Experimental study of thermodynamic and environmental performance in diesel engines operating with diesel-palm/sunflower green biodiesel blends

Estudio experimental del desempeño termodinámico y ambiental en motores diésel operando con mezclas de diésel y biodiésel verde de palma/girasol

Marta Sofia Orjuela Abril ⬤
Universidad Francisco de Paula Santander. Cúcuta (Colombia)
sofiaorjuela@ufps.edu.co

Abstract

Introduction— Currently, the consumption of fossil resources is increasing due to industrial processes and economic growth. This has caused severe environmental problems and accelerated the depletion of these resources.

Objective— This study evaluates the influence of different biodiesel blends produced from sunflower oil residues and industrial liquid palm oil residues on the characteristics of the combustion process, performance, and polluting emissions of CO_2, HC, NOx, and opacity of smoke.

Methodology— Experimental tests were carried out on a single-cylinder diesel engine. In which, two biodiesel blends PB2SB4 and PB4SB4 were tested. Four different operational modes were measured. Additionally, a diagnostic model was developed to monitor the effect of biodiesel on the pressure and heat transfer rates of the combustion process.

Results— The in-cylinder pressure decreases as the percentage of biodiesel in the fuel increases. Similarly, the results show a reduced rate of heat transfer for biodiesel blends. This effect was observed considering the brake efficiency, that reduced in3.8% and 5.4% for PB2SB4 and PB2SB4 as compared to diesel. The analysis of polluting emissions shows that the use of biodiesel from palm and sunflower oil residues reduces the emissions of CO_2, HC, and the smoke opacity by 21%, 18.5%, and 10% as compared to the emissions of diesel. However, increased emissions of NOx were observed.

Conclusions— Biodiesel blends from palm oil and sunflower oil residues under 8% of biodiesel, have limited effects on the combustion process, fuel consumption, and engine performance. These biodiesel blends reduce the emissions of CO_2, HC emissions, and smoke opacity.

Keywords— Combustion process; diesel engine, polluting emissions; biodiesel blends

Resumen

Introducción— En la actualidad, el consumo de recursos fósiles cada vez es mayor debido a los procesos industriales y el crecimiento económico. Esto ha provocado graves problemas ambientales y un riesgo de agotamiento de estos recursos.

Objetivos— En este estudio se evalúa la influencia de diferentes mezclas de biodiesel producidas a partir de los residuos de aceite de girasol y los residuos líquidos industriales de aceite de palma, en las características del proceso de combustión, rendimiento y emisiones contaminantes de CO_2, HC, NOx y opacidad de humo.

Metodología— Se desarrollaron pruebas experimentales en un motor diésel monocilíndrico. En el cual, se probaron dos mezclas de biodiesel PB2SB4 y PB4SB4. El motor funcionó en cuatro modos diferentes. Además, se realizó un modelo de diagnóstico para monitorear el efecto del biodiesel en la presión del proceso de combustión y en las tasas de liberación de calor.

Resultados— Las curvas de presión en el cilindro disminuyen a medida que aumenta el porcentaje de biodiesel en el combustible. Del mismo modo, los resultados mostraron una disminución en la tasa de liberación de calor para las mezclas de biodiesel. Este efecto se puede apreciar al considerar la eficiencia de freno, en el cual las mezclas PB2SB4 y PB2SB4 muestran una reducción de 3.8% y 5.4% en comparación con diésel. El análisis de las emisiones contaminantes mostró que el biodiesel procedente de los residuos de aceite de palma y girasol permite una disminución en las emisiones de CO_2, HC y opacidad de humo en un 21%, 18.5% y 10% al compararlo con el diésel comercial, respectivamente. Sin embargo, se observó un incremento en las emisiones de NOx.

Conclusiones— Las mezclas de biodiesel procedentes de los residuos de aceite de palma y aceite de girasol no producen un cambio significativo en el proceso de combustión, consumo, y en el rendimiento del motor, siempre que el porcentaje de sustitución se mantenga en un nivel inferior al 8%. Adicionalmente, este tipo de biodiesel permite reducciones en las emisiones de CO_2, HC y opacidad de humo.

Palabras clave— Proceso de combustión; motor diésel, emisiones contaminantes; mezclas de biodiesel

I. Introduction

The growth of the industrial sectors and the high consumption of modern life, increase the use of fossil fuel, which has caused severe environmental problems. This has driven a global interest in alternative fuels, especially for diesel engines. Alternative fuels must be economically viable, renewable, and more environmentally friendly [1], [2].

Biodiesel is currently the main alternative to diesel. One of its main advantages is the possibility to use it in diesel engines without technological changes [3]. Additionally, its low aromatic and sulfur content, and high flash point, are similar to the characteristics of biodiesel of diesel [4]. Additionally, biodiesel shows lower emissions of hydrocarbons, carbon dioxide, soot, and carbon monoxide than diesel [5], [6].

Edible oils are the most used raw material for the production of biodiesel. Particularly, palm oil is used because its properties are very close to diesel properties [7]. However, the extensive use of palm oil causes some environmental issues like deforestation, the use of vast arable land, and destruction of soil [8]. Additionally, the use of palm oil for fuel production has risen criticism for its competing use with food products. This affects its economic viability [9]. Consequently, the use of palm oil for fuel production cannot be considered as a long-term solution.

An alternative to palm oil is the production of biodiesel using residues from edible oils [10]. In the case of palm oil, it has been observed that its transformation to food oil produces different solid and liquid wastes [11]. Studies show that only 10% of the biomass from palm oil is transformed for human consumption. The remaining 90% is wasted, causing pollution problems [12], [13]. These wastes include industrial effluents, empty bunches, residues in palm decanter cakes, and fatty acids [14]. The use of these wastes might contribute to economic viability while reducing environmental impacts. Using palm oil residues reduces the cost of biodiesel production by 25%, as compared to the use of refined vegetable oil [15], [16].

There are other wastes like used cooking oils from residential houses, restaurants, and food industries, which for its high availability, is used for biodiesel production [17]-[19] However, residual cooking oil has a high percentage of water and fatty acids, which reduces the calorific value as compared to diesel [14]. This has reduced its viability as raw material for biodiesel production. However, among the different residual oils, sunflower oil has a relatively high density. Therefore, it is a promising material for the production of biodiesel [10], [20].

Research by University of Malaya [21] showed that biodiesel produced from sunflower oil has the physicochemical properties necessary to meet international ASTM standards. However, its high viscosity considerably limits its application. The production of biodiesel from blends of different types of materials has been investigated to obtain a fuel with closer properties to commercial diesel. Other investigations studied different biodiesel blends made from soybean oil and sunflower oil [22]. Results indicated that the blend allows a reduction in HC and CO emissions. As a negative aspect, an increase in fuel consumption was observed. In addition, biodiesel blends using residual palm oil and fish oil have been studied [23]. They concluded that blends of these materials allow obtaining fuels that meet ASTM standards. De Almeida et al. [24] studied biodiesel blends using palm and fish residual oil. The results indicated that the oxidation stability and viscosity properties are improved when mixing these two products. Similarly, other studies demonstrated that olive oil could be used to improve the properties of biodiesel produced from the fishing industry [25].

The previous investigations show that, with the blends of different materials, it is possible to produce biodiesel with better physicochemical properties as compared to the use of each material. The present investigation seeks to evaluate the performance, combustion, and polluting emissions characteristics of a biodiesel blend obtained from the residues of sunflower oil and the industrial liquid residues of palm oil production. Since both materials have characteristics close to commercial diesel, and it is a biodiesel blend little studied in the literature. In this way, a useful application is identified for these wastes, which reduces their negative polluting effects on the environment, while reducing the demand for diesel. A stationary single-cylinder diesel engine was used in the study, in which diagnostic models were developed, analysis of the combustion process and recording of polluting emissions of CO_2, NOx, HC, and smoke opacity.

II. Experimental Methodology

A. *Diagnostic model*

The general methodology used for diagnosing the diesel engine is shown in Fig. 1.
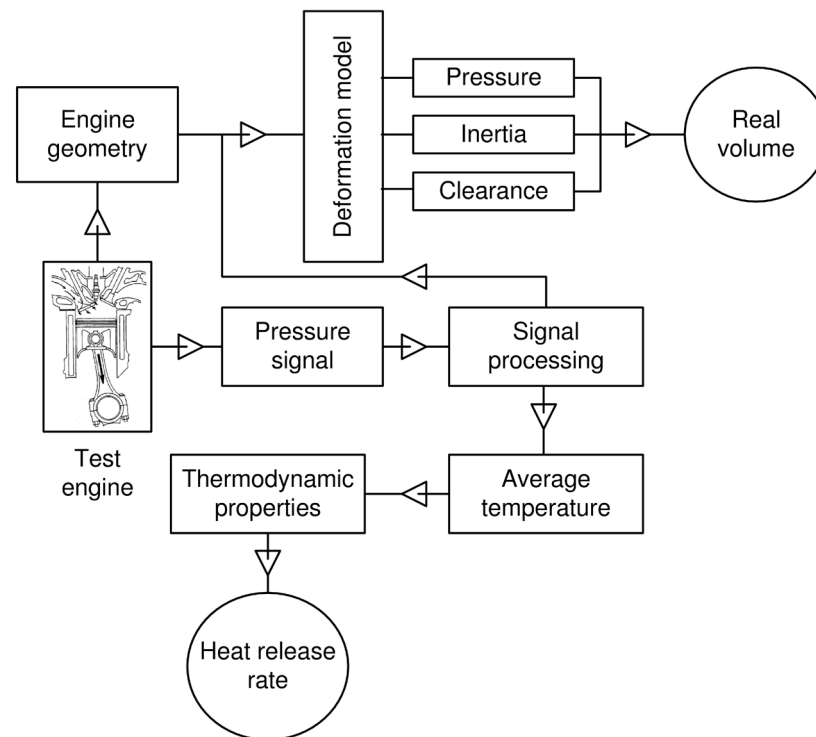

Fig. 1. Diagnostic model.
Source: Own elaboration.

The diagnostic starts by measuring the position of the crankshaft angle and the pressure signal in the combustion chamber with optical encoders and piezoelectric transducers. The signals are processed through average cycles and low-pass filters. The chamber volume and pressure functions obtained from data processing are used to calculate the instantaneous average temperature of the combustion gases. Subsequently, the thermodynamic properties of gases, heat release, and heat transfer processes are calculated to obtain the curves corresponding to the rate of heat release.

The first law of thermodynamics was used to calculate the rate of heat released, as it is shown (1) [26]:

$$\frac{dQ}{d\theta} = \frac{\gamma}{\gamma - 1} P \frac{dV}{d\theta} + \frac{1}{\gamma - 1} V \frac{dp}{d\theta} \tag{1}$$

Where dQ/dθ is the heat released as a function of the crankshaft angle, θ is the crankshaft angle, γ is the specific heat ratio, *V* is the volume of the cylinder, and *P* is the pressure of the combustion gases.

The specific heat (γ) is calculated as (2) [27].

$$\gamma = 1.34 - 60 \times 10^{-5} \cdot T + 10^{-8} \cdot T^2 \tag{2}$$

Additionally, the Brake Specific Fuel Consumption (BSFC) and Thermal Brake Efficiency (BTE) were used to assess the engine performance as (3), (4):

$$BSFC = \frac{\dot{m}_{fuel}}{2\pi \cdot N \cdot T_r / 60} \tag{3}$$

$$BTE = \frac{2\pi \cdot N \cdot T_r / 60}{\dot{m}_{fuel} \cdot LHV} \tag{4}$$

Where N, T_r, $\dot{m}_{fuel}$ and LHV are the rotation speed, torque, mass flow, and lower heating value of the fuel.

B. *Experimental instruments*

Experimental tests were carried out on a 4-stroke, stationary, single-cylinder diesel engine. The technical characteristics of the engine are shown in Table 1.

TABLE 1. ENGINE TECHNICAL SPECIFICATIONS.

Model	SK-MDF300
Type of engine	Single-cylinder
Manufacturer	SOKAN
Number of cycles	4
Diameter x stroke	78 mm × 62.57 mm
Compression ratio	20:1
Maximum power	4.6 hp a 3600 rpm
Intake system	Naturally
Injection system	Direct injection

Source: [5], [2].

Fig. 2 shows the connections of the measuring equipment on the diesel engine. A dynamometer coupled to the engine was used to vary the engine load conditions. A piezoelectric sensor (KISTLER, 7063-A) was installed in the cylinder head of the engine to measure the pressure in the cylinder chamber. The high temperatures of the combustion gases were measured with K-type thermocouples. A crankshaft angle sensor (Beck Arnley 180-0420) was used to measure the rotational velocity. Fuel consumption was measured using a gravimetric meter (OHAUS PA313). A hot wire type meter (BOSCH 22680 7J600) was used to measure the intake airflow.
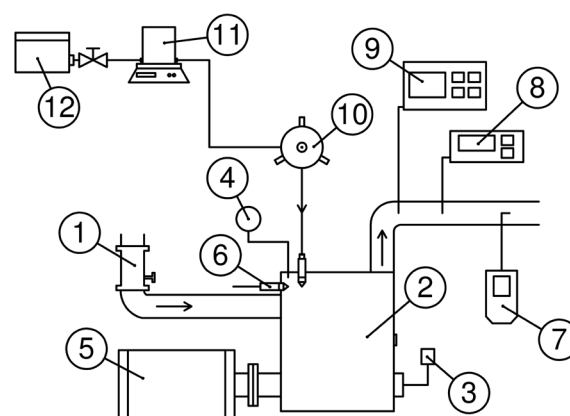

Fig. 2. Diagram of the experimental test bench.
1. Air Flow Meter, 2. Diesel Engine, 3. Crankshaft Angle Sensor, 4. Thermocouple, 5. Dynamometer, 6. Piezo Sensor, 7. PCA®400, 8. BrainBee AGS-688, 9. BrainBee OPA-100, 10. Injection pump, 11. Gravimetric fuel gauge, 12. Fuel tank.
Source: self-made.

The polluting emissions of NOx, CO_2, and HC were measured with a PCA® 400 and Brain-Bee AGS-688 gas analyzers. Additionally, smoke opacity measurements were recorded using an opacimeter (BrainBee OPA-100). Using a data acquisition system, the measured parameters were recorded for further analysis. The characteristics of the measuring instruments are shown in Table 2.

TABLE 2. CHARACTERISTICS OF THE MEASURING INSTRUMENTS.

Instrument		Accuracy	Range
BrainBee AGS-688	CO_2	± 0.01%	0 ÷ 19.9 vol%
	HC	± 1%	0 ÷ 19.99 [ppm]
PCA® 400	NOx	± 0.5%	0 ÷ 3000 [ppm]
BrainBee OPA-100	Opacity	± 0.1%	0 ÷ 99.9%
KISTLER 7063-A	Pressure	< ± 0.5%	0-250 bar
Termopar (K Type)	°C	0.1%	-200 - 1370 °C
BOSCH 22680 7J600	Intake flow	1%	0-125 g/s

Source: [5].

C. *Conditions of the experimental tests*

Two biodiesel blends produced from industrial palm oil residues and sunflower oil residues were assessed in the study. A commercial diesel was used to compare the result. The nomenclature of each of the fuels is shown in Table 3.

TABLE 3. TEST FUELS.

Nomenclature	Composition
PB2SB4	94% Diesel + 2% Palm oil biodiesel + 4% Sunflower oil biodiesel
PB4SB4	92% Diesel + 4% Palm oil biodiesel + 4% Sunflower oil biodiesel
Diesel	100% Diesel

Source: Own elaboration.

Studies of biodiesel blends show that blend with less than 10% of biodiesel results in fuels with properties similar to diesel with no negative effects on the engine [28]. Therefore, blends with palm and sunflower oil residue under 8% were considered. The properties of each fuel were measured in a standard US ASTM test lab. The physicochemical characteristics are shown in Table 4.

TABLE 4. PROPERTIES OF TEST FUELS [5].

Property	Units	Standard	Diesel	PB2SB4	PB4SB4
Density	kg/m^3	ASTM D1298	821.5	829	832
Viscosity	cSt	ASTM D445	2.64	2.48	2.59
Pour point	°C	ASTM D97	3.1	3.8	4.1
LHV	MJ/kg	ASTM D240	44.05	42.25	41.5

Source: [5].

Four experimental conditions were considered during the experimental tests, which are shown in Table 5.

TABLE 5. ENGINE OPERATING CONDITIONS

Operation mode	Torque [Nm]	Rotation speed [rpm]
A	3	3000
B		3400
C	6	3000
D		3400

Source: Own elaboration.

These conditions were selected based on typical engine operations. Additionally, the difference between the two levels of torque and rotation speed allows evaluating in a wide range the effect of fuels on the combustion process and engine emissions.

D. *Uncertainty analysis*

In general, experimental measurements are exposed to different types of uncertainties or errors. These may be a consequence of instrument calibration, sensor type, experimental procedure, among others. For the present study, uncertainty was defined as the standard deviation (*o*), as shown in (5).

$$\sigma = \sqrt{\frac{\sum_{i=1}^{n}(\overline{X} - X_i)^2}{n(n-1)}} \tag{5}$$

Where *X* and *n* are the measured parameters and the number of measurements made. In Fig. 5, Fig. 6, Fig. 7, Fig. 8, Fig. 9 and Fig. 10, this statistic is used to estimate the error bars.

III. RESULTS AND ANALYSIS

A. *Pressure in the combustion chamber*

The pressure in the combustion chamber for the different fuels in each operating condition is shown in Fig. 3.
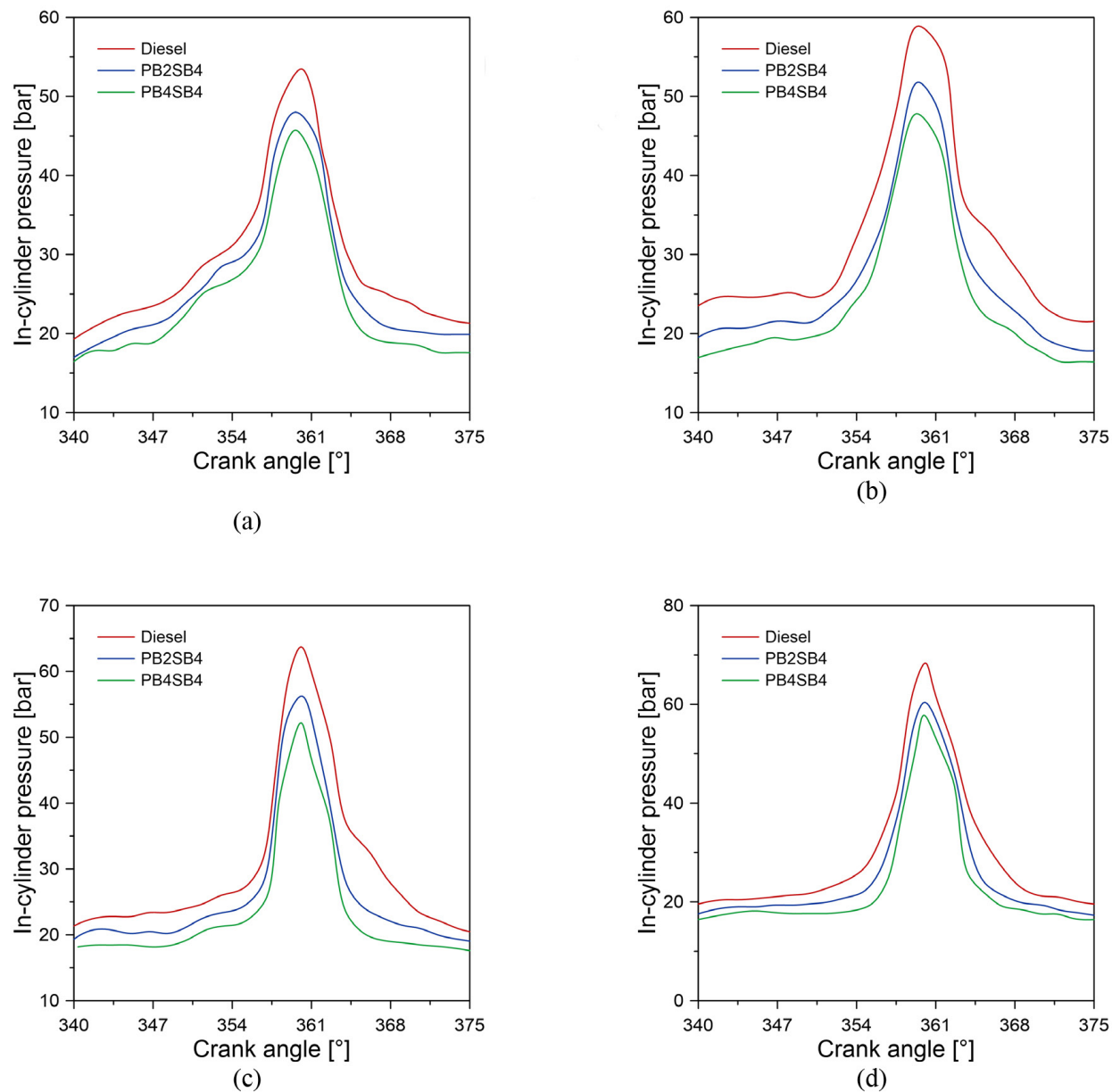

Fig. 3. Influence of fuel on combustion pressure for (a) mode A, (b) mode B, (c) mode C, and (d) mode D.
Source: Own elaboration.

Fig. 3 shows that in all operating conditions, diesel results in the highest in-cylinder pressures. Operating condition D resulted in the highest pressure levels of 68, 61, and 58 bars for diesel fuels, PB2SB4, and PB4SB4, respectively. This behavior is in agreement with studies of other biodiesel types [28].

The blend with biodiesel from palm and sunflower oil residues results in lower combustion pressure by 10% and 14.7% for PB2SB4 and PB4SB4 as compared to commercial diesel. The reduction is similar to other studies of biodiesel blends [29]. The main factor influencing this behavior is the lower calorific values of PB2SB4 and PB4SB4 blends.

The higher pressures in the combustion chamber imply an increase in the effective mean pressure on the piston. Therefore, the mechanical work capacity of the engine is higher [30]. A reduction of engine efficiency is expected when operating with biodiesel blends, taking into account what is observed in Fig. 3.

B. *Rate of combustion heat*

Fig. 4 shows the rate of combustion heat for the crankshaft angle for biodiesel blends and commercial diesel. The rate of combustion heat indicates how much chemical energy from the fuel is converted to thermal energy. The results obtained show a behavior similar to combustion pressure analysis.

Diesel fuel has the highest rate of combustion heat, followed by biodiesel blends PB2SB4 and PB4SB4, respectively. This behavior is attributed to the higher viscosity of biodiesel blends that delays the combustion process. Similar behavior is reported in the literature [31]. On average, the highest rate of combustion heat for PB2SB4 and PB4SB4 is 3.32% and 9.45% lower than for commercial diesel.
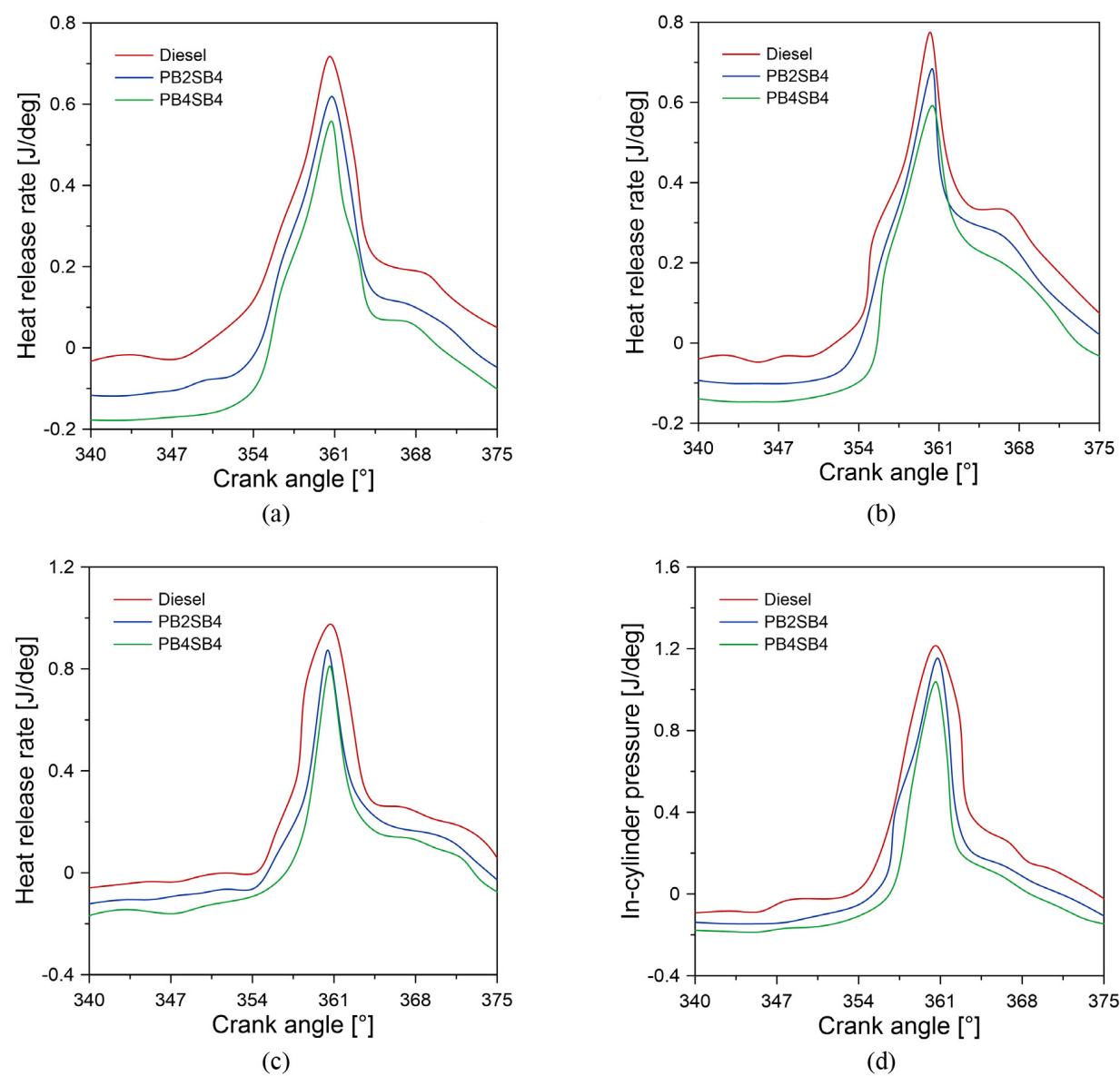

Fig. 4. Influence of fuel on the rate of heat release for (a) mode A, (b) mode B, (c) mode C, and (d) mode D.
Source: Own elaboration.

C. *Engine performance*

Fig. 5 shows the effect of biodiesel and diesel blends on the brake specific fuel consumption for the different modes of operation.
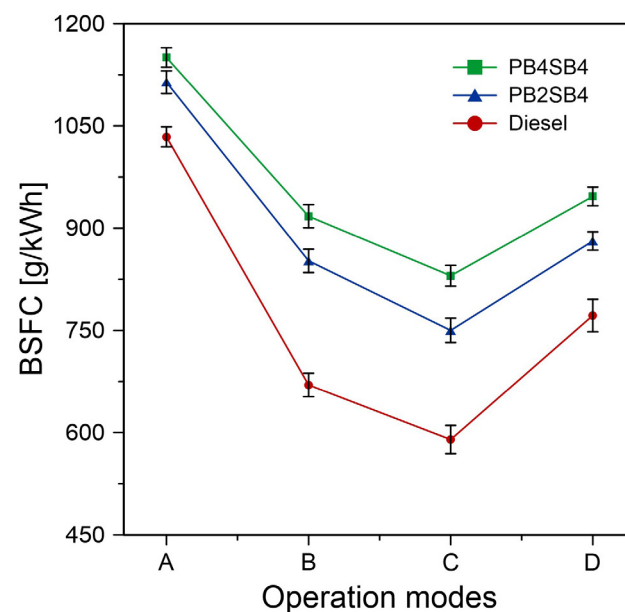

Fig. 5. BSFC for (a) mode A, (b) mode B, (c) mode C and (d) mode D.
Source: Own elaboration.

The use of PB2SB4 and PB4SB4 blends resulted in 8% and 13% higher specific fuel than commercial diesel. This might be explained by the lower calorific value of biodiesel blends, as shown in Table 4. Therefore, higher fuel consumption is necessary. Additionally, the use of palm oil and sunflower oil residues results in higher viscosity and density, so the fuel injected into the combustion chamber is higher [32], [33].

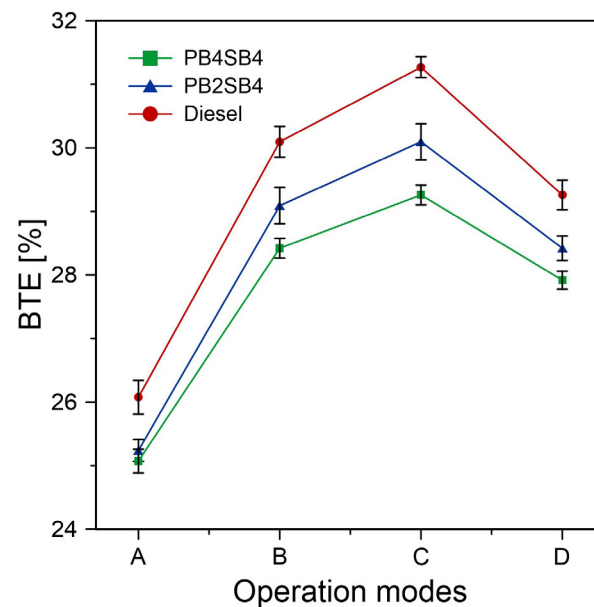Fig. 6 shows the thermal brake efficiency in the different test fuels.

Fig. 6. BTE for (a) mode A, (b) mode B, (c) mode C, and (d) mode D.
Source: Own elaboration.

Fig.6 shows a reduction in the thermal brake efficiency when using biodiesel blends, compared to commercial diesel. For the tested modes of operation, a maximum brake thermal efficiency of 29.5%, 30%, and 31.2% was achieved for PB4SB4, PB2SB4, and diesel fuel, respectively. This behavior can be explained by the sum of the factors of higher fuel consumption and lower calorific value in biodiesel blends, which were previously discussed.

D. *Carbon dioxide emissions*

Fig. 7 shows the emissions of carbon dioxide (CO_2) for blends of biodiesel and commercial diesel.
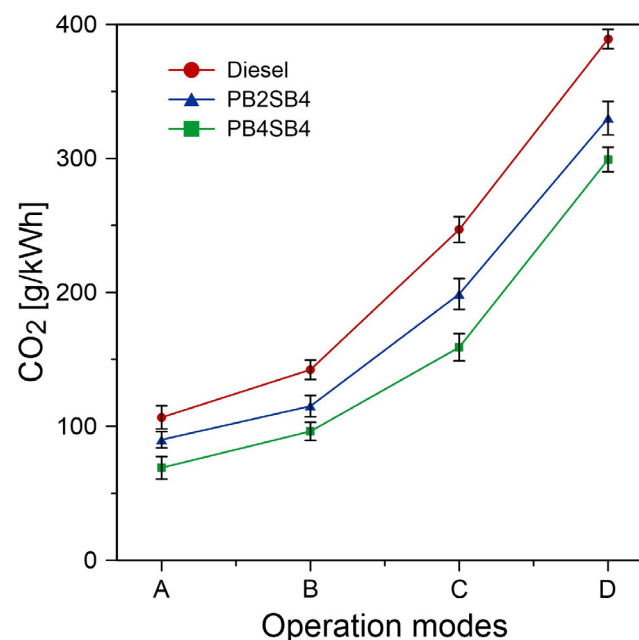

Fig. 7. Carbon dioxide emissions for (a) mode A, (b) mode B, (c) mode C and (d) mode D.
Source: Own elaboration.

Fig. 7 shows that the addition of palm oil and sunflower oil residues reduces CO_2 emissions in an average 18% and 25% for PB2SB4 and PB4SB4 blends, compared to commercial diesel. This might be explained by a cleaner and complete combustion process [34]. The improved combustion process for biodiesel blends might be explained by the lower carbon content of blends with palm oil and sunflower oil residues.

E. *Nitrogen oxide emissions*

Fig. 8 shows the nitrogen oxide (NOx) emissions in the different operating modes tested.
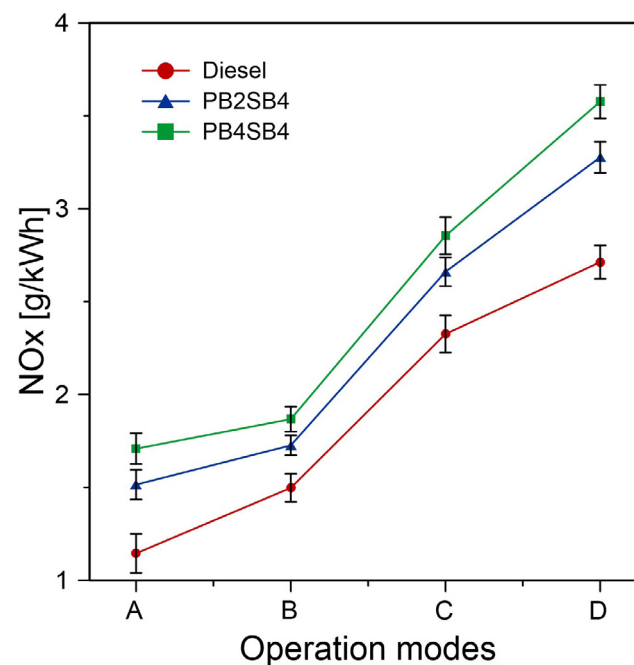

Fig. 8. Nitrogen oxide emissions for (a) mode A, (b) mode B, (c) mode C and (d) mode D.
Source: Own elaboration.

An increase in NOx emissions is observed when using the blends PB2SB4 and PB4SB4 in the fuel. This behavior remained the same for all tested operating modes. The highest NOx levels were obtained with the use of PB4SB4. On average, the NOx emissions increase by 14% and 18% for the PB2SB4 and PB4SB4 blends, compared to diesel, respectively.

NOx emissions are directly related to combustion temperature and oxygen availability. In the particular case of used biodiesel, there is a higher amount of oxygen molecules compared to diesel. Therefore, the formation of NOx is increased when using the blends with the residues of palm oil and sunflower oil.

F. *Hydrocarbon emissions*

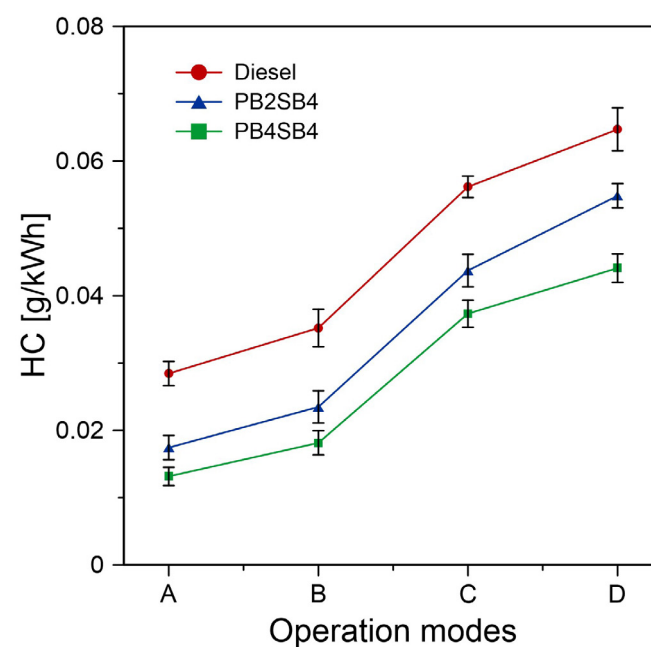Analysis of hydrocarbon (HC) emissions is shown in Fig. 9 for all test fuels.

Fig. 9. Hydrocarbon emissions for (a) mode A, (b) mode B, (c) mode C and (d) mode D.
Source: Own elaboration.

Fig 9 shows that the addition of palm oil and sunflower oil residues allows reducing HC emissions. This could be attributed to complete combustion as it occurs in CO_2 emissions. On average, HC emissions for PB2SB4 and PB4SB4 blends were 16% and 21% lower compared to diesel.

G. *Smoke opacity*

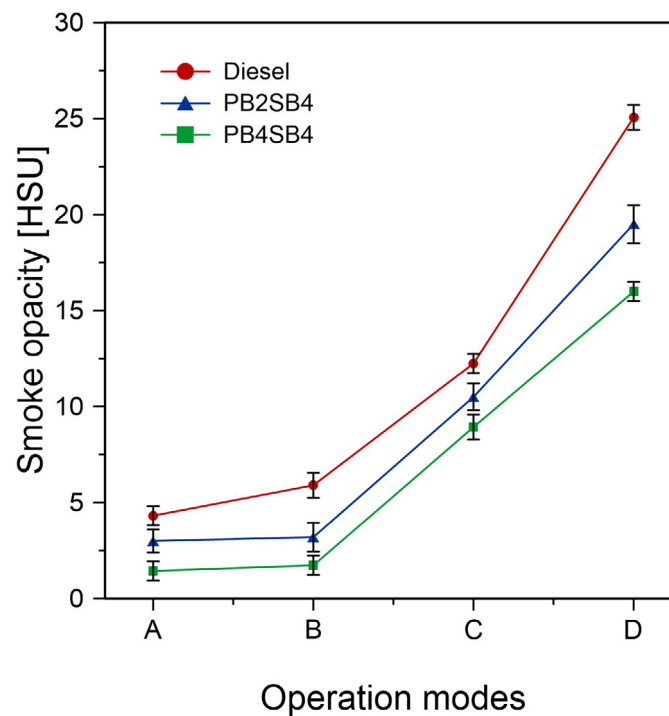The smoke opacity of the biodiesel and diesel blends are shown in Fig. 10.

Fig. 10. Smoke opacity levels for (a) mode A, (b) mode B, (c) mode C and (d) mode D.
Source: Own elaboration.

Results indicate an increased density of the smoke for higher engine loads. However, in each operating mode, biodiesel blends reduce the smoke density. A maximum smoke density of 25 HSU, 19.5 HSU, and 16 HSU were observed for diesel PB2SB4, and PB4SB4, respectively. On average, the blends of PB2SB4 and PB4SB4 show a 22% and 27% decrease in smoke density compared to commercial diesel.

IV. Conclusions

In the present study, an analysis of the effect of two biodiesel blends (PB2SB4 and PB4SB4) produced with palm oil and sunflower oil residues, on the characteristics of combustion, consumption, performance, and emissions in a single-cylinder diesel engine are carried out.

The results indicate that the use of the studied biodiesel blends reduces the in-cylinder pressure during combustion. For the tested operating conditions, maximum pressures of 58 bar, 61 bar, and 71 bar were measured for PB4SB4, PB2SB4, and commercial diesel fuels, respectively. Similarly, the use of palm oil and sunflower oil residues reduces the rate of combustion heat. Overall, this reduction was around 6.5%. Consequently, the percentage of these residual materials is limited to the production of biodiesel. However, the use of other biodiesel blends resulted in similar reductions.

Another important aspect of the studied biodiesel blends is their higher viscosity that increases fuel consumption in some 10% as compared to diesel. This effect is highlighted by assessing the brake efficiency, in which the PB2SB4 and PB2SB4 blends show a 3.8% and 5.4% reduction compared to commercial diesel.

The analysis of polluting emissions showed that biodiesel from palm and sunflower oil residues reduce polluting emissions of CO_2, HC, and smoke opacity by 21%, 18.5%, and 10% as compared to commercial diesel. These results are a consequence of more complete and cleaner combustion with biodiesel blends. However, an increase in NOx emissions was observed when using this type of biodiesel.

References

[1] H. Yoo, B. Y. Park, H. Cho, & J. Park, "Performance Optimization of a Diesel Engine with a Two-Stage Turbocharging System and Dual-Loop EGR Using Multi-Objective Pareto Optimization Based on Diesel Cycle Simulation," *Energies*, vol. 12, no. 22, pp. 1–26, Nov. 2019. https://doi.org/10.3390/en12224223

[2] H. Tian, J. Cui, T. Yang, Y. Fu, J. Tian, & W. Long, "Experimental Research on Controllability and Emissions of Jet-Controlled Compression Ignition Engine," *Energies*. vol. 12, no. 15, pp. 1–14, Jul. 2019. https://doi.org/10.3390/en12152936

[3] A. Dhar & A. K. Agarwal, "Effect of Karanja biodiesel blend on engine wear in a diesel engine," *Fuel*, vol. 134, no. 1, pp. 81–89, Oct. 2014. https://doi.org/10.1016/j.fuel.2014.05.039

[4] F. S. Hirner, J. Hwang, C. Bae, C. Patel, T. Gupta, & A. K. Agarwal, "Performance and emission evaluation of a small-bore biodiesel compressionignition engine," *Energy*, vol. 183, no. 1, pp. 971–982, Sep. 2019. https://doi.org/10.1016/j.energy.2019.07.015

[5] A. Mejía, M. Leiva, A. Rincón, A. Gonzalez-Quiroga, & J. Duarte-Forero, "Experimental assessment of emissions maps of a single-cylinder compression ignition engine powered by diesel and palm oil biodiesel-diesel fuel blends," *Case Stud Therm Eng*, vol. 19, no. 1, pp. 1–13, Jun. 2020. https://doi.org/10.1016/j.csite.2020.100613

[6] G. Valencia, C. Acevedo, & J. Duarte, "Combustion and Performance Study of Low-Displacement Compression Ignition Engines Operating with Diesel–Biodiesel Blends," *Applied Sciences*, vol. 10, no. 3, pp. 1–19, Jan. 2020. https://doi.org/10.3390/app10030907

[7] S. Bari & S. N. Hossain, "Performance and emission analysis of a diesel engine running on palm oil diesel (POD)," *Energy Procedia*, vol. 160, no. 1, pp. 92–99, Feb. 2019. https://doi.org/10.1016/j.egypro.2019.02.123

[8] B. Sajjadi, A. A. A. Raman, & H. Arandiyan, "A comprehensive review on properties of edible and non-edible vegetable oil-based biodiesel: Composition, specifications and prediction models," *Renew Sustain Energy Rev*, vol. 63, no. C, pp. 62–92, Sep. 2016. https://doi.org/10.1016/j.rser.2016.05.035

[9] H. J. Berchmans & S. Hirata, "Biodiesel production from crude Jatropha curcas L. seed oil with a high content of free fatty acids," *Bioresour Technol*, vol. 99, no. 6, pp. 1716–1721, Apr. 2008. https://doi.org/10.1016/j.biortech.2007.03.051

[10] P. G. I. Thushari & S. Babel, "Biodiesel Production From Waste Palm Oil Using Palm Empty Fruit Bunch-Derived Novel Carbon Acid Catalyst," *J Energy Resour Technol*, vol. 140, no. 3, pp. 1–10, Mar. 2018. https://doi.org/10.1115/1.4038380

[11] S. Sumathi, S. P. Chai, & A. R. Mohamed, "Utilization of oil palm as a source of renewable energy in Malaysia," *Renew Sustain Energy Rev*, vol. 12, no. 9, pp. 2404–2421, Dec. 2008. https://doi.org/10.1016/j.rser.2007.06.006

[12] J. C. Kurnia, S. V. Jangam, S. Akhtar, A. P. Sasmito, & A. S. Mujumdar, "Advances in biofuel production from oil palm and palm oil processing wastes: A review," *Biofuel Res J*, vol. 3, no. 1, pp. 332–346, Mar. 2016. https://doi.org/10.18331/BRJ2016.3.1.3

[13] S. A. Sulaiman & F. F. F. Taha, "Drying of Oil Palm Fronds Using Concentrated Solar Thermal Power," *Appl Mech Mater*, vol. 699, no. 1, pp. 449–454, Nov. 2014. https://doi.org/10.4028/www.scientific.net/AMM.699.449

[14] S. S. Lam, Y. F. Tsang, P. N. Yuh Yek, R. K. Liew, M. S. Osman, W. Peng, W. H. Lee & Y.-K. Park, "Co-processing of oil palm waste and waste oil via microwave co-torrefaction: A waste reduction approach for producing solid fuel product with improved properties," *Process Saf Environ*, vol. 128, no. 1, pp. 30–35, Aug. 2019. https://doi.org/10.1016/j.psep.2019.05.034

[15] H. J. Cho, J.-K. Kim, H.-J. Cho, & Y.-K. Yeo, "Techno-Economic Study of a Biodiesel Production from Palm Fatty Acid Distillate," *Ind Eng Chem Res*, vol. 52, no. 1, pp. 462–468, 2013. https://doi.org/10.1021/ie301651b

[16] W. Liew, K. Muda, M. Azraai, A. Affam, and S. Loh, "Agro-industrial waste sustainable management – a potential source of economic benefits to palm oil mills in Malaysia," *J Urban Environ Eng*, vol. 11, no. 1, pp. 108–118, May. 2017. https://doi.org/10.4090/juee.2017.v11n1.108118

[17] M. A. Ahmad Farid et al., "Production of methyl esters from waste cooking oil using a heterogeneous biomass-based catalyst," *Renew Energy*, vol. 114, part. B, pp. 638–643, Dec. 2017. https://doi.org/10.1016/j.renene.2017.07.064

[18] M. R. Anuar & A. Z. Abdullah, "Ultrasound-assisted biodiesel production from waste cooking oil using hydrotalcite prepared by combustion method as catalyst," *Appl Catal A Gen*, vol. 514, pp. 214–223, Mar. 2016. https://doi.org/10.1016/j.apcata.2016.01.023

[19] I. K. Hong, H. Jeon, H. Kim, & S. B. Lee, "Preparation of waste cooking oil based biodiesel using microwave irradiation energy," *J. Ind Eng Chem*, vol. 42, pp. 107–112, Oct. 2016. https://doi.org/10.1016/j.jiec.2016.07.035

[20] A. Saydut, A. B. Kafadar, Y. Tonbul, C. Kaya, F. Aydin, & C. Hamamci, "Comparison of the Biodiesel Quality Produced from Refined Sunflower (Helianthus Annuus L) Oil and Waste Cooking Oil," *Energy Explor Exploit*, vol. 28, no. 6, pp. 499–512, Dec. 2010. https://doi.org/10.1260/0144-5987.28.6.499

[21] M. Saifuddin and A. N. Boyce, "Biodiesel production from waste cooking sunflower oil and environmental impact analysis," *Kuwait J Sci*, vol. 43, no. 3, pp. 110–117, 2016. Available: https://journals-kuwait.org/kjs/index.php/KJS/article/view/1723

[22] M. Elkelawy, H. A.-E. Bastawissi, K. K. Esmaeil, A. M. Radwan, H. Panchal, K. K. Sadasivuni, D. Ponnamma & R. Walvecar, "Experimental studies on the biodiesel production parameters optimization of sunflower and soybean oil mixture and DI engine combustion, performance, and emission analysis fueled with diesel/biodiesel blends," *Fuel*, vol. 255, no. 1, pp. 1–12, Nov. 2019. https://doi.org/10.1016/j.fuel.2019.115791

[23] J. Gupta, M. Agarwal, & A. K. Dalai, "Optimization of biodiesel production from mixture of edible and nonedible vegetable oils," *Biocatal. Agric. Biotechnol*, vol. 8, no. 1, pp. 112–120, Oct. 2016. https://doi.org/10.1016/j.bcab.2016.08.014

[24] V. F. de Almeida, P. J. García-Moreno, A. Guadix, & E. M. Guadix, "Biodiesel production from mixtures of waste fish oil, palm oil and waste frying oil: Optimization of fuel properties," *Fuel Process Technol*, vol. 133, no. 1, pp. 152–160, May. 2015. https://doi.org/10.1016/j.fuproc.2015.01.041

[25] J. F. Costa, M. F. Almeida, M. C. M. Alvim-Ferraz, & J. M. Dias, "Biodiesel production using oil from fish canning industry wastes," *Energy Convers Manag*, vol. 74, no. 1, pp. 17–23, Oct. 2013. https://doi.org/10.1016/j.enconman.2013.04.032

[26] J. Heywood, *Internal combustion engine fundamentals*. NY, USA: McGraw-Hill Education, 1988. https://doi.org/10.5860/CHOICE.26-0943

[27] M. F. J. Brunt, H. Rai, & A. L. Emtage, "The Calculation of Heat Release Energy from Engine Cylinder Pressure Data," presented at *SAE Technical Paper 981052*, Inter. Con. & Exp., Bhm., En., pp. 1596–1609, Feb. 1998. https://doi.org/10.4271/981052

[28] M. A. Asokan, S. Senthur Prabu, P. K. K. Bade, V. M. Nekkanti, & S. S. G. Gutta, "Performance, combustion and emission characteristics of juliflora biodiesel fuelled DI diesel engine," *Energy*, vol. 173, no. 1, pp. 883–892, Apr. 2019. https://doi.org/10.1016/j.energy.2019.02.075

[29] M. M. Musthafa, T. A. Kumar, T. Mohanraj, & R. Chandramouli, "A comparative study on performance, combustion and emission characteristics of diesel engine fuelled by biodiesel blends with and without an additive," *Fuel*, vol. 225, no 1, pp. 343–348, Aug. 1, 2018. https://doi.org/10.1016/j.fuel.2018.03.147

[30] Y. Du, X. Yu, J. Wang, H. Wu, W. Dong, & J. Gu, "Research on combustion and emission characteristics of a lean burn gasoline engine with hydrogen direct-injection," *Int J Hydrogen Energy*, vol. 41, no. 4, pp. 3240–3248, Jan. 30, 2016. https://doi.org/10.1016/j.ijhydene.2015.12.025

[31] Ö. Can, "Combustion characteristics, performance and exhaust emissions of a diesel engine fueled with a waste cooking oil biodiesel mixture," *Energy Convers Manag*, vol. 87, no. 1, pp. 676–686, Nov. 2014. https://doi.org/10.1016/j.enconman.2014.07.066

[32] M. Canakci, "Combustion characteristics of a turbocharged DI compression ignition engine fueled with petroleum diesel fuels and biodiesel," *Bioresour Technol*, vol. 98, no. 6, pp. 1167–1175, Apr., 2007. https://doi.org/10.1016/j.biortech.2006.05.024

[33] S. Murillo, J. L. Míguez, J. Porteiro, E. Granada, & J. C. Morán, "Performance and exhaust emissions in the use of biodiesel in outboard diesel engines," *Fuel*,vol. 86, no. 12–13, pp. 1765–1771, Aug. 2007. https://doi.org/10.1016/j.fuel.2006.11.031

[34] H. C. Ong, H. H. Masjuki, T. M. I. Mahlia, A. S. Silitonga, W. T. Chong, & T. Yusaf, "Engine performance and emissions using Jatropha curcas, Ceiba pentandra and Calophyllum inophyllum biodiesel in a CI diesel engine," *Energy*, vol. 69, no. 1, pp. 427–445, May. 1, 2014. https://doi.org/10.1016/j.energy.2014.03.035

Marta Sofia Orjuela Abril. Industrial Engineer, with a Master degree in projects, and a full-time professor at the Francisco de Paula Santander University (Colombia). Her interests are studies in the area of Thermal Engines and polluting emissions. https://orcid.org/0000-0002-9742-8673