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Experimental Investigation of the Performance and Emissions of a Diesel Engine Fuelled by Blends Containing Diesel S10, Pyrolysis Oil from Used Tires and Biodiesel from Waste Cooking Oil

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Using tire-derived fuels can offer an alternative solution for tackling the problem of tire disposal. Similarly, biodiesel from waste cooking oil allows for the reduction of most environmental impacts caused by the incorrect disposal of oil. Thus, an analysis of blends containing traditional diesel, different amounts of pyrolysis oil from used tires and biodiesel from waste cooking oil has been proposed herein, with the aim of investigating the feasibility of using them in a diesel engine and analyzing their emissions and power in comparison with traditional diesel fuel. Tests were carried out using a single-cylinder diesel engine with a maximum rated power of 5.6 kW and its emissions were measured with a gas analyzer. The results revealed that using small amounts of tire pyrolysis oil in the blends (up to 5%) leads to a very small decrease in brake thermal efficiency (BTE) while emitting fewer CO and NO_x pollutants, when compared to neat diesel. However, adding higher quantities of tire-pyrolysis oil causes a notable loss in BTE while increasing CO, decreasing NO_x and emitting considerably more sulfur. Finally, replacing portions of diesel with biodiesel in diesel-tire pyrolysis oil blends decreased CO, but at the cost of increasing NO_x emissions. © 2019 American Institute of Chemical Engineers Environ Prog, 38:e13199, 2019

Keywords: diesel engine, pyrolysis oil from tires, biodiesel, exhaust gases

INTRODUCTION

It has become increasingly evident that the environment has limited resources, thus there has been a significant increase in concern regarding the issues of waste generation, pollution and disposal in general [1]. Therefore, used tires deserve special attention due to their extremely long decomposition time and large-scale production. As a matter of fact, according to a report from National Tyre Industry Association (ANIP) in 2015, over 68 million tires have been produced in Brazil alone [2].

Another environmental problem that has been increasingly discussed is the incorrect disposal of waste cooking oil, which can cause problems in sewage piping systems and leads to water and soil pollution.

Meanwhile, the worldwide growing energy demand has raised concerns. Fossil fuels, which are being widely used today, are able to meet energy needs, but are nonrenewable sources and account for a significant amount of greenhouse gas emissions, and generate the largest amount of emissions in strategic sectors, such as the energy/heat generation, industry, and transport sectors [3]. Thus, fuels produced from renewable sources (such as biodiesel) and waste in general (such as fuels derived from used tires) represent not only an alternative for energy generation, but also a solution to some major environmental problems in the world.

There are several alternatives for reusing waste tires which have already been proposed in the literature and are still under study and development, for example, coprocessing (cement, pulp and paper mills, and thermoelectric plants), granulation, lamination, devulcanization, civil construction applications, asphalt paving, and pyrolysis [4].

Tire pyrolysis (Figure 1) is a process in which used tires undergo thermal degradation without an oxidizing agent, so that no gasification reactions occur extensively [5–7]. This thermochemical process yields three main products: solids, gases, and liquids, the last one being used as a fuel due to its high calorific content.

Following this idea, Baškovič *et al.* have studied a diesel engine fueled by 100% tire pyrolysis oil, and have analyzed how performance improvements can be achieved by controlling fuel injection [8]. Tire pyrolysis oil was also used as a blend with diethyl ether (DEE) by Hariharan *et al.*, who concluded that the use of DEE can lead to less NO_x, while increasing HC, CO, and smoke emissions [9].

Hürdoğan *et al.* have evaluated performance and emissions of a DI four-stroke diesel engine fueled by blends of diesel with tire pyrolysis oil. The authors concluded that such blends present similar torque and power when compared to pure diesel fuel. The same study recommends further work to investigate the use of biodiesel in diesel-tire pyrolysis oil blends [10].

Martínez *et al.* [11] have compared the performance and emissions of a four-stroke diesel engine fueled by diesel only,

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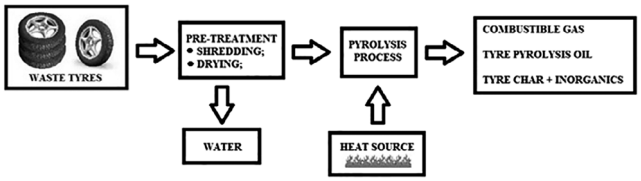

Figure 1. Simplified scheme of tire pyrolysis process.

and a blend containing 5% in volume of pyrolysis oil. The authors have observed that these fuels did not show significant differences in their combustion. They concluded that the blend containing pyrolysis oil presented a worse performance in terms of power output and fuel consumption and an increase of NO_x and particulate matter. Other researchers have shown that it is also possible to use tire pyrolysis oil in direct injection Diesel engines in the form of blends with other fuels, such as Jatropha Methyl Ester [12,13] and diesel [10,14].

Another commonly used biofuel is biodiesel, which is a biodegradable fuel produced with renewable resources from biomass, and can be produced from waste cooking oil [15]. Its application in compression ignition engines can be either in its raw form or in the form of blends with different proportions of diesel.

Many researches have been carried out on direct injection Diesel engines running on biodiesel, usually in the form of blends with diesel oil [16–18] and several other fuels such as tire pyrolysis oil [19,20], ethanol, diethyl ether [17], and methanol [21]. Generally, using biodiesel to fuel a diesel engine offers several advantages, such as less HC, CO, particulate, soot and sulfur emissions, and provides improved lubrication due to its low viscosity, besides presenting a higher cetane number when compared to regular petroleum diesel. However, the addition of biodiesel can lead to increased NO_x, corrosion in the fuel line and increased consumption as it has a lower heating value. Moreover, biodiesel products from different sources have different physical and chemical characteristics, which can lead to variable performance depending on the production source [22–24].

Alternative blends could be particularly useful in countries like Brazil, where there is no law defining waste cooking oil destination and there is a few used tires being used in pyrolysis plants. Furthermore, these fuels could not only result in an alternative to disposal of some environmental pollutants, but could also represent a way to reduce diesel prices in Brazil, which have increased by 27% from 2015 to 2017 [25].

In this context, the present work aims to study the use of one of these fuels—pyrolysis oil from used tires—in diesel cycle internal combustion engines, in the form of various blends containing traditional diesel oil and biodiesel from waste cooking oil. Specific consumption and BTE of a diesel engine were measured using these blends and also an emission analysis was also done in order to evaluate environmental impacts of the blends studied.

METHODOLOGY

Three fuels were used in the present research: biodiesel from waste cooking oil; used tire pyrolysis oil; and diesel S10, which is a commercial kind of diesel that contains about 7% of biodiesel usually sold in the Brazilian market. The nomenclatures adopted herein are: Biodiesel-UNIFEI, OPPU-UNIFEI, and diesel S10, which refers to biodiesel from waste cooking oil, used tire pyrolysis oil and diesel S10, respectively.

Biodiesel-UNIFEI was produced from waste cooking oil, methanol, and a basic catalyst through a transesterification process. OPPU-UNIFEI was donated for our use by a company named POLIMIX CONCRETO LTD. Diesel S10 was obtained from a local fuel station.

BIODIESEL PRODUCTION FROM WASTE COOKING OIL

In biodiesel production, 99.9% pure methanol was used as a reactant alcohol and sodium hydroxide (NaOH) as a catalyst, both manufactured by Synth™. An alcohol reaction in excess was chosen at a ratio of 6:1 with respect to the stoichiometric reaction required for waste cooking oil and a temperature of 60°C, which is commonly adopted for methanolysis [18]. The catalyst was added at a ratio of 0.45% in relation to the waste cooking oil mass.

For each liter of cooking oil, 257 mL of methanol and 4.20 g of catalyst were used, thus producing about 780 mL of biodiesel as a product. A detailed procedure to produce biodiesel is shown by the flowchart in Figure 2. Pictures of the process are shown in Figure 3.

Physicochemical characterization of fuels—diesel S10, used tire pyrolysis oil (OPPU-UNIFEI) and Biodiesel-UNIFEI

Pyrolysis oil [26] was characterized by the Institute of Technological Research (IPT). The characterization of biodiesel from waste cooking oil was adopted from the National Renewable Energy Laboratory (NREL) in the fourth edition of a report entitled "Biodiesel - Handling and Use Guide" [27]. The characterization of diesel S10 was in accordance with the ratio of carbon and hydrogen defined by ISO 8178-1, and sulfur content was adopted in accordance with the maximum percentage accepted by Brazilian legislation through Resolution ANP 50. A 7% biodiesel content in diesel S10 was designated, under Brazilian law 13.033 in 2016 [28]. All specific weight values were obtained experimentally. The measured and adopted parameters are presented in Table 1.

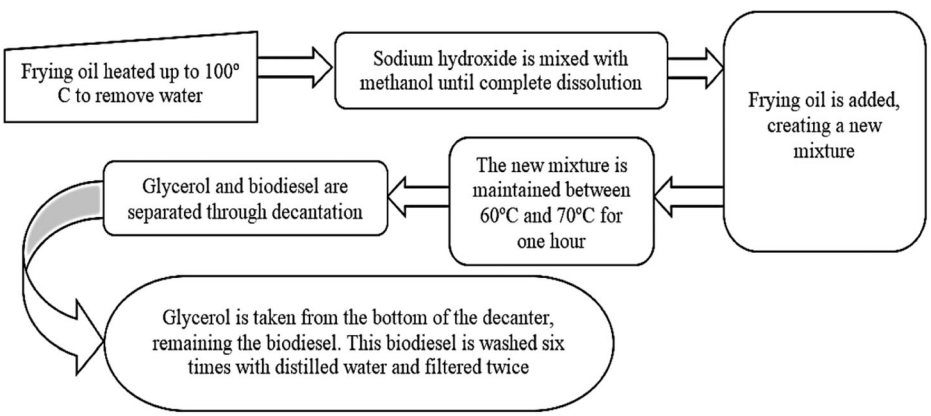

Figure 2. Cooking oil biodiesel production through transesterification process.

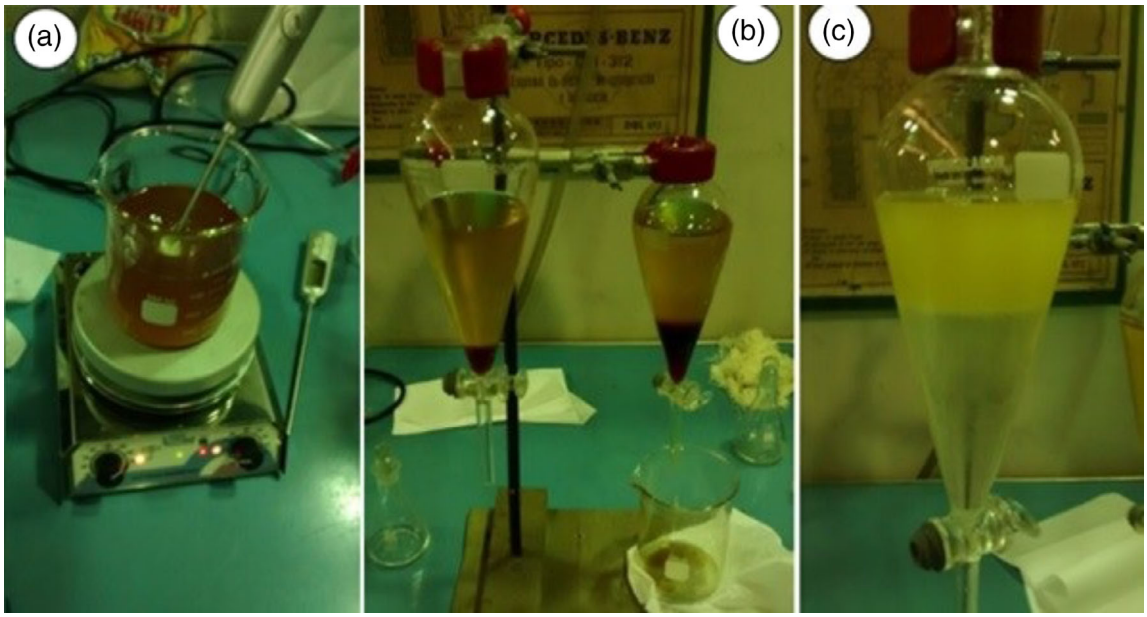

Figure 3. (a) mixture alcohol-catalyst-oil; (b) separation between biodiesel (above) and glycerol (below); (c) biodiesel (above) washed with distilled water (below). [Color figure can be viewed at **wileyonlinelibrary.com**]

Test Bench

Tests were conducted with a YANMAR NSB 75 R single cylinder diesel engine (see Table 2). For this purpose, the engine was set at a certain engine speed and left for some time to reach stabilization. Once stabilized, five measurements of fuel consumption and emissions were made for each test condition.

The internal combustion engine test bench used to carry out the experiments in the present research is located in the Thermal Machines Laboratory (LMT) in the Institute of Mechanical Engineering at the Federal University of Itajubá (UNIFEI), Brazil. The test bench is composed of a single cylinder engine that has its axis coupled to a hydraulic brake, which applies a certain load (fixed at 5.9 N) to the engine, set by its force control valve.

Engine fuel consumption was measured under different conditions to evaluate engine specific consumption and BTE. All items of equipment that make up the test bench are shown in Figure 4 according to their disposition in the LMT.

Table 1. Description of the fuels used for preparing the mixtures.

Property	Diesel S10	OPPU-UNIFEI	BIODIESEL-UNIFEI
C (%)	85.83*	87.1††	77**
H (%)	13.40*	9.65††	12**
N (%)	–	0.6††	–
O (%)	0.77**	1.76††	11**
S (%)	0.001†	0.89††	0.0024**
Specific Weight (g/mL)	0.8270††	0.9207††	0.8568††
Kinematic viscosity (cSt)	2.0–4.5†	5.153††	4.0–6.0**
Lower heating value (kJ/kg)	42,277††	39,890††	37,652**

*Based on ISO 8178-1.
**Based on biodiesel composition according to NREL, 2009.
†Based on brazilian legislation.
††Measured value.

A LANCOM III meter was used to measure exhaust emissions. For this purpose, the probe tube must be inserted into a hole in the engine exhaust and a sealing cone must be used to prevent gases from leaking. Gases in the probe are directed to an emission analyzer and results are processed and supplied by the equipment.

Accuracy of devices used in this research is shown in Table 3. These values were set according to the manufacturers' instructions for each piece of equipment.

CHARACTERIZATION OF FUEL BLENDS AND EXPERIMENTAL DATA FROM TESTS

The blends used consisted of combinations of diesel S10 oil, OPPU-UNIFEI and Biodiesel-UNIFEI. Properties and LHV for each blend are presented in Table 4. Firstly, the blends containing only Diesel and OPPU-UNIFEI were made, in order to check how the latter would affect engine operation. Then, the blends containing Biodiesel-UNIFEI were made, to verify how they could reduce emissions of the diesel-pyrolysis oil blends that had been made. Five measurements were taken per test condition and all procedures were carried out according to Brazilian standard NBR 6396. As engine stabilization is not fully defined by the standard, it was decided to carry out the measurements during the stabilization period, thus premeditating their subsequent disposal with the aim of tracking data variation over time. An analysis of these values allowed observation from the moment these values became constant, after

Table 2. Engine characteristics.

Diesel engine	
Brand	YANMAR NSB 75 R
Type	Alternative
Characteristics	4 Strokes 1 Cylinder Water cooled
Cylinder diameter	8.0 cm
Piston stroke	8.5 cm
Rotation	1800–2400 rpm
Power rating	5.5–7.5 CV
Compression ratio	21:1

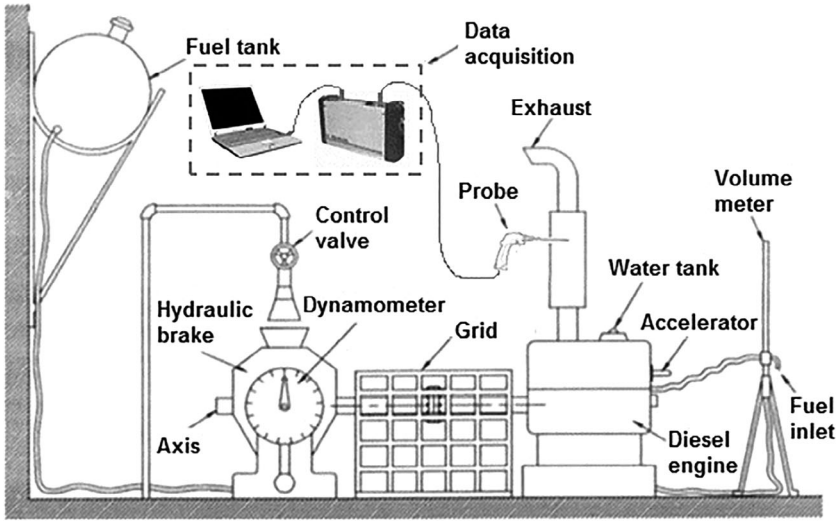

Figure 4. Sketch of test bench.

Table 3. Accuracy of some devices used.

Equipment		Brand	Accuracy
Speed meter device		Microtest	± 1 rpm
Chronometer		Guepardo	± 0.01 s
Hydraulic brake		Junkers Bremsen	± 0.1 kgf
Portable gas analyzer	O_2	LANCOM III	± 1%
	CO Low		± 2%
	CO (H_2 compensated)		± 2%
	CO High		± 2%
	SO_2		± 2%
	NO		± 2%
	NO_2		± 2%
	CO_2		± 0.5% vol.
	H_2S		± 2%
	C_xH_y		Application dependent

which there would be a satisfactory stabilization for the present research.

As the test in question involves partial loads, Brazilian standard NBR 6396 determines that values referring to fuel consumption should not vary any more than 5% in relation to the average of each test condition. Values which did not meet standard conditions were discarded. Emissions should also be in accordance with the procedure for analyzing average consumption, and those values which were not in accordance with the Brazilian Standard were discarded. These values, however, underwent a statistical analysis according to the Thompson Tau method, aiming to remove outliers—values significantly different from the standard of each condition.

Moreover, regarding the emissions' analysis, the values presented by the gas analyzer were corrected and processed by following the procedure determined by the ISO 8178-1 standard.

RESULTS ANALYSIS

As mentioned previously, the experimental results underwent transformations so that the final result presented would meet the ISO 8178-1 standard. The flowchart in Figure 5 shows the procedure that was adopted to perform the calculations and obtain the final results.

The results were obtained through the equation presented by the NBR 6396 standard. Table 5 presents the equations used.

SPECIFIC CONSUMPTION AND ENGINE PERFORMANCE

For each engine speed range, values of fuel consumption, consumption time, actual speed, and force exerted on the dynamometer were measured during the experiments (loading was kept at 5.9 N). Parameters such as specific consumption, mechanical power and mechanical performance were calculated from the data obtained during the tests by following the

Table 4. Mixtures composition.

Mixture name	Diesel S10 (% mass)	OPPU-UNIFEI (% mass)	BIODIESEL-UNIFEI (% mass)	Specific weight (kg/m^3)	Lower heating value (kJ/kg)
Diesel	100	–	–	827.68	42,277.02
OPPU 5	95	5	–	834.92	42,157.65
OPPU 10	90	10	–	840.00	42,038.28
OPPU 5—B5	90	5	5	833.32	41,926.40
OPPU 10—B10	80	10	10	839.84	41,575.78

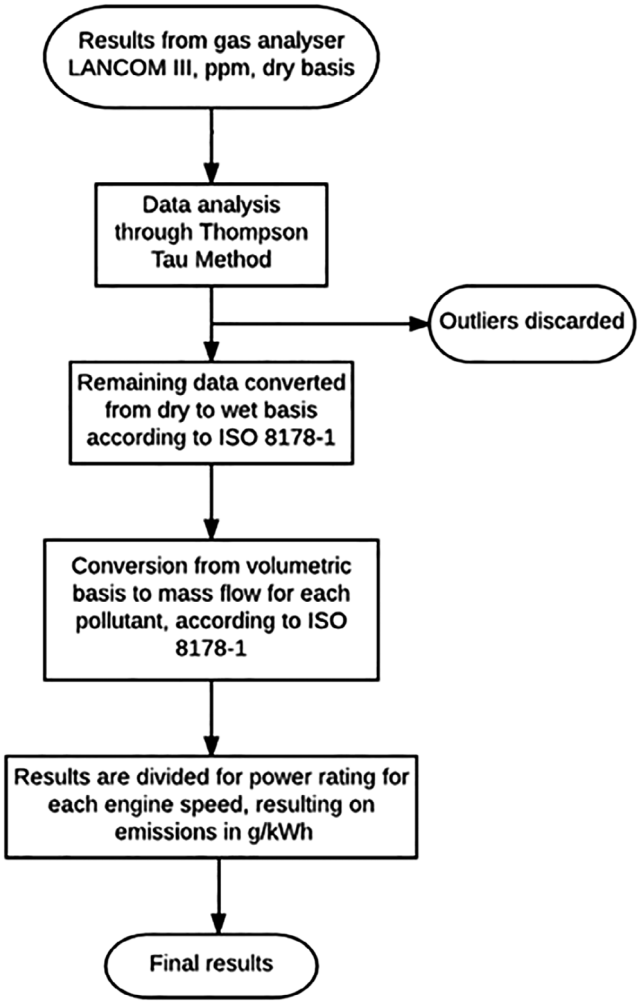

Figure 5. Experimental emission analysis procedure.

calculation procedure described in Brazilian standard NBR 6396. Calculated values are presented in Figures 6 and 7.

As expected, specific consumption (Figure 6) increased as there was a reduction of diesel S10 in the blend, which is mainly due to the difference of lower heating values, as can be seen in Table 4. Thus, blends with a smaller amount of diesel should consume more fuel to maintain constant power.

The blend that presented the highest specific consumption value was OPPU 10-B10, followed by OPPU 10 and OPPU 5-B5, which obtained very similar results, as they contain the same amount of diesel S10. The biodiesel blend presented a slightly lower consumption at low speeds, probably due to better combustion of biodiesel, as it has a relatively large amount of oxygen in its composition and therefore provides a local source of oxidant.

The BTE curves (Figure 7) presented exactly what was expected when compared to specific consumption curves. OPPU 10-B10 presented the lowest BTE. These curves follow an opposite pattern in comparison with the specific consumption curves, as BTE increases as consumption decreases (for the same power). In general, BTE values were found to be lower than those of modern diesel engines, both due to the wear of the used engine and the fact that it was not built for using the tested blends. As mentioned, even diesel S10, sold as fuel for diesel engines, and does not consist of pure diesel, but a mixture of diesel and about 7% of biodiesel.

Table 5. Equations for power and consumption in internal combustion engines.

	Equation	Symbols legend
Fuel consumption	$m_c = \frac{V \cdot \rho}{t} \cdot 3.6 \cdot 10^{-3}$	m_c = fuel mass flow rate (kg/h); V = consumed fuel volume (cm^3); ρ = fuel specific weight (kg/m^3); t = fuel consumption time (s).
Shaft power	$P_e = 0.001 \cdot F \cdot n$	P_e = shaft power (CV) n = rotation (rpm); F = dynamometer force (kgf).
Torque	$T = \frac{P_e \cdot 716.2}{n}$	T = torque ($kgf \cdot m$); P_e = shaft power (CV); n = rotation (rpm)
Fuel power	$PC = 1.360 \cdot m_c \cdot PCI$	PC = fuel power (CV); m = fuel mass consumed per time unit (kg/s); PCI = fuel lower heating value (kJ/kg).
Fuel specific consumption	$Ce = \frac{1000 \cdot m_c}{P_{ef}}$	C_e = fuel specific consumption (g/CV·h); m = consumed fuel mass flow rate (kg/h); Pe = shaft power (CV).
Global efficiency	$\eta_g = \frac{P_e}{PC} \cdot 100$	η_g = global efficiency (%); P_e = shaft power (CV); PC = fuel power (CV).
Power lost in the engine	$P_{pm} = PC - P_e$	P_{pm} = power lost in the engine (CV); P_e = shaft power (CV); PC = fuel power (CV).
Effective power	$P_{efR} = \frac{P_e}{\alpha A}$	P_{efR} = effective power (CV); P_e = shaft power (CV); αA = correction fator for environmental conditions according to NBR 6396.

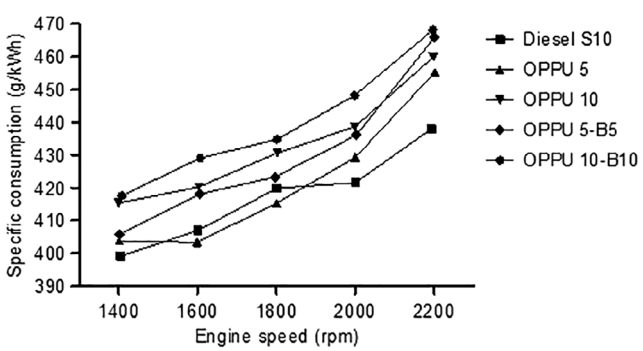

Figure 6. Variation of specific consumption with engine speed.

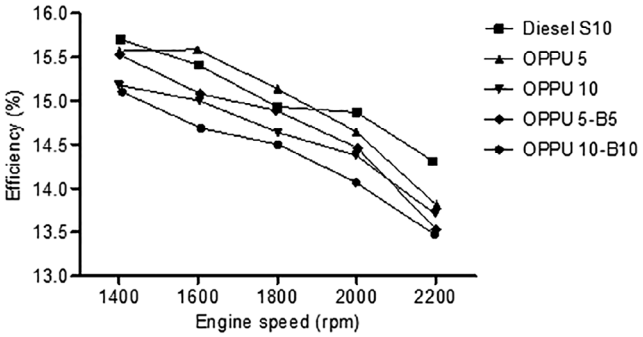

Figure 7. Variation of global efficiency with engine speed.

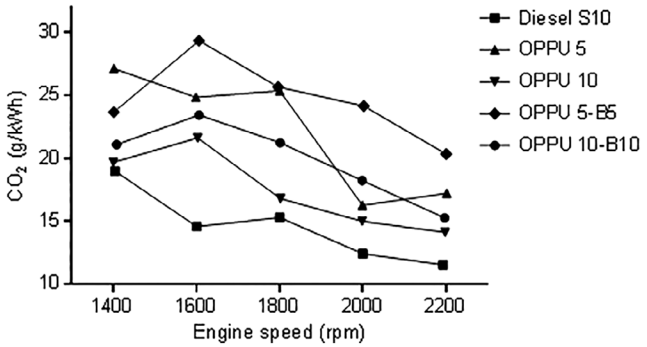

Figure 9. Variation of CO_2 emissions with engine speed.

EXHAUST GAS EMISSIONS

The results obtained by the gas analyzer are presented in Figures 8–10. For sulfur dioxide emissions (Figure 11), a theoretical analysis was conducted according to section 7.5.3.8 of ISO standard 8178-1, which suggests that "the emission of SO_2 must be calculated from the sulfur content of the fuel being used, since it has been demonstrated through experience that the use of a direct measurement method for SO_2 does not provide more accurate results." Thus, the emission factor of this pollutant is obtained by the ratio between gas mass flow (calculated according to ISO 8178-1 procedures) and uncorrected brake power (according to NBR 6396).

DISCUSSION OF EMISSIONS RESULTS

Carbon monoxide is basically the result of an incomplete combustion of the fuel; thus it was expected that as diesel mass concentration in the blends is reduced, CO emission becomes larger. However, this assumption was not as expected, which can be justified by the presence of oxygen in the composition of biodiesel and OPPU-UNIFEI. For blends OPPU 5 and OPPU 5-B5, emissions presented the lowest values, especially OPPU 5-B5 which has more oxygen in its composition. OPPU 10 has the same amount of diesel as OPPU 5-B5, but the former has a relatively larger emission than the latter, as biodiesel has more oxygen than OPPU-UNIFEI in its composition. On the other hand, OPPU 10-B10 emitted more CO than other blends, thus demonstrating that the presence of oxygen in fuel composition is not the only determining factor in carbon monoxide generation. This is because combustion is more incomplete, regardless of the presence of oxygen, as it contains an even smaller amount of diesel, which compromises combustion; thus CO is not oxidized.

Carbon dioxide emissions confirm what was mentioned regarding CO emissions, i.e., as there is more oxygen in the component's composition, more CO can be oxidized into CO_2. It can be observed that, in descending order, the largest emissions of CO_2 were from OPPU 5-B5, OPPU 5, OPPU 10-B10, OPPU 10, and finally regular diesel. The lower CO_2 emissions of diesel can be explained by the fact that there is less oxygen in its composition.

Nitrogen oxides can be formed from atmospheric air as thermal NO_x (which is formed at high temperatures) or prompt NO_x (which is formed in the frontal region of the flame and is prevalent in rich blends). There is also the so-called fuel NO_x which is generated from nitrogen that is present in the composition of the fuel itself. In this context, NO_x formation levels depend on factors such as combustion chamber temperature and the presence of nitrogen in the fuel, as well as the stoichiometric reaction. Although blends with only OPPU-UNIFEI and diesel S10 present nitrogen in their composition, there were, in general terms, smaller NO_x emissions by such blends in comparison with diesel. For diesel S10, it is plausible that high emission levels were due to higher temperatures in the combustion chamber on account of their higher heating value. In addition to this factor, the lower viscosity of diesel S10 limits the fuel spray cloud in the combustion chamber, thus the blend reaches a smaller region than the one that could have been reached by more viscous oils. Moreover, the combustion reaction approximates the stoichiometry reaction and prompt NO_x generation is increased.

Lower NO_x values were observed for OPPU-10, which is probably due to its lower heating value, thus resulting in a flame at a lower temperature and reducing NO_x formation. Blends containing biodiesel also presented lower NO_x levels than regular diesel, although they were generally higher than those observed in blends containing only OPPU-UNIFEI and regular diesel.

It is expected that practically all sulfur contained in the fuel is going to be oxidized into SO_2, which makes it reasonable to expect that OPPU 10-B10 would obtain the highest emission levels of this pollutant, followed by the blend with 5% OPPU-UNIFEI. These results indicate that the main environmental

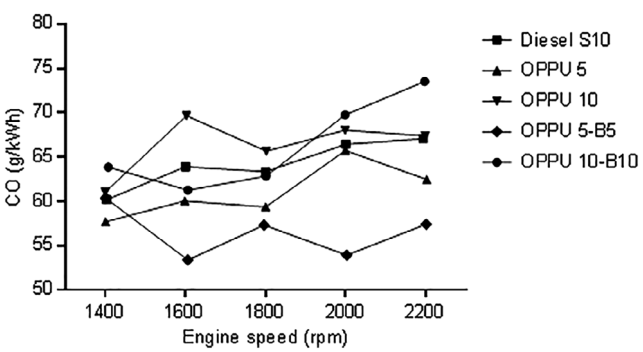

Figure 8. Variation of CO emissions with engine speed.

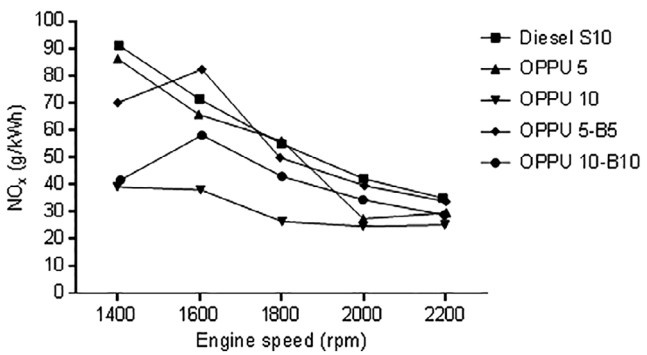

Figure 10. Variation of NO_x emissions with engine speed.

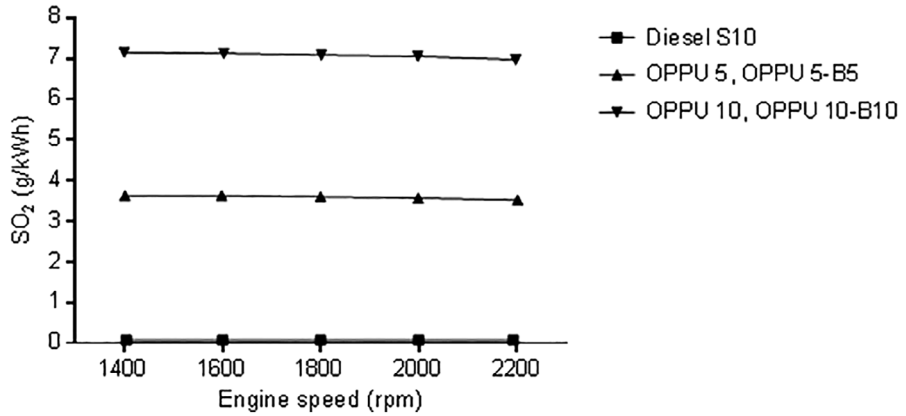

Figure 11. Variation of SO_2 (theoretical) emissions with engine speed.

concern regarding the combustion of crude tire oils, such as OPPU-UNIFEI, is its high sulfur level, which directly reflects the amount of SO_2 and other sulfur compounds emitted by the exhaust.

Although not experimentally measured, smoke is expected to be higher for diesel-tire pyrolysis oil blends, as this fuel has often been related to increased smoke opacity [4,12]. However, the addition of biodiesel in the mixture tends to decrease smoke, creating a compensation for the pyrolysis oil effect [12,29,30].

CONCLUSION

The present research evaluated the performance and emissions pattern of a 5.6 kW Diesel engine fueled by different blends of diesel S10, used tire pyrolysis oil and biodiesel from waste cooking oil. The tests were carried out maintaining a constant load and measuring the parameters for each speed.

From the data analysis, it is possible to verify the feasibility of using blends containing diesel S10 and small amounts (up to 5% by mass) of OPPU-UNIFEI in internal combustion diesel cycle engines. These blends show BTE and consumption that is similar to those of S10 diesel, with lower CO and NO_x levels in most tested aspects. However, caution is recommended regarding sulfur emissions, as the analysis indicates that all the blends used would result in significantly higher SO_2 levels than traditional fuels. Solutions to this problem are possible by desulphurising the fuel and treating the exhaust gas. Besides the sulfur emissions, using higher portions of tire-pyrolysis oil causes a more significant loss in BTE while increasing CO and decreasing NO_x. Finally, it was noticed that CO in diesel-tire pyrolysis oil blends can be reduced by replacing a small amount of diesel with biodiesel sourced from waste cooking oil. However, this change has the side effect of leading to increased NO_x emissions.

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Nomenclature

ANIP	National Tyre Industry Association
ANP	National Petroleum Agency
BTE	brake thermal efficiency
CO	carbon monoxide
CO_2	carbon dioxide
DEE	diethyl ether
DI	direct injection
HC	hydrocarbon
IPT	Institute of Technological Research
LHV	lower heating value
LMT	thermal machines laboratory UNIFEI
NaOH	sodium hydroxide
NO_x	nitrogen oxide
NREL	National Renewable Energy Laboratory
OPPU	pyrolysis oil from used tires
SO_2	sulfur dioxide
UNIFEI	Federal University of Itajubá

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