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Experimental study of emissions in single-cylinder diesel engine operating with diesel-biodiesel blends of palm oil-sunflower oil and ethanol

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ABSTRACT

This study investigates an alternative fuel methodology for diesel engines that focus on the influence of ethanol as an additive agent in biodiesel blends derived from the industrial liquid waste of palm oil and sunflower oil residues. Specifically, the study addresses relevant aspects of the combustion performance and emissions characteristics in a single-cylinder diesel engine. For the experimental development, four different fuels were tested: commercial diesel, a blend of biodiesel formed from the residual material of palm oil and sunflower oil (PB3SB2), two blends with an addition of 2%, and 4% ethanol in the biodiesel produced (PB3SB2E2 and PB3SB2E4). The engine operated under nine different operation modes following international testing methodologies. Results indicated that incorporating ethanol in the PB3SB2 biodiesel blend improves thermal efficiency by 0.8%. Increasing the ethanol mixing ratio to 4% provides a further efficiency improvement of up to 1.2%. The emissions analysis showed that the addition of ethanol below 4% in the biodiesel blend facilitates the minimization of pollutant levels of CO, CO_2, NOx, HC, and smoke opacity compared to the biodiesel formed by the two residual oils (PB3SB2). Overall, ethanol incorporation reduced emissions levels between 7.5 and 13.87% compared to PB3SB2. In conclusion, integrating biodiesel and ethanol as additive agent emerges as a promising alternative to promote a reliable and sustainable operation in diesel engines.

1. Introduction

Global environmental pollution is a direct consequence of the uncontrollable rate of fossil fuel consumption and the high-scale emissions derived from conventional energy sources. Specifically, Internal Combustion Engines (ICE) has been a determinant contributor to the development of current societies while remaining as the primary energy source in non-interconnected areas [1–3]. However, a great share of global emissions derived from the wide applications of ICEs in various sectors. In this sense, several strategies, such as Waste Heat Recovery (WHR) systems [4–6], control strategies [7], exhaust gas recirculation [8,9], design improvements [10,11], among others, have been proposed to embrace a more sustainable and reliable operation. Particularly, the current efforts of academia are predominantly inclined to implement alternative fuels that decelerate pollution and fossil fuel depletion with direct

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Nomenclature

C	Carbon
H	Hydrogen
O	Oxygen
$D100$	Diesel 100% $[vol\,\%]$
$PB3SB2$	Blend Residual palm oil 3% + Residual sunflower 2% + Diesel 95% $[vol\,\%]$
$PB3SB2E2$	Blend Residual palm oil 3% + Residual sunflower 2% + Ethanol 2% + Diesel 93% $[vol\,\%]$
$PB3SB2E4$	Blend Residual palm oil 3% + Residual sunflower 2% + Ethanol 4% + Diesel 91% $[vol\,\%]$
$BSFC$	Brake Specific Fuel Consumption $[g/kWh]$
BTE	Brake Thermal Efficiency $[\%]$
CO	Carbon monoxide $[g/kWh]$
CO_2	Carbon Dioxide $[g/kWh]$
HC	Hydrocarbon $[g/kWh]$
NOx	Oxides of Nitrogen $[g/kWh]$
HSU	Hartridge Smoke Unit $[-]$
CV	Lower calorific value $[MJ/kg]$

applications on diesel and gasoline engines [12,13]. In Direct Injection (DI) engines, biodiesel stands as the most favorable solution since it is not necessary to make significant modifications to the engine [14]. Additionally, the physical and chemical properties of biodiesel allow reducing emissions such as carbon monoxide (CO), carbon dioxide (CO_2), soot, and hydrocarbons (HC) [15].

There is a great variety of raw materials for the production of biodiesel. In particular, palm oil provides clear advantages since it resembles the properties of regular diesel [12]. The latter has consolidated the wide implementation of Palm oil Biodiesel (PB) as an alternative fuel. However, the production of edible vegetable oils such as palm oil causes severe environmental damage, such as deforestation, consumption of arable land, and soil destruction [16]. Also, the production of biodiesel from edible raw materials has been criticized due to its evident utilization as a food product [17]. Hence, the use of raw materials for biodiesel production features significant limitations since some are not economically profitable, and edible derivates cannot be considered as a definitive solution [18].

From a different perspective, the production of biodiesel from residual feedstock could be a solution to eliminate the problem associated with the use of edible raw materials and while reducing the environmental damage [19]. For instance, there are two consolidated production methodologies to obtain biodiesel: (1) using residual palm oil waste by means of the esterification process and (2) Used Cooking Oil (UCO) through the transesterification process. In general, the palm oil production industry generates huge amounts of waste in liquid and solid derivates [20]. Kurnia et al. [21] indicated that only 10% of palm oil matter is converted into edible oil, and the other 90% is contaminant waste material. Thus, implementing the use of waste derivates from the palm oil industry to produce biodiesel stands as an economical and feasible alternative. In fact, the production cost of biodiesel from palm oil residues is 10%–30% lower compared to refined vegetable oil [22], which supports the techno-economic advantages of this mechanism [23].

On the other hand, biodiesel production from UCO affects a large amount of useful waste due to the massive utilization in homes, restaurants, and food industries, which has been previously investigated for biodiesel production [24,25]. However, the fatty acid content, water content, and reduction of calorific value have limited the use of UCO for biodiesel production, which elucidates the pressing need for alternative methods [26].

Blends of different oils for biodiesel production have been investigated [27,28]. De Almeida et al. [29] outlined that these types of blends allow improving the characteristics of biodiesel, such as viscosity and oxidation stability. However, the use of UCO biodiesel derivates continues to present problems such as filter plugging, inefficient atomization, among others [30].

On the other hand, ethanol fuel is typically used as a substitute in Spark-Ignition (SI) engines. However, several studies have proved its advantages as an additive in diesel-biodiesel blends. Shahir et al. [31] showed that in small quantities, the addition of ethanol improves the stability of the blend and its physicochemical properties. In the same disposition, P. Kwanchareon et al. [32] demonstrated that the addition of ethanol to palm oil biodiesel promotes similar thermophysical properties of standard diesel. Park et al. [33] investigated the properties of 20% diesel-biodiesel-ethanol blends to reveal the influence of emissions minimization, especially on HC and CO pollutants. The main contribution of this investigation was the exploration of different injection angles that, combined with the biodiesel implementation, resulted in a concrete emission reduction.

The main objective of this paper is to present an alternative fuel methodology that integrates biodiesel blends from wasted raw materials and ethanol as an additive agent to unravel the impact on the overall performance and emissions characteristics of a diesel engine. The proposal focuses on the implementation of sustainable biodiesel blends from two different sources: (1) palm oil industrial liquid waste and (2) residual sunflower oil. Moreover, the study completely describes the main design characteristics of the experimental test bench that focus on the instrumentation and conditioning devices of a low-displacement diesel engine for power generation applications in non-interconnected areas. The performance evaluation in a wide range of operation modes stands as a remarkable aspect from published research. Specifically, the performance evaluation addresses fuel metrics, thermal efficiency, as well as pollutant emissions of CO, CO_2, HC, NOx, and smoke opacity. Therefore, this work contributes to reducing the knowledge gap immersed in the implementation of biodiesel blends from waste raw materials and subsequent characterization of performance metrics. This paper is structured as follows: Section 2 depicts the main characteristics of the experimental test bench, fuel properties, biodiesel production methodologies, test procedure, and uncertainty analysis. Section 3 outlines the core findings of the investigation and sets critical discussions. Finally, Section 4 provides the concluding remarks and future opportunities on the topic.

2. Materials and method

2.1. Engine test bench

For the development of the experimental tests, a stationary diesel engine, four strokes, and naturally aspirated was used. The engine details are shown in Table 1.

The engine is installed on an experimental test bench equipped with a dynamometer that can measure up to 9 Nm of torque and 3600 rpm of engine speed. Engine emissions were measured through exhaust gas analyzers. Specifically, a BrainBee AGS-688 (electromagnetic class E2) and PCA® 400 gas analyzers were used to measure gaseous emission following the international recommendation OIML R 99-1&2. Additionally, a BrainBee OPA-100 opacimeter serves to monitor the exhaust gas opacity. Fig. 1 shows the experimental test bench used in this research, and Table 2 shows the main specifications of emission measurement equipment.

Generally, for the analysis of the exhaust emissions of an engine, the concentration units (ppm or vol%) obtained from the gas analyzers are converted into specific fuel consumption (g/kWh) that serves for comparison in international standards. This conversion was made by using the following correlations [34]:

$$CO\left(\frac{g}{kWh}\right) = 35.91 \times CO(vol\%) \tag{1}$$

$$CO_2\left(\frac{g}{kWh}\right) = 63.470 \times CO_2(vol\%) \tag{2}$$

$$HC\left(\frac{g}{kWh}\right) = 2.002 \times 10^{-3} HC(ppm) \tag{3}$$

$$NOx\left(\frac{g}{kWh}\right) = 6.636 \times 10^{-3} NOx(ppm) \tag{4}$$

2.2. Fuel production and properties

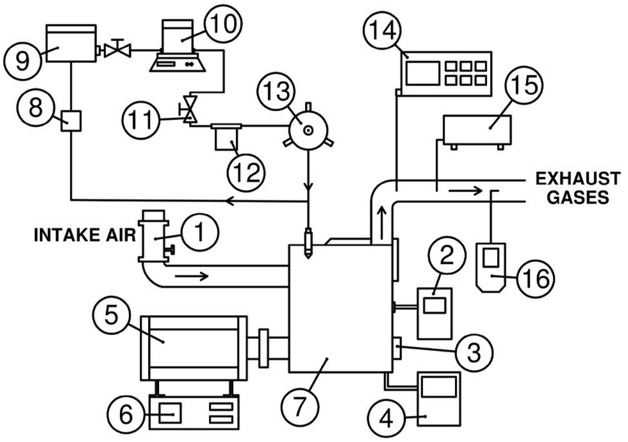
Palm oil biodiesel is produced from palm fatty acid distillate (PFAD), which is a by-product of wastes from palm industrial processes. The selection of this raw material is based on its low cost and its high content of free fatty acids (FFA). PFAD is composed of 93% by weight of FFA and 7% composed of products triglyceride, monoglycerides, diglycerides, and impurities.

For the production of palm oil biodiesel (PB), an esterification process begins, in which the previously heated PFAD is poured into a stirred tank reactor. Subsequently, methanol and an inorganic acid catalyst (H_2SO_4) are added. The molar ratio of methanol to PFAD is 8:1, and for the catalyst, an amount of 1.83% (weight of H_2SO_4/weight of PFAD) is used. The tank is subjected to a heating process in oil at 75 °C, for a time of 60 min. The stirring speed was set at 700 rpm. The resulting mixture is poured into a separating funnel, in which it is allowed to settle until the separation phase is reached. The fatty acid methyl ester (FAME) produced (bottom layer) is removed from the bottom and transferred to an evaporation phase for the remaining elimination of methanol. Due to the presence of residual FFA, an additional purification process is performed. For this, a mixture of sodium hydroxide with methanol (NaOH–MeOH) is added at a reaction temperature of 85 °C. Finally, the FAME is separated and washed at a temperature of 90 °C to remove impurities. The wastewater is separated through an evaporation process. A clarifying diagram of the described process is shown in Fig. 2a.

For biodiesel production from sunflower oil (SB), the used cooking oil was considered as raw material because the use of this residue allows reducing the economic cost of biodiesel and avoiding the contamination of water sources. The method used for the production of biodiesel is transesterification. Fig. 2 b describes the stages for obtaining biodiesel from sunflower oil.

Table 1
Main characteristics of the tested engine.

Equipment	Parameter	Type o value
Engine	Manufacture	SOKAN
	Model	SK-MDF300
	Cycle	Four strokes
	Bore x Stroke	0.078 x 0.6257 m
	Maximum rated power (@3600 rpm)	3.43 kW
	Cylinders	1
	Compression ratio	20:1
	Injection system	Direct injection
	Intake system	Naturally aspirated
	Injection angle	20° BTDC
	Cooling type	Air



1. Air flow meter
2. Data acquisition system (DAQ)
3. Encoder
4. Median variables DAQ
5. Alternator
6. Resistive test bench
7. Engine
8. Pressure regulator
9. Fuel tank
10. Gravimetric fuel meter
11. Fuel inlet valve
12. Fuel filter
13. Injection pump
14. BrainBee AGS-688 Emission gas analyzer
15. Opacimeter
16. PCA® 400 Emission gas analyzer

Fig. 1. Engine test bench.

Table 2
Specifications of emission measurement devices.

Equipment	Parameter		Range [units]
BrainBee AGS-688	Emissions measurement:	CO	0 – 9.99 [vol%]
		CO_2	0 – 19.9 [vol%]
		HC	0 – 9999 [ppm]
BrainBee OPA-100	Opacity		0 – 99.9 [%]
PCA® 400	Emissions measurement:	NOx	0 – 3000 [ppm]

The first stage consists of the removal of particles and residual water from the residual sunflower oil. For this, a heating process is carried out at a temperature of 80 °C. By using a funnel and filter paper, particulate matter is removed. To eliminate residual water, a heating process is carried out again at a temperature of 120°C for 60 min. The second stage consists of mixing methanol and sodium hydroxide (NaOH) with the residual sunflower oil. The above mixture was added to a flask and dissolved with the aid of a mechanical stirrer at a speed of 600 rpm. During this process, the mixture was kept at a constant temperature of 60 °C. After standing the mixture for 15 h, a glycerin separation process is carried out using a chromatographic column. The biodiesel separated from the glycerin is washed with water at a temperature of 85 °C. The separation of biodiesel and water is carried out by means of a separating funnel. Finally, the biodiesel is subjected to a heating process at a temperature of 105 °C to remove the remaining water particles.

Moreover, 2% and 4% of ethanol were added to the diesel-biodiesel blend. In total, four different fuels were analyzed. The properties of these fuels are shown in Table 3.

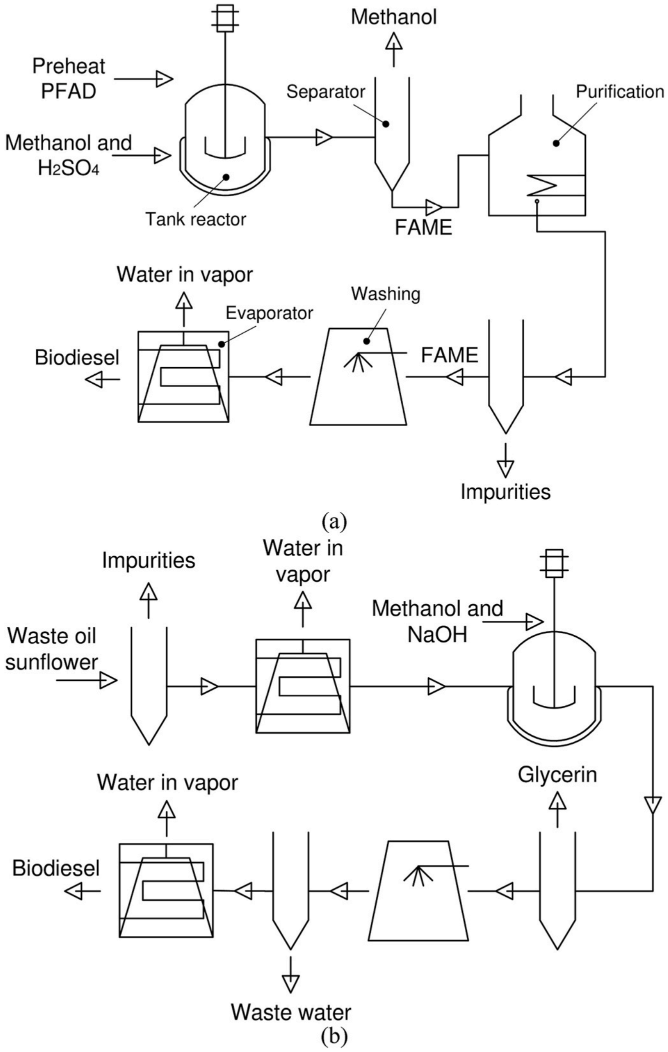
To determine the viscosity of the different types of fuels, the TV2000 visibility bath measuring instrument (Tamson instruments) was used, which is based on the ASTM D445 methodology. In the case of the density measurement, the hydrometer method was adopted using the Tamson ASTM D1298 apparatus (Tamson instruments). The lower calorific value was determined following the ASTM D240 standard and using the IKA calorimeter (model C2000).

2.3. Test procedure

The experiments were performed under nine modes of operation, A, B, C, D, E, F, G, H, and I. Under these conditions, the engine speed ranged from 3200 to 4000 rpm, and the engine torque from 3.5 to 6.5 Nm. The operating conditions were selected below the area of the characteristic curve of the engine. Accordingly, the selected modes cover a wide spectrum while facilitating the characterization of the engine conditions on the performance metrics of the proposed alternative fuel methodology. Moreover, the testing procedure methodology is in agreement with the European Stationary Cycle (ESC) that sets specific testing guidelines to relate emissions levels in ICEs according to international regulations [35]. One of the main advantages of evaluating the engine operation according to the ESC standard is that it facilitates the examination of the brake torque and engine speed independently, which expands the performance evaluation outcomes. It is worth mentioning that extreme load conditions (maximum torque and maximum rotational speed) are not considered since the engine experiences considerable efficiency losses in these operating zones. Fig. 3 summarizes the operation modes selected in the experimental testing.

2.4. Uncertainty analysis

Due to the degree of uncertainty of the measurement equipment used, an uncertainty analysis is performed for the measurements of



(a)

(b)

Fig. 2. Procedure for the production of biodiesel from (a) palm fatty acid distillate and (b) waste sunflower oil.

Table 3
Properties of the fuels.

Fuel	Blend ratio [%]				Fuel properties						
					ASTM D1298	ASTM D445	ASTM D240	Chemical composition			
	D	PB	SB	E	Density [kg/m^3]	Viscosity [cSt]	CV [MJ/kg]	C [wt.%]	H [wt.%]	O [wt.%]	C/H [−]
D100	100	–	–	–	820.5	2.63	45.05	87.02	12.98	0	6.70
PB3SB2	95	3	2	–	824.4	2.66	44.29	86.49	12.93	0.58	6.68
PB3SB2E2	93	3	2	2	822.9	2.65	44.07	85.89	12.94	1.17	6.64
PB3SB2E4	91	3	2	4	821.1	2.64	43.84	85.10	13.04	1.86	6.53

the engine performance parameters. For the development of the uncertainty analysis, the Type A evaluation method was used, which is based on the statistical analysis of a set of measurements $(x_1, x_2, x_3 \ldots x_n)$. The best estimate of a measurement set $(\overline{x})$ is determined by equation (5).

$$\overline{x} = \frac{\sum_{i=1}^{n} x_i}{n} \tag{5}$$

The calculation of the dispersion of the measurements $(\overline{s})$ is carried out using the standard deviation, as shown in equation (6).

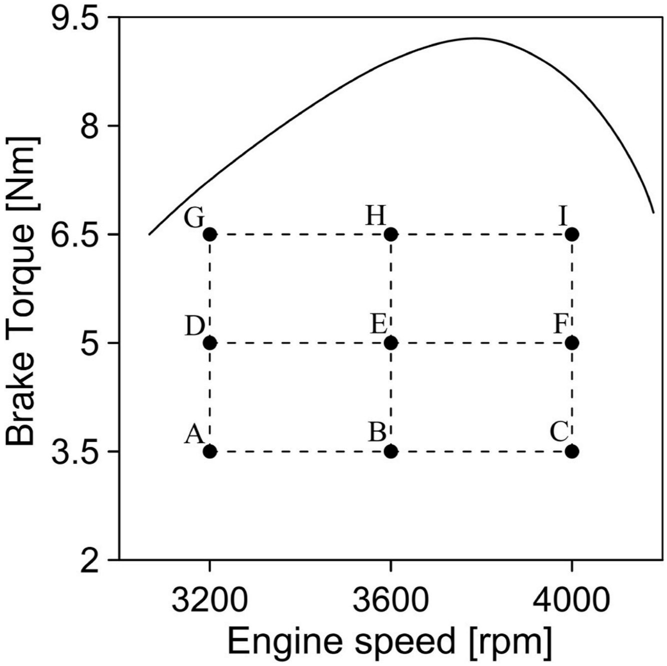


Fig. 3. Operation modes based on ESC standard.

$$\overline{s} = \sqrt{\frac{\sum_{i=1}^{n}(x_i - \overline{x})^2}{n-1}} \tag{6}$$

The measurement uncertainty (μ) used is determined from the calculation of the mean, standard deviation, as shown in equation (7).

$$\mu = \sqrt{\frac{\sum_{i=1}^{n}(x_i - \overline{x})^2}{n \cdot (n-1)}} \tag{7}$$

The experimental tests were replicated three times ($n = 3$) for each mode of operation and each type of fuel since a higher number implies a longer experimentation time, which could aggravate the uncertainty of the measurements. The uncertainty of each measured parameter is shown in Table 4.

3. Results and discussion

The aim of this section is to provide the main outcomes of the experimental evaluation. First, the study addresses fuel metrics and thermal efficiency. Afterward, a complete characterization of the emissions levels of different pollutants is described. As a first approximation, it is important to relate the mass flow rates of each operation mode that assist in the performance evaluation. Table 5 lists the experimental values of the mass flow rate for each tested fuel.

The mass flow rate values described in Table 5 serve as input data for the analysis of the fuel consumption and brake thermal efficiency.

Table 4
Uncertainty of engine performance parameters.

Measurement	Uncertainty
CO	±0.50
CO_2	±0.75
HC	±0.80
NOx	±0.95
Opacity	±1.5
Fuel consumption	±1.25
Torque	±0.25
Rotation speed	±0.20

Table 5
Mass flow rates of the operation modes.

Mode	Power [kW]	Mass flow [g/s]			
		D100	PB3SB2	PB3SB2E2	PB3SB2E4
A	1.173	0.102	0.108	0.109	0.110
B	1.246	0.099	0.104	0.106	0.106
C	1.319	0.098	0.103	0.105	0.105
D	1.676	0.120	0.126	0.127	0.128
E	1.780	0.123	0.130	0.131	0.132
F	1.885	0.130	0.137	0.138	0.139
G	2.178	0.151	0.159	0.161	0.161
H	2.314	0.165	0.173	0.175	0.175
I	2.450	0.182	0.193	0.194	0.194

3.1. *Brake specific fuel consumption (BSFC)*

The Brake Specific Fuel Consumption (BSFC) relates the ratio between the fuel mass rate and the power unit of the engine. Specifically, variables such as density, viscosity, and calorific value represent a significant influence on the BSFC. Accordingly, Fig. 4 depicts the BSFC for each fuel type on the different operation modes.

According to Fig. 4, it can be observed the magnification of the BSFC as the percentage of ethanol in the biodiesel blends escalates. In a general sense, the diesel standalone operation features the lowest fuel consumption from the cases analyzed, whereas the PB3SB2E4 displays the highest share. The average increase of the BSFC was 5.08%, 2.96%, and 1.24% for the PB3SB2E4, PB3SB2E2, and PB3SB2 fuels, respectively when compared to conventional diesel. This behavior is mainly attributed to the higher oxygen content as a result of using ethanol, which minimizes the calorific value of the fuel blend. Das et al. [36] reported a similar behavior for different biodiesel-ethanol blends.

3.2. *Brake thermal efficiency (BTE)*

This section aims to characterize the Brake Thermal Efficiency (BTE) that takes relevance in the study, considering that it defines to a great extent the energy contribution of the fuel while relating the useful power output of the engine for each fuel tested. Fig. 5 shows the BTE of each fuel for the operating modes.

Based on Fig. 5, the pure diesel presents the best performance in terms of the BTE, followed by the biodiesel blend with the highest ethanol value (PB3SB2E4). In this sense, the results indicate that maximizing the presence of ethanol improves the overall performance of the blends. The maximum BTE recorded in the experimental tests was 32.28%, 31.45%, 30.97% and 30.7% for the D100, PB3SB2E4, PB3SB2E2 and PB3SB2 fuels, respectively. The performance enhancement on the BTE induced by ethanol implementation can be explained due to the better combustion process as a result of its oxygenated nature. The latter compensates for the intensification of fuel consumption metrics, as corroborates in Fig. 4. This trend is in line with the results reported in the literature [30]. It is important to note that ethanol incorporation reduces the cetane number as a result of the oxygen enrichment that eventually affects ignition delay, and subsequently, the combustion efficiency. Therefore, some studies have proposed the implementation of cetane improvers as additive agents to further improves the quality of the fuels [37].

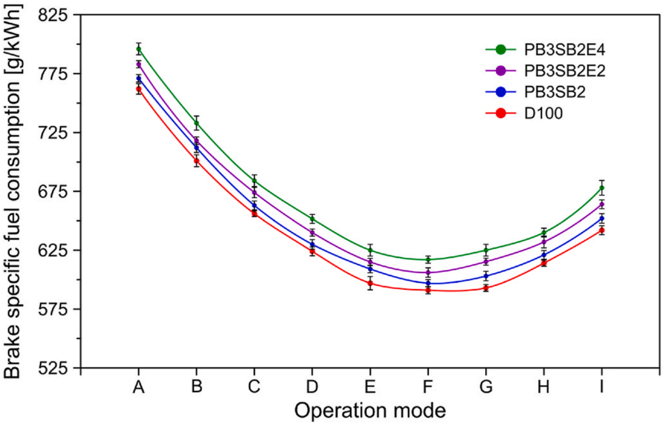


Fig. 4. Effect of fuel blends on fuel consumption metrics (BSFC).

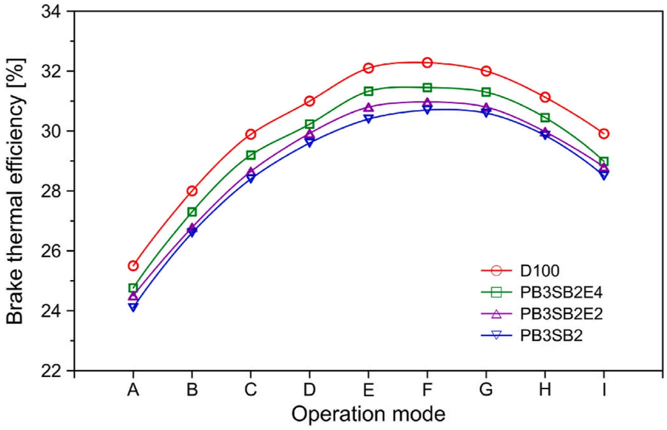


Fig. 5. Brake thermal efficiency (BTE) of the fuel blends under different operation modes.

3.3. Carbon monoxide

This section displays the emissions characteristics of the fuels tested to verify the overall behavior of pollutant levels according to each fuel blend and the operation modes. Firstly, carbon monoxide (CO) emissions of the fuel blends are displayed in Fig. 6.

Mainly, PB3SB2E4 and PB3SB2E2 fuel blends have the lowest CO emissions, whereas regular diesel features the highest CO levels. This pattern is in agreement with the chemical composition shown in Table 3, in which it can be confirmed that the presence of ethanol in the biodiesel blend of palm and sunflower oil reduces the carbon content.

In general, CO emissions decrease by 6.98%, 11.63% and 15.39% for PB3SB2, PB3SB2E2, and PB3SB2E4 fuels respectively, compared to conventional diesel. This fashion can be explained since the presence of ethanol produces efficient and complete combustion, resulting in a decrease in CO emissions. In other words, ethanol enhances the combustion oxidation in which CO compounds are converted into CO_2. Kandasamy et al. [38] show a similar reduction pattern for this emission type when experimenting with several biodiesel blends.

3.4. Carbon dioxide

Fig. 7 shows the variation of carbon dioxide (CO_2) emissions for the selected modes of operation.

According to the outcomes, CO_2 emissions decrease with the addition of ethanol content in the fuel blends. Moreover, diesel standalone operation stands as the highest level of carbon dioxide emissions. On average, PB3SB2E2 and PB3SB2E4 fuels showed a reduction in CO_2 emissions of 20.26% and 24.68% compared to PB3SB2. These types of emissions depend mainly on carbon atoms, the C/H ratio, and oxygen content [39]. The imminent reduction of CO_2 from ethanol incorporation is derived from its lower amount of carbon and low C/H ratio, as shown in Table 3. The PB3SB2E2 and PB3SB2E4 ethanol blends show a 1.60% decrease in the C/H ratio compared to the PB3SB2 biodiesel blend, which explains the lower CO_2 emissions. Similar results are reported in similar studies with biodiesel blends [40].

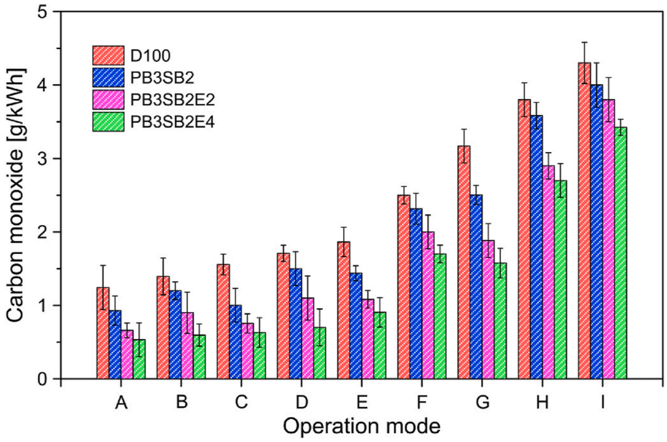


Fig. 6. CO levels of the tested fuels.

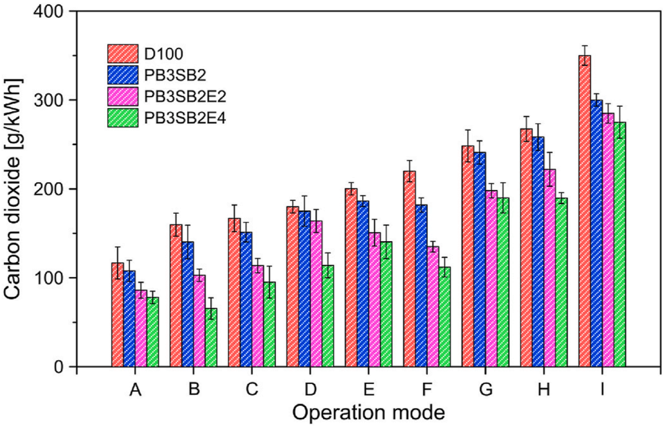


Fig. 7. CO_2 levels of the tested fuels.

3.5. Hydrocarbon

The emissions of unburned hydrocarbons (HC) for the different fuel blends are shown in Fig. 8.

It was observed that HC emissions decreased as the percentage of ethanol in biodiesel enlarges. On average, there was a reduction of 8.66%, 15.62%, and 19.07% in HC emissions for PB3SB2, PB3SB2E2, and PB3SB2E4 fuels, respectively, compared to conventional diesel.

The PB3SB2E2 and PB3SB2E4 ethanol blends have approximately twice the oxygen content compared to palm oil and sunflower biodiesel. The additional oxygen content obtained by the addition of ethanol fosters hydrocarbons burning, thus reducing HC emissions. Paul et al. [41] mentioned similar results for other percentages of ethanol.

3.6. Oxides of nitrogen

Fig. 9 shows the emissions of oxides of nitrogen for each fuel tested. It is worth mentioning that the intensification of NOx emissions can be mainly attributed to augmented combustion temperatures [42].

According to the results, the PB3SB2 blend raises NOx emissions by up to 12.4% when compared to pure diesel. However, the addition of 2% and 4% ethanol to the previous blend (PB3SB2) reduces the NOx emissions by 5% and 8.3%, respectively. This fashion can be attributed to the high latent heat of ethanol vaporization that promotes a large amount of heat to be absorbed inside the combustion chamber, thus reducing the combustion temperature. In this way, the formation of NOx is restricted. The aforementioned condition compensates for the higher oxygen content present in the PB3SB2E2 and PB3SB2E4 fuels, which could favor the formation of NOx emissions, as verified in the case of the biodiesel blend from by palm oil and sunflower oil (PB3SB2). M.K. Yesilyurt and M. Aydin [43] found a similar trend in the NOx emissions for other biodiesel blends that improve combustion oxidation.

3.7. Smoke opacity

Fig. 10 shows the smoke opacity levels for each tested fuel. The smoke opacity is mainly generated by incomplete combustion.

Based on the results of Fig. 10, the addition of ethanol showed an improvement in the smoke quality of the flue gases. Particularly, it was observed that the fuels PB3SB2E2 and PB3SB2E4 reduce the smoke opacity by 10.52% and 20.31% compared to PB3SB2. The latter can be associated with the oxygen content enrichment and lower viscosity (see Table 3), which favors complete and clean combustion. The analysis of the characterization of the fuels indicates that the addition of ethanol in the blend of palm and sunflower oil (PB3SB2) reduces the viscosity of the fuel by 0.56%. The overall trend encountered for the smoke emissions while altered by ethanol additive is in agreement with similar investigations [38].

4. Conclusions

This investigation outlines a combined fuel methodology that integrates biodiesel blends from waste raw materials and ethanol as an additive to evaluate its influence on the overall engine performance and emission characteristics of a low-displacement diesel engine. In particular, the study implemented biodiesel blends produced from the industrial liquid waste of palm oil and sunflower oil. Moreover, the study stressed the prospective benefits of incorporating ethanol in diesel engines, which further contributes to the penetration of alternative fuels. The characterization of a wide operation spectrum in the engine emerges as a unique aspect of the investigation.

The results demonstrated that incorporating ethanol increased the fuel consumption in the engine since it reduces the calorific value of the fuel blend. Specifically, the BSFC rises by up to 1.84% and 3.98% with a percentage of ethanol of 2% and 4%, respectively,

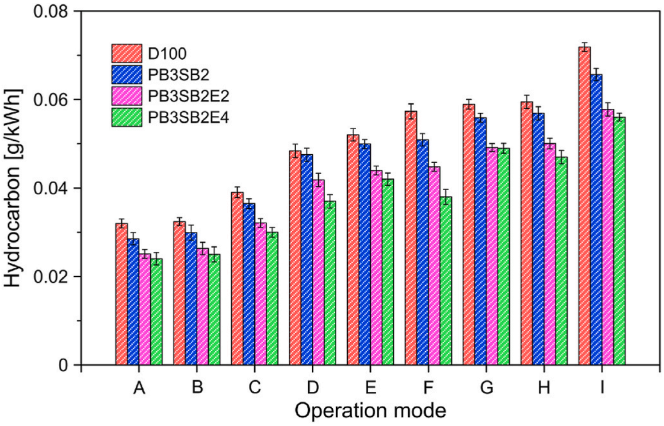


Fig. 8. Hydrocarbon emissions of the fuel blends.

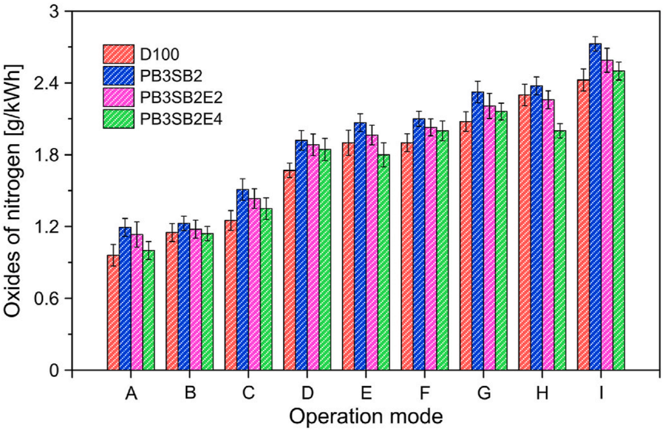


Fig. 9. NOx emissions of the tested fuels.

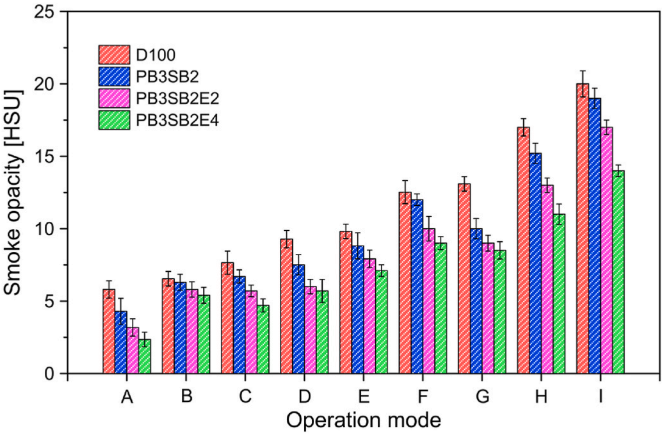


Fig. 10. Smoke opacity levels of the tested fuels.

compared to pure diesel. In contrast, ethanol improved the fuel mixture process due to its improved oxygenated nature, which reflects on enhanced combustion efficiency. Consequently, the results indicated an increase of 0.8% and 1.2% in the BTE for the PB3SB2E2 and PB3SB2E4 fuels compared to PB3SB2.

In terms of pollutant emissions, the fuel blends with additional ethanol content showed a reduction in pollutant emissions, which is primarily associated with their higher oxygen content and a low C/H ratio, which facilitates the minimization of emissions such as CO, CO_2, HC, and smoke opacity. Specifically, the utilization of PB3SB2E2 and PB3SB2E4 fuels recorded an average reduction between 7.5 and 13.87% in CO, CO_2, HC, and smoke opacity emissions compared to PB3SB2. In addition, the incorporation of ethanol in the fuel blends suppresses the magnification of NOx levels induced by the biodiesel standalone operation. The latter can be attributed to the reduced combustion temperature from the ethanol-enriched blends. Particularly, the results showed a NOx decrease of 5% and 8.3% when using ethanol as an additive in a percentage share of 2% and 4% compared to biodiesel-based blends.

Incorporating ethanol in a mixing ratio below 4% to biodiesel blends from residuals waste demonstrated to be a reliable alternative to promote an achievable and economical fuel operation mode while maintaining decent thermal performance. Besides, ethanol displayed promising results towards emissions minimization, which fosters the conceptualization of clean and sustainable operation in diesel engines. In future studies, there is a relevant need to integrate additional technologies such as WHR systems that improve fuel efficiency and reduce the environmental impact of diesel engines.

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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