fiat Doblo 1.9 DS diesel engine. The results showed an 8.9% reduction in CO emissions and a 2.62% decrease in CO_2 emissions, albeit with a 5.03% increase in NOx emissions. Similarly, Adailey and Alqdah [15] observed improved combustion characteristics and reduced emissions when biodiesel was used in compression ignition engines, with notable increases in brake thermal efficiency and exhaust gas temperature.

Further studies have compared biodiesels derived from different esters. Şanlı et al. [16] compared methyl ester and ethyl ester biodiesels, concluding that ethyl esters demonstrated superior emission profiles. Singh and Paul [17] explored the use of waste cooking oil and waste poly-ethylene co-pyrolysis oil blends into diesel engines. Their findings indicated that 70% diesel and 30% co-pyrolysis oil blend (D70P30) provided an efficient, sustainable, and cost-effective alternative fuel option.

Blending biodiesel with nanoparticles has also emerged as a strategy to enhance fuel properties and combustion efficiency. Yusuff et al. [18] analyzed biodiesel-petroleum diesel blends at different ratios (B20, B50, and B80). The study highlighted that the B20 blend, containing 20% biodiesel, emitted lower levels of CO and CO_2, making it the most effective dual-fuel option for diesel engines. Similarly, Gaur and Goyal [19] studied biodiesel production from waste cooking oil and its engine performance, emphasizing its viability as an alternative fuel.

The addition of nanoparticles to biodiesel and diesel blends has garnered attention for improving combustion efficiency and emission control. Nanoparticles can be synthesized from various organic and inorganic materials, including plant-based sources such as roots, fruits, and stems [23]. For instance, Nouri et al. [24] examined the effects of Fe_2O_3 and Al_2O_3 nanoparticles on diesel fuel, concluding that hybrid fuel blends achieved a balance be-tween improved performance and reduced emissions.

Chinnasamy et al. [25] studied aluminum oxide (Al_2O_3) nanoparticles in diesel-plastic oil blends and found that incorporating nanoparticles significantly enhanced combustion efficiency while reducing emissions. Similarly, El-Adawy [26] reported that adding zinc oxide (ZnO) nano-particles to biodiesel blends improved combustion proper-ties, resulting in better engine performance. Anish et al. [27] investigated biosynthesized zirconium nanoparticles, finding that they enhanced combustion efficiency and reduced harmful emissions in diesel engines.

In another study, Rajak et al. [28] demonstrated that diesel fuel blended with ZnO nanoparticles led to decreased exhaust pollutants and improved combustion efficiency. Özer et al. [29] specifically analyzed the effects of borax decahydrate nanoparticles on single-cylinder diesel engines.

Despite the wealth of studies on diesel/biodiesel/nanoparticle blends, limited research exists on fuel blends involving waste cooking oil and borax decahydrate. This gap highlights the need for further investigation into the thermodynamic, economic, and environmental impacts of such blends. The use of borax decahydrate nanoparticles, dissolved in methanol at varying concentrations (1%, 3%, and 5% by mass), offers a novel approach to improving the performance and sustainability of diesel engines. Comparative literature review is given in Table 1.

This study explores the potential of a ternary blend composed of diesel, waste frying oil biodiesel, and borax decahydrate nanoparticles. Thermodynamic analyses, including energy, energy, and exergoenvironmental assessments, were conducted to evaluate the performance, emissions, and sustainability of these fuel blends. Unlike conventional studies that focus solely on first-law thermodynamics, this research integrates second-law analyses to provide a comprehensive evaluation of energy efficiency and environmental impacts.

This study is one of the research efforts investigating the effects of adding borax decahydrate nanoparticles to diesel and waste frying oil biodiesel blends on engine performance, emissions, and sustainability. It aims to evaluate thermodynamic and environmental performance by contributing to the limited studies conducted on the use of borax decahydrate as a fuel additive. It integrates energy and exergy analyses to reveal the improvement potentials for determining the efficiency of fuel blends.

Table 1. Comparative literature review.

Reference	Engine Specifications	Test Parameters	Test Fuels	Purpose
30	Diesel engine, constant speed, variable load	CO, HC, NOx, smoke emissions, thermal efficiency, specific fuel consumption (SFC)	Waste sunflower and cotton oil biodiesel + MgO nanoparticle (50, 75, 100 ppm)	The effect of MgO nanoparticle addition on emission and performance values
31	Three-cylinder direct injection diesel engine	CO, CO_2, HC, NOx, smoke emissions, exhaust temperature, specific fuel consumption	Canola, soybean, waste sunflower oil biodiesel + diesel (B5, B10, B20)	Investigation of the performance and emission values of biodiesel blends
32	Diesel engine, constant speed, variable load	CO, HC, NOx, smoke emissions, thermal efficiency, specific fuel consumption	Waste sunflower and grape seed oil biodiesel + ZnO nanoparticle (50, 100 ppm)	Effect of biodiesel and ZnO nanoparticle additives on emission and performance values
33	3-cylinder, water-cooled diesel engine (Lombardini LDW 1003)	4 different load conditions (10, 20, 30, 40 Nm), 1800 rpm	Cottonseed-based biodiesel + CeO_2 nano additive (50 ppm and 75 ppm)	Investigation of the effect of CeO_2 nano additive on biodiesel fuel performance and emissions
34	Single-cylinder, naturally aspirated, direct injection diesel engine (Katana Km 178 F)	6 different load conditions (0, 0.4, 0.8, 1.2, 1.6, 2 kW), 3000 rpm	Diesel + 1-pentanol blends (Pt10: 10% pentanol, Pt20: 20% pentanol, Pt30: 30% pentanol)	Investigation of the effect of 1-pentanol/diesel blends on engine performance and emissions
35	Single-cylinder, air-cooled, four-stroke diesel engine (Antor 3LD510)	6 different load conditions (0%, 20%, 40%, 60%, 80%, 100%), 1800 rpm	Diesel + biodiesel blends (B10: 10% biodiesel, B20: 20% biodiesel)	Comparison of the effects of diesel and biodiesel blends on engine performance, emissions, noise, and vibration
36	Single-cylinder, four-stroke, water-cooled, variable compression ratio (VCR) diesel engine, 3.5 kW power, 1500 rpm	Nanoparticle levels: 50, 75, 100 ppm	Diesel, cottonseed-based biodiesel, cerium oxide (CeO_2) nanoparticle-added biodiesel	Investigation of the effect of biodiesel and cerium oxide nanoparticle additive on engine performance and emissions
37	Four-stroke, three-cylinder, water-cooled, turbocharged direct injection (DI) diesel engine, 41 kW power, 2300 rpm	Constant engine speed: 1800 rpm, Load levels: 25%, 50%, 75%, 100%	Pure diesel, 25 ppm, 50 ppm, 75 ppm TiO_2 added diesel	Determining the effect of TiO_2 nanoparticles on engine performance and emissions
38	Three-cylinder, direct injection diesel engine	Constant engine speed: 1500 rpm, Load levels: 25%, 50%, 75%, 100%	Diesel, poppy oil biodiesel (POME), canola oil biodiesel (COME), 5%, 10%, 20% biodiesel blends, 50 ppm and 100 ppm CuO nanoparticles	Investigation of the effects of POME and COME-based biodiesel on engine performance and emissions
39	Single-cylinder, four-stroke, air-cooled SI engine, 1.2 kW power, 7:1 compression ratio	Constant full load, variable engine speed (2100-3200 rpm)	Gasoline, 10% ethanol (E10), 10% methanol (M10)	Comparison of the effects of methanol and ethanol additives on SI engine performance and emissions

The environmental impacts of the fuels are addressed from a broad perspective with exergy-environmental analyses and sustainability indices. Promoting the conversion of waste frying oil into biodiesel can provide environmental and economic benefits.

In this study, the effect of borax decahydrate on combustion efficiency and emissions is evaluated, providing an alternative to other nanoparticle studies in literature. Lastly, by assessing its usage potential in commercial diesel engines, a roadmap for sustainable fuel solutions has been established.

2. Material and Methods

2.1. Test Fuels

The biodiesel used in the engine experiments was produced from waste vegetable oil sourced from the Muş Alparslan University cafeteria. For the production process, 10 liters of waste vegetable oil were first passed through coarse and fine filters with a 100-micron mesh to remove impurities. The filtered oil was then heated to 110°C while being continuously stirred for 2 hours to eliminate moisture content. Once treated, the waste vegetable oil was mixed with methanol at a ratio of 20% by volume and a sodium hydroxide (NaOH) catalyst at 1% by mass. This reaction was carried out at 60°C for 3 hours. After the reaction was completed, the resulting mixture was transferred to a separation funnel and allowed to rest for 24 hours to enable the separation of glycerin and biodiesel. The biodiesel was then washed multiple times with water at a 50% volume ratio until the acidity of the fuel was consistently reduced to an acceptable level. Following the washing process, the biodiesel was heated to 110°C for 1 hour while being stirred to remove any remaining water. The final fuel was passed through a diesel fuel filter to ensure purity and was subsequently stored for use in the experiments. The experimental setup used for biodiesel production is illustrated in Figure 1.

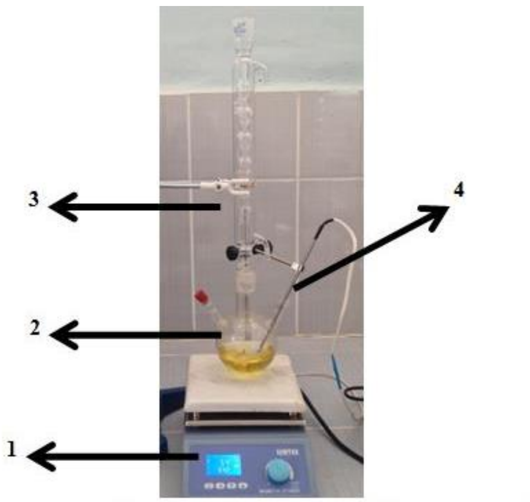

Figure 1. Biodiesel production scheme [40].1. Heater with magnetic stirrer 2. Glass balloon 3. Back cooler 4. Thermometer

The borax decahydrate (disodium tetraborate decahydrate) used in the experiments has the chemical formula $Na_2B_4O_7{\cdot}10H_2O$ and a CAS number of 1303-96-4. It was supplied by Eti Maden Enterprises in Türkiye. A precision balance was employed to measure the required quantities, and methanol-borax decahydrate mixtures were prepared by mass. The schematic process followed for fuel preparation is illustrated in Figure 2. For experimental purposes, 5 g, 15 g, and 25 g of borax decahydrate were added to 500 g of methanol. This mixture was stirred at 550 rpm for 24 hours at 40°C, ensuring complete dissolution of the borax without any precipitation, even after 24 hours of rest. The resulting methanol-borax solution was then mixed with the biodiesel/diesel blends derived from waste vegetable oils. This second mixing stage was carried out for 3 hours using an ultrasonic mixer operating at 35 kHz frequency.

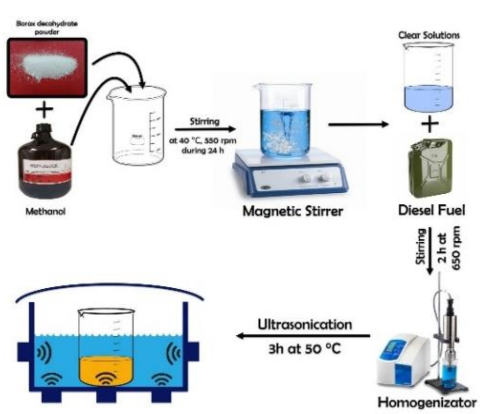

Figure 2. Experimental fuels mixing scheme

To ensure consistency, the fuel mixtures were freshly prepared before each engine experiment and used immediately to prevent precipitation. The blend ratios and their respective abbreviations are detailed in Table 2, while the physical and chemical properties of the resulting fuel blends are presented in Table 3.

Table 2. Experimental fuels and abbreviations.

Fuel Mixture	Diesel	Biodiesel	Methanol (5 g Borax Deka Hydrate)	Methanol (15 g Borax Deka Hydrate)	Methanol (25 g Borax Deka Hydrate)
D100	100	-	-	-	-
Biodiesel	-	100	-	-	-
D50W50	50	50	-	-	-
D50W50P1	40	50	5		
D50W50P2	40	50	-	15	-
D50W50P3	40	50	-	-	25

Table 3. Physical and chemical properties of experimental fuels.

Abbreviation	Calorific value (kJ/kg)	Viscosity (mm2/s) (at 40 ˚C)	Density (g/cm3) (at 20 ˚C)
D100	43010	3.4	834
Biodiesel	39819	4.3	863
D50W50	39145	5.4	895
D40W50P1	39054	4.8	877
D40W50P2	38933	4.7	863
D40W50P3	38714	4.2	841

2.2. Experimental Setup and methodology

The experimental study utilized a naturally aspirated, four-stroke, air-cooled, direct injection, single-cylinder compression ignition engine. Detailed specifications of the engine can be found in Table 4.

Table 4. The technical specifications of test engine

Parameters	Specification
Cylinder number	1
Engine cycle	4
Maximum engine power	6.35 kW @ 3600 rpm
Maximum engine torque	21 Nm @ 3600 rpm
Powertrain	Camshaft in block with pushrod
Valve system	2 valves per cylinder
Type of fuel injection	Direct injection
Ignition	Compression-ignition
Cooling system	Air cooled
Swept volume	395 cm^3
Cylinder bore	86 mm
Stroke	68 mm
Compression ratio	18:1
Injector nozzle	0.24 (mm) * 4 holes * 160°
Nozzle opening pressure	200 bar
Fuel injection timing	24° BTDC

The experimental tests involved operating a diesel engine at a constant speed of 3000 rpm while varying the load incrementally from 1 kW to 5 kW. Fuel consumption was measured by recording the time required to burn 10 g of fuel, with a high-precision electronic scale offering 0.01 g accuracy. Exhaust gas temperature was monitored using a K-type thermocouple, and emissions data for HC, CO, CO_2, and smoke were obtained using a Mobydic 5000 COMBI exhaust gas analyzer. Table 5 outlines the technical specifications and uncertainties associated with the measurement instruments, and Figure 3 and Figure 4 illustrates the layout of the experimental setup.

Table 5. The technical specifications of measurement instruments

Exhaust Emission Analyzer (Mobidicy 5000)				
No	Parameter	Unit	Measurement range	Resolution (%)
1	Carbon monoxide (CO)	(%Vol)	%0-15	±1
2	Carbon dioxide (CO_2)	(%Vol)	%0-20	±1
3	Hydrocarbon (HC)	(ppm)	0-20000	±12
4	Nitrogen oxide (NO_x)	(ppm)	0-5000	±1
5	Oxygen (O_2)	(%Vol)	%0-21	±1
6	Smoke opacity	(%Vol)	0-99	±2
7	Particulate matter	(mg/m^3)	0-200	±0.1
Dynamometer (Netfren)				
1	Power capacity	(kW)	0-26	±1
2	Speed	(rpm)	0-5000	±50
3	Torque	(Nm)	0-80	±1

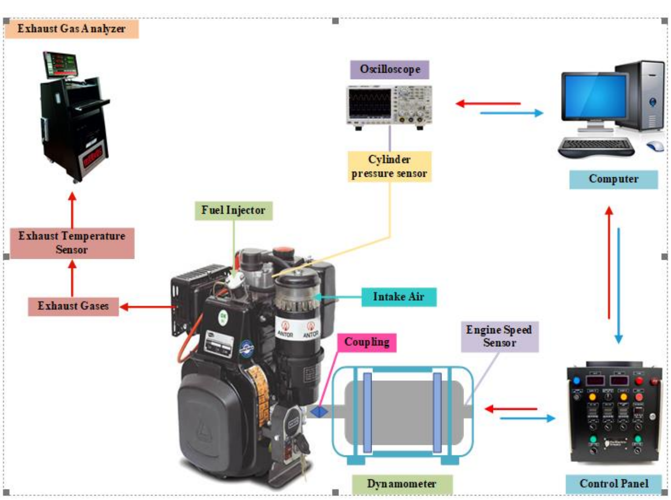

Figure 3. The schematic view of the experimental apparatus [41]

Figure 4. The experimental setup

3. Thermodynamic Analysis

In these engine experiments, a diesel engine consistently operated at 3000 rpm while varying the load in increments of 1 kW, ranging from 1 kW up to 5 kW. Fuel consumption was measured by timing how long it took for the engine to consume 10 grams of fuel, using a highly precise electronic scale with an accuracy of 0.01 grams. The exhaust gas temperature was monitored using a K-type thermocouple. Emissions of hydrocarbons (HC), carbon monoxide (CO), carbon dioxide (CO_2), and smoke were analyzed utilizing a Mobydic 5000 COMBI exhaust gas analyzer. The experimental studies were carried out under dynamic test conditions to evaluate engine performance and emissions based on thermodynamic principles. The following assumptions were made:

1. The gases entering and exiting the cylinder are assumed to behave as ideal gases.

2. The temperature of the cylinder walls remains constant during the experiments.

3. Ambient conditions are maintained at 20°C and atmospheric pressure (1 atm).

4. The engine is assumed to operate under continuous, steady-state conditions.

Technical specifications and uncertainty analyses of the measurement devices are detailed in Table 4. A schematic diagram of the experimental setup is presented in Figure 5.

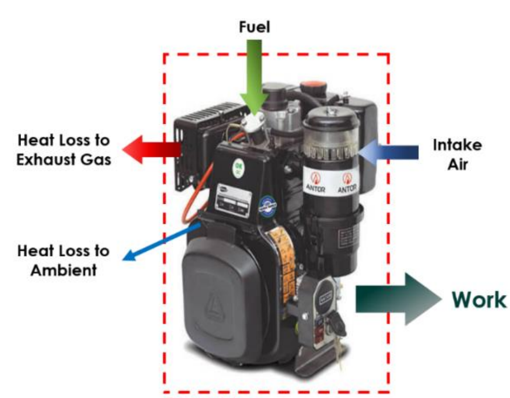

Figure 5. Control volume for thermodynamic analyses [41]

3.1. Energy Analysis

The engine acts as the core power generation system, converting fuel energy into mechanical work (Ẇ). This useful work can be calculated based on the engine's rotational speed (n) and torque (T) using Eq. (1) [37]:

$$\dot{W} = 2\pi \frac{n}{60} T \quad (1)$$

The energy contribution of the air entering the control volume under atmospheric conditions is considered negligible. As a result, the total energy entering the control volume is attributed entirely to the fuel energy, as expressed in Eq. (2). In this context, the fuel energy encompasses both the air energy ($\dot{E}_{air}$) and the thermal losses ($\dot{E}_{loss}$).

$$\dot{E}_{fuel} + \dot{E}_{air} = \dot{E}_{in} \quad (2)$$

fuel energy is equivalent to the total of the useful work produced and the thermal losses, as outlined in the following equation [38-39].

$$\dot{E}_{in} = \dot{W} + \dot{E}_{loss} \quad (3)$$

The fuel energy is calculated using the fuel flow rate $\dot{m}_{fuel}$ obtained from the engine test rig and the lower heating value LHV_{fuel} derived from fuel analysis, as shown in the following equation [40-41]."

$$\dot{E}_{fuel} = \dot{m}_{fuel}\ LHV_{fuel} \quad (4)$$

Energy losses and thermal efficiency are crucial metrics for assessing the motor's performance and identifying areas for improvement. This data serves as a valuable resource for understanding and optimizing the motor's operation. Thermal efficiency is determined using the following equation [42].

$$\eta_{th} = \frac{\dot{W}}{\dot{E}_{fuel}} \quad (5)$$

3.2. Exergy Analysis

Based on the second law of thermodynamics, energy conversion and heat transfer between energy sources and systems are inherently limited in efficiency. In this framework, exergy serves as a key indicator, quantifying the portion of transferred energy that can be converted into useful work. The exergy balance is expressed as follows [43].

$$\dot{E}x_{air} + \dot{E}x_{fuel} = \dot{E}x_{w} + \dot{E}x_{ex} + \dot{E}x_{heat} + \dot{E}x_{dest} \quad (6)$$

Fuel exergy ($\dot{E}x_{fuel}$), the exergy of heat lost from the engine body ($\dot{E}x_{heat}$), the exergy of exhaust gases released into the environment and exergy ($\dot{E}x_{ex}$) destruction are key components in exergy analysis. Since the air entering the engine is sourced directly from the environment, its exergy contribution is assumed to be zero [44]. The exergetic power ($\dot{E}x_{w}$) corresponds to the engine's output power. The exergy of liquid fuel is determined using the following equation [45, 46].

$$\dot{E}_{fuel} = \dot{m}_{fuel}\ \varphi LHV_{fuel} \quad (7)$$

Here (φ) is the exergy factor. The exergy factor is calculated using the data obtained by analyzing the fuel [47].

$$\varphi = 1.0401 + 0.1728\frac{h}{c} + 0.0432\frac{o}{c} + 0.2169\frac{\alpha}{c}\left(1 - 2.0628\frac{h}{c}\right) \quad (8)$$

Calculating exhaust exergy is a complex step in exergy analysis. It begins with measuring emissions, followed by formulating the actual combustion equation based on the proportions of fuel, air, and emissions. From this equation, the mole fraction of each gas is determined. The total exhaust gas flow rate ($\dot{m}_{total}$) is estimated as 98% of the fuel flow rate entering the control volume [48]. The exhaust gas exergy is then calculated by summing the physical exergy (ε_p) and chemical exergy (ε_c) of each component.

$$\dot{E}x_{ex,i} = \sum\left(\varepsilon_p + \varepsilon_c\right)_i \quad (9)$$

Chemical and physical exergies were calculated using the equations given in Eq. (10-11). [48].

$$\varepsilon_p = [(h - T_0 s) - (h_0 - T_0 s_0)] \quad (10)$$

$$\varepsilon_{ch} = \bar{R}T_0 ln\frac{1}{y^e} \quad (11)$$

The chemical exergy calculations were based on literature values for atmospheric gas percentages (ye) [50]. Furthermore, the temperature of the engine casing was recorded during the experiments to determine the exergy of heat transferred from the engine casing to the surroundings, as described in Eq. (12) [51].

$$\dot{E}x_{heat} = \sum\left(1 - \frac{T_0}{T_s}\right)\dot{Q}_{loss} \quad (12)$$

Where (T_s) is the engine causing temperature. The entropy produced can be determined according to Eq. (13) given below [51].

$$\dot{s}_{gen} = \frac{\dot{E}x_{dest}}{T_0} \quad (13)$$

Exergy efficiency, calculated using Eq. (14) [52], represents the ratio between the system's input and output exergy values. This metric provides insight into how effectively the energy within the system is converted into useful work.

$$\eta_{ex} = \frac{\dot{E}x_W}{\dot{E}x_{in}} \quad (14)$$

3.3. Sustainability Analysis

This analysis is employed to calculate the sustainability index of fuels, which is determined using Eq. (15) [53]. The sustainability index evaluates the efficiency of energy conversion processes and the sustainable use of resources. Additionally, it serves as a crucial parameter for comparing the sustainability performance of different energy systems.

$$\mathrm{SI} = \frac{1}{1-\eta_{ex}} \quad (15)$$

3.4. Exergy Environmental Analysis

Carbon dioxide emissions play a significant role in global warming and climate change, making their reduction essential for a sustainable future. The mass of CO_2 emitted into the atmosphere is calculated using the following equation [54].

$$C_{xCO_2} = N_{CO_2} \dot{E}x_{in} t_{year} \quad (16)$$

The economic value of CO2 emissions of the fuel blends used in the study is determined by Eq. (17). In the economic evaluation, P_{CO_2} = 0.0145 $/kg CO2 [36].

$$ExC_{CO_2} = C_{xCO_2}\ P_{CO_2} \quad (17)$$

4. Result and Discussions

4.1. Energy Analysis

In a thermodynamic cycle, a system undergoes a series of processes and eventually returns to its initial state. Energy analysis is employed to examine the transfer and transformation of energy throughout these processes, assess system performance, and optimize energy efficiency. Energy flow within the system indicates the movement or transformation of energy, and the corresponding data is presented in Figure 6. The highest energy flow recorded was 20.986 kW for the D50W50 fuel blend at 5 kW engine power. In contrast, diesel fuel exhibited the lowest energy flow across all tested engine power levels. Specifically, the energy flow for diesel fuel was measured as 5.974 kW, 11.350 kW, 15.054 kW, 13.620 kW, and 17.443 kW at 1 kW, 2 kW, 3 kW, 4 kW, and 5 kW engine power, respectively. When waste cooking oil biodiesel was added to diesel fuel, an increase in energy flow was observed. For instance, at 3 kW engine power, the energy flow for pure diesel fuel was 15.054 kW, while it increased to 16.669 kW for the D50W50 blend.

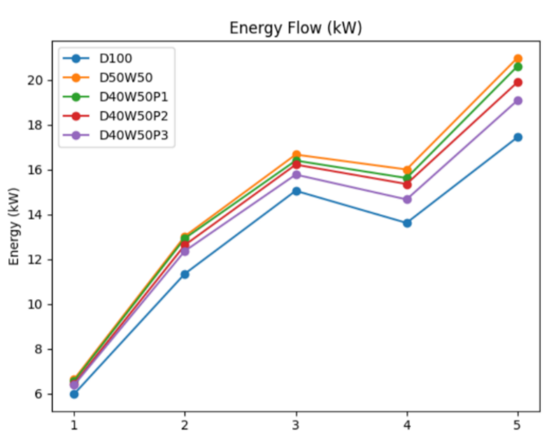

Figure 6. Energy flows of fuel blends

Additionally, incorporating borax decahydrate into the diesel /waste cooking oil fuel blends further influenced the energy flow. At 4 kW engine power, the energy flow for the D50W50 blend was 16.006 kW, whereas it slightly decreased to 15.622 kW for the D40W50P1 blend. However, as the concentration of borax decahydrate increased, a reduction in energy flow was observed. At 5 kW engine power, the energy flow decreased from 20.612 kW for the D40W50P1 blend to 19.088 kW for the D40W50P3 blend. This indicates that while borax decahydrate enhances energy flow to a certain extent, higher ratios may lead to diminishing returns. Figure 7. Generally, as engine power increases, the heat losses in the fuel blends also rise. For instance, in the D40W50P2 fuel blend, heat losses measured at 1 kW engine power were 5.563 kW, but at 3 kW engine power, this value increased to 13.222 kW, approximately 2.4 times higher. The addition of waste cooking oil to diesel fuel was observed to increase heat losses. At 2 kW engine power, the heat losses for diesel fuel were recorded as 9.350 kW, while for the D50W50 blend, they rose to 11.027 kW. The lowest heat losses occurred at 1 kW engine power for diesel fuel, measured at 4.974 kW. In contrast, introducing borax decahydrate particles into the diesel and waste frying oil blend was found to reduce heat losses. For example, at 4 kW engine power, the heat losses in the D50W50 blend were 12.006 kW, whereas they decreased to 10.668 kW in the D40W50P3 blend at the same engine power level. This indicates that borax decahydrate has a positive effect in mitigating thermal losses within the system.

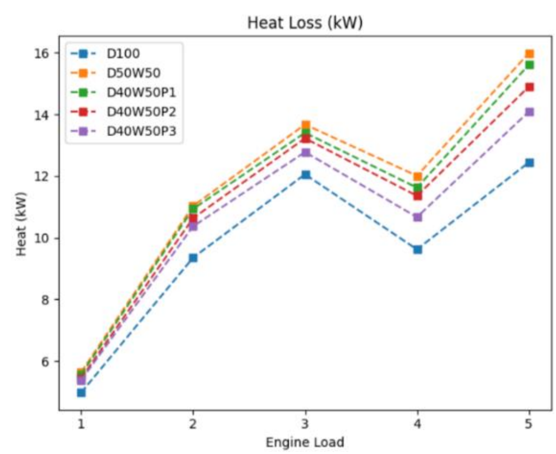

Figure 7. Heat losses of fuel blends at different engine speeds

Thermal efficiency reflects how effectively energy is converted within a system, typically evaluating the transformation of thermal energy into mechanical or electrical output. Figure 8 illustrates the thermal efficiency values for different fuel blends. The highest thermal efficiency was recorded as 29.369% for diesel fuel at an engine power of 4 kW. In general, thermal efficiency improves as engine power increases. For example, in the D40W50P1 fuel blend, thermal efficiencies were measured as 15.236%, 15.466%, 18.290%, 25.606%, and 24.258% at engine powers of 1 kW, 2 kW, 3 kW, 4 kW, and 5 kW, respectively. Within the tested fuel blends, increasing the proportion of borax decahydrate was observed to enhance thermal efficiency at similar engine power levels. At 3 kW engine power, the thermal efficiencies were 18.290%, 18.493%, and 19.016% for the D40W50P1, D40W50P2, and

D40W50P3 blends, respectively. Mohapatra et al. [55] conducted similar research on biofuels derived from waste rice straw blended with diesel in varying ratios (e-diesel: R10, R15, R20). They also examined diesel-bioethanol blends with the addition of 25 ppm Al_2O_3 nanoparticles (nano fuels: NF0, NF10, NF15, NF20) under different compression ratios and loads, performing detailed thermodynamic analyses. Their findings revealed a maximum energy efficiency of 30.42% for the NF0 blend at full engine load.

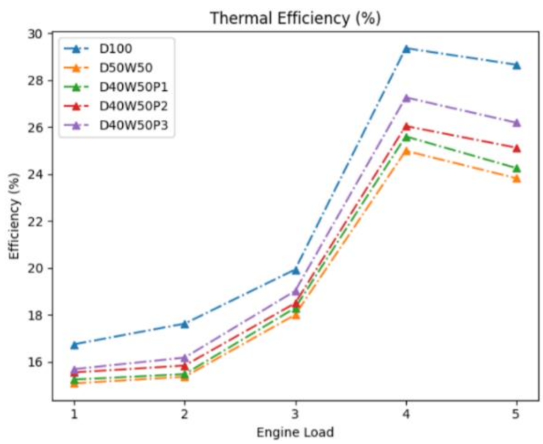

Figure 8. Thermal efficiency of fuel blends

4.2. Exergy Analysis

Exergy measures the efficiency of a system's interaction with its environment and determines the portion of energy that can be converted into useful work. Figure 9 shows the exergy flows for the fuels tested in the engine experiments. Among all tested fuels, diesel exhibited the lowest exergy flow across all engine power levels. Adding waste frying oil to diesel fuel was found to increase the input exergy flow. For example, at 2 kW engine power, the input exergy flow for diesel fuel was 15.796 kW, while it increased to 17.891 kW for the D50W50 blend. However, incorporating borax decahydrate particles into the fuel blends with waste cooking oil led to a reduction in input exergy flow. At 3 kW engine power, the input exergy flow decreased from 22.894 kW for the D50W50 fuel blend to 22.157 kW when 50 ppm borax decahydrate was added.

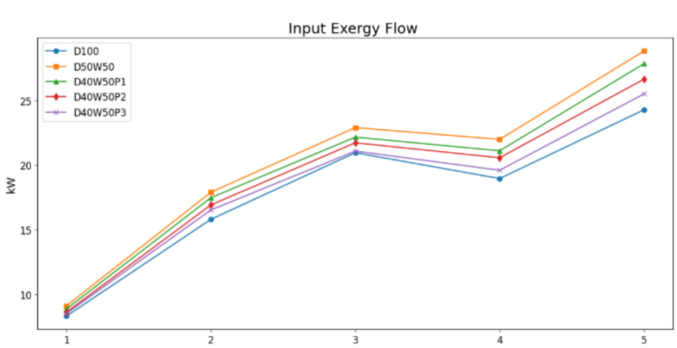

Figure 9. Input exergy flow of fuel blends

This trend highlights that higher concentrations of borax decahydrate result in lower input exergy flows. For instance, at 1 kW engine power, the input exergy flow was measured as 8.866 kW for the D40W50P1 blend and dropped to 8.520 kW for the D40W50P3 blend. The maximum input exergy flow observed during the experiments was 28.823 kW for the D50W50 fuel blend at 5 kW engine power.

Exhaust exergy refers to the energy lost during processes or energy transformations within the system, which lowers overall energy efficiency as it is expelled into the environment without being utilized. Figure 10 presents the exhaust exergy values for various fuel blends at different engine power levels. The highest exhaust exergy was recorded as 1.489 kW for the D50W50 fuel blend at 5 kW engine power. Adding waste frying oil to diesel fuel was observed to increase exhaust exergy. For instance, at 4 kW engine power, diesel fuel showed an exhaust exergy of 1.291 kW, while the D50W50 blend exhibited a slightly higher value of 1.310 kW. On the other hand, incorporating borax decahydrate into the fuel blends and increasing its concentration led to a reduction in exhaust exergy. At 2 kW engine power, the exhaust exergy for the D50W50 blend was measured at 0.899 kW. For the D40W50P1, D40W50P2, and D40W50P3 blends, the exhaust exergy values were slightly lower, at 0.900 kW, 0.896 kW, and 0.891 kW, respectively. This trend indicates that borax decahydrate contributes to reducing energy losses in the exhaust stream as its concentration increases.

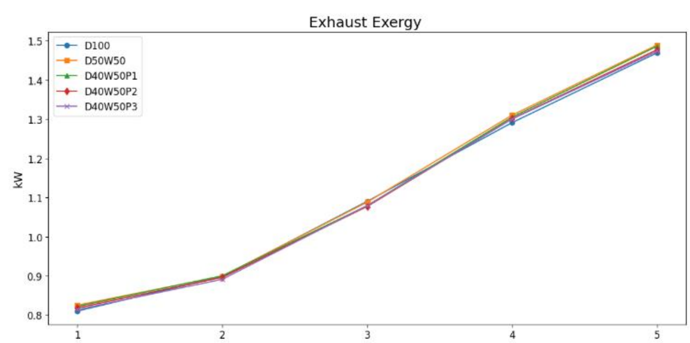

Figure 10. Exhaust exergy of fuel blends at different engine loads

The exergy of thermal losses represents the thermodynamic impact on energy availability within a system, influencing its efficiency in performing work. Figure 11 illustrates the thermal loss exergy values for various fuel blends at different engine power levels. The highest thermal loss exergy was recorded at full engine power, reaching 1.165 kW for commercial diesel fuel. Diesel consistently showed the highest thermal loss exergy across all engine powers, with values of 0.261 kW, 0.784 kW, 1.128 kW, 0.825 kW, and 1.165 kW for 1 kW, 2 kW, 3 kW, 4 kW, and 5 kW engine powers, respectively. Incorporating waste frying oil into diesel fuel was found to reduce thermal loss exergy. For example, at 2 kW engine power, the thermal loss exergy decreased from 0.784 kW for pure diesel (D100) to 0.691 kW for the D50W50 blend. Additionally, the inclusion of borax decahydrate particles further reduced thermal loss exergy. At 5 kW engine power, the thermal exergy decreased from 1.064 kW for the D50W50 blend to 0.907 kW for the D40W50P3 blend. This trend highlights the beneficial impact of waste frying oil and borax particles in minimizing thermal energy losses.

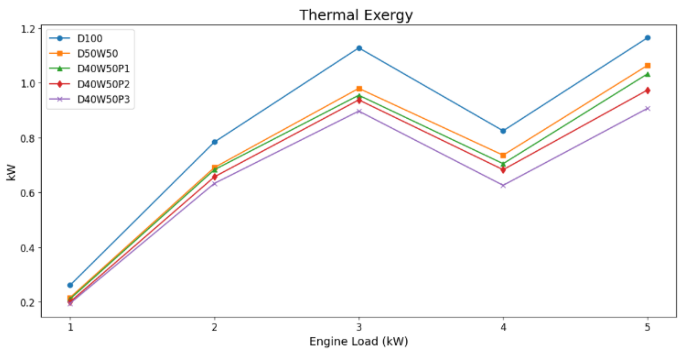

Figure 11. Thermal exergy of fuels at different speeds

Exergy destruction refers to the portion of exergy in an energy system that becomes unusable, representing lost energy potential due to entropy generation. Ideally, exergy destruction would be zero, meaning all available energy could be converted into useful work. However, in real systems, exergy destruction is inevitable during energy processes. Figure 12 presents the exergy destruction values for various fuel blends. The highest exergy destruction was recorded at 26.270 kW for the D50W50 fuel blend (50% commercial diesel + 50% waste cooking oil by volume) at 5 kW engine power. For the same fuel, exergy destruction generally increases with engine power. For instance, in the D40W50P2 blend, exergy destruction increased from 7.511 kW at 1 kW engine power to 23.122 kW at 5 kW, representing a 3.07-fold rise. The addition of borax decahydrate particles to the fuel blends was observed to decrease exergy destruction at constant engine power levels. At 2 kW engine power, the exergy destruction for the D40W50P1 blend was 15.885 kW, while it decreased to 14.998 kW for the D40W50P3 blend. In contrast, the inclusion of waste frying oil in diesel fuel increased exergy destruction. For example, at 4 kW engine power, exergy destruction rose from 16.840 kW for pure diesel fuel to 19.937 kW for the D50W50 blend. Rajpoot et al. [56] conducted a thermodynamic analysis on fuel blends incorporating biodiesel derived from third-generation Botryococcus braunii microalgae mixed with nanoparticles such as lanthanum oxide (La_2O_3), copper peroxide (CuO_2), and cerium oxide (CeO_2). Their findings indicated that the addition of nanoparticles reduced exergy destruction by 0.61-0.91%, further emphasizing the potential of nanoparticles in enhancing energy efficiency.

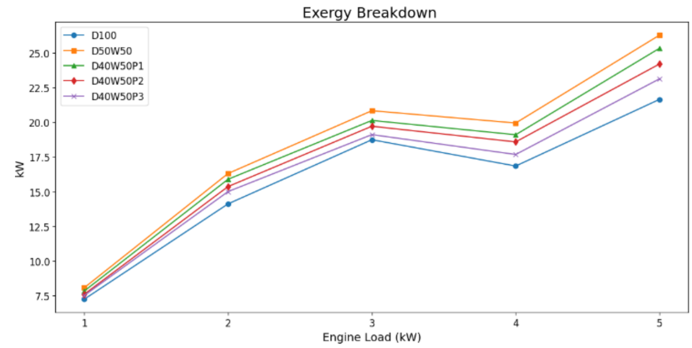

Figure 12. Exergy breakdown for fuel blends

Total exergy losses represent the portion of usable energy's work potential that is lost or discarded within a system without being utilized. These losses occur when energy that could otherwise be converted into useful work exits the system due to processes, heat transfers, or interactions, or transforms into an unusable form. Total exergy loss is calculated as the sum of exhaust exergy and thermal loss exergy. Figure 13 presents the exergy losses for different fuel blends at varying engine power levels. The highest total exergy loss was recorded at full engine power, reaching 2.634 kW for diesel fuel. Incorporating waste frying oil into diesel fuel was observed to reduce total exergy losses. For example, at 3 kW engine power, the exergy losses decreased from 2.218 kW for diesel fuel to 2.068 kW for the D50W50 blend. Further reductions in exergy losses were achieved by adding borax decahydrate to the fuel mixtures of waste cooking oil and diesel. At 2 kW engine power, the exergy losses were measured as 1.590 kW for the D50W50 blend, 1.583 kW for D40W50P1, and 1.524 kW for the D40W50P3 blend. In general, total exergy losses increase with rising engine power. For the D40W50P2 blend, the exergy losses were calculated as 1.018 kW, 1.553 kW, 2.016 kW, 1.984 kW, and 2.451 kW at engine powers of 1 kW, 2 kW, 3 kW, 4 kW, and 5 kW, respectively. This trend highlights the influence of both waste frying oil and borax decahydrate on improving the overall energy efficiency of the system by minimizing exergy losses.

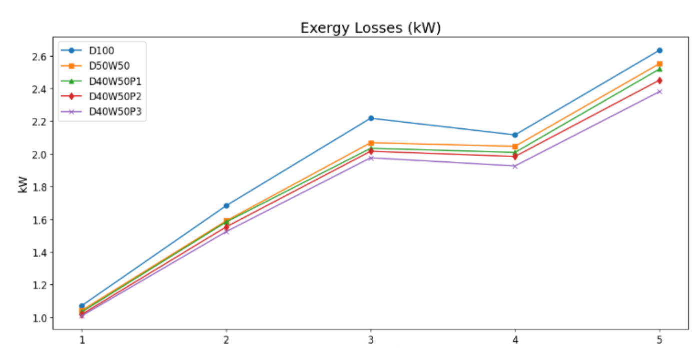

Figure 13. Exergy losses of fuels at different engine loads

Entropy production refers to the increase in entropy within a system where entropy serves as a measure of disorder or uncertainty in thermodynamics. Higher entropy production indicates greater energy dissipation and disorder within the system. Figure 14 shows the entropy generation data for various fuel blends. The highest entropy production was consistently observed in the D50W50 blend across all engine powers, reaching a peak value of 0.090 kW/K at 5 kW engine power. Adding borax decahydrate particles to diesel/waste cooking oil blends was found to slightly reduce entropy production. For instance, at 4 kW engine power, entropy production decreased from 0.068 kW/K in the D50W50 blend to 0.065 kW/K in the D40W50P1 blend. Increasing the borax decahydrate concentration in the fuel blends further reduced entropy production. At 2 kW engine power, entropy production values were recorded as 0.052 kW/K for the D40W50P2 blend and 0.051 kW/K for the D40W50P3 blend. Yildiz et al. [57] reported that engines fueled with biodiesel exhibited lower entropy production rates compared to those using pure diesel, both with and without after-treatment systems. Similarly, Özcan [58] investigated the effects of blending 5% biodiesel with pure diesel and adding Al_2O_3 nanoparticles at various ratios. Their thermodynamic analyses demonstrated reductions in brake specific fuel consumption (BSFC), entropy production, and unaccounted losses by averages of 7.57%, 13.49%, and 31.89%, respectively. These findings highlight the potential benefits of nanoparticle and biodiesel additions in reducing energy dissipation and improving system performance.

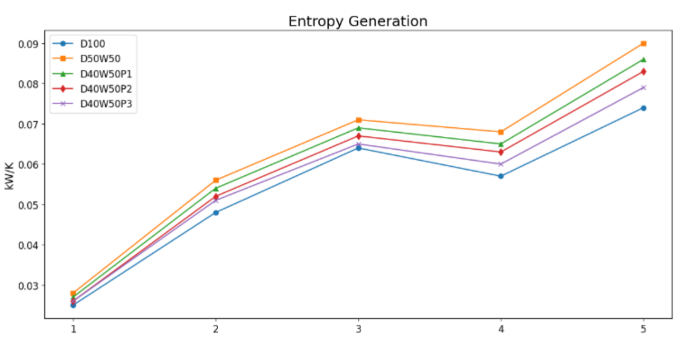

Figure 14. Exergy losses of fuels at different engine loads

Exergy efficiency indicates the extent to which the fuel's exergy is effectively utilized for power generation, representing the ratio of engine power output to the fuel's exergy input. Figure 15 presents the exergy efficiencies for various fuel blends. The highest exergy efficiency was observed for D100 fuel across all engine power levels. Specifically, the exergy efficiencies for diesel fuel were calculated as 12.03%, 12.66%, 14.32%, 21.10%, and 20.60% at engine powers of 1 kW, 2 kW, 3 kW, 4 kW, and 5 kW, respectively. When waste cooking oil biodiesel was added to diesel fuel, a reduction in exergy efficiency was noted. For instance, at 3 kW engine power, the exergy efficiency for diesel fuel was 14.32%, while it decreased to 13.10% for the D50W50 blend. However, adding borax decahydrate to the D50W50 fuel blend improved exergy efficiency. At 4 kW engine power, the exergy efficiency for the D50W50 blend was 18.20%, whereas it increased to 19.45% for the D40W50P2 blend. An increase in the proportion of borax decahydrate further enhanced exergy efficiency in Diesel/Waste Frying Oil blends. At 2 kW engine power, the exergy efficiency rose from 11.28% in the D40W50P1 blend to 11.74% in the D40W50P3 blend. Jafarmadar and Niaki [59] conducted energy and exergy analyses on a four-cylinder, four-stroke DI diesel engine using TiO_2 nanoparticle-enhanced diesel fuel. Their findings showed that adding 2.5 ppm of TiO_2 nanoparticles increased energy efficiency by 4.1% and exergy efficiency by 3%. Similarly, Özcan [58] investigated diesel/biodiesel/nanoparticle fuel blends and reported that the exergy efficiency improved by 7.28% with the addition of nanoparticles. These studies highlight the significant role of nanoparticles in enhancing energy and exergy performance in diesel engines.

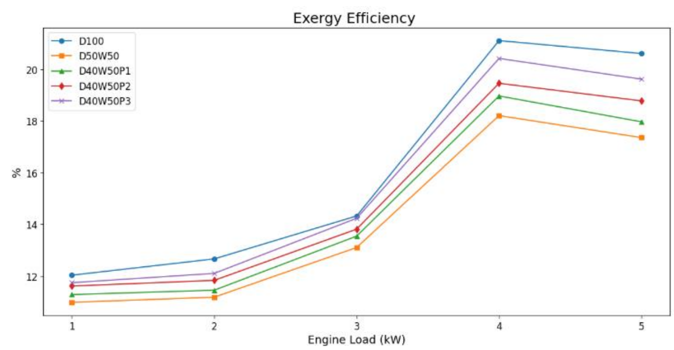

Figure 15. Exergy efficiencies of fuel blends

4.3. Sustainability

The sustainability analysis of internal combustion engines is essential for evaluating the effectiveness of fuel utilization. The sustainability index (SI) for Diesel/Waste Frying Oil/Borax fuel blends consistently exceeds 1 at all engine power levels, indicating favor-able sustainability. This index is calculated as the ra-tio of total exergy entering the control volume to the total exergy losses. An increase in engine speed can enhance both exergy efficiency and the sustainability index, if the increase in engine power surpasses the growth in exergy losses. Table 6 presents detailed sustainability index values for various engine powers and fuel mixtures. Diesel fuel demonstrated the highest sustainability index, achieving a value of 1.267. However, the addition of waste cooking oil to diesel fuel led to a reduction in the sustainability index. For instance, at 5 kW engine power, the index dropped from 1.259 for pure diesel to 1.21 for the D50W50 blend. Conversely, adding borax decahydrate particles to the diesel/waste frying oil blends improved the sustainability index, bringing it closer to the levels observed for pure diesel fuel. Rajpoot et al. [60] conducted thermodynamic analyses on fuel blends incorporating 200 ppm nanoparticles (cerium oxide, manganese dioxide, and titanium dioxide) into Prosopis juliflora biodiesel for internal combustion engines. Their results showed sustainability index improvements ranging from 3.6% to 6.8%. Similarly, Şimşek et al. [61] performed comprehensive exergy, exergoeconomic, environmental, and sustainability analyses on biodiesel blends derived from waste ani-mal fats. They reported a peak sustainability index of 1.98 for the D90B10 blend (90% diesel + 10% biodiesel) at 3 kW engine power. These findings highlight the role of alternative fuels and additives in enhancing the sustainability of internal combustion engines [62].

Table 6. Sustainability index of fuels at different engine loads

Engine Load (kW)	D100	D50 W50	D40W50 P1	D40W50 P2	D40W50 P3
1	1,137	1,123	1,127	1,131	1,133
2	1,145	1,126	1,129	1,134	1,138
3	1,167	1,151	1,157	1,160	1,166
4	1,267	1,222	1,234	1,242	1,256
5	1,259	1,210	1,219	1,231	1,244

4.4. Environmental Analysis

Environmental analysis focuses on achieving sustainability goals and formulating strategies for efficient re-source utilization. In this study, monthly CO_2 emissions were calculated based on energy and exergy analysis data for various fuel types. Figure 16 shows the corresponding CO_2 emissions values. The highest CO_2 emissions were recorded at 588.705 kg CO_2/month for the D40W50P1 fuel blend at 5 kW engine power. In contrast, D100 fuel consistently exhibited the lowest CO_2 emissions across all engine powers. For example, at 1 kW engine power, D100 fuel emitted 218.388 kg CO_2/month, while the D50W50 blend emitted 237.195 kg CO_2/month, indicating that the addition of waste cooking oil biodiesel increases CO_2 emissions. Although higher engine power generally result-ed in reduced CO_2 emissions, changes in energy flow sometimes counteracted this trend. For instance, in the D40W50P2 blend, CO_2 emissions increased from 435.338 kg CO_2/month at 2 kW engine power to 587.293 kg CO_2/month at 5 kW engine power. Increasing the concentration of borax decahydrate in diesel/waste frying oil blends was found to decrease CO_2 emissions. At 1 kW engine power, CO_2 emissions decreased from 236.195 kg CO_2/month for the D40W50P1 blend to 231.923 kg CO_2/month for the D40W50P3 blend.

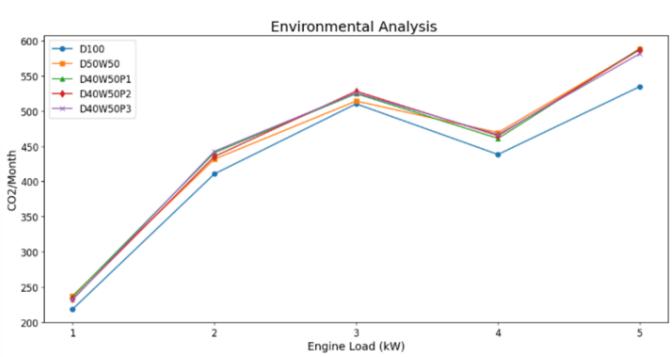

Figure 16. Monthly CO_2 amount of fuel blends according to environmental analysis

Ağbulut et al. [44] highlighted that increasing engine load generally led to higher environmental impact ratios due to greater fuel consumption. However, they noted that the environmental impact ratio per exergy unit decreased as engine load increased, emphasizing the complex relationship between engine performance and environmental impacts.

Environmental analysis using exergy data evaluates monthly CO_2 emissions from energy-efficient processes through exergoenvironmental analysis. Figure 17 presents the CO_2 emissions results for different fuel blends. The highest CO_2 emissions were recorded as 806.753 kg/month for the D50W50 fuel blend. Incorporating waste frying oil into diesel fuel was found to increase monthly CO_2 emissions. For example, at 2 kW engine power, D100 fuel emit-ted 571.469 kg CO_2/month, whereas emissions increased to 592.751 kg CO_2/month for the D50W50 blend. In general, CO_2 emissions tend to rise with increasing engine power, as indicated by exergoenvironmental analysis. For the D40W50P2 blend, emissions were recorded as 311.699 kg/month at 1 kW, 582.889 kg/month at 2 kW, 707.781 kg/month at 3 kW, 622.795 kg/month at 4 kW, and 786.346 kg/month at 5 kW engine power. The addition of borax decahydrate to diesel/waste frying oil blends demonstrated a reduction in monthly CO_2 emissions. At 5 kW engine power, the CO_2 emissions were 806.753 kg/month for the D50W50 blend, 795.235 kg/month for the D40W50P1 blend, 786.346 kg/month for the D40W50P2 blend, and 776.950 kg/month for the D40W50P3 blend. This trend highlights the potential of borax decahydrate to mitigate emissions in fuel mixtures.

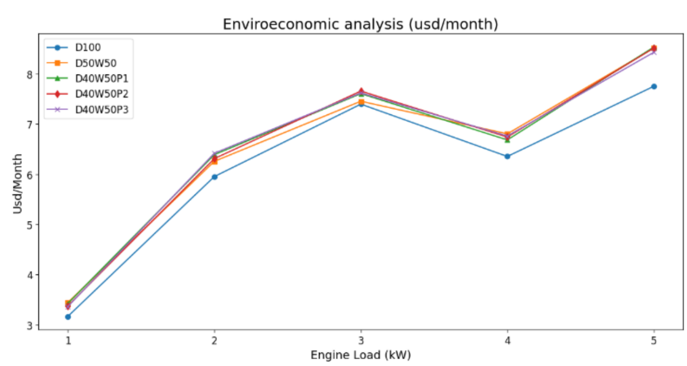

Figure 17. Monthly CO_2 amount of fuel blends according to exergoenvironmental analysis

Following the environmental analysis, the monthly CO_2 emissions from various fuel blends at different engine powers were assessed, and the associated environmental cost was evaluated through enviro-economic analysis. The results for the different fuel blends are presented in Figure 18. Diesel fuel consistently demonstrated the lowest CO_2 emission costs across all engine power levels. For example, at 1 kW engine power, the monthly CO_2 emission cost for diesel fuel was calculated as \$3.16, whereas it increased to \$3.44 per month for the D50W50 blend due to the addition of waste frying oil. The inclusion of borax decahydrate particles in diesel/waste frying oil biodiesel blends generally led to a reduction in CO_2 emission costs. At 4 kW engine power, the CO_2 emission cost was \$6.80/month for the D50W50 blend but decreased to \$6.68/month for the D40W50P1 blend. Increasing engine power correspondingly raised the environmental cost of CO_2 emissions. For instance, in the D40W50P2 blend, the monthly CO_2 emission cost rose from \$3.37 at 1 kW engine power to \$8.51 at 5 kW engine power. Moreover, increasing the concentration of borax decahydrate nanoparticles further reduced CO_2 emission costs. At 5 kW engine power, the monthly CO_2 emission cost decreased from \$8.53 for the D40W50P1 blend to \$8.43 for the D40W50P3 blend. These results highlight the positive impact of borax decahydrate in mitigating the economic costs associated with CO_2 emissions in fuel blends. The study evaluated the cost of carbon dioxide emissions resulting from fuel exergy using exergoenviroeconomic analysis. The results of this analysis are presented in Figure 19. Among the analyzed fuel blends, the diesel/waste cooking oil blend (D50W50) exhibited the highest monthly CO_2 emission cost. However, the addition of borax decahydrate to the D50W50 blend effectively reduced the CO_2 emission cost at equivalent engine power levels. For example, at 1 kW engine power, the exergoenviroeconomic analysis showed a CO_2 emis-sion cost of \$4.72/month for the D50W50 blend. This cost decreased to \$4.62/month for the D40W50P1 blend and further to \$4.51/month for the D40W50P2 blend. Diesel fuel demonstrated the lowest monthly CO_2 emission cost, calculated as \$4.40. In contrast, the highest monthly CO_2 emission cost was recorded at \$11.69 for the D50W50 blend, highlighting the impact of waste cooking oil on in-creasing emission costs without

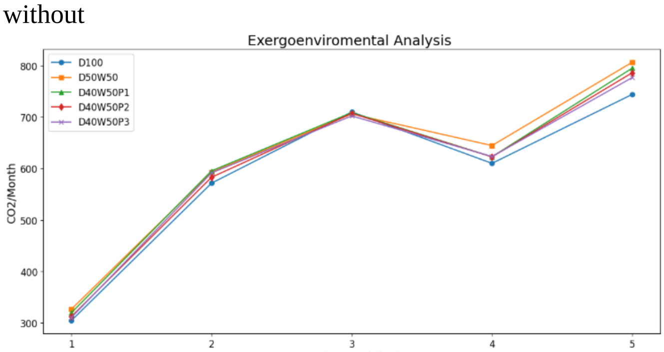

Figure 18. Cost of environmental impact according to Enviroeconomic analysis.

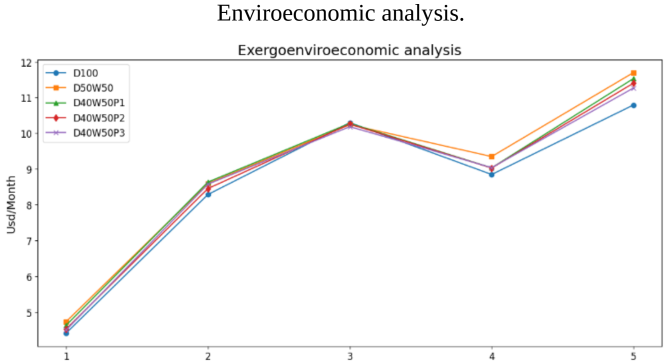

Figure 19. Cost of environmental impact according to exergoenviro-economic analysis.

5. Conclusion

The discovery of alternative fuels not only addresses energy production processes but also emphasizes environmental sustainability and economic benefits. This study examines the effects of different types of fuels, which are critical for evaluating the potential of alternative fuels, on engine performance, emission characteristics, and energy conversion efficiencies. Experimental research was conducted in a compression-ignition diesel engine using biodiesel derived from waste frying oil, diesel, and nanoparticle mixtures at various engine power levels. The analysis includes energy, exergy, exergoenvironmental, and sustainability methodologies based on the collected experimental data. In compression-ignition engines, fac-tors such as chemical reactions and heat transfer contribute to a decrease in engine efficiency by affecting both thermal and exergy efficiencies in thermodynamic analyses. These inefficiencies lead to energy losses from the engine. Increasing engine power and speed raises in-cylinder pressure, which in turn increases heat transfer and exergy losses, resulting in exergy destruction caused by irreversibilities. However, mixing waste frying oil with diesel fuel reduces exergy losses. For example, at 3 kW engine power, exergy losses in the D50W50 fuel mixture dropped from 2.218 kW to 2.068 kW for diesel fuel. While adding biodiesel to diesel fuel decreases exergy efficiency, adding nanoparticle additives to diesel/waste cooking oil mixtures improves exergy performance. For instance, at 4 kW engine power, exergy efficiency increased from 18.20% in the D50W50 mixture to 19.45% with the addition of 150 ppm borax decahydrate. Entropy production, which significantly affects the exergetic performance of the engine, generally increases with rising engine power. In the D40W50P1 mixture, entropy production increased approximately 3.19 times from 0.027 kW/K at 1 kW engine power to 0.086 kW/K at 5 kW. Environmental analyses based on energy and exergy data show that diesel fuel emits the lowest monthly CO_2 emissions of 218.38 kg at 1 kW engine power. In contrast, the highest monthly CO_2 emissions were recorded for the D40W50P1 mixture at 5 kW engine power, amounting to 588.70 kg of CO_2. This study makes a significant contribution to literature by expanding the thermodynamic analyses of using biodiesel and waste cooking oil in diesel engines and revealing the effects of nanoparticle additives on exergy performance. It has been demonstrated that borax decahydrate additives increase exergy efficiency and can optimize the rate of entropy production. These findings highlight the effects of nanoparticle additives not only on engine performance but also on energy conversion efficiency and sustainability. Additionally, the environmental analyses obtained provide assessments from an exergoenvironmental perspective, detailing the impact of different fuel types on carbon emissions. In this regard, the study makes an important contribution to the existing literature on sustainable fuel technologies and the effectiveness of alternative fuels in engineering applications. Future economic analyses regarding the integration of borax decahydrate into diesel engines will be essential for advancing research on alternative fuels and increasing their applicability in practical applications.

Conflict of Interest Statement

In the article, authors declare that there is no conflict of interest.

CRediT Author Statement

Salih Özer: Conceptualization, Methodology, Validation, Supervision,
Ahmet Aslan: Writing-original draft, Validation, Formal analysis
Battal Doğan: Data curation, Formal analysis
Erdal Tuncer: Writing-original draft, Formal analysis
Ömer Arslan: Writing-original draft, Validation, Formal analysis

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