PERFORMANCE AND EMISSIONS IN AN AGRICULTURAL ENGINE FUELED ON MACAÚBA COCONUT BIODIESEL

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ABSTRACT

Macaúba coconut (Acrocomia Aculeata) is a palm native in South America, mainly Brazil, and with presence in Central America, Caribe and South region of Florida (USA), and it has been outstanding as feedstock for oil production with good characteristics for pharmacy industry, cosmetics and biofuels. The objective of this work was to evaluate the applicability of this oil for biodiesel production followed by its use in an agricultural engine, evaluating its power and torque when fueled on blends of 10 and 20% in fossil diesel, as well as perform emissions tests and fuel consumption evaluation. Biodiesel has been experimentally produced through methyl route, using homogeneous basic catalyst in a ultrasonic reactor with mechanical stirring, characterized at laboratory and tested on bench., through NRSC cycle. Lab tests have shown good performance and compatibility with biodiesel currently commercialized in Brazilian Market. Emissions are in conformity with PROCONVE MAR-I legislation for agricultural engines, with a trend of reduction of carbon monoxide and particulate matter. Tests have also shown that macaúba biodiesel is a good option to be added to fossil diesel for commercialization in Brazilian Market.

PREFACE

Rudolf Diesel did his tests using peanut oil, around one hundred years ago, and he probably didn’t wonder how much that kind of engine would be present in the future of coming generations. Not only passenger cars, but trucks, busses, ships or even trains. Diesel fuel is used in urban and rural areas, in the most remote and inhospitable areas around the Earth. Preoccupation with depletion of world petroleum reserves, prices oscillation in different markets, political disputes e more recently, efforts for reduction of global warming effects have been driving the scientists and researchers to develop new fuels, mainly those renewable.

Some countries have larger territories, where it is possible to develop agriculture activities and with favorable weather, for instance, Brazil. On the other hand, the use of nuclear energy, coal burn, or even fuel oil for power generation still are part of energy matrix in several countries around the world, in Asia or even in Europe. Brazil is recognized world widely thanks to its energy matrix, with considerable use of renewable energy. Ethanol is widely used for decades and today the most part of passenger cars sold in Brazil has flexfuel technology, able to run on gasoline or ethanol, in whatever proportion. Ethanol drives an important industrial chain, generating thousands of employment opportunities, and in a similar way, other alternative fuels have been increasing their participation, for example biodiesel and biomethane. They make possible to Brazil important emissions reductions, what can make feasible, for decades, the use of internal combustion engines without the obligation of electric cars, traffic prohibitions, among other strategies already applied in other parts of the world.

Biodiesel is commonly obtained from several feedstocks, being vegetable or animal sources. There are more than 350 different feedstocks, form first, second or third generations, competing directly with food, reusing waste residues (from agriculture, animal fat, among others) or even those that have no relation with food, for instance algae and wood, among others. Brazilian biodiesel is composed mostly by soya bean oil and tallow, but there are also other sources, for example chicken fat, cotton, among others. Brazilian biodiversity makes possible the development of several souces, as macaúba.

The new fuel shall have good behavior and characteristics in comparison with fossil fuels to become feasible. But unavoidably, it brings some challenges. Difficulties with long storage (due to the oxidation), lower performance when applied in higher dilution percentages due to lower calorific power, increased consumption and in more critical situations, the reduction in engine useful life. Macaúba biodiesel can contribute for reduction in emissions, outstanding as a good choice for use in diesel engines in the next years.

Macaúba, a palm tree present mainly in southeast and middle west regions of Brazil, but with incidence also in north and northeast, other countries in South America and Caribe and even in the South region of United States, has been object of several studies focusing the species improvement and productivity increase, since it has capacity of oil production tem times higher than soya been, considering the same planted area. Good results as these have brought some discussions about the fuel quality itself, as well as effective emissions reduction, possible impacts on the fuel consumption and performance, among other characteristics. In this research, it was described a set of several characteristics of this oleaginous, biodiesel produced from it and its outcomes when fueled in an agricultural engine.

The fuel was produced from macaúba oil supplied by Cooper Riachão, a cooperative of small agriculture producers located in north region of Minas Gerais state. Biodiesel has been characterized in accordance with ANP resolution 45 from 2014 and used as a fuel in an agricultural engine N67 in dynamometer tests, according to ISO 14396 and ISO 8178 standards.

1. BIODIESEL

Biodiesel is defined as methyl or ethyl esters obtained from vegetable oils or animal fat [1]. It is produced from the transesterification of oil or fat with the addition of an alcohol, for instance, methanol, under controlled conditions, in the presence of a catalyst. It is used in internal combustion engines with compression ignition. It is produced from several sources, such as oleaginous plants, recycled cooking oil or animal fat. Since the plants produce oils using sun light and air, these oils are considered as renewable. Animal fats are produced when the animal eats plants or other animals, and those ones are also renewable. Recycled cooking oils are mostly obtained from plants, but they can also contain animal fat. These oils are recycled and renewable. The production process of biodiesel transforms oils and fats in long chain esters, known as FAME (*Fatty Acid Methyl Esters*) or FAEE (*Fatty Acid Ethyl Esters*). This process is known as transesterification.

2. MACAÚBA

Macaúba palm (*Acrocomia aculeata*) (Figure 1) is a native specie that has been outstanding among the exotic forest species, successfully adapted to Brazilian conditions. Minas Gerais is one of the main states where this specie occurs, having a law that gives incentives for the cultivation, extraction, commercialization, consumption and transformation of Macaúba and other oleaginous palms, named Pró-macaúba (Law no. 19.485).

The north region of the state outstands because of its harvest and fruits processing, for instance, Mirabela, district of Montes Claros, where it is installed Cooper Riachão.

The major interest in this species is the utilization of oil extracted from its fruit for biodiesel production. Since it is a species with big potential of utilization, not only for biodiesel, but also for other products, its study becomes relevant, mainly to encourage researches about habits still unknown and development of technologies that favor the sustainable exploitation.

This palm three is a native species whose vegetable formation varies, and it can be found in savannah, open forests and other vegetable formations in tropical America. The family to which it belongs, Arecaceae, has, only in central region of Brazil, around 11 kinds of palms, with at least 44 members, and Acrocomia aculeata is one of the most important ones (Jacq.) Lodd. Ex Mart [2].

Figure 1 – Macaúba palm *(Acrocomia aculeata)*

2.1. Macaúba oil production

It was used in this project a macaúba oil batch with initial acidity as 46%, and, after its recuperation by glycerolysis – procedure through what the free fatty acids, under controlled conditions of temperature and pressure are transformed in triglycerides, making possible the transesterification – achieved 0,71%, being then prone for biodiesel production. The oil has been characterized at laboratory, according to table 1.

Table 1 – Macaúba oil profile in comparison w/ soya + animal fat oil

Carbon chain: nº of unsaturations	Fatty acid	Chemical formula	Macaúba (% weight)	Soya bean (% weight)	Animal fat (% weight)
C8:0	Caprylic	$C_8H_{16}O_2$	0,163	-	-
C10:0	Capric	$C_{10}H_{20}O_2$	0,142	-	0,160
C12:0	Lauric	$C_{12}H_{24}O_2$	1,343	-	0,190
C14:0	Myristic	$C_{14}H_{28}O_2$	0,483	0,200	1,590
C16:0	Palmitic	$C_{16}H_{32}O_2$	15,346	11,350	22,400
C16:1	Palmitoleic	$C_{16}H_{30}O_2$	2,913	0,050	4,200
C16:2	Palmitic	$C_{16}H_{32}O_2$	-	-	0,330
C16:3	Palmitic	$C_{16}H_{32}O_2$	-	-	0,430
C18:0	Stearic	$CH_3(CH_2)_{16}COOH$	1,701	4,150	15,270
C18:1	Oleic	$C_{18}H_{34}O_2$	56,681	25,300	40,400
C18:2	Linoleic	$C_{18}H_{32}O_2$	17,381	50,600	12,430
C18:3	Linolenic	$C_{18}H_{32}O_2$	1,504	8,200	2,230
C20:0	Arachidonic	$C_{20}H_{40}O_2$	0,143	0,150	0,200
C20:1	Eicosenoic	$C_{20}H_{40}O_2$	0,254	-	0,010
Others			1,946	-	0,150
Saturated			19,960	15,850	39,870
Unsaturated			60,488	25,350	44,660
Poli unsaturated			19,552	58,800	15,470

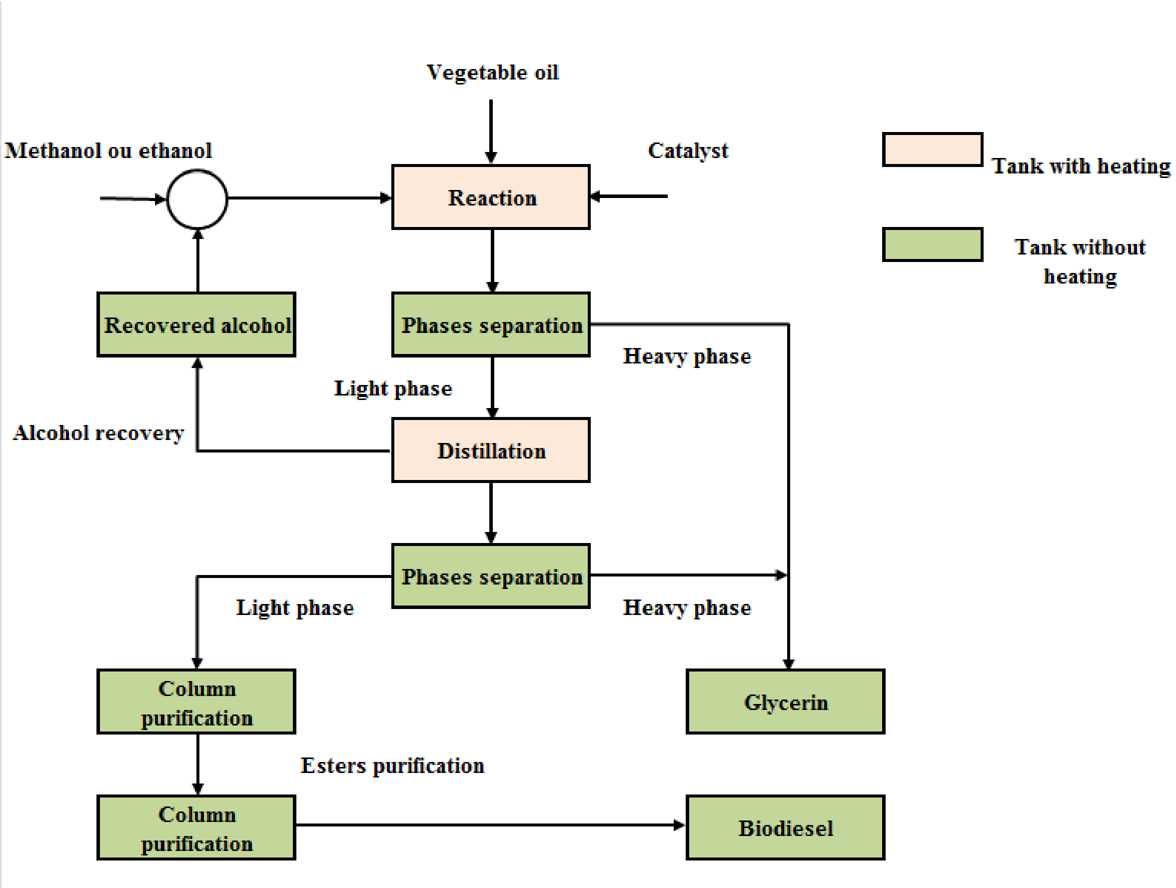
2.2. Oil pre-treatment

Chemical and physical properties of raw materials used in transesterification process are directly related to process efficiency and, as a consequence, to the quality of product for fuel purposes. Depending on their origins, the oil or fat can presente some characteristics that shall be controlled, such as acidity, humidity, residues, phosphorus contente, among others.

3. MACAÚBA BIODIESEL PRODUCTION

All the vegetable oils are composed mainly by triglycerides (one glycerin molecule bonded to three molecules of fatty acids) and free fatty acids (FFA). In transesterification process (figure 2), for biodiesel production, triglycerides in the oil are transformed in smaller molecules of fatty acid (biodiesel), through a transesterificant agent (primary alcohol) and a catalyst (basic or acid). For macaúba biodiesel production, it was chosen the use of methanol, since it produces lower volumes of soap and higher process efficiency, and sodium methylate solution.

Figure 2 – Transesterification reaction flow chart [3]



The process of biodiesel production occurs when macaúba oil is added into the reactor with heating (figure 3), and after that, alcohol and catalyst (Table 2) are added under Strong mechanical stirring to force the reagents mixture (Figure 4). This mixture can keep for the time enough for the entire reaction occurrence in conventional process, mechanical stirring, or receiving ultrasound radiation emitted by the reactor. The biodiesel production occurs under chemical reaction, named transesterification, that converts triglycerides (oils and fats) in esters (biodiesel) and glycerin as a byproduct.

Table 2: Reactants used in methyl transesterification of Macaúba oil

Reaction	**Oil mass [g]**	**Molar ratio**	**Moles**	**Catalyst %**	**Alcohol mass [g]**	**Catalyst mass [g]**
1	4595,0	(6:1)	6,0	2,0	1068,09	91,90
2	4595,0	(6,8:1)	6,8	2,3	1210,50	105,69
3	4135,5	(6:1)	6,0	2,0	961,28	82,71
4	4135,5	(6,8:1)	6,8	2,3	1089,45	95,12

Figure 3: Ultrasonic reactor

Figure 4: Reactor with mechanical stirring

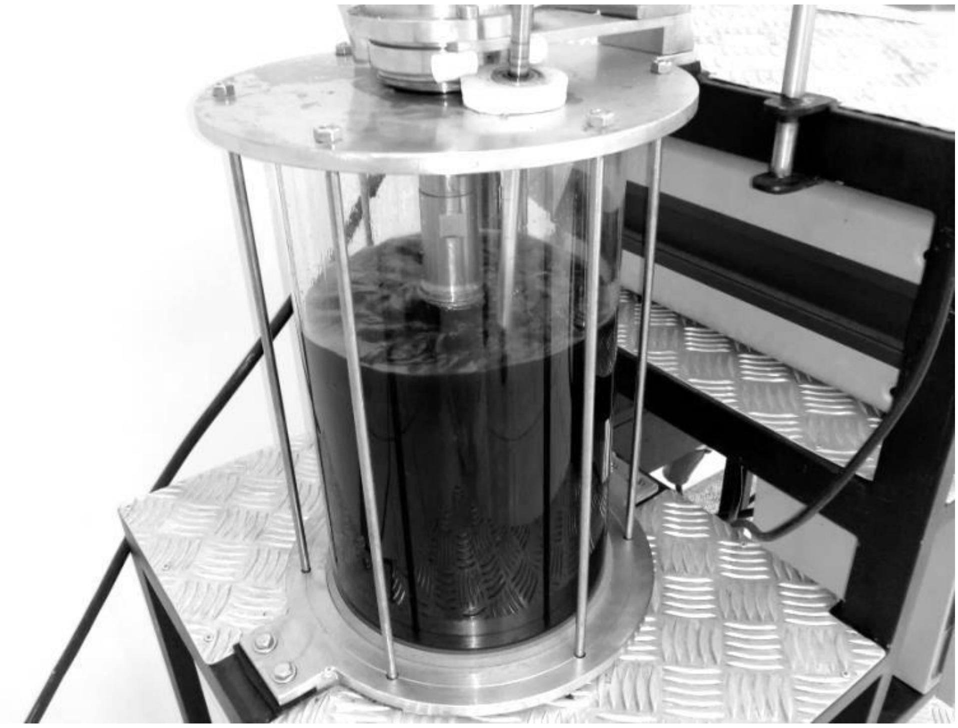


Figure 5: Recovery of metanol excess

Figure 6: Fluid decantation for phases separation

Figure 7: Oil purification through column of ion exchange resin

Figure 8: Resin used for biodiesel purification

4. TESTS

Macaúba biodiesel B100 has been carefully diluted into standard diesel phase VII, used for engine homologation. Blends with 10 and 20% in volume were prepared, now named B10 and B20, respectively. As a base line, it was used commercial diesel S10 B10, composed by 70% soya bean + 30% animal fat, also in volume.

The tests have been performed at the emissions laboratory of engine development center of FPT Industrial, in Betim/MG (860 meters above sea level), in November/2018. It was used a diesel engine N67, with electronic diesel control, usually applied to agricultural tractors (Figure 9) and whose features are listed in table 3.

Figure 9: FPT Industrial N67 engine installed on dynamometer

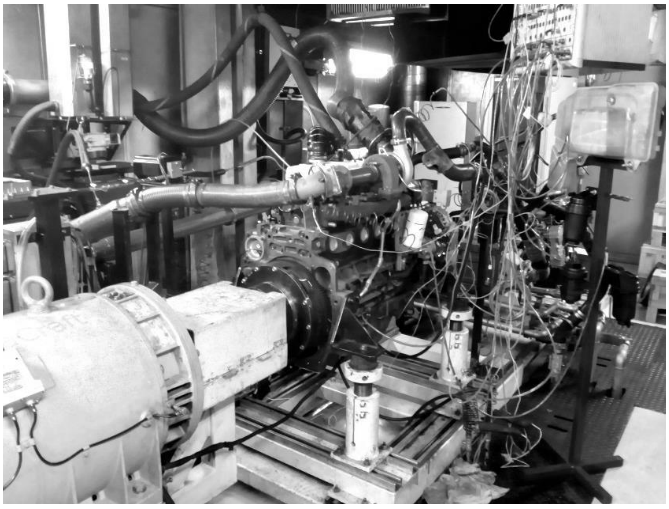


Table 3: Engine base features

Parameter	Specs
Power (kW @ 2200 rpm)	150
Torque (Nm @ 1600 rpm)	750
Number of cylinders and configuration	6 in line
Bore x stroke (mm)	104 x 132
Engine displacement (cm3)	6728
Compression ratio	17,5:1
Fuel injection system	Electronic Injection *common rail*
Air intake system	Turbocompressor with air cooler

The test cycle applied has been ISO 8178, known as NRSC (chart 1) and whose emissions measurement points and limits to be respected are listed in tables 4 and 5, respectively.

Chart 1: NRSC cycle – Emissions in agricultural engines

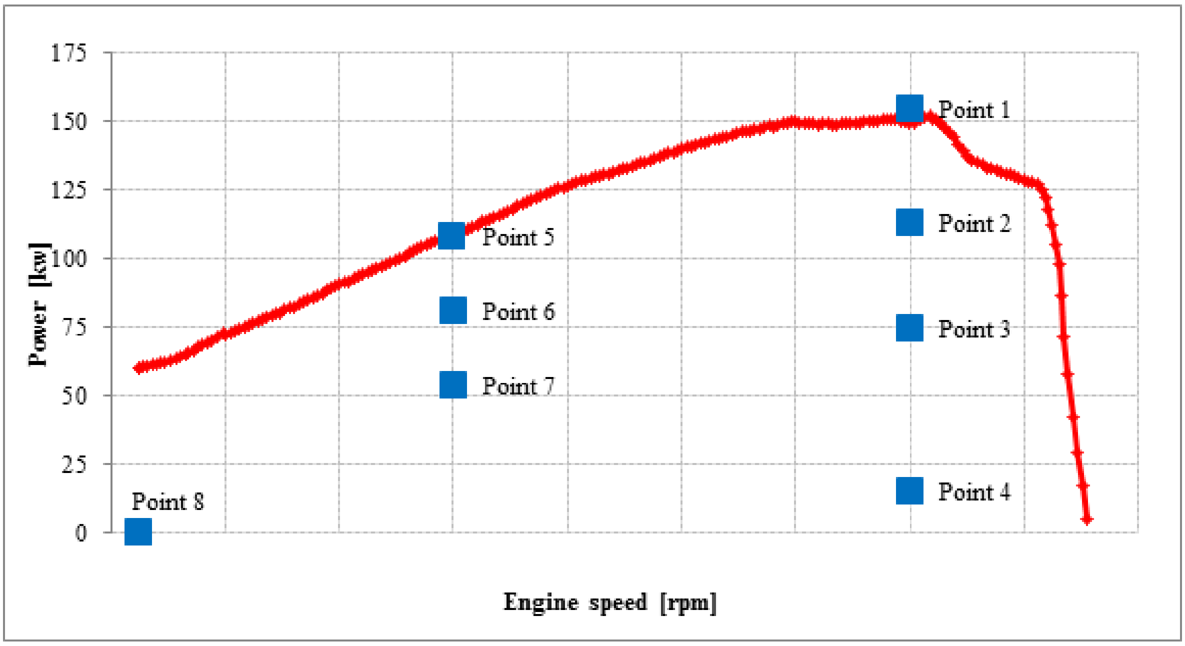


Table 4: Measurement points in NRSC cycle

Point	Speed	Load [%]	Factor
1	A	100	0,15
2	A	75	0,15
3	A	50	0,15
4	A	10	0,10
5	B	100	0,10
6	B	75	0,10
7	B	50	0,10
8	Low idle	0	0,15

Table 5: Emissions limits for agricultural engines

Power [kW]	CO [g/kWh]	HC + NOx [g/kWh]	PM [g/kWh]
$130 \leq P \leq 560$	3,50	4,00	0,20
$75 \leq P < 130$	5,00	4,00	0,30
$37 \leq P < 75$	5,00	4,70	0,40
$19 \leq P < 37$	5,50	7,50	0,60

5. RESULTS

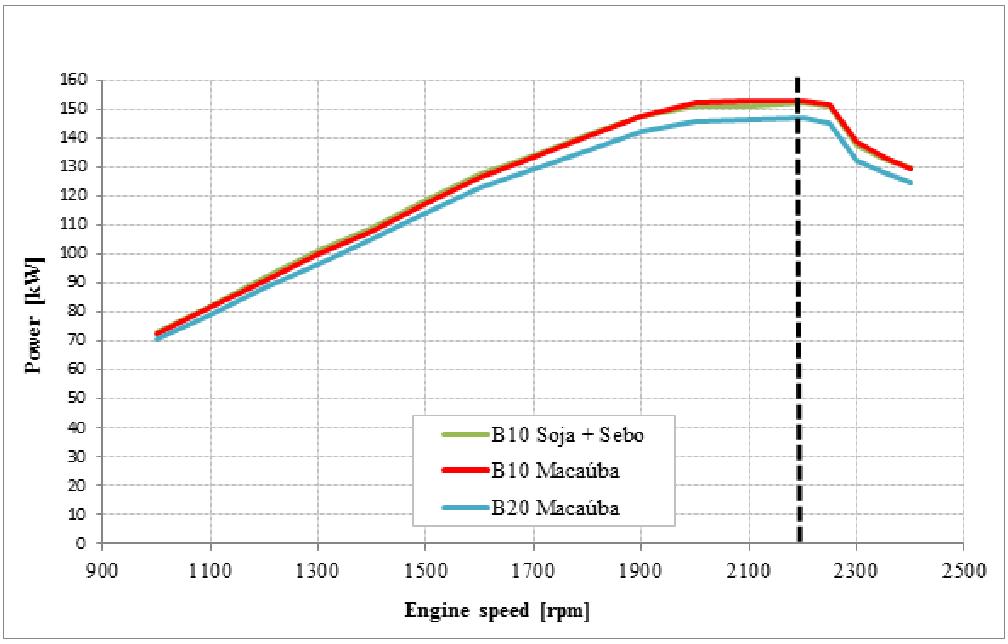
5.1. Power

Chart 2 shows full load power curve, fueled firstly with commercial B10 (soya bean + animal fat), and after that, fueled on experimental blends of B10 and B20 macaúba biodiesel. The tests have been performed in accordance with ISO 14396. Each curve is composed by measurements performed at each 50 rpm, along the interval between 1000 and 2400 rpm.

Power curves were almost overlapping when it is compared Macaúba B10 with reference B10 (soya bean + animal fat). Values ranging between +0,85 and -1,15%, while the tolerance established by the standard is +/- 2%.

Higher difference was observed in comparison with reference diesel (average 3,65%), when it was fueled on experimental blend of 20% of Macaúba biodiesel, and 3,39% of power reduction at 2200 rpm. The increase of biodiesel concentration in diesel fossil causes calorific power reduction, and due to this, such engine power reduction is expected.

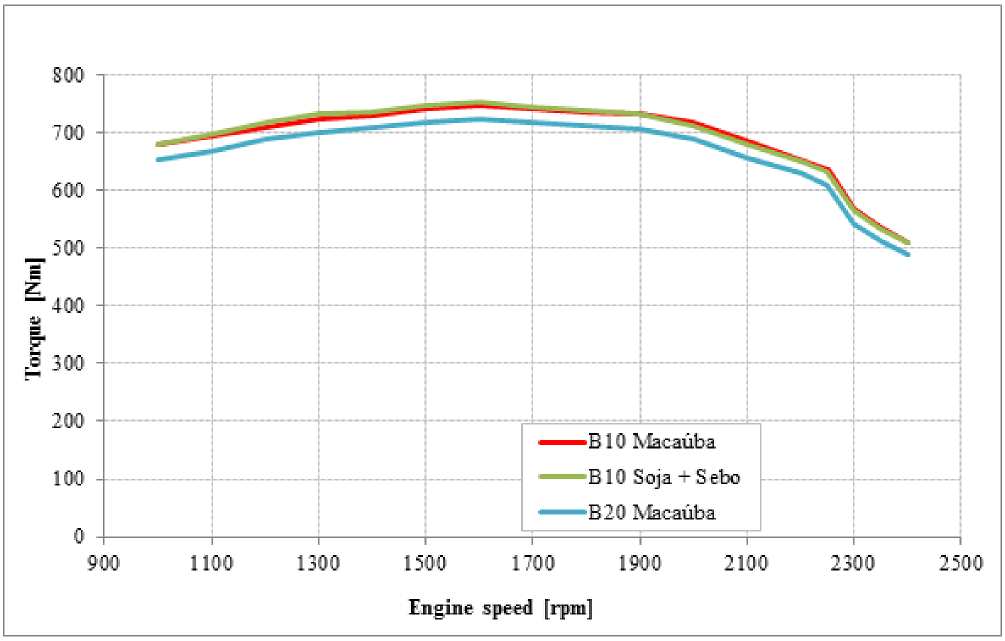
Chart 2: Engine power



5.2. Torque

Torque has similar behavior as power, with curves almost overlapping (chart 3). At 1.600 rpm, maximum torque region declared by the manufacturer, it is possible to note 0,55% of reduction in comparison with commercial diesel. Such variations are within the tolerance established by the standard. Fueled on 20% of macaúba biodiesel, it is possible to note a reduction still higher, as expected, of 3,59% at the same engine speed.

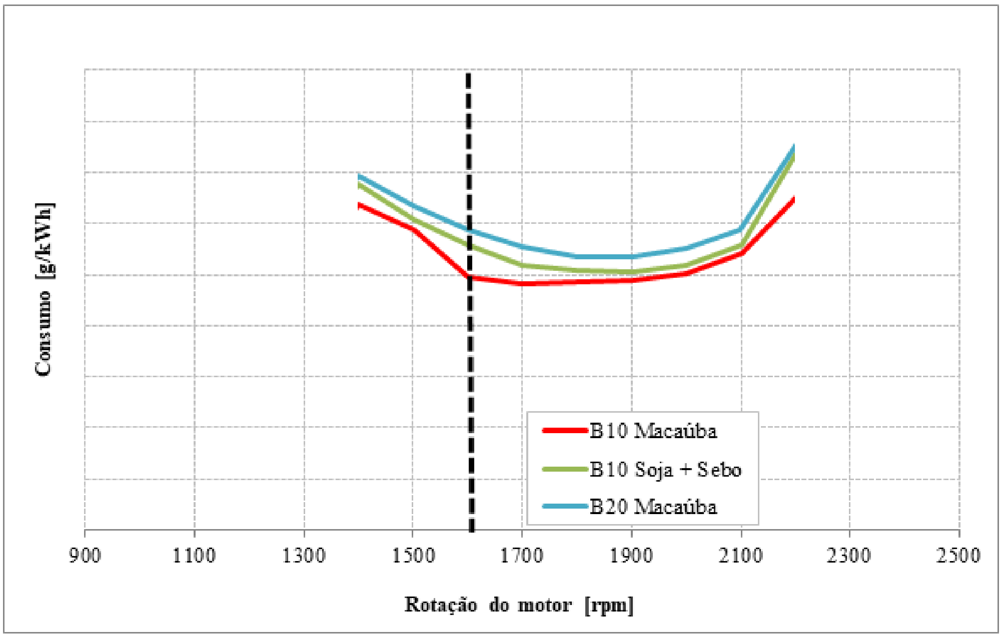
Chart 3: Engine torque



5.3. Fuel consumption

Over all the operation zone of the engine, lower SFC was obtained when fueled on 10% of macaúba biodiesel in comparison with commercial biodiesel (10% soya bean + animal fat), what corresponds to fuel consumption difference of -1,99% in mass, within the tolerance values established by the standard (chart 4).

Chart 4: SFC – Specific fuel consumption

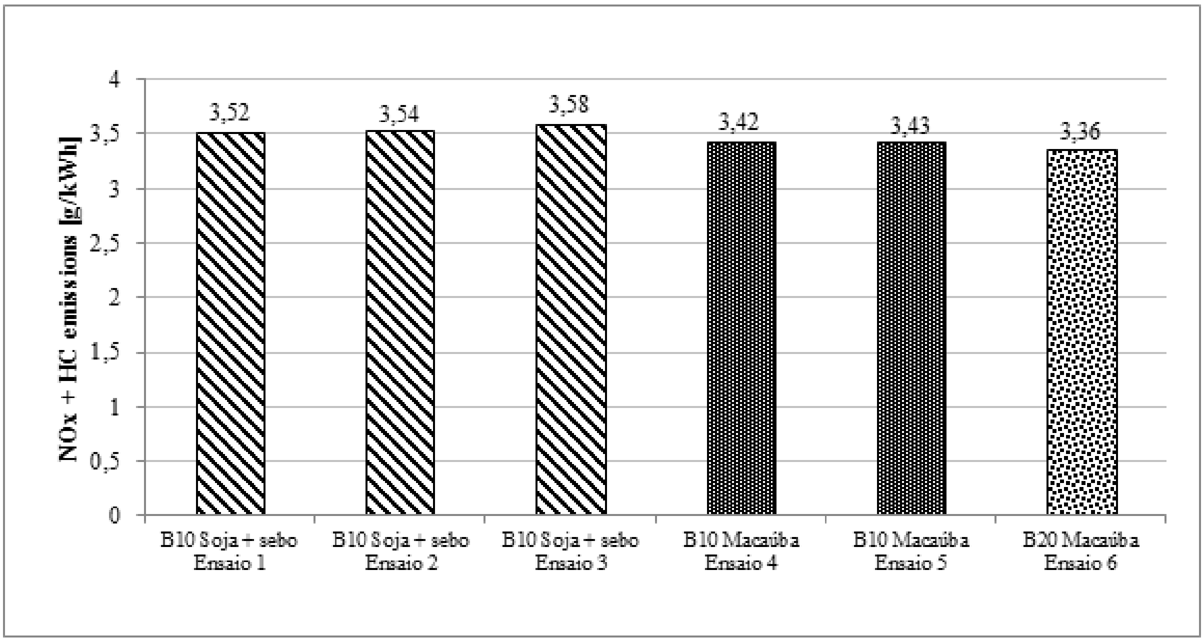


5.4. NOx + HC emissions

Nitrogen oxides associate with other gases and cause acid rain, with serious damages to forest and plantations, and photo chemical *smog*, that causes irritations in air ways, among other effects. Unburned hydrocarbons (HC) in the same way cause irritations and several other problems. Because of that, it is mandatory the control of those emissions, that are declared summed according to CONAMA resolution 433 from 2011, because of similar effects. Chart 5 shows NOx and HC emissions in the engine fueled on B10 and B20 from macaúba, in comparison with commercial diesel.

Fueled on commercial diesel, the engine emitted in average 3,55 g/kWh of NOx + HC, and when fueled on biodiesel B10 from macaúba, it emitted in average 3,43 g/kWh. This corresponds to a -3,38% reduction. Such difference does not correspond to an affective reduction, since the values were within the tolerance of measurement instruments, +/- 2% in each test. Fueled on B20, the difference is still higher, -5,35%.

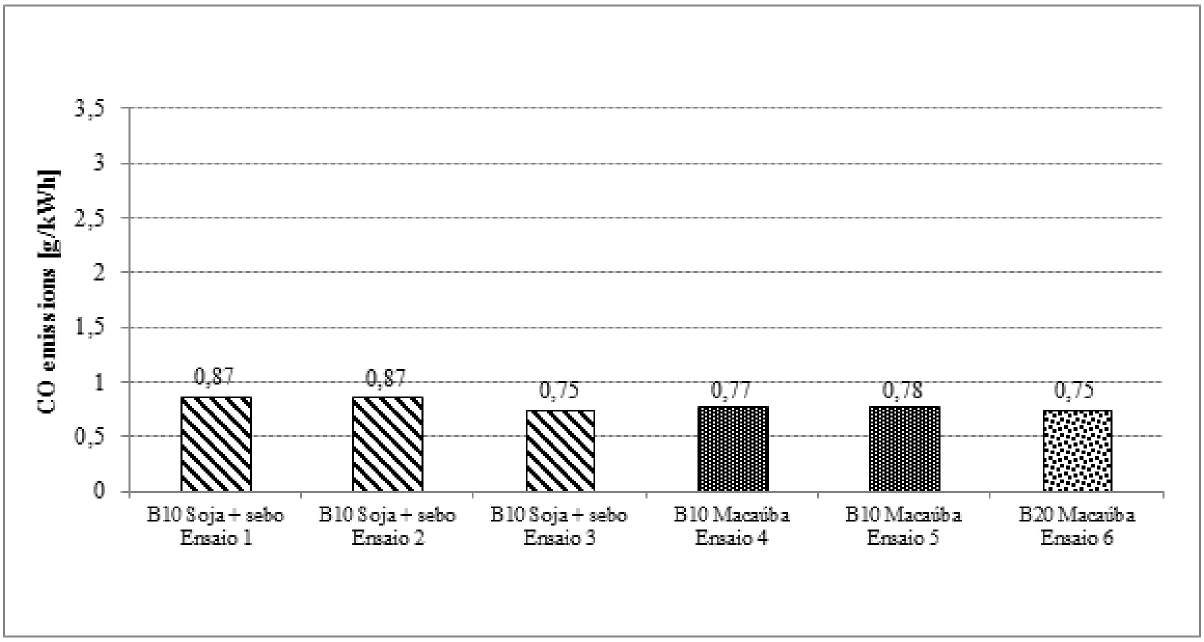
Chart 5: NOx + HC emissions



5.5. CO emissions

Chart 6 shows CO (carbon monoxide) emissions, when the engine is fueled on macaúba biodiesel in comparison with commercial diesel B10 (soya bean + animal fat). It is possible to note that the engine has emitted 0,83 g/kWh of CO in average when fueled on B10 commercial, and 0,78 g/kWh fueled on biodiesel B10 from macaúba.

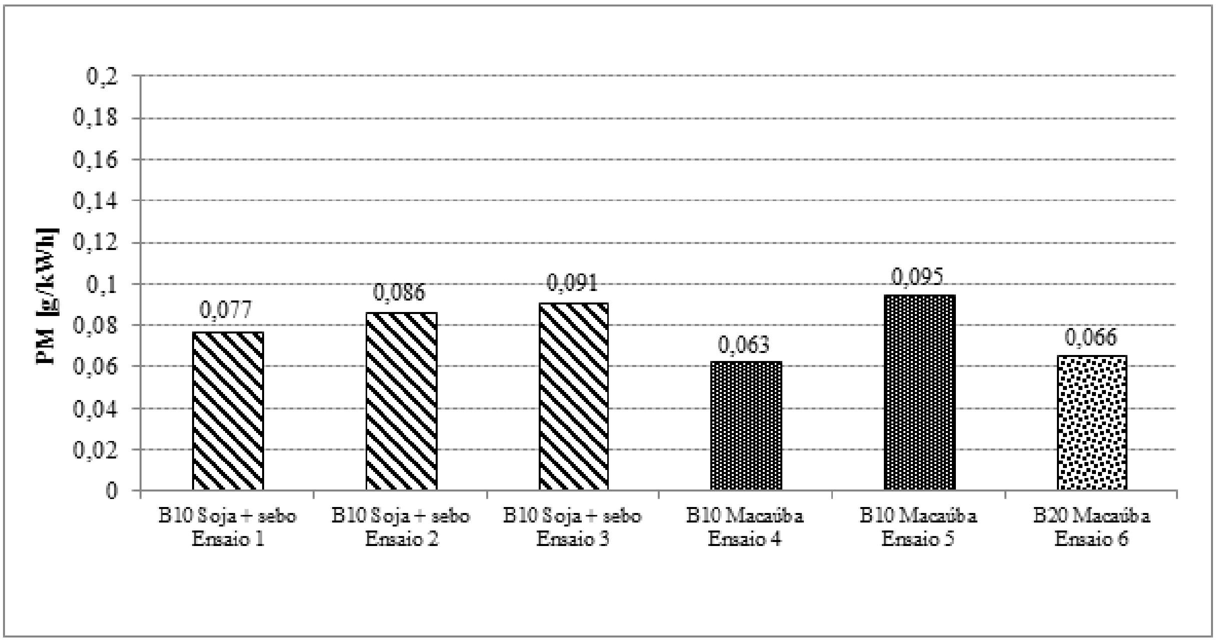
Chart 6: CO emissions



5.6. Particulate matter emissions

It was obtained 0,079 g/kWh as average particulate matter emissions when the engine was fueled on macaúba B10, and on the other hand, when fueled on commercial diesel (B10 soya bean + animal fat), the value was 0,085 g/kWh. Both the values are accepted for engine homologation, but macaúba biodiesel had a difference of -7,17% in particulate matter emissions. When fueled on macaúba B20, the difference has been -16,5% (chart 7).

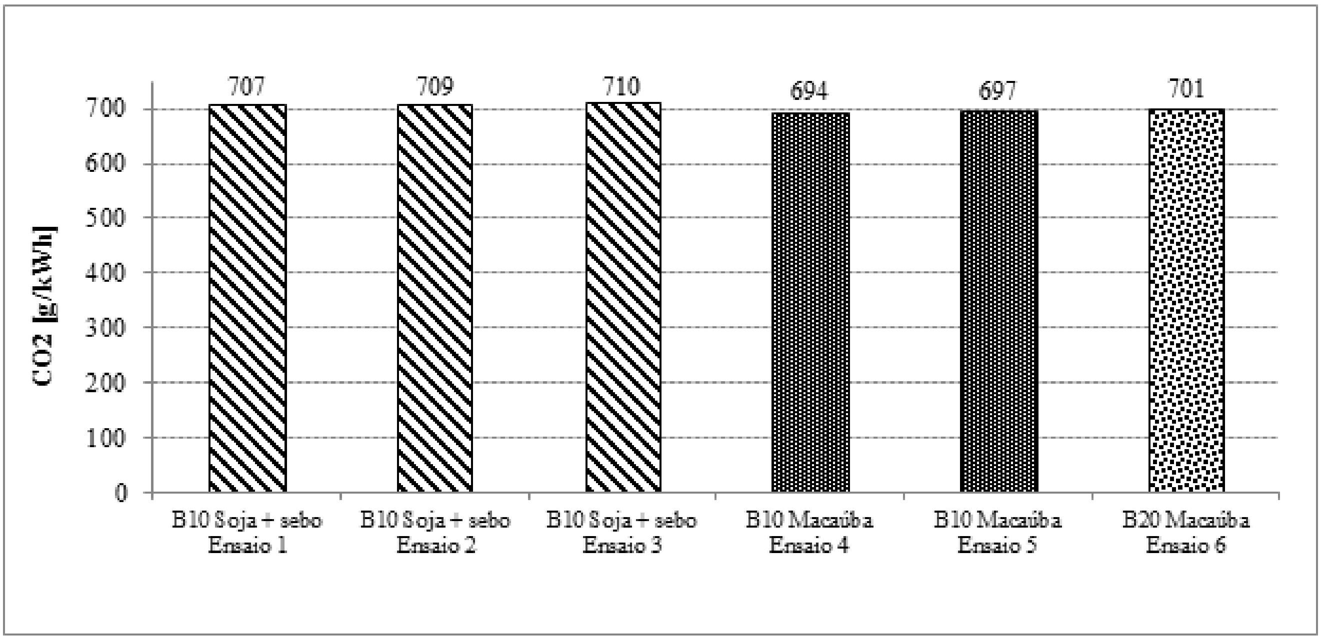
Chart 7: Particulate matter emissions



5.7. Carbon dioxide emissions (CO_2)

Chart 8 shows CO_2 (carbon dioxide) emissions. It was obtained in average 708,67 g/kWh when the engine was fueled on commercial diesel (10% biodiesel composed by soya bean + animal fat) and 695,50 g/kWh when fueled on macaúba B10. The values show emissions almost overlapping, since the average difference of 1,75% does not represent an actual CO_2 reduction, since it is within the tolerance established by the standard.

Chart 8: CO_2 emissions



CONCLUSION

Biodiesel produced from macaúba has shown, in laboratorial tests, performance compatible with biodiesel currently commercialized in Brazilian market, basically composed by soya bean + animal fat. Nitrogen oxides, unburned hydrocarbons and carbon dioxide emissions remained almost the same, while carbon monoxide and particulate matter presented a trend of reduction when fueled on Macaúba. In both cases, the engine achieved the limits established by the legislation for agricultural engines.

Without the need of blend with other feedstock for properties correction, macaúba presents acceptable lubricity and cetane index, among other characteristics. Macaúba oil is composed mostly by unsaturated molecules (containing only a double bond between carbon atoms), while soya contains mostly poly unsaturated molecules (two or more double bonds). This characteristic makes macaúba biodiesel less susceptible to the oxygen action, minimizing its harmful effects, for instance corrosion in fuel injection components or premature filter clogging.

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