Performance, environmental and economic impact study in a Low Displacement Diesel Engine Operating with Biodiesel Mixtures

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Abstract- In the present study, an energetic, exergetic, and economic sustainability investigation of different blends of diesel and tire pyrolytic oil is carried out. For the study, a single-cylinder diesel engine was used, which operates with a load condition of 3, 5, and 7 Nm and a constant rotation speed of 3600 rpm. The studied fuel blends are identified as TPO4D96 and TPO8D92, which were compared with commercial diesel. The results obtained show that the addition of tire pyrolytic oil to diesel causes an average increase of 9% in the energy and exergetic efficiency of the engine. Additionally, the economic parameters allowed defining that the TPO4D96 and TPO8D92 blends have a better economic performance, compared to commercial diesel. The addition of a percentage greater than 4% of tire pyrolytic oil, produces a decrease in the efficiency of the blend. In general, the results allow us to conclude that TPO is considered a suitable additive to improve the capacity of diesel engines without the need for modifications.

Keywords – Diesel, Tire pyrolytic oil, Exergy, Thermoeconomic, Sustainability.

I. Introduction

The economic activities developed worldwide have caused a risk of fossil resource depletion, increased environmental pollution, and high energy demand, which has caused climate change in the world. Among the problems indirectly associated with the increased use of fossil resources, is the accumulation of waste tires, caused by the growth of the vehicle sector. Discarded tires are characterized by high mechanical resistance and need a long time for their degradation. The study by Torreta et al. [1], indicates that it takes more than 100 years to degrade a tire by microorganisms. In addition, the accumulation of tires causes fire hazards and are habitats that can be occupied by disease-transmitting animals [2].

Reports indicate that approximately 1.5 billion tires are produced globally over a year of this amount, a total of 17 million tons of discarded tires are generated [3]. Techniques such as pyrolysis and gasification have been used as methodologies for recycling and recovering discarded tires. The use of these techniques avoids the formation of oils, fumes, and toxic substances that cause additional contamination in the soil, the atmosphere, and in the water, compared to the direct burning of tires. In addition, the pyrolysis technique allows obtaining products with a high degree of combustion, which can be used in other processes to obtain energy. The study by Ayanoglu and Yumrutas [4] shows that through catalytic distillation and the pyrolysis technique, it is possible to generate pyrolytic tire oil (TPO) from the waste. By mixing with zeolite and natural lime, improvements in the properties of the TPO were obtained. The result of these blends shows that TPOs can achieve a heating power close to gasoline and commercial diesel. Idris et al. [5] used pyrolysis techniques using microwave induction to produce pyrolytic oil from tires. The TPO produced has a calorific value of 42.39 MJ/kg and chemical characteristics close to pure diesel. Due to the characteristics in TPOs, its implementation in internal combustion engines has been investigated.

Bodisco et al. [6] analyzed diesel blends with TPOs in a diesel engine. The results indicate that NOx emissions remain the same as commercial diesel. Frigo et al. [7] investigated the effect of diesel blends with 20% and 40% TPO percentage on engine performance. Performance was reported not to change significantly for a 20% replacement percentage of TPO in fuel. Increasing this percentage causes a reduction in power and an increase in polluting emissions. Koc and Abdullah [8] studied CO, $CO_{2,}$ and NOx emissions in a light internal combustion engine using diesel and biodiesel blends combined with TPO. The study shows that the addition of TPO reduces CO and NOx emissions. Hurdogan et al. [9] carried out an investigation to evaluate the effect of various diesel blends with TPO. Results show that engine torque and mechanical power were similar to commercial diesel when 10% TPO was used in the fuel. Additionally, no engine adaptation was required to use this type of blend. Uyumaz et al. [10] evaluated the efficiency of the engine by adding a percentage of TPO in the fuel. In their results, it was observed that the thermal efficiency for the TPO blends was 25%, and in the case of the pure fuel efficiency of 28% was reached. Shahir et al. [11] investigated Brake Thermal Efficiency (BTE) in a diesel engine powered by TPO fuel blends. In the study, it was concluded that the TPO blends allow increasing the BTE of the engine compared to pure diesel. Similarly, Mikulski et al. [12] studied the effect of blends of TPO, rapeseed oil, and diesel on the performance and emissions of a compression ignition engine. It was reported that this type of blends with a percentage of 30% rapeseed oil and 5% tire pyrolytic oil, does not meet the safety criteria to be used as fuel due to its high flash point. Tudu et al. [13] found that the addition of 4% diethyl ether in the TPO and pure diesel blends cause an improvement in performance and a reduction in emissions.

In addition to performance and emissions analyzes on engines, exergy studies allow quantifying power quality and determining the actual work potential that can occur. Additionally, exergetic analysis also allows considering the irreversibility of the system. Therefore, it provides more accurate conclusions compared to energy analysis. Due to this, several researchers have chosen exergetic analysis to study internal combustion engines [14]–[20]. Parallel to the exergy study, there is the sustainability analysis, which allows determining the benefit of fuel blends through economic considerations. The integration of exergy analysis and sustainability has been used to study different systems and sectors [21]–[25].

The literature indicates that the analysis of the pyrolytic tire oil and diesel oil blends has been carried out through studies focused on the engine's energy efficiency and exhaust emissions. However, few studies involve exergy and sustainable analysis in this type of fuel blend. Due to the above, the present study aims to carry out a study focused on energy analysis, economic sustainability, and exergy of a single-cylinder stationary diesel engine fed with different percentages of tire pyrolytic oil, under different conditions of rotation speed and engine load.

II. EXPERIMENTAL SET-UP

2.1. Test fuels –

The tires discarded by a commercial industry were used to obtain the pyrolytic oil from tires. The technique used for the production of TPO is vacuum pyrolysis. For the preparation of the TPO, washing and drying processes were applied through the application of hydro-sulfuric acid, calcium bentonite, and vacuum distillations. In the case of diesel fuel, commercially available fuel was used. The properties of diesel and tire pyrolytic oil are shown in Table 1.

Table-1. Physicochemical properties of fuels.

Fuel	Viscosity @40°C [cSt]	Density @15°C [g/ml]	Lower heating value [MJ/kg]
Diesel	2.94	0.83	45
Tire pyrolytic oil	2.14	0.89	41

Table 2 shows the different blends of diesel fuel with tire pyrolytic oil.

Table-2. Composition and nomenclature of test fuels.

Nomenclature	Composition
D100	100% Diesel
TPO4D96	96% Diesel + 4% Tire pyrolytic oil
TPO8D92	92% Diesel + 8% Tire pyrolytic oil

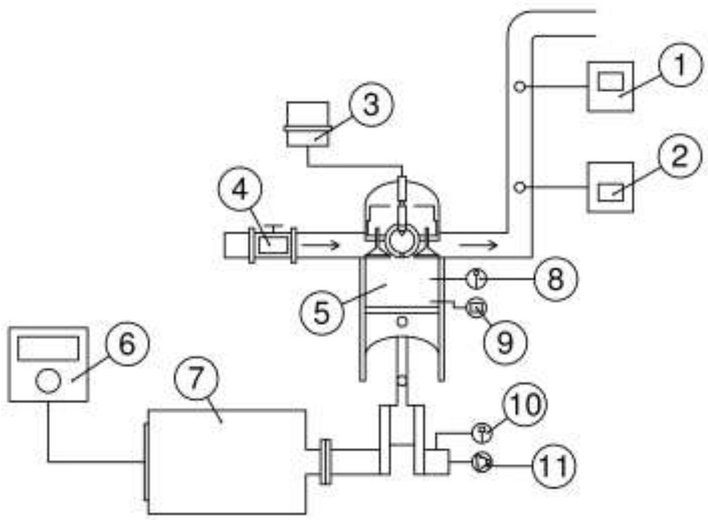
2.2. Experimental setup –

The engine used for the experimental tests consists of a 4-stroke, single-cylinder, direct injection, naturally aspirated, air-cooled diesel engine. The technical characteristics of the engine are described in Table 3.

Table-3. Engine specifications.

Manufacturer	**SOKAN**
Cycle	4 Strokes
Intake system	Naturally Aspirated
Injection Angle	20° BTDC
Maximum power	3.43 kW at 3600 rpm
Number of cylinders	1
Compression ratio	20:1
Displaced volume	300 cm^3
Stroke x Bore	62.57 mm x 78 mm
Model	SK-MDF300

The diesel engine test bench is shown in Figure 1. This bench is formed by a dynamometer controlled by a control panel to vary the conditions of rotation speed and load of the engine. The pressures in the combustion chamber were measured by piezoelectric sensors. Type K sensors are used for the temperature inside the chamber. The analysis of the exergy in the engine requires knowing the chemical components of the exhaust gases. Due to this, the PCA® 400 and BrainBee AGS-688 gas analyzers were used to measure the chemical characteristics of the exhaust gases. Table 4 shows the characteristics of the measuring instruments.



1. PCA® 400, 2. BrainBee AGS-688, 3. Fuel tank, 4. Intake air meter, 5. Engine, 6. Control Panel, 7. Dynamometer, 8. Thermocouple, 9. Cylinder pressure sensor, 10. Encoder, 11. Torque meter.

Figure 1. Experimental test bench.

Table-4. Measuring equipment on the test bench.

Instrument	**Manufacturer**	**Range**	
Piezoelectric transducer	KISTLER type 7063-A	bar	0-250 bar
Thermocouple	Type K	°C	-200 - 1370 °C
Exhaust gas analyzer	PCA® 400	NOx	0 - 3000 ppm
	BrainBee AGS-688	CO_2	0 - 19.9 vol%
		CO	0 - 9.99 vol%
		HC	0 - 19.999 ppm

2.3. Test engine –

Four different load conditions (3, 5, and 7 Nm) were selected for the experimental tests at a fixed engine speed condition of 3600 rpm, with each of the fuel blends shown in Table 2. To ensure the reliability of the experimental data, the test engine was left in operation for 6 minutes and waited until the data from the measuring instruments stabilized. Additionally, each of the experimental tests was repeated 3 times to reduce the measurement error and perform the uncertainty calculation. The following equation was used to calculate uncertainty[26]:

$$U_R = \sqrt{\left(\frac{\partial r}{\partial x_1} U_1\right)^2 + \left(\frac{\partial r}{\partial x_2} U_2\right)^2 + \cdots + \left(\frac{\partial r}{\partial x_n} U_n\right)^2} \quad (1)$$

where U_R, U_n and r are the total uncertainty of the experiment, the dimensional shape factor, and the uncertainty function. The accuracy of the measuring instruments is shown in Table 5.

Table-5. Accuracy of measurement instruments.

Instrument	**Accuracy**
Pressure (KISTLER type 7063-A)	1%
Temperature (K type thermocouple)	0.1°C
NOx	0.1%
CO_2	0.01%
CO	0.01%
HC	1%

III. THEORETICAL ANALYSIS

In the present study, an energetic, exergetic, and economic study is carried out on a diesel engine. The following considerations were established for the analysis:

- The diesel engine runs in a steady-state condition.
- Intake air and exhaust gases are modeled as ideal gases.
- Potential and kinetic energy are neglected.
- The environmental conditions are established at a temperature of 27 °C and a pressure of 1 atmosphere, respectively.

The energy analysis equations (2) and (3) were defined, which are based on the conservation of energy.

$$\sum \dot{E}_{in} = \sum \dot{E}_{out} \quad (2)$$

$$\dot{E}_{fuel} + \dot{E}_{air} = \dot{E}_{loss} + \dot{W}_{engine} + \dot{E}_{exhaust} \quad (3)$$

where $\dot{E}_{fuel}, \dot{E}_{air}, \dot{E}_{loss}, \dot{W}_{engine}$ and $\dot{E}_{exhaust}$ are the energy rate supplied by the fuel blends, the intake air energy rate, the lost energy rate, the mechanical power produced by the engine, and the released energy rate to the atmosphere by exhaust gases. Taking the above into account, the energy efficiency of the diesel engine is defined by equation (4).

$$\eta = \frac{\dot{W}_{engine}}{\dot{E}_{fuel} + \dot{E}_{air}} \quad (4)$$

The exergy balance for a steady-state system can be expressed by the following equations:

$$\sum \dot{E}x_{in} = \sum \dot{E}x_{out} + \sum \dot{E}x_{dest} \quad (5)$$

$$\dot{E}x_{fuel} + \dot{E}x_{air} = \dot{E}x_{exhaust} + \dot{E}x_{loss} + \dot{W}_{engine} + \dot{E}x_{dest} \quad (6)$$

where $\dot{E}x_{fuel}$, $\dot{E}x_{air}$, $\dot{E}x_{exhaust}$, $\dot{E}x_{loss}$, $\dot{W}_{engine}$ and $\dot{E}x_{dest}$ are the exergy rate of the fuel blends, the exergy rate of the intake air, the exergy rate of the exhaust gases, the exergy rate of the lost energy, the exergy of the engine work and the rate of exergetic destruction. The exergetic efficiency of the engine is determined by equation (7).

$$\eta_{exer} = \frac{\dot{W}_{engine}}{\dot{E}x_{fuel} + \dot{E}x_{air}} \quad (7)$$

For the analysis of the economic sustainability of fuel blends, the following thermoeconomic parameters are considered:

$$C_{ener} = \frac{\dot{E}_{loss}}{K_{cap}} \quad (8)$$

$$C_{exer} = \frac{\dot{E}x_{loss}}{K_{cap}} \quad (9)$$

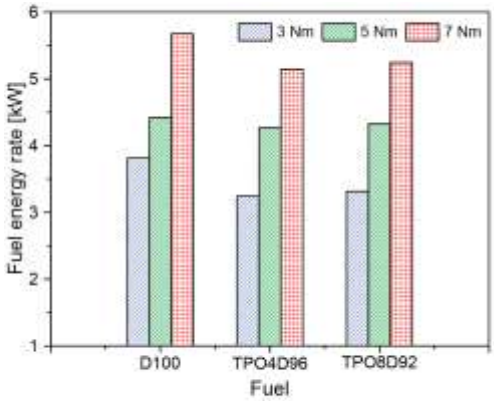
$$C_{dest} = \frac{\dot{E}x_{dest}}{K_{cap}} \quad (10)$$

where C_{ener}, C_{exer} and C_{dest} are the thermoeconomic parameters to determine the cost of lost energy, the lost exergy, and the destruction of exergy. K_{cap} is the cost of capital investment.

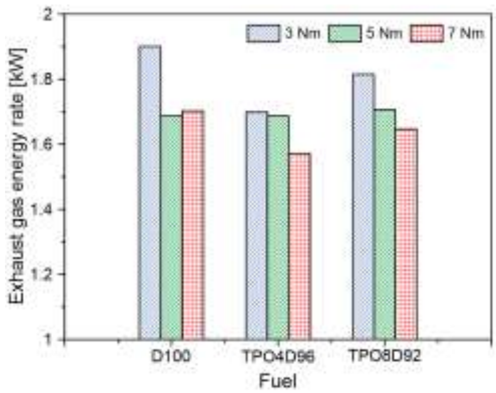
IV. RESULTS AND DISCUSSIONS

4.1. Energy analysis –

Figure 2 shows the results of the energy analysis for each of the fuel blends.



(a)



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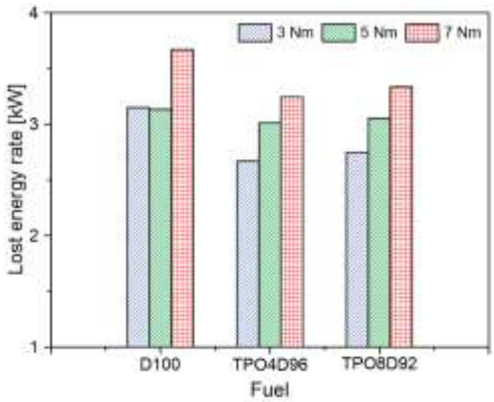

(c)

Figure 2. Analysis of energy flow rates for D100, TPO4D96 and TPO8D92 fuel blends, (a) Fuel energy rate, (b) Exhaust gas energy rate, and (c) Lost energy rate.

In the results of Figure 2, it is observed that, in general, the energy flows of the fuel blends increase with increasing engine load. The highest fuel energy rate is obtained in pure diesel fuel (D100), which indicates a higher energy consumption for engine operation with the use of diesel, compared to TPO blends. It was observed that the fuel blends TPO4D96 and TPO8D92 show a reduction in the fuel energy rate by 7.63% and 9.26%. This is attributed to the decrease in the calorific value of the fuel by increasing the percentage of tire pyrolytic oil. The analysis of energy losses shows that diesel generally has the highest losses, especially at the lowest engine load levels. The foregoing is a consequence of the low efficiency in these operating conditions. For the 7 Nm load condition, the results indicate that the loss from the exhaust gases is 1.70, 1.57, and 1.64 kW for the D100, TPO4D96, and TPO8D92 fuel blends, respectively. Similarly, engine losses for this operating condition were 3.67, 3.24, and 3.33 kW, with diesel and TPO4D96 and TPO8D92 blends.

Figure 3 shows the energy efficiency for the different fuels.

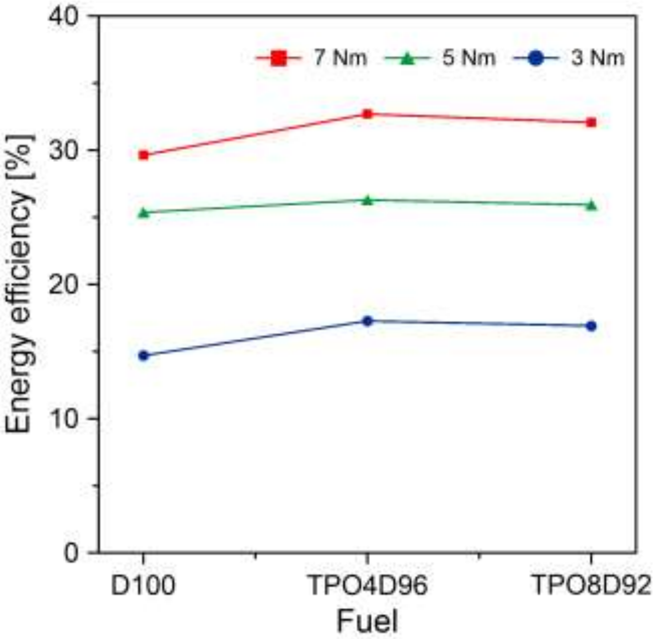

Figure 3. Energy efficiency.

In general, it was observed that the increase in engine load allows to increase energy efficiency. This behavior was presented for the three fuels tested. The results indicate that the addition of tire pyrolytic oil to commercial diesel increases the efficiency of the engine. This behavior is attributed to the lower energy losses in this type of blends. The maximum energy efficiencies reached were 29.62%, 32.68%, and 32% for fuels, D100, TPO4D96, and TPO8D92, respectively.

4.2. Exergy analysis –

The results of the exercise analysis are shown in Figure 4. This figure shows that the fuel exergy rate increases with increasing engine load for all test fuels. The results show that for a load of 3 Nm the exergy of the consumed fuel is kept in a range of 4.69-5.40 kW, and in the case of a load of 7 Nm this range is between 7.43-8.03 kW, which is a consequence of the higher fuel consumption at higher load levels.

The exergy rate lost in the engine shows that the blends of TPO4D96 and TPO8D92 have a lower loss compared to pure diesel. For a load of 7 Nm, the fuels D100, TPO4D96, and TPO8D92 produce a loss of exergy in the engine of 0.40, 0.35, and 0.39 kW. On average, pure diesel fuel and blends with tire pyrolytic oil show maximum exergy destruction of 4.57, 3.99, and 4.06 kW.

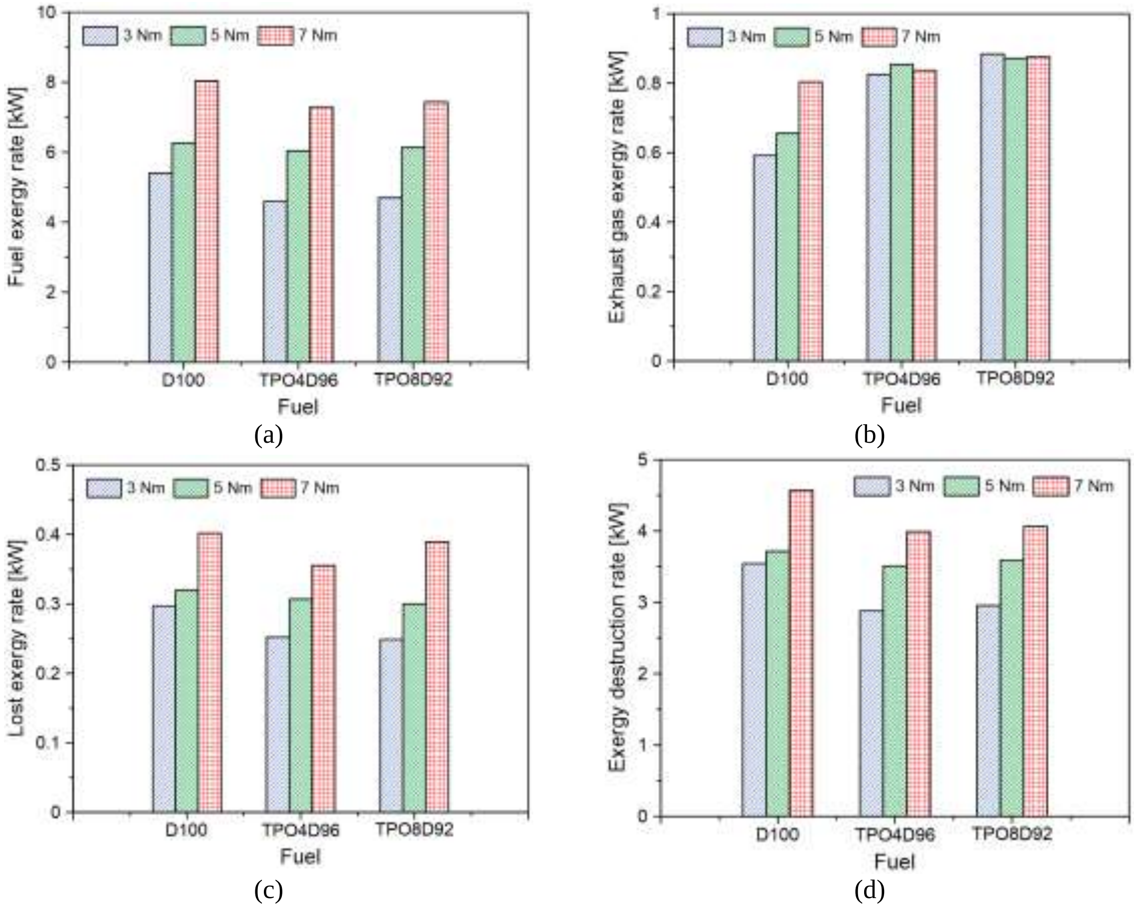

Figure 4. Analysis of exergy flow rates for D100, TPO4D96, and TPO8D92 fuel blends, (a) Fuel exergy rate, (b) Exhaust gas exergy rate, (c) Lost exergy rate and (d) Exergy destruction rate.

Figure 5 shows the exergy efficiency for the different fuels.

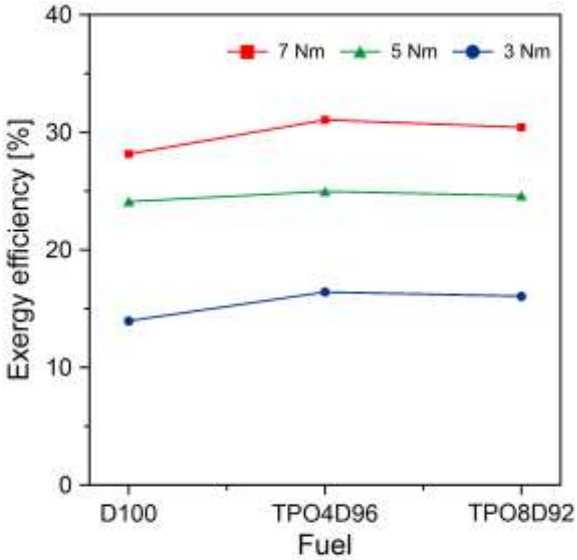

Figure 5. Exergy efficiency.

The exergetic efficiency results indicate that the TPO4D96 and TPO8D92 blends have higher efficiency compared to pure diesel. In general, blends with tire pyrolytic oil produce an increase in exergy efficiency by 10% and 8%, compared to commercial diesel.

4.3. Economic sustainability analysis –

To assess the sustainability of fuel blends, a capital investment cost of USD 50,000 $ was determined. The results of the calculated economic parameters are shown in Figure 6.

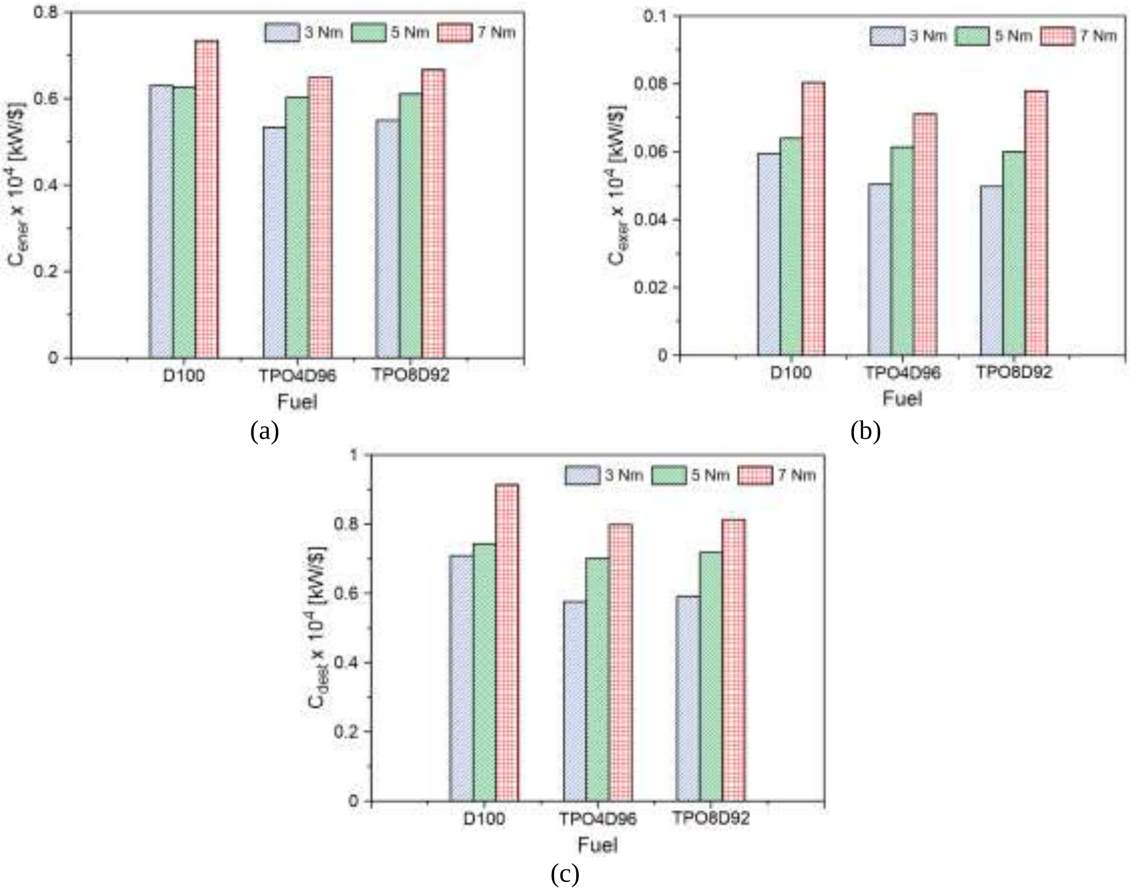

Figure 6. Economic parameters, (a) C_{ener}, (b) C_{exer} and (c) C_{dest}.

The analysis of economic sustainability indicates that the highest C_{ener} values are found in commercial diesel and in the TPO8D92 blend. The economic parameters focused on exergy (C_{exer} and C_{dest}) indicate that the best economic performance is obtained for the TPO4D96 fuel blend. In general, the lowest economic costs are found at the highest engine load levels. This is attributed to the fact that the highest energy and exergetic efficiencies are obtained under these operating conditions.

V. CONCLUSIONS

In the present study, an investigation of diesel blends with tire pyrolytic oil is carried out through an analysis focused on energy, exergy, and economic sustainability. The studied fuel blends are identified as TPO4D96 and TPO8D92. The addition of tire pyrolytic oil to diesel causes an improvement in fuel energy efficiency. Fuel blends TPO4D96 and TPO8D92 were observed to cause an increase of 10.31% and 8.20%, compared to commercial diesel. Additionally, the blends of TPO4D96 and TPO8D92 cause an average increase of 9% in the exergy efficiency of the diesel engine. The analysis of the economic sustainability parameters shows that TPO blends, in general, show a reduction in the costs of energy losses and exergy compared to commercial diesel. This allows us to conclude that the TPO blends have a higher economic performance.

The results obtained indicate that the addition of more than 4% of tire pyrolytic oil decreases the energy, exergy, and economic performance of the fuel blend. Therefore, TPO4D96 fuel is considered the most suitable blend.
In general, pyrolytic tire oil is considered a suitable additive to improve the capacity of diesel engines without the need for modifications. In addition, the implementation of TPOs as an additive in fuel reduces the environmental and health problems caused by the accumulation of waste tires.

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