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Energy, exergy, greenhouse gas emission impact and economic analysis of a water-cooled diesel engine running on different proportions of waste cooking oil biodiesel

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ABSTRACT

The use of petroleum-based fuels in diesel engines results in the release of significant amounts of toxic substances into the environment. Moreover, the increasing number of vehicles with internal combustion engines (ICEs) continues to raise the demand for diesel fuels, leading to a sharp rise in fuel prices. Therefore, the use of clean, inexpensive, and renewable alternative fuels in diesel engines has become increasingly important. Biodiesel derived from waste cooking oils is one such alternative—it is biodegradable, clean, cost-effective, and highly suitable for diesel engines. In this study, the energy, exergy, greenhouse gas (GHG) emission, and economic impacts of a diesel engine fuelled with waste cooking oil biodiesel (WCOB) were analysed under different load conditions. The experiments were conducted at a constant engine speed under varying load conditions ranging from 10 Nm to 50 Nm, with 10 Nm increments. The fuel blend ratios used in the study are as follows: 100% diesel; 90% diesel + 10% WCOB; 80% diesel + 20% WCOB; 50% diesel + 50% WCOB; and 100% WCOB. The results were compared with those of conventional diesel fuel. The findings indicate that increasing the biodiesel proportion reduces exergy efficiency and increases exergy destruction. Operating the diesel engine with 100% WCOB increases the lost energy and exhaust energy ratio by an average of 4.3% and 2.2%, respectively, while reducing the energy efficiency by an average of 3%. In addition, the exergy efficiency decreases by 3.6%, whereas the exergy destruction increases by 4.8%. Additionally, it led to a higher GHG emission impact and economic cost due to increased CO_2 emissions.

Keywords: Biodiesel blend ratio, energy, exergy, greenhouse gas emission, waste cooking oil.

1. Introduction

Petroleum and petroleum-derived fuels meet a large portion of today's energy needs and are called primary energy sources. Although developed countries have made significant investments in renewable energy sources, the use of fossil fuels is increasing in countries with a population of over one million, such as India and China, and this situation leads to the depletion of petroleum-derived fuels [1]. The

increasing demand for petroleum and petroleum-derived fuels both causes the depletion of these products and contributes to the increase in their prices [2]. On the other hand, diesel engines are frequently preferred especially in important sectors such as transportation, agriculture, and electricity generation [3]. However, the frequent use of these engines causes significant amounts of GHG emissions to be released into the environment [4]. These gases create the global threat of climate change [5]. Therefore, the use of clean, biodegradable, sustainable, and low-cost alternative fuels in diesel engines can lead to a more sustainable situation in terms of both cost and environmental impact [6]. In fact, it can be said that various alternative fuels have attracted significant attention in recent years in order to reduce the emissions emitted from ICEs and their environmental impact [7]. Because petroleum-derived fuels cause irreversible environmental and health problems, researchers and scientists are directed to new, clean, sustainable fuels. Biodiesel is a very suitable alternative fuel for diesel engines. It is possible to find various studies showing that biodiesel improves oxygen content, combustion efficiency and reduces emissions [8].

In recent years, many studies have been carried out on the use of biodiesels produced from various products in diesel engines. Tiwari et al. [9] studied the variation in energy and exergy of biodiesel usage from 0% to 100% volumetrically for different loads. It was emphasized that exergy efficiency decreases and engine cooling loss increases with the increase in biodiesel ratio. It was also reported that exhaust energy loss decreases with the increase in biodiesel ratio in the mixture. In his study conducted in 2019, Özcan [10] examined the energy and exergy analysis of the addition of 50 ppm and 100 ppm AL_2O_3 nanoadditives to diesel fuel containing 5% biodiesel by volume. In the experiments carried out at four different loads from 25% to 100%, it was reported that BSFC increased and BTE decreased with the addition of 5% biodiesel. However, it was reported that BTE increased by approximately 8% and exergy efficiency increased by approximately 7% with Al_2O_3 nanoadditive, and engine irreversibility

decreased by approximately 7.5%. In another study conducted in 2017, Hoseinpour et al. [11] investigated the energy and exergy balance of a mixture containing 20% biodiesel in diesel by volume under gasoline fumigation. The authors reported that energy and exergy efficiencies decreased as a result of gasoline fumigation in the engine operated with the mixture added with biodiesel, but increased by about 5% when used with diesel alone. In another study, Kul and Kahraman[12] investigated the addition of 5% bioethanol to diesel-biodiesel fuel in terms of energy and exergy. The study was carried out between 1000 and 3000 rpm, while the biodiesel ratio in diesel varied between 3% and 20%. The results showed that the exergetic performance decreased compared to the reference diesel fuel with the increase in the biodiesel ratio and bioethanol addition. Khoobbakht et al.[13] focused on the effect of biodiesel and ethanol levels in diesel on energy and exergy for different load and speed conditions. The authors reported that exergy efficiency decreased and exergy destruction increased with the increase in biodiesel and ethanol content in diesel. Canakci and Hosoz[14] reported in their study that the energy and exergy results of different biodiesel fuels are very close to pure diesel fuel. Panigrahi et al.[15] conducted thermodynamic studies of diesel and blended fuels containing 20% simarouba Biodiesel. The results showed that biodiesel blend fuel energy increased slightly compared to diesel fuel. However, when exergy efficiencies were examined, it was reported that biodiesel blend had higher efficiency. Kavitha et al.[16] observed the energy and exergy performance changes by adding 0.5%, 1.25% and 2.5% ethanol to blends containing 1.5%, 3.5% and 7.5% Jatropha curcas oil by volume in diesel, respectively. The results showed that the addition of Jatropha curcas oil and ethanol increased the exhaust energy but reduced the unaccounted losses when compared to the reference fuel (diesel). Odibi et al.[17] conducted a study on the energy and exergy effects of triacetin addition to waste cooking oil biodiesel(WCOB) in a turbocharged common rail engine. The authors emphasized that the use of 100% biodiesel can increase

energy efficiency by 6% and exergy efficiency by 10% compared to the reference fuel (diesel). It was also reported that the use of oxygenated fuel contributes to the reduction of exhaust losses. Karthikeyan and Jayaprabakar[18] performed the performance analysis of rice bran biodiesel in diesel fuel from 0% to 30% through energy and exergy. The results showed that the use of rice bran biodiesel reduced the exhaust energy loss and cooling losses compared to the reference fuel but increased the exergy destruction at certain loads. In another study, Meisami and Ajam[19] investigated the energy and exergy performance of biodiesel produced from castor oil in diesel engines. The authors reported that the use of biodiesel as an additive to diesel improves combustion efficiency due to its oxygen content, but reduces energy efficiency due to its low energy density. The authors also stated that 15% biodiesel ratio is the optimum operating ratio, but 5% biodiesel ratio is more economically viable. Gülcan et al.[20] analyzed the exergy and economic effects of different types and proportions of nanoadditives in a diesel engine running on rapeseed oil biodiesel. The results reported that with the rise in nanoadditive content in biodiesel, exergetic performance improved, exergy destruction decreased and environmental-economical aspects improved. In their study, Şanlı and Uludamar[21] investigated the effects of using hazelnut oil biodiesel and canola oil biodiesel in a diesel engine on energy and exergy performance. The authors reported that effective power and exergy efficiency decreased with the use of biodiesel compared to the reference fuel. Madheshiya and Vedrtnam [22] conducted energy and exergy analyses of biodiesels produced from mustard oil and waste cooking oil. The volumetric ratios of biodiesel in diesel ranged from 10% to 30%. Additionally, the tests were carried out under varying loads and engine speeds. The results showed that the addition of biodiesel led to an increase in BSFC, while soot emissions in the exhaust decreased. Overall, the exergy performance of diesel and diesel–biodiesel blends followed similar trends. In his study, Panigrahi [23] performed energy and exergy analyses of blends of polenga oil methyl ester and diesel fuel. The volumetric ratio of polenga oil methyl ester in the diesel fuel was 20%. It was observed that the use of biodiesel in diesel fuel increased the heat transfer rate but reduced the exhaust energy by approximately 13%. Additionally, it was found that using 20% biodiesel reduced exergy destruction by about 3%.

The above study summaries indicate that most of the research conducted on biodiesel has primarily focused on energy and exergy aspects, while there are relatively few studies that examine its environmental and economic dimensions. Investigating the environmental impact of using different proportions of biodiesel, as well as pure biodiesel (100%), is of great importance. Additionally, in this study, biodiesel produced from waste cooking oil (WCO) was preferred as an alternative fuel. The main reason for this choice is that WCOB offers both environmental and economic advantages. Waste cooking oils are abundantly discarded into the environment from households, restaurants, and the food industry. If improperly disposed of, they can cause significant water and environmental pollution. However, due to the low collection cost and widespread availability of this feedstock, converting waste cooking oil into biodiesel can enhance sustainability from both environmental and economic perspectives. For these reasons, biodiesel derived from waste cooking oil was selected in this study. The aim of this study is to evaluate the energy and exergy performance of various biodiesel blends and pure biodiesel, while also assessing their greenhouse gas emission impacts and economic aspects. The experiments were conducted under varying loads (from 10 Nm to 50 Nm with 10 Nm increments) at a constant engine speed.

2. Materials and Method
2.1. Materials

The experiments were carried out on a single-cylinder, direct injection (mechanical) diesel engine mounted on an AC electric dynamometer. The visual of the experimental setup is given in Fig. 1. In addition, the characteristics of the single-cylinder diesel engine are presented in Table 1.

Fig. 1. The visual of the test and engine setup

Table 1. The characteristics of the Erin Motor brand diesel engine

Characteristics	Erin Motor brand diesel engine
Engine type	Four stroke, single cylinder
Cooling type	Water-cooled
Cylinder volume	1160 cm^3
Bore diameter	10.8 cm
Stroke diameter	12.7 cm
Compression ratio	14.6:1
Peak engine power @rpm	18 kW @ 2400 rpm
Peak engine torque @rpm	80 Nm @ 1800 rpm

The biodiesel fuel utilized in the experimental studies was supplied by TBE Biodiesel Agricultural Energy Production Industry and Trade Inc., a company actively engaged in commercial operations within Kocaeli province. The diesel fuel used as the reference fuel in the comparative analyses was procured from the Kırıkkale branch of a reputable corporate fuel company operating nationwide across Türkiye. In the experimental studies, five different test fuels, namely 100% diesel (WCOB0), 10% biodiesel (WCOB10), 20% biodiesel (WCOB20), 50% biodiesel (WCOB50) and 100% biodiesel (WCOB100), were meticulously prepared and used in order to comprehensively analyze the engine performance, fuel efficiency and emission parameters. These different fuel blends were selected to systematically investigate the engine's varying operational characteristics and environmental impacts as a function of the biodiesel content.

In this study, experimental tests were conducted at a constant engine speed of 1500 rpm to investigate the engine's performance and emission characteristics under varying load conditions. Within this context, the engine was tested at five distinct torque levels (10 Nm, 20 Nm, 30 Nm, 40 Nm, and 50 Nm) to comprehensively evaluate its performance and emission characteristics under varying load conditions. The selected torque levels were chosen to evaluate the engine's behavior across a range of load conditions, from low to high, enabling a systematic comparison of its performance and emission responses. In this context, the control of the 22 kW AC-type dynamometer was managed using an ABB-brand electronic drive system. Engine speed measurements were conducted using an Autonics brand E50S8-360-3-T-1 model encoder, which was mounted on the rear section of the dynamometer shaft. This encoder is capable of accurately measuring rotational speeds within the range of 0 to 5000 rpm. A Baykon brand BT610 model load cell with a capacity of 500 kg was employed to measure the mechanical loads generated by the dynamometer. Additionally, K-type and PT-100 thermocouples were strategically installed at the intake air inlet, cooling water inlet, and outlet, as well as the exhaust outlet of the internal combustion test engine to enable accurate temperature measurements. During the experimental studies on the engine test systems, a Data Acquisition System (DAQ) was employed to accurately and reliably record real-time data from the sensors within a computer environment. In the experimental studies, MoTest software, developed by Tuzeks company, was utilized for real-time monitoring, precise recording, and comprehensive analysis of measurement data. The software facilitated seamless data acquisition from various sensors, enabling detailed performance evaluation and ensuring efficient management of the experimental process. This software operates in full integration with the engine test system, enabling instantaneous display of sensor data and providing precise control over test parameters, thereby facilitating efficient and accurate experimental management.

To ensure the experimental studies were conducted under optimal conditions, a specially designed cooling system was developed to maintain the test engine's operating temperature at a constant and stable level. This system comprises a specialized radiator, an electric fan, a water tank, a water circulation pump, a flow meter, and PT-100 type thermocouples, all working together to

effectively monitor and regulate the cooling process. By placing these components at the cooling water inlet and outlet points, the system's thermal behavior could be accurately observed, enabling precise measurement of temperature and flow rates throughout the cooling circuit.

Fuel consumption during the tests was determined using the volumetric method to ensure precise measurement of the fuel utilized. In the experimental studies, for each engine load condition, the time required for the internal combustion engine to consume a fixed volume of 80 cc fuel was meticulously measured using a specially designed fuel metering system. This method provided accurate and consistent quantification of fuel consumption across varying operating conditions. These time measurements were performed using a high-precision Onstart 500 model chronometer to ensure accurate and reliable recording of fuel consumption durations. Each measurement was repeated three times per engine load level, and the final results used in the analysis were derived by averaging the collected data to maintain accuracy and reliability.

During the experimental tests, a BİLSA MOD2210 model exhaust gas analyzer was employed to measure pollutant gases emitted into the atmosphere from the internal combustion engine. Prior to the measurements, software and calibration updates were performed remotely by the manufacturer via internet connection to ensure the device provided accurate and reliable data throughout the testing process. In addition, prior to the start of the tests, the gas filters within the device were replaced with new ones to enhance measurement sensitivity and ensure the accuracy of the emission readings. The MOD2210 model exhaust gas analyzer is capable of measuring carbon monoxide (CO), carbon dioxide (CO_2), and oxygen (O_2) concentrations in the exhaust gas as percentages (%), while hydrocarbons (HC) and nitrogen oxides (NO_x) levels are measured in parts per million (ppm).

The measurement devices used during the experiments and their accuracies are presented in Table 2. In addition, the uncertainty analysis of the measurement parameters is also given in Table 2.

2.2. Method

Before the experiments, the reference fuel was supplied from a local petrol station and the WCOB was supplied from a local biodiesel production facility. Then, five different fuel mixtures were prepared before the experiments. After the fuel mixture was prepared, the engine was operated without load until it reached stable operating temperature and stability before the experiments began. Then, five different load and constant speed experiments were carried out with the reference fuel, diesel fuel. Following this, experiments were carried out with the mixture containing 10% biodiesel by volume. Then, experiments were carried out with fuels containing 20%, 50% and 100% biodiesel. The test matrix and biodiesel proportion ratios are given in Table 3 below.

Table 2. Accuracy of measuring devices and uncertainty analysis of measurement parameters.

Measured parameter	Device	Sensibility
Engine torque	AC dynamometer	±0.01 Nm
Engine speed	Digital tachometer	±1 rpm
Temperature	K type thermocouple	± 0.1 °C
Fuel consumption	Volumetric fuel flow meter	±1 ml
CO	Bilsa MOD2210	±0.001%
HC	Bilsa MOD2210	±1 ppm
CO_2	Bilsa MOD2210	±0.001%
O_2	Bilsa MOD2210	±0.01%
NO_x	Bilsa MOD2210	±1 ppm
Uncertainty analysis of measurement parameters		
Brake power (kW)	%1.16	
Brake torque (Nm)	%1.24	

Table 3. The test matrix and biodiesel proportion ratios.

No	Operating speed, rpm	Operating loads, Nm	Diesel, vol. %	WCOB, vol. %
1	1500	10, 20, 30, 40 and 50	100	0
2	1500	10, 20, 30, 40 and 50	90	10
3	1500	10, 20, 30, 40 and 50	80	20
4	1500	10, 20, 30, 40 and 50	50	50
5	1500	10, 20, 30, 40 and 50	0	100

3. Theoretical Process
3.1. First law analysis

In diesel engines, the energy input to the system is provided by the fuel, then this fuel energy is converted into different forms as useful and lost during combustion [24]. In general, fuel energy($\dot{Q}_{in}$) consists of useful work (shaft work)(P_{shaft}), energy transferred from exhaust gases($\dot{Q}_{exhaust}$), cooling water and lost energy transferred from unaccountable situations($\dot{Q}_{lost}$) [25]. The energy balance of the system is presented in Eq. (1).

$$\dot{Q}_{in} = P_{shaft} + \dot{Q}_{exhaust} + \dot{Q}_{lost} \tag{1}$$

Eq. (2)[20] is used to determine the energy input($\dot{Q}_{in}$) to the system . Here H_u represents the energy density in kJ.kg^{-1}, while $\dot{m}_{fuel}$ represents the fuel consumption in kg.s^{-1} [26].

$$\dot{Q}_{in} = \dot{m}_{fuel}H_u \tag{2}$$

To determine the shaft work(P_{shaft}) of the diesel engine, the shaft speed(n) and torque(T) are used as in Eq. (3)[27].

$$P_{shaft} = (n \; x \; T)9549^{-1} \tag{3}$$

The exhaust energy transferred by pollutant gases($\dot{Q}_{exhaust}$) can be calculated with Eq. (4)[28]. Here $\dot{m}_{exh}$ represents the flow rates for pollutant gases, while Δh_{exh} represents the enthalpy difference between pollutant gas and ambient temperatures.

$$\dot{Q}_{exhaust} = \sum_{i=1}^{n} \dot{m}_{exh} x \Delta h_{exh} \tag{4}$$

After determining the $\dot{Q}_{in}$, P_{shaft}, and $\dot{Q}_{exhaust}$, the energy transferred from the cooling water and unaccounted losses($\dot{Q}_{lost}$) is calculated with Eq. (5) [28].

$$\dot{Q}_{lost} = \dot{Q}_{in} - \left(P_{shaft} + \dot{Q}_{exhaust} \right) \tag{5}$$

After the energy input and output to the system, the first law efficiency of the system can be calculated with Eq. (6) [29].

$$\psi_I = \frac{P_{shaft}}{\dot{Q}_{in}} \tag{6}$$

3.2. Second law analysis

Exergy analysis expresses the way in which energy reveals its potential to do work, and this is known as availability [30]. The availability input ($\dot{A}_{in}$) of the system consists of shaft work or shaft availability($P_{shaft} = A_{shaft}$), availability transferred from pollutant gases($\dot{A}_{exhaust}$), availability transferred from cooling water($\dot{A}_{cooling}$) and exergy destroyed($\dot{A}_{destruction}$). Eq. (7) [31] shows the exergy balance for a diesel engine.

$$\dot{A}_{in} = A_{shaft} + \dot{A}_{exhaust} + \dot{A}_{cooling} + \dot{A}_{destruction} \tag{7}$$

In a diesel engine, the available input is directly proportional to the specific chemical exergy, fuel consumption and energy density. The specific chemical exergy for diesel fuel is calculated by Eq. (9)[32]. Here, the chemical composition of the diesel fuel in terms of carbon (C) and hydrogen (H) is taken into account.

$$\dot{A}_{in} = \dot{m}_{fuel}H_u\varepsilon^{ch} \tag{8}$$

$$\varepsilon^{ch} = 1.0401 + 0.1728\left(\frac{H}{C}\right) + 0.0432\left(\frac{O}{C}\right) \tag{9}$$

The availability associated with pollutant gases($\dot{A}_{exhaust}$) is a function of the physical exergy that constitutes the difference in molar enthalpy($\bar{h}_i - \bar{h}_{i,0}$) and molar entropy($\bar{s}_i - \bar{s}_{i,0}$), the chemical exergy that constitutes the composition of pollutant gases and the molar ratio of pollutants. Equation (10) gives the availability associated with pollutant gases[26].

$$\dot{A}_{exhaust} = \sum_{k=1}^{n} \dot{m}_i[(\bar{h}_k - \bar{h}_{k,0}) - T_a(\bar{s}_k - \bar{s}_{k,0})^{ph} + (\bar{R}T_a ln\frac{t_{env,k}}{t_{exh,k}})^{ch}] \tag{10}$$

The availability associated with cooling loss in a water-cooled diesel engine can be calculated

by Eq. (11). T_{cw} refers to the average temperature of water entering and leaving the cooling system[33].

$$\dot{A}_{cooling} = \dot{Q}_{lost} \left[1 - \frac{T_a}{T_{cw}} \right] \tag{11}$$

Eq. (12) is used to calculate the second law efficiency of the system[34, 35].

$$\psi_{II} = \frac{P_{shaft}}{\dot{A}_{in}} \tag{12}$$

3.3. Greenhouse gas impact analysis

A greenhouse gas (GHG) emission impact analysis is performed to determine the total environmental impact and environmental-economic impact of CO_2 emissions generated as a result of the use of biodiesel in a water-cooled diesel engine. Eq. (13) gives the greenhouse gas emissions that will be released into the environment as a result of the water-cooled diesel engine operating for eight (8) hours a day during the week for one year [36, 37].

$$GHG_{CO2} = \dot{m}_{CO2} \ P_{shaft} \ t_{op} \tag{13}$$

Eq. (14) shows the damage cost due to CO_2 emitted to the environment as a result of the operation of a water-cooled engine for 1 year [38]. Here, the carbon price is taken as the average of the last year, 70 € [39].

$$GHG_{economic} = ec_{CO2} GHG_{CO2} \tag{14}$$

4. Analysis Results and Discussion
4.1. Energy analysis

Fig. 2 presents the energy distribution (fuel, effective power, exhaust, and losses) of the test fuels at different loads. When examining the fuel energies required to provide the current power, the lowest values are recorded at 10 Nm, while the highest values are observed at 50 Nm. At 10 Nm, the addition of WCOB to diesel fuel and the use of 100% WCOB increase the fuel energy. For example, compared to WCOB0 at 10 Nm, the fuel energies of WCOB10, WCOB20, WCOB50, and WCOB100 increase by approximately 5%, 4.8%, 2.4%, and 4.6%, respectively. This is likely due to the delayed molecular breakdown of biodiesel with high carbon chain and viscosity under low temperature conditions. In general, within the specified load range, WCOB10 and WCOB20 fuels do not show

significant variation compared to WCOB0, and the average change remains below 1%. However, when the volumetric ratio of WCOB increases to 50% and 100%, the change in fuel energy increases by approximately 1.2% and 3.2%, respectively. This is probably due to the decrease in the calorific value of the mixture as the WCOB content in diesel increases. Furthermore, the high viscosity and density of WCOB negatively affect the ionization process of the fuel, leading to increased fuel consumption.

The experimental study is carried out at constant speed (1500 rpm) and five different loads (10, 20, 30, 40 and 50 Nm). In the experiments carried out under the same conditions for all fuels, the effective power recorded at the specified loads for all fuels are 1.57 kW, 3.14 kW, 4.71 kW, 6.28 kW and 7.85 kW, respectively.

When examining the exhaust energy variation, a significant exhaust energy loss is observed at 10 Nm, while WCOB10 appears to reduce exhaust energy losses at higher loads. For instance, at 10 Nm, compared to WCOB0, the exhaust energy losses of WCOB10, WCOB20, WCOB50, and WCOB100 increase by approximately 1.8%, 0.5%, 5%, and 4.2%, respectively. At low loads, the low combustion temperatures cause the WCOB fuel—with its high carbon chain and density—to ionize later. Additionally, the low calorific value of WCOB reduces the overall calorific value of the blend, leading to a further decrease in combustion temperatures. These factors cause the main combustion phase to shift toward the expansion stroke at low loads, resulting in significantly increased exhaust gas temperatures. Consequently, exhaust energy losses increase. Overall, among the given load conditions, WCOB10 reduces exhaust energy loss by approximately 1.7% on average compared to WCOB0, while WCOB20, WCOB50, and WCOB100 increase it by about 0.7%, 2.5%, and 2.2%, respectively. The improved combustion performance of WCOB10 at high combustion temperatures may be attributed to the high cetane number of WCOB.

Loss energy constitutes the highest share among all energy losses. An increase in the biodiesel blending ratio within diesel fuel and

the operation of the diesel engine with 100% biodiesel lead to an increase in loss energy. In general, the lowest loss energy is recorded at 10 Nm, where the loss energies for WCOB0, WCOB10, WCOB20, WCOB50, and WCOB100 are 7.76 kW, 8.24 kW, 8.23 kW, 7.96 kW, and 8.18 kW, respectively. Compared to WCOB0, the increases in loss energy for WCOB10, WCOB20, WCOB50, and WCOB100 are approximately 6.3%, 6.2%, 2.7%, and 5.5%, respectively. The highest

increase in loss energy throughout the study occurs at 10 Nm. Although the loss energy values slightly decrease with increasing load, the increase in loss energy continues for fuels containing 50% and 100% WCOB. Overall, compared to WCOB0, the WCOB10, WCOB20, WCOB50, and WCOB100 fuels increase the average loss energy by approximately 1.2%, 0.8%, 1.7%, and 4.3%, respectively, within the specified load range.
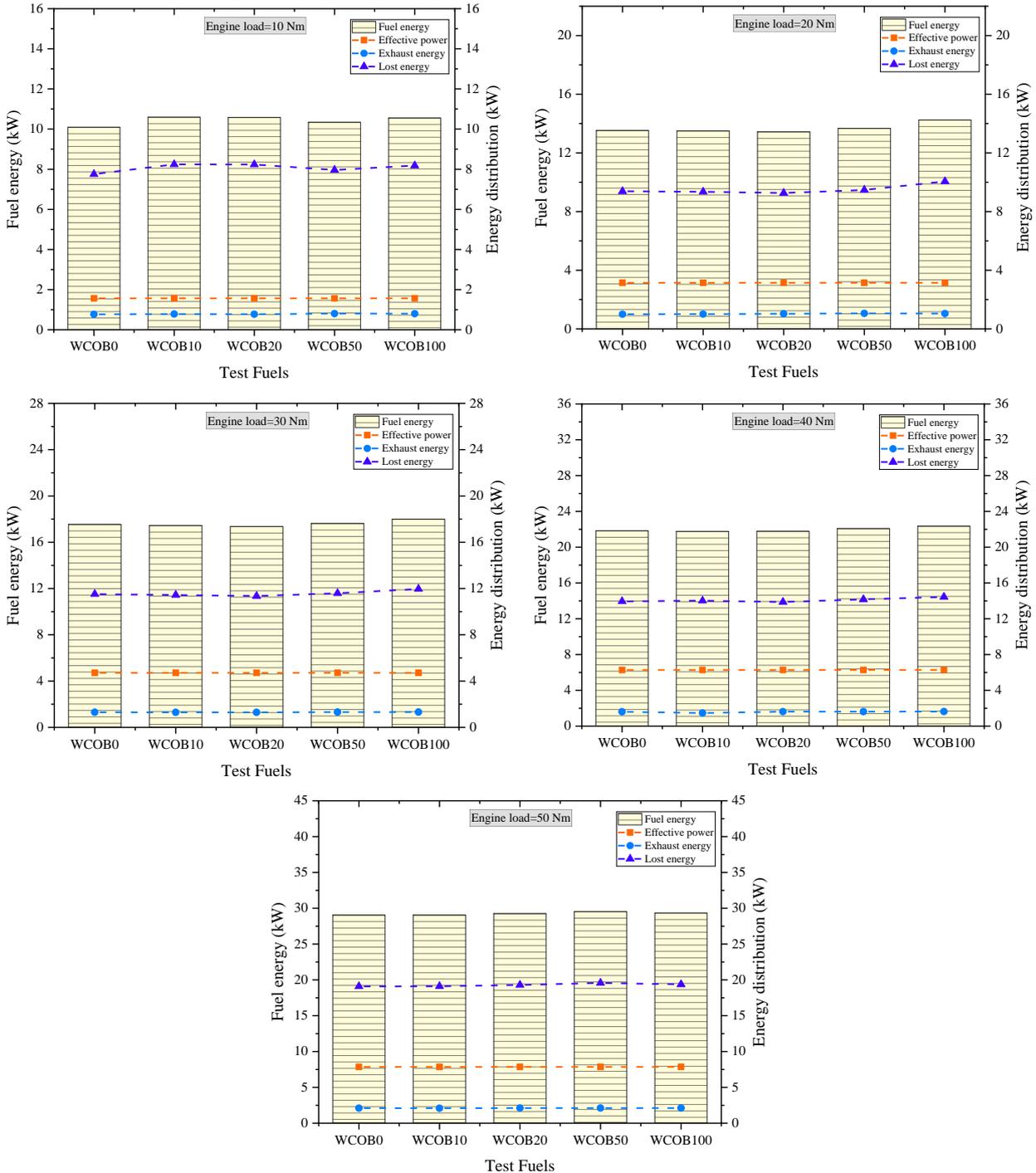

Fig. 2. Variation of the energy distribution (fuel, effective power, exhaust, and losses) of the test fuels at different loads

Figure 3 shows the energy efficiency of diesel,   WCOB, and diesel-WCOB blended fuels at

different loads. The highest energy efficiency is recorded at 50 Nm with WCOB0 and WCOB10 fuels, both achieving an energy efficiency of 27.04%. The fact that WCOB10 exhibits maximum energy efficiency similar to WCOB0 is attributed to its relatively better performance in some aspects of exhaust and loss energy compared to WCOB0.
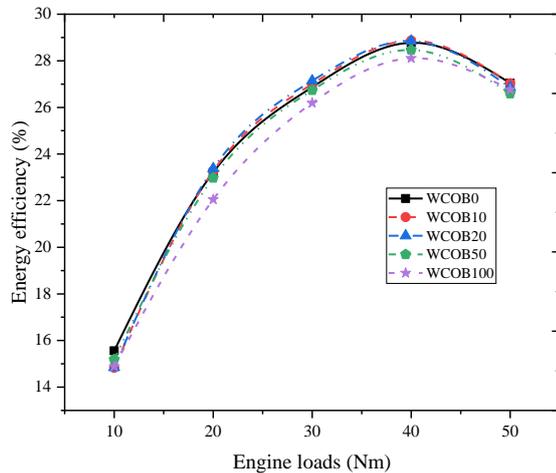

Fig. 3. Variation of the energy efficiency of the diesel and WCOB mixtures at different loads

Additionally, the oxygen content of WCOB10 contributes to the development of combustion, thereby improving combustion efficiency. This is one of the factors that enhances thermal efficiency. However, the gradual increase WCOB content in diesel reduces the energy density of the fuel and increases the viscosity and density of the blend. The higher carbon chain of WCOB100 compared to WCOB0 is also one of the main factors negatively affecting the combustion performance of the fuel. All these factors lead to a decrease in energy efficiency. Nevertheless, the drop in energy efficiency from 0% to 100% biodiesel in a water-cooled engine remains below 5%. In fact, the reductions in energy efficiency for 10% and 20% biodiesel fuels are less than 1% within the specified load range. Overall, in a water-cooled engine operating between 10 Nm and 50 Nm, the energy efficiencies of WCOB10, WCOB20, WCOB50, and WCOB100 fuels decrease by an average of approximately 0.7%, 0.7%, 1.3%, and 3%, respectively, compared to WCOB0. Similarly, Pullagura et al. [40] reported that addition of Pongamia pinnata oil to diesel fuel decreased the exergetic performance and reduced energy efficiency.

4.2. Exergy analysis

Fig. 4 presents the exergy distribution (fuel, heat, exhaust, and destruction) of the test fuels at different loads. The addition of 10% and 20% WCOB to diesel fuel reduces fuel exergy at medium loads, whereas the opposite trend is observed at low (10 Nm) and full loads (50 Nm). The use of 50% and 100% WCOB, on the other hand, significantly increases fuel exergy. This is likely due to WCOB's high carbon and hydrogen content, long carbon chains, and high viscosity. The higher carbon and hydrogen content of WCOB compared to diesel leads to an increase in the chemical exergy factor, resulting in higher fuel exergy. The highest increase in fuel exergy is recorded at 10 Nm, where compared to WCOB0, the fuel exergy of WCOB10, WCOB20, WCOB50, and WCOB100 increases by approximately 5%, 5%, 2.8%, and 5.1%, respectively. Higher fuel consumption at 10 Nm also contributes to WCOB demonstrating a higher fuel exergy characteristic. Overall, within the specified load range, the fuel exergy of WCOB10 and WCOB20 shows no significant increase compared to WCOB0, with values remaining below 1% (0.9%). However, WCOB50 and WCOB100 show average increases in fuel exergy of approximately 1.7% and 3.2%, respectively, compared to WCOB0.

For all fuels, the lowest exhaust exergy losses are recorded at 10 Nm, with exhaust exergy losses of WCOB0, WCOB10, WCOB20, WCOB50, and WCOB100 measured as 0.78 kW, 0.79 kW, 0.78 kW, 0.79 kW, and 0.80 kW, respectively. This is likely due to the shorter combustion duration resulting from lower fuel supply required to produce the available power at low loads. As the load increases from 10 Nm to 50 Nm, the highest exhaust exergy losses are recorded. For example, at 50 Nm, the exhaust exergy losses for WCOB0, WCOB10, WCOB20, WCOB50, and WCOB100 are 1.58 kW, 1.57 kW, 1.59 kW, 1.59 kW, and 1.60 kW, respectively. Overall, WCOB20 reduces the average exhaust exergy loss by about 0.3% within the given load range, while WCOB10, WCOB50, and WCOB100 increase the exhaust exergy loss by approximately 1.5%, 0.6%, and 2.2%, respectively.

In heat transfer resulting from engine coolant, the coolant temperature plays a significant role. In this study, the highest heat transfer is observed in the B50 and B100 fuel operations. The main reason for this is the considerable increase in fuel consumption and the extended combustion duration. This prolongs the heat transfer period to the coolant, thereby resulting in greater heat losses. The lowest heat transfer occurs at 10 Nm, likely due to shorter combustion duration and lower combustion temperatures. For instance, at 10 Nm, the heat transfer rates of WCOB0, WCOB10, WCOB20, WCOB50, and WCOB100 fuels are

0.24 kW, 0.23 kW, 0.46 kW, 0.36 kW, and 0.35 kW, respectively. At 50 Nm, where the maximum heat transfer occurs, the heat transfer rates for WCOB0, WCOB10, WCOB20, WCOB50, and WCOB100 fuels are 1.82 kW, 1.77 kW, 1.99 kW, 2.09 kW, and 1.72 kW, respectively. Overall, WCOB10 reduces heat transfer by an average of approximately 1.8% across the specified load range. This could be attributed to WCOB10 slightly improving the cetane number of the blend, thereby shortening the combustion duration.
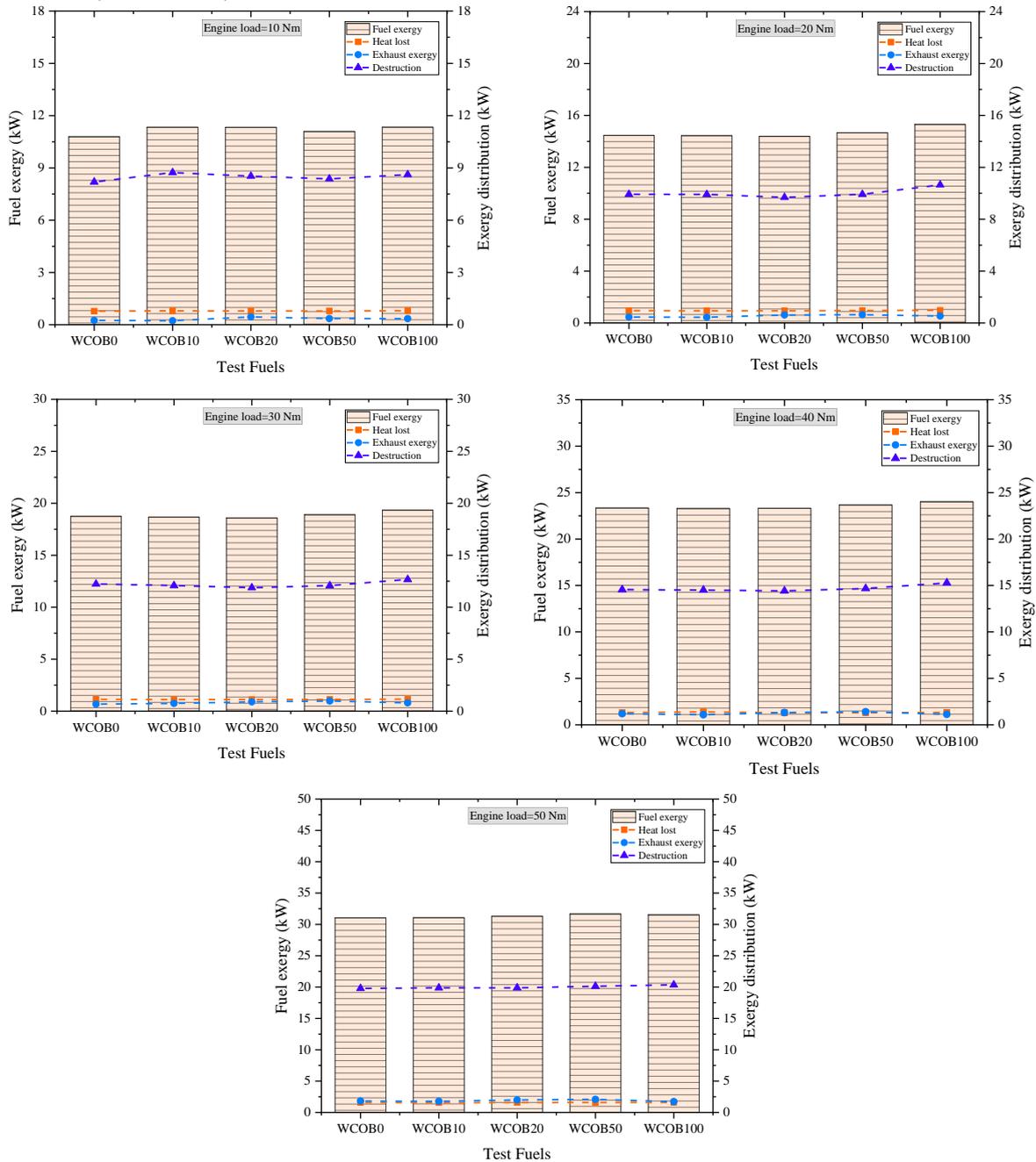

Fig. 4. Variation of the exergy distribution (fuel, effective power, exhaust, and losses) of the test fuels at different loads

Exergy destruction constitutes the highest portion of exergy loss in the exergy balance.

The lowest exergy destruction is recorded at 10 Nm. For instance, the exergy destructions of WCOB0, WCOB10, WCOB20, WCOB50, and WCOB100 fuels are 8.19 kW, 8.73 kW, 8.52 kW, 8.37 kW, and 8.61 kW, respectively.

Lower fuel consumption and reduced heat transfer losses at low loads result in lower exergy destruction compared to higher loads. The highest exergy destruction is observed at 50 Nm. For example, at this load, the exergy destructions for WCOB0, WCOB10, WCOB20, WCOB50, and WCOB100 fuels are 19.79 kW, 19.87 kW, 19.87 kW, 20.13 kW, and 20.35 kW, respectively. The increase in load from 10 Nm to 50 Nm leads to greater fuel injection into the combustion chamber and more complex chemical reactions. Furthermore, the increase in combustion products affects the fresh charge in the next cycle, enhancing irreversibilities and thus increasing exergy destruction. In general, among the specified loads, the highest exergy destruction is recorded with WCOB100 fuel, showing an average increase of approximately 4.8% compared to WCOB0. High biodiesel content reduces combustion stability due to its physicochemical properties and results in increased fuel consumption. Moreover, the higher carbon and hydrogen content in its chemical structure prolongs and complicates the combustion process, further increasing irreversibility. Additionally, increased fuel injection and longer combustion durations lead to more residual gases, which affect the fresh charge in the following cycle. This raises irreversibility and subsequently increases exergy destruction. On the other hand, WCOB20 fuel shows a slight reduction in exergy destruction of about 0.4% compared to WCOB0 across the given load range. In their study, Bayramoğlu et al. [41] investigated the energy and exergy aspects of hydrogen enrichment in biodiesel–diesel blends and showed that using 20% biodiesel increased exergy destruction.

Fig. 5 presents the exergy efficiency of the diesel, WCOB, and diesel-WCOB blends at different loads. With the increase of engine load from 10 Nm to 40 Nm, the maximum exergy efficiency is achieved, whereas further increasing the load from 40 Nm to 50 Nm

results in a declining trend in exergy efficiency. At low loads, higher combustion instability and lower combustion temperatures contribute to reduced exergy efficiency. With increasing load, the elevated combustion temperatures improve combustion efficiency and enhance combustion stability.
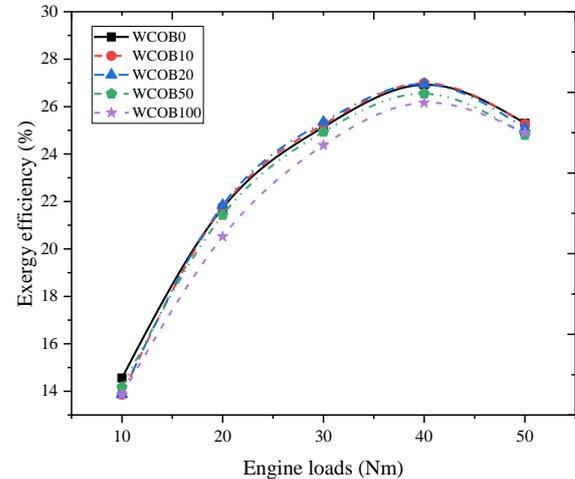

Fig. 5. Variation of the exergy efficiency of the diesel and WCOB mixtures at different loads

Additionally, the exhaust gases formed due to the higher load preheat the fresh charge, increasing end-of-compression temperatures. This raises the peak combustion temperatures, thereby improving combustion efficiency. As a result, the same power output is achieved with less fuel, leading to higher exergy efficiency. At 50 Nm, however, greater fuel injection leads to the formation of richer mixture zones. This reduces combustion stability and decreases combustion efficiency. Consequently, fuel consumption increases, and exergy efficiency starts to decline. The highest exergy efficiency is recorded at 40 Nm with WCOB10 fuel at 26.99%. The exergy efficiencies of WCOB0, WCOB20, WCOB50, and WCOB100 fuels are 26.92%, 26.95%, 26.54%, and 26.16%, respectively. In general, across the specified load range, the exergy efficiencies of WCOB10 and WCOB20 fuels are very close to those of WCOB0. Compared to WCOB0, the exergy efficiencies of WCOB50 and WCOB100 fuels decrease by an average of approximately 1.6% and 3.6%, respectively. Similarly, Bikkavolu et al. [42] determined that exergy efficiency decreased with the addition of 20% biodiesel into diesel fuel.

4.3. Greenhouse gas impact and economic analysis

Carbon dioxide (CO_2) emissions constitute a major component of GHG emissions, and large amounts of CO_2 are produced as a result of combustion in ICEs. It is therefore highly important to investigate the impact of waste-oil-derived fuels on CO_2 formation in ICEs. Fig. 6 (a) presents the GHG emission impact of the diesel, WCOB, and diesel-WCOB blends at different loads. It has been observed that the use of diesel, WCOB, and diesel–WCOB blends in a water-cooled diesel engine operating for a total of 2,088 hours per year results in approximately 11 tons of GHG emissions. While the GHG emission impact at a 10 Nm engine load remains below 1 ton per year, increasing the engine torque from 10 Nm to 50 Nm elevates the annual GHG impact to around 11 tons. This is likely due to higher fuel consumption and improved combustion efficiency at increased loads, which lead to greater chemical reaction rates. At 10 Nm, WCOB10, WCOB20, and WCOB50 fuels reduce the GHG impact by 1.6%, 1.8%, and 1.5%, respectively, compared to diesel fuel. However, WCOB100 increases the GHG impact by 3.2%. The consistent increase in GHG emissions with WCOB100 across all loads can be attributed to its physicochemical properties. Specifically, its higher carbon-to-hydrogen ratio and longer carbon chains contribute to greater CO_2 formation. Furthermore, the generally higher fuel consumption associated with biodiesel fuels leads to increased CO_2 emissions, thereby elevating the overall GHG impact. Overall, the use of WCOB fuels in a water-cooled diesel engine tends to increase the GHG impact with rising engine load. For instance, compared to WCOB0, the average GHG impacts of WCOB10, WCOB20, WCOB50, and WCOB100 across the evaluated load range increase by approximately 0.3%, 0.4%, 1.2%, and 6.3%, respectively.

Fig. 6 (b) presents the GHG economic impact of the diesel, WCOB, and diesel-WCOB blends at different loads. As a result of operating a water-cooled diesel engine at 10 Nm, the GHG economic impacts of WCOB0, WCOB10, WCOB20, WCOB50, and WCOB100 fuels are calculated as €51.38/year, €50.55/year, €50.45/year, €50.63/year, and €53.03/year, respectively. With an increase in

engine load from 10 Nm to 50 Nm, the GHG economic impact increases significantly. For example, at 50 Nm, the GHG economic impacts for WCOB0, WCOB10, WCOB20, WCOB50, and WCOB100 fuels are €755.53/year, €753.93/year, €743.32/year, €773.12/year, and €788.71/year, respectively. In general, both the GHG impact and its associated economic cost increase with engine load in a water-cooled diesel engine. However, the use of WCOB10 and WCOB20 fuels results in negligible increases and, particularly under low to medium loads, these fuels exhibit relatively lower GHG impacts compared to conventional diesel fuel.
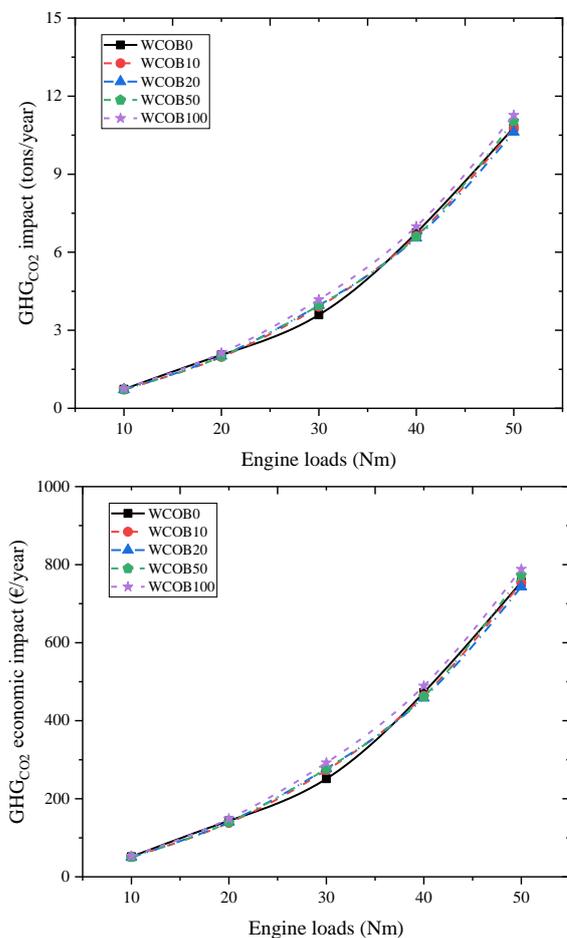

Fig. 6. Variation of the GHG_{CO2} impact and economic impact of the diesel and WCOB mixtures at different loads

4.4. Limitations

The present study includes performance and emission tests of diesel, diesel-WCOB blends, and WCOB fuel in a water-cooled, direct injection diesel engine. Additionally, the findings obtained from these tests were used for energy, exergy, GHG impact, and GHG economic impact analyses. Although the diesel

engine used in the tests is single-cylinder, its large displacement, power, and torque capacity make it somewhat comparable to modern automobile engines in terms of characteristics; however, the absence of key components such as a turbocharger and EGR system is considered a significant disadvantage. Furthermore, since the engine fuel system uses a mechanical injector, it lacks controllable parameters such as injection pressure, timing, and quantity, which are common in modern engines. All these disadvantages limit the applicability of the results and cause a deviation from real-world outcomes.

5. Conclusions

In this study, energy, exergy, GHG emission effect and economic analysis were performed in diesel engine operated with waste cooking oil biodiesel in different proportions. Experiments were carried out under 5 different loads and constant speed, under stable operating conditions of the engine. The main findings of the study are summarized below.

- While the fuel energy of WCOB10 and WCOB20 fuels yielded results very close to the reference diesel fuel, WCOB50 and WCOB100 fuels increased the fuel energy by more than 1.5%.
- At the specified load conditions, WCOB10 reduced exhaust energy losses by an average of 1.7% compared to the reference fuel, whereas increasing the proportion of WCOB in the diesel blend led to higher exhaust energy losses.
- An increase in the proportion of WCOB also significantly raised the energy and exergy losses through heat transfer.
- The most notable increase in exergy destruction was observed with WCOB100 fuel, showing approximately a 5% rise. However, a reduction in WCOB proportion improved exergy destruction levels and overall irreversibilities.
- Compared to the reference fuel, the exergy efficiencies of WCOB10 and WCOB20 decreased by approximately 0.8%, while the use of 100% WCOB resulted in a 3.6% decrease in exergy efficiency.
- The GHG impact of WCOB10 and WCOB20 fuels was negligible. However, due to increased CO_2 emissions from WCOB, the average GHG emission impact rose by approximately 6.3%.
- Overall, the energy, exergy, and GHG impact results of WCOB10 and WCOB20 fuels were found to be quite similar to those of the reference fuel. Therefore, WCOB10 and WCOB20 appear to be viable alternatives in terms of exergetic performance and environmental-economic considerations.
- Increasing the percentage of WCOB usage causes a maximum performance loss of approximately 5–6% within the engine load range of 10–50 Nm. However, using 10% WCOB provides energy and exergy results that are relatively similar to those of conventional diesel combustion.
- In future studies, to assess its economic sustainability, thermoeconomic, exergoeconomic, and techno-economic analyses can be conducted for the use of high WCOB ratios in diesel engines.

CRediT authorship contribution statement

Derviş Erol: Conceptualization, Data curation, Investigation, Methodology, Validation, Visualization, Writing - original draft, Writing - review & editing. **Halil Erdi Gülcan:** Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Validation, Visualization, Writing - original draft, Writing - review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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