Research

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Experimental Assessment of the Emissions Characteristics of Low-Displacement Diesel Engines Operating with Biodiesel Blends from Algae Oil

Análisis experimental de las características de emisión de motores diésel de baja cilindrada operando con mezclas de biodiésel de aceite de alga

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Recibido: 02/02/2021. Modificado: 25/11/2021. Aceptado: 09/12/2021.

Abstract

Context: The imminent concern regarding greenhouse gas emissions associated with internal combustion engines has motivated both the industrial and academic sectors to propose reliable solutions in order to mitigate the adverse effects of thermal machines. Partial fuel substitution with biodiesel blends is a promising, convenient, and diverse technology that can contribute to minimizing emission levels.

Method: This study incorporated an experimental test bench for a low-displacement diesel engine that enabled control of the operating conditions in order to evaluate thermal performance, fuel metrics, and emission levels. An algae oil biodiesel blend at replacement percentages of 5 % (AB5) and 15 % (AB15) was produced via a transesterification technique. The performance evaluation was centered on the impact of the variable compression ratio and torque ranges of the engine.

Results: The implementation of algae oil as a biodiesel blend reduced the emission levels of CO, CO_2, and HC by 40-95 % compared to diesel standalone operation. In contrast, it boosted NOx emissions in a reasonable proportion (<45 %). Further emission minimization of CO and HC could be reached by increasing the compression ratio, but CO_2 and NOx emissions were negatively affected. Moreover, increasing the compression ratio intensified the combustion pressure while improving both fuel consumption and thermal performance. Contrarily, a higher algae oil content in the biodiesel blend reduced the in-cylinder pressure, thus increasing the fuel consumption and reducing the thermal performance.

Conclusions: In conclusion, biodiesel implementation demonstrated to be a robust tool to mitigate the global emissions of the engine to a great extent. The negative results regarding thermal performance and fuel consumption are a consequence of the higher density and lower heating value. However, this can be partially offset by increasing the compression ratio of the engine. The exploration of hydrogen and hydroxy is strongly recommended to contribute to enhancing the overall performance of partial fuel substitution technologies.

Keywords: fuel consumption, thermal performance, biodiesel blend, diesel engine, emission levels, partial fuel substitution

Language: English

Cite as: D. Maestre, S. Orjuela, and J. Duarte. “Experimental assessment of the emissions characteristics of low-displacement diesel engines operating with biodiesel blends from algae oil”. *Ing*, vol. 27, no. 2, 2022. e17539.

`https://doi.org/10.14483/23448393.17539`

Resumen

Contexto: La inminente preocupación en torno a la emisión de gases de efecto invernadero asociada a los motores de combustión interna ha motivado a la industria y la academia a proponer soluciones confiables para mitigar los efectos adversos de las maquinas térmicas. La sustitución parcial de combustible es una diversa, conveniente y prometedora tecnología que puede contribuir a minimizar los niveles de emisión.

Método: El estudio incorporó un montaje para pruebas experimentales de un motor diésel de baja cilindrada que permite controlar las condiciones de operación para evaluar el desempeño térmico, de consumo de combustible y de niveles de emisión. Se produjo una mezcla biodiésel de aceite de alga a un porcentaje de substitución del 5 % (AB5) y 15 % (AB15) a través de una técnica de transesterificación. La evaluación de desempeño se centró en el impacto de la relación de compresión variable y el margen de torque del motor.

Resultados: La implementación del aceite de alga como mezcla biodiésel redujo los niveles de emisión del CO, CO_2 y HC en un 40-95 % en comparación con la operación autónoma de diésel comercial. En contraste, se incrementaron las emisiones de NOx en una proporción razonable (<45 %). Se pudo obtener una minimización adicional de las emisiones de CO y HC al incrementar la relación de compresión, pero las emisiones de CO_2 y NOx fueron negativamente afectadas. Adicionalmente, al aumentar la relación de compresión se incrementó la presión durante la combustión, lo cual mejoró el consumo de combustible y el desempeño térmico. Contrariamente, un mayor contenido de aceite de alga en la mezcla biodiesel redujo la presión dentro del cilindro, lo que aumentó el consumo de combustible y redujo el desempeño térmico.

Conclusiones: En conclusión, la implementación de biodiésel demostró ser una herramienta robusta para mitigar en gran medida las emisiones globales del motor. Los resultados negativos en cuanto a desempeño térmico y consumo de combustible son consecuencia de la alta densidad y la menor capacidad calorífica. Sin embargo, esto puede ser parcialmente contrarrestado al incrementar la relación de compresión del motor. La exploración del hidrógeno e hydroxy es alta recomendada para contribuir a mejorar el desempeño global de las tecnologías de sustitución parcial de combustible.

Palabras clave: consumo de combustible, desempeño térmico, mezcla biodiésel, motor diésel, niveles de emisión, sustitución parcial de combustible

Idioma: Inglés

1. Introduction

Fossil fuels have been essential for socio-economic development worldwide due to their central role in the energy, mobility, industrial, and agricultural sectors. The massive utilization of oil and gas derivatives has led to the dramatic exploitation of non-renewable resources, which represents a significant environmental problem that sets an intensified pressure on the energy crisis [1], [2]. However, the main concern of both governmental and international organizations is centered on the unprecedented rate of greenhouse emissions derived from convectional energy practices [3], [4]. Particularly, Internal Combustion Engines (ICEs) represent almost 65 % of global CO_2 emissions, given that they are extensively implemented in transportation and energy production [5]–[7]. Therefore, both the industrial and academic sectors have focused on the exploration of alternative fuels that contribute to minimizing the global warming potential of ICEs [8].

Particularly, due to its various advantages, biodiesel is one of the most promising alternatives for partial-fuel substitution technology in compression-ignited ICEs [9], [10]. First, it features similar physicochemical characteristics to commercial diesel, exhibiting clever perspectives on combustion performance [8]. Moreover, it can be incorporated into the engine without requiring any modification below fuel replacement grades of 20 % (B20) [11].

Lastly, it represents a cost-effective alternative, given that the production process is significantly less complex, prolongs engine life, and reduces lubrication cost. It is also biodegradable, which is a direct advantage from an environmental perspective [12]. Hence, different countries foster the massive penetration of biodiesel technology through the implementation of national policies [13].

Biofuels can be produced via mechanical and chemical techniques. Particularly, the chemical process of transesterification is massively implemented due to its relative simplicity [14]. Another vital factor in the production of biofuels is feedstock selection since it constitutes nearly 75 % of the production cost [15]. More than 350 oil-bearing crops have been identified as potential raw materials, while the availability is mainly determined by the location [8]. In this sense, the main raw materials can be classified as animal fats and vegetable oils [16]. Specifically, there is an inclined preference for vegetable oils, which is due to bast variety, reduced costs, and fast growth. Said oils can be classified as edible and non-edible. For instance, palm oil is an edible oil that has been extensively implemented in dual-fuel technologies [17], [18] studied the combustion and emissions characteristics of a light-duty diesel engine operating with palm oil biodiesel. The results indicated that the presence of this biodiesel blend significantly reduces CO emissions (between 20 and 50 %), but NOx emissions rise at a lower proportion (5-10 %) depending on the load condition. Similarly, [19] reported that palm oil biodiesel enables a reduction of HC emissions and smoke opacity by 38 and 19 %, respectively. Despite the wide variety of applications with edible-based blends, their imminent impact on the food industry hinders their massive implementation. Hence, non-edible vegetable oils stand as a convenient alternative for biodiesel production. In particular, algae biodiesel blends emerge as a prospective candidate based on the rapid growth, high content of lipids, diversification of cultivated habitats, and outstanding productivity, which reinforce the potential to meet the global fuel demand [20].

Accordingly, [21] evaluated the prospective application of algae oil blends for partial fuel substitution. The results showed that the physicochemical properties feature a concrete similarity to commercial diesel in terms of density, viscosity, flashpoint, calorific value, cetane number, and oxidation stability. [22] studied the influence of partial fuel replacement with biodiesel blends from microalgae oil (*Crypthecodinium cohnii*) on the overall performance and emissions levels of a diesel engine. The study addressed biodiesel replacement grades of 10, 20, and 50 %, whereas the operating margin examined the influence on engine speed. The results indicated that both NO and NOx emissions could be reduced by up to 22 %. In contrast, this produced a slight reduction in the thermal performance of the engine. Despite the intensive assessments on dual-fuel operation in diesel engines in the last two decades, the evaluation of the overall operating margin relies on the torque and engine speed, whereas the influence of variable pressure ratios is rarely characterized. Specifically, the impact of the aforementioned parameters on fuel consumption metrics, thermal performance, and emissions control could reveal vital information for biodiesel implementation. Moreover, the implementation of microalgae oil from the species *Spirulina platensis*¸ in biodiesel operation of ICEs appeared to be a recent trend which has not drawn much attention from researchers [23].

The main contribution of this research is that it presents an experimental analysis of the overall performance of a low-displacement diesel engine operating with a biodiesel blend from algae oil of the species *Spirulina platensis*. The constructed test bench allows controlling the engine speed (3.500 rpm), torque (1-7 Nm), and fuel mode operation with a biodiesel replacement grade from 5 to 15 %. In addition, the study incorporates the impact of variable pressure ratio (17 and 19) on fuel consumption, thermal behavior, and emissions characteristics, which emerge as a differential factor from former studies. Therefore, this work contributes to gaining a deeper understanding of partial fuel substitution on diesel engines with variable operating ranges while closing the knowledge gap regarding *Spirulina platensis* biodiesel implementation. The paper is structured as follows: the next section describes the main features of the experimental setup, fuel characteristics, and instrumentation specifications. Section 3 outlines both thermal and fuel consumption metrics. Then, Section 4 displays the main results of this research, and, finally, Section 5 provides concluding remarks.

2. Experimental setup

Experimental testing was conducted in an in-house test bench for a single-cylinder diesel engine whose specifications are listed in Table I. Fig. 1 displays the main components of the experimental test bench, while Fig. 2 is a real representation of the engine's module.

Table I. Engine specifications

Engine type	**Single cylinder**
Model	SK-MDF300
Manufacturer	SOKAN
Bore	78 mm
Stroke	62,57 mm
Cycle	4 Strokes
Maximum power	3,43 kW at 3.600 rpm
Injection	Direct injection
Intake systema	Naturally
Displacement	299 mL

The operating conditions of the engine accounted for torque conditions from 1 to 7 Nm with a constant rotation speed of 3.500 rpm. Additionally, two different compression ratios (CR) were incorporated in the analysis, namely 17:1 (CR 17) and 19:1 (CR 19). Notice that the compression ratio is changed by replacing the piston series, which has a direct impact on the clearance volume. Table II summarizes the test conditions.

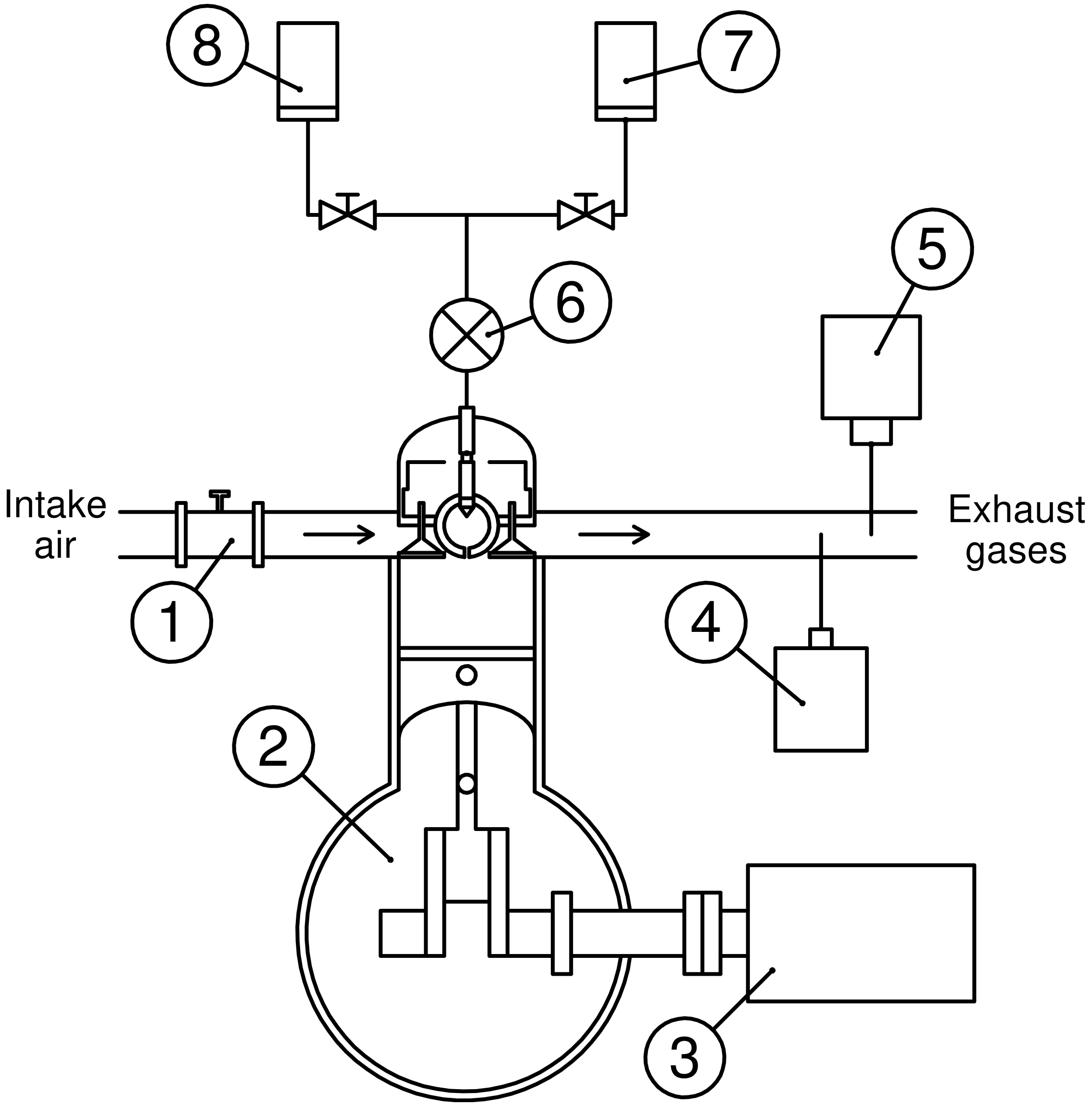


Figure 1. Schematics of the test bench: 1) air flow meter, 2) diesel engine, 3) dynamometer, 4) Bacharach PCA® 400, 5) BrainBee AGS-688, 6) Fuel meter, 7) diesel tank, 8) biodiesel tank

Table II. Conditions tested with the experimental bench

Test condition	Compression ratio	Torque [Nm]
1	17	1
2		3
3		5
4		7
5	19	1
6		3
7		5
8		7

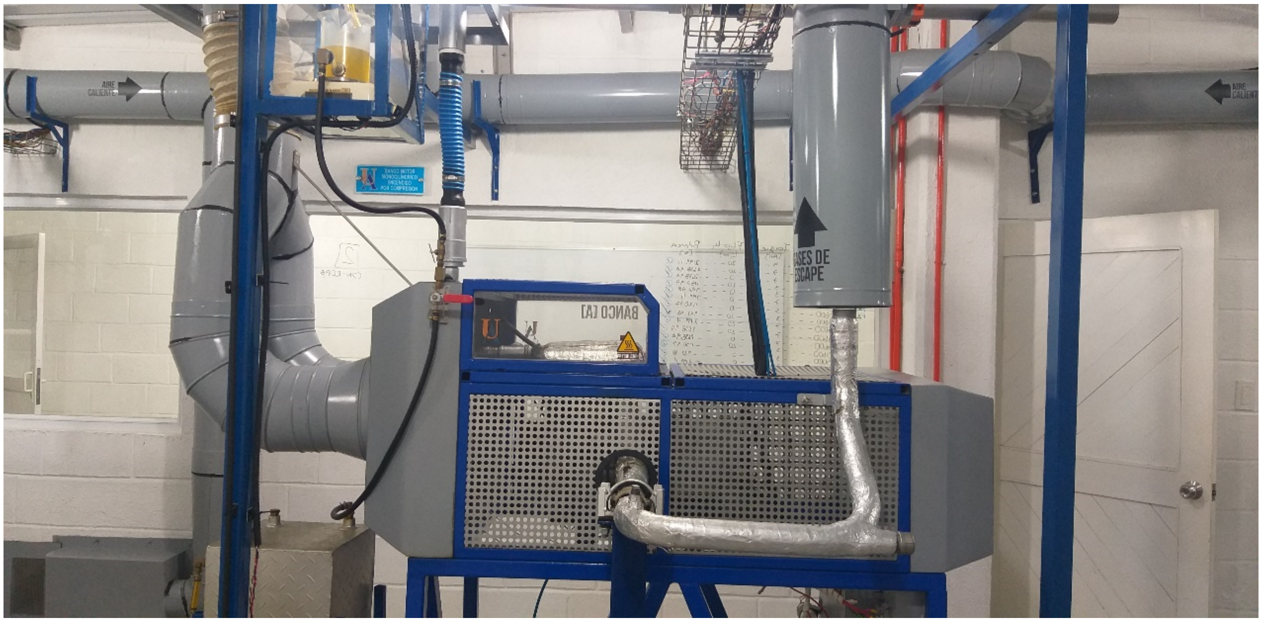


Figure 2. Experimental engine test bench

To control the load condition of the engine, a dynamometer was coupled to the experimental test bench. The emission analysis of the exhaust stream was performed using two gas analyzers, Brain-Bee AGS-688 and Bacharach PCA 400, in order to account for the pollution levels of CO, CO_2, HC, and NOx. Table IV shows the specifications of the emission measurement instruments.

Table III. Tested fuels and nomenclature

Nomenclature	Composition
Diesel	Diesel 100 %
AB5	Diesel 95 % + Algae oil biodiesel 5 %
AB15	Diesel 85 % + Algae oil biodiesel 15 %

Table IV. Gas analyzer specifications

Measured emission	Measuring range	Resolution
CO_2	0÷19,99 vol %	0,1 % vol
CO	0÷9,99 vol %	0,01 % vol
HC	0÷19,999 [ppm]	1 % vol
NOx	0÷3.000 [ppm]	1 ppm

The total uncertainties of the measurements of the experimental bench were calculated according to the Kline and McClintock method [24]. The results are summarized in Table V.

As for the biodiesel blend, algae oil produced from cyanobacteria (*Spirulina platensis*) was employed in the study. Transesterification was performed for the extraction of the algae oil by using zinc oxide and methanol. A three-necked flask was used to mix the compounds. The first stage of

Table V. Uncertainty list of main measurements

Measurement	**Uncertainty (%)**
Fuel flow meter	±0,3
Pressure transducer	±0,25
Crank angle encoder	±0,2
Time	±0,35
Engine torque	±0,2
Engine speed	±0,05
BSFC	±0,4
BTE	±0,5
CO_2	±0,1
CO	±0,1
HC	±0,25
Nox	±0,2

the process involved heating 50 mL of the mixture for 20 minutes. Then, the zinc oxide catalyst and methanol were added. The blend was maintained at a stirring speed of 550 rpm and a constant temperature of 65 °C for 60 minutes. Consequently, the biofuel layer was extracted with a separation funnel, which was washed in distilled water and dried in an oven at a temperature of 105 °C for 130 minutes.

The percentage of algae oil biodiesel substitution remained below 20 %, as previous research indicates that a higher percentage can cause engine problems that require modifications [11]. Therefore, two algae oil biodiesel blends were defined: AB5 and AB15. The composition of the fuels used in the study is shown in Table III. Notice that commercial diesel fuel was used as the baseline for the dual-fuel evaluation.

3. Thermal and fuel consumption metrics

This section provides a framework to evaluate the overall performance of the engine in dual-fuel operation mode according to thermodynamic features and fuel consumption. First, it is important to relate how much chem- ical energy (fuel) is converted into power. This is done by means of the brake thermal efficiency (BTE), which is calculated based on the first law of thermodynamics, as presented in Eq. (1).

$$BTE = 3,77 \times 10^{-4} \cdot \frac{T_q \cdot r}{\dot{m}_{fuel} \cdot LHV} \cdot 100\,\% \tag{1}$$

where T_q represents the brake torque of the engine in Nm, and r relates the rotational speed of the engine in rpm. $\dot{m}_{fuel}$ relates the mass flow rate of the fuel consumed, and LHV is the low heating value of the tested fuel.

The main fuel consumption metric of the experimental assessment corresponds to the brake-specific fuel consumption (BSFC), which relates the brake power of the engine (P_{br}) with the consumed fuel, as shown in Eq. (2).

$$BSFC = \frac{\dot{m}_{fuel}}{P_{br}} \tag{2}$$

4. Results

4.1. Calculation of fuel properties

The first approximation of the study corresponds to the calculation of the main physicochemical properties of the tested fuels, as presented in Table VI. Notice that these properties were calculated according to ASTM standards [25].

Table VI. Test fuel composition and nomenclature

Fuel	Units	ASTM D4868 Calorific value [MJ/kg]	ASTM D1448 Density [kg/cm^3]	ASTM D93 Flashpo int [°C]
Diesel	°C	42	0,826	67
AB5	MJ/kg	41,47	0,829	69
AB15	g/cm^3	39,98	0,833	72

Based on the results, it can be confirmed that biodiesel blends of algae oil feature lower calorific values in comparison with the baseline fuel. Particularly for the AB5 and AB15 blends, reductions of 1,26 and 3,59 % were obtained, respectively, compared to the standard diesel. This reduction will be examined in detail when discussing the thermal performance, since it might indicate a minimization of the energy discharged during combustion.

On the other hand, both the density and flashpoint of the biodiesel blends were significantly higher compared to pure diesel. Specifically, for the AB5 and AB15 blends, the density rose around 0,3-0,48 %, whereas the flash-point increased between 2-4,3 %. The latter indicates a positive pattern for implementing biodiesel blends since the manipulation of the fuel becomes much safer [8].

4.2. Cylinder pressure

Measuring the in-cylinder pressure throughout the cycle plays a central role in engine diagnosis, given that it provides valuable information about the combustion phenomena. Accordingly, Fig. 3 shows the pressure curve as a function of the crank angle for the tested fuels with compression ratios of 17:1 (CR 17) and 19:1 (CR 19).

According to Fig. 3, higher compression ratios boost the maximum cylinder pressure for all the tested fuels. In general, the peak pressure was achieved by pure diesel for both compression conditions, followed by the biodiesel blend with lower content of algae oil (AB5). The latter demonstrates that the incorporation of algae oil as a replacement fuel minimizes the pressure in the combustion chamber, reaching a maximum decrease of 6,83 %. Therefore, increasing the compression ratio of the engine can be considered to be a reliable mechanism to mitigate the pressure drop produced by implementing algae oil as a biodiesel blend. The results agree with the overall trend of different biodiesel blends while analyzing the same parameter [10], [24].

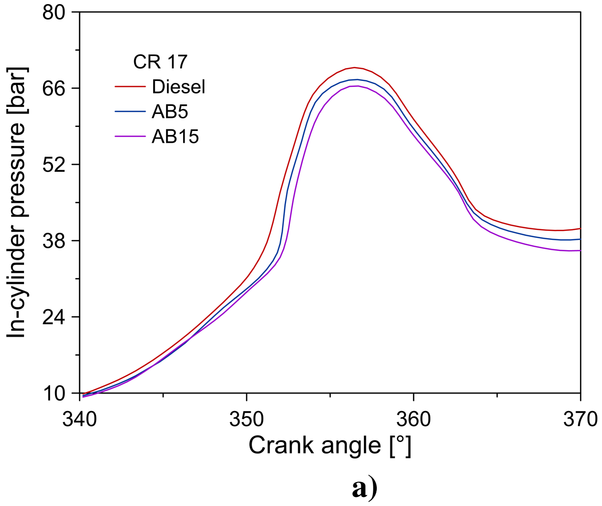


Figure 3. Cylinder pressure for an engine compression ratio of (a) CR 17 and (b) CR 19

4.3. Brake-specific fuel consumption (BSFC)

Fig. 4 shows the BSFC for the different fuels tested across the operating margin while analyzing the influence of the compression ratio.

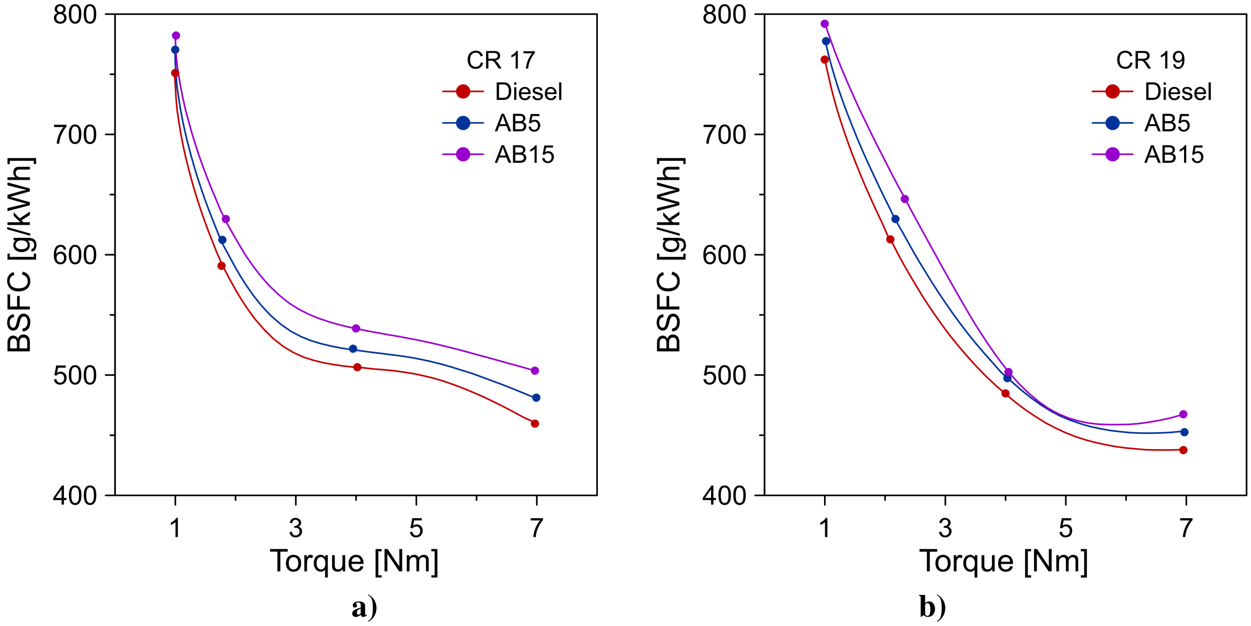
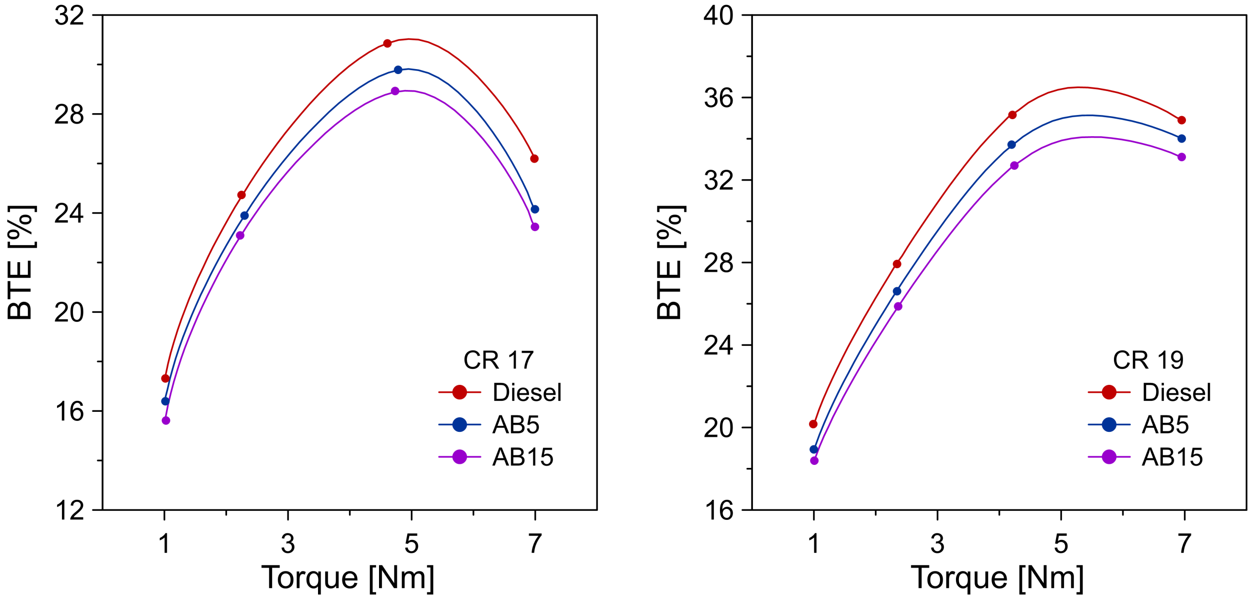


Figure 4. BSFC for an engine compression ratio of (a) CR 17 and (b) CR 19

Fig. 4 demonstrates that increasing the content of algae oil (Spirulina platensis) in the biodiesel blend intensifies the fuel consumption per power unit. On average, AB5 and AB15 fuels enlarge the BSFC by 3,07 % and 5,93 %, respectively, in comparison with diesel. This behavior can be attributed to the higher density of the biodiesel blend, as shown in Table IV. In line with the above, a higher density implies an increase in the fuel injected into the combustion chamber. The lower heating value of the biodiesel blends in comparison with commercial diesel can be regarded as a contributor to the intensification of the BSFC. Different studies have ratified this pattern with different biodiesel blends [8], [24]. On the other hand, a higher compression ratio minimizes the BSFC of all the tested fuels, especially at medium-high torque ranges. The latter is a consequence of higher combustion pressure, which contributes to increasing the power output of the engine [10], [24].

4.4. Brake thermal efficiency

The incidence of the implementation of biodiesel blends and variable compression ratios on the brake thermal efficiency (BTE) is depicted in Fig. 5.



a) **b)**

Figure 5. Brake thermal efficiency for an engine compression ratio of (a) CR 17 and (b) CR 19

According to the results, the main pattern is that the BTE has a bell-shaped curve with a maximum value for the middle range (5 Nm) of the torque. Diesel standalone operation features the highest BTE among the tested fuels, followed by the AB5 biodiesel blend, which ratifies the overall trend obtained from the cylinder pressure and fuel metrics.

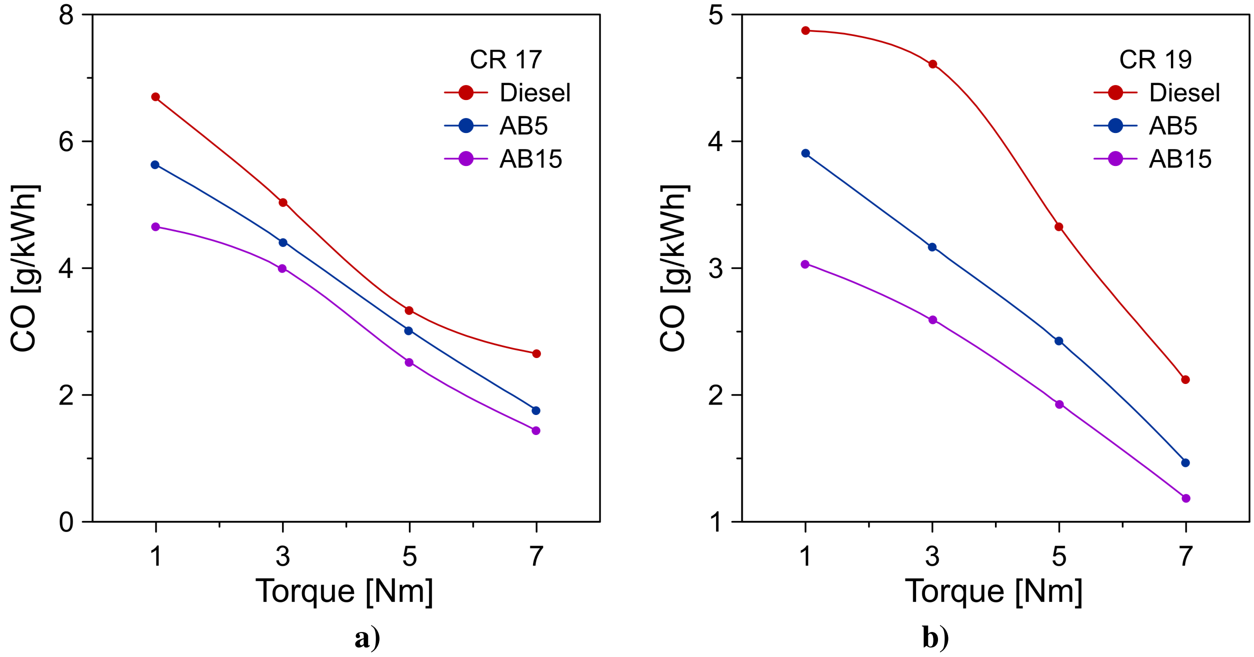
Moreover, increasing the compression ratio enhances the thermal performance by up to 13 %, which might be an indication that higher pressure ranges ensure a better mixing process in the combustion chamber. Specifically, increasing the algae oil in the biodiesel blend from 5 to 15 % reduced the BTE by around 2-5 %. This behavior can be explained by the higher density and lower calorific value compared to pure diesel (see Table VI). The next section provides a detailed examination of the emissions characteristics of the tested fuels at different operating conditions.

4.5. Emissions results

4.5.1. CO emissions

The first approximation to the pollution evaluation corresponds to the carbon monoxide (CO) emission levels by the biodiesel blends of algae oil under different operating conditions. Please note that commercial diesel has been used as the baseline for comparison. It is worth mentioning that CO formation is a consequence of partial oxidation of the fuel during combustion, which is governed by factors such as fuel type, in-cylinder pressure, fuel-air mixture, among others.

Fig. 6 shows that the incorporation of the biodiesel blend of algae oil produces a significant drop in CO emissions (between 15 and 30 % compared to pure diesel). This behavior can be attributed to the improved oxygen content in the fuel, which fosters complete combustion [17]. In general, lower load rates promote the emissions of CO, which may be a consequence of poor air-fuel mixture when the engine operates at low torque. An inappropriate temperature for combustion at low rates can also be mentioned as a possible reason for poor oxidation (formation of CO) [23].



a) b)

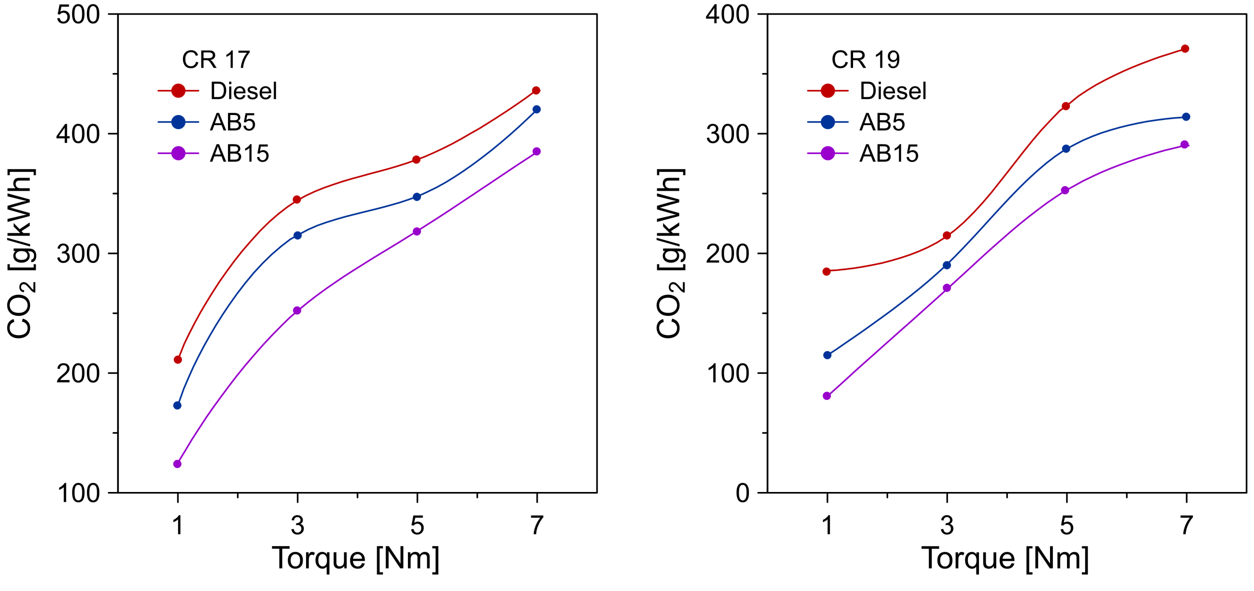
Figure 6. Carbon monoxide emissions for an engine compression ratio of (a) CR 17 and (b) CR 19

In terms of the biodiesel blend, increasing the algae oil fuel replacement from 5 to 15 % reduces the CO levels between 5 and 10 %, which demonstrates the positive features of the dual-fuel operating model in diesel engines.

This is a direct result of a higher oxygen content and a high cetane number, which results in shorter ignition delays. Lastly, increasing the compression ratio has a substantial impact on the emission levels, since it minimizes CO levels between 10 and 25 %, which can be attributed to the shorter ignition delay produced by the increased heat discharged during com- bustion. The aforementioned explanations for CO formation agree with related research works [12], [24].

4.5.2. CO_2 emissions

Fig. 7 shows the carbon dioxide (CO_2) emissions for the tested fuels along the operating margin. CO_2 formation is mostly associated with the CO levels, given that it is related to the oxidation process during combustion.



a) **b)**

Figure 7. Carbon dioxide emissions for an engine compression ratio of (a) CR 17 and (b) CR 19

Based on the results, the overall behavior of the CO_2 formation displays a direct relation with the torque, which is in agreement with the CO emissions presented in the previous subsection. This pattern is an indication of complete combustion as the engine load increases, which may be related to higher temperatures at high torque levels and faster ignition. This type of behavior has been reported in other biodiesel blends [10], [18]. Once again, the standalone diesel operation features the highest emission levels (190-440 g/kWh), whereas increasing the algae oil content in the biodiesel blend promotes CO_2 minimization (89-360 g/kWh). Specifically, both biodiesel blends, AB5 and AB15, reduced the CO_2 levels between 9 and 24 % compared to commercial diesel. Lastly, a higher compression ratio plays a central role in reducing CO_2 emission levels, which can be attributed to improved combustion performance.

4.5.3. HC emissions

Fig. 8 shows the hydrocarbon (HC) emissions for the tested fuels as a function of the operating torque. It should be pointed out that HC, just as CO, is produced during combustion, as a consequence of the partial oxidation of the air-fuel mixture.

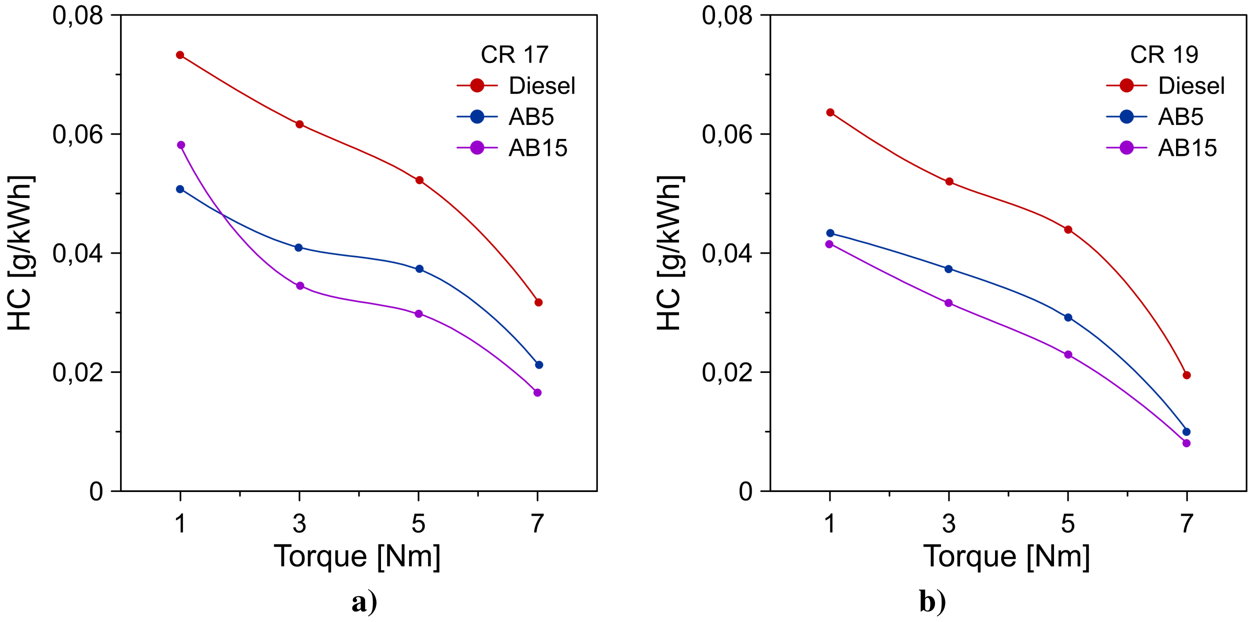


Figure 8. Hydrocarbon emissions for an engine compression ratio of (a) CR 17 and (b) CR 19

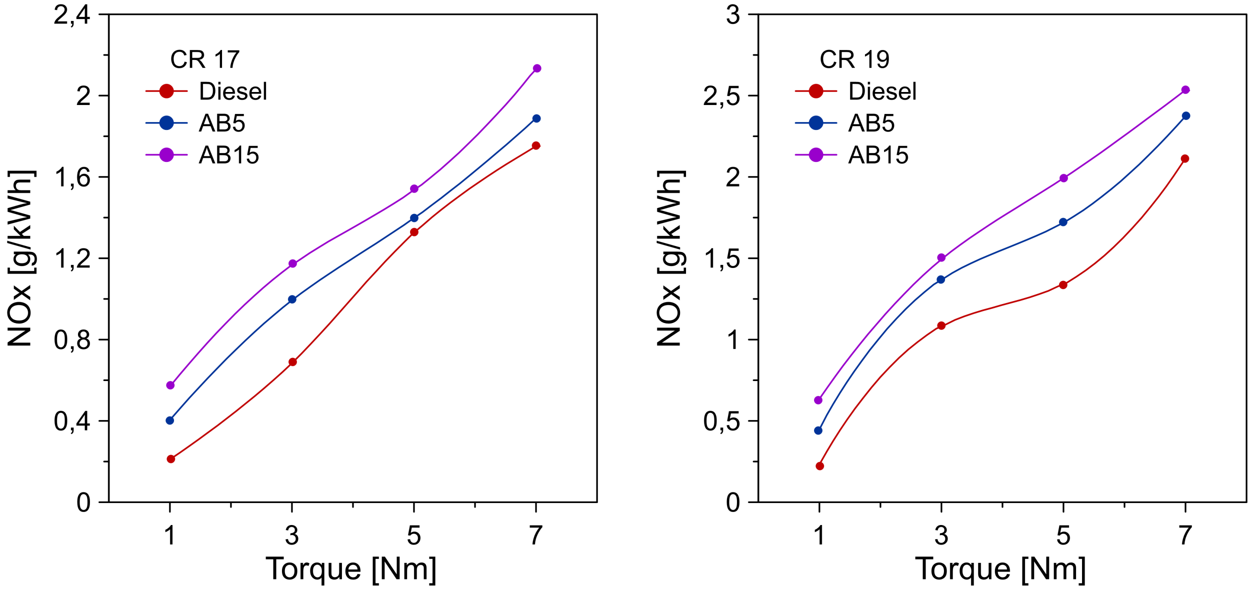
Fig. 8 shows that increasing both the torque and the compression ratio produces a substantial reduction of the HC emissions. Accordingly, the highest HC emission levels occurred in association with the lowest torque, which is attributed to the incomplete combustion under these operating conditions. Surprisingly, in the case of CR 17, the HC emission levels of AB15 were higher than the AB5 blend at the lowest torque condition (1 Nm). However, as the torque increased, the AB15 surpassed the decreasing trend.

On average, the algae oil biodiesel blends AB5 and AB15 reduced HC emissions by 31 and 45 %, respectively, in comparison with commercial diesel. This pattern can be attributed to the higher oxygen content in the biodiesel blends. Notice that increasing the algae oil content in the biodiesel blend contributes to lowering the HC levels. This behavior is supported by the results of other non-edible biodiesel blends based on the presence of methyl ester and the unsaturation of the structure of biodiesel. The contribution of a higher cetane number can be outlined as a possible explanation for HC reduction by the biodiesel blends, since it contributes to shortening the ignition delay.

4.5.4. NOx emissions

The formation of nitrogen oxides greatly depends on the temperature experienced during combustion (>1.000 °C), which creates an auspicious environment for reactions between oxygen and nitrogen [17]. The term NOx refers mainly to two major components, NO and NO 2 . Fig. 9 displays the results of the NOx emissions levels.

According to Fig. 9, the implementation of biodiesel blends of algae oil negatively impacts the minimiza- tion of NOx emissions. This behavior is explained by the enriched-oxygen nature of the biodiesel blends, which fosters nitrogen oxide formation [23]. Particularly, an increase of 13 and 38 % was observed for AB5 and AB15, respectively, in comparison with pure diesel. Similarly, hig-



a) **b)**

Figure 9. NOx emissions for an engine compression ratio of (a) CR 17 and (b) CR 19

her load rates represented by high torque ranges promoted NOx formation between 2-2,89 g/kWh, which can be attributed to higher in-cylinder pressure and temperatures which contribute to the reaction of nitrogen and oxygen to produce nitrogen oxides. In line with that, increasing the compression ratio also increases both temperature and pressure during combustion, which facilitates NOx formation. The overall pattern of the results ratifies this trend.

5. Conclusions

This research aimed to present a complete experimental assessment based on emissions and thermal characteristics in order to evaluate partial fuel substitution in a diesel engine with a biodiesel blend of algae oil from the species Spirulina platensis. The study incorporated different torque conditions (1-7 Nm) to examine a wide range of operations, and the effect of the compression ratio (CR 17 and CR 19) emerged as a unique contribution from former research. The operational performance was measured with commercial diesel as the baseline for comparison, while the algae oil content in the biodiesel blend was set to 5 % (AB5) and 15 % (AB15).

The results indicated that the implementation of algae oil as a biodiesel blend did not produce a dramatic variation in the fuel properties. In general, the behavior of the studied biodiesel blends can be summarized as follows: a 2,42 % reduction in calorific value, a 0,45 % density increase, and a flashpoint enlarged by around 3,67 %. On the other hand, increasing the CR fostered an almost 10 % higher pressure in the combustion chamber. Overall, turning operation from CR 17 to CR 19 boosted the in-cylinder pressure by 9,36, 9,28, and 7,08 % for pure diesel, AB5, and AB15, respectively. Consequently, the intensified pressure range magnified the BTE of the tested fuels. On average, the BTE increment for the biodiesel blends was around 17 % by raising the CR. Similarly, the impact of higher compression ratios was reflected on the minimization of fuel consumption metrics.

On average, diesel fuel, AB5, and AB15 showed reductions of 1,74 %, 1,97 %, and 2,05 % in the BSFC, respectively. Contrarily, increasing the content of algae oil from 5 to 15 % in the biodiesel blend produced a negative impact on combustion pressure, BTE, and BSFC, which is a direct consequence of the higher density and lower calorific values. Therefore, increasing the CR stands as a suitable mechanism to offset the undesired effects on thermal performance and fuel metrics. Despite reducing the overall performance, algae oil enrichment in the biodiesel blend exhibits remarkable results in terms of greenhouse gas mitigation.

In general, by establishing the algae oil content at 15 % (AB15), a maximum reduction of 38, 95 %, and 35 % was obtained for CO, CO_2, and HC emissions, respectively, compared to commercial diesel. This behavior can be attributed to the higher oxygen content and the high cetane number in the biodiesel blend. In contrast, the NOx emissions were intensified for higher algae oil replacement grades. This pattern can be explained by the enriched-oxygen nature of the biodiesel blend, which promotes complete combustion in the air-fuel mixture. It is worth mentioning that increasing both the compression ratio and torque range produced higher pressure (70-78 bar) and temperature during combustion, which entails an additional maximization of NOx formation (10-25 %). Higher ignition delay as a result of higher combustion pressure can also be mentioned as a potential explanation for the NOx increase. Lastly, the torque operating range had a significant impact on emission levels. Accordingly, increasing the torque range from 1 to 5 Nm minimized the CO and HC emissions, on average, by 64 and 55 %, respectively, whereas it boosted CO_2 and NOx levels. The maximization trend of the torque is related to the oxidation process of the air-fuel mixture during combustion, given that a maximum torque enables the appropriate environment (higher temperature and pressure) for the formation of oxides.

Finally, this study could verify the applicability of a compound methodology involving the implementation of an algae oil-biodiesel blend and increasing the CR, which stands as a suitable tool to improve the overall performance of diesel engines from a thermal and emissions perspective.

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