Exhaust gas characterization of biofuel blends in an open cycle gas turbine

Caracterización de gases de escape de mezclas de biocombustibles en una turbina de gas de ciclo abierto

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This research offers a sustainable alternative solution to a global problem of environmental pollution produced by the aviation sector, by proposing specific fuel-biofuel mixtures. The methodology in the design of the applied experiment, for the characterization of gases in the reaction turbine and the proper functioning of the Brayton cycle. Among the main conclusions of the research, the best environmentally friendly blend (lower production of CO_2 and NO_2), with adequate lubrication and acceptable propulsion was obtained: BK20 (20% biodiesel and 80% paraffin).

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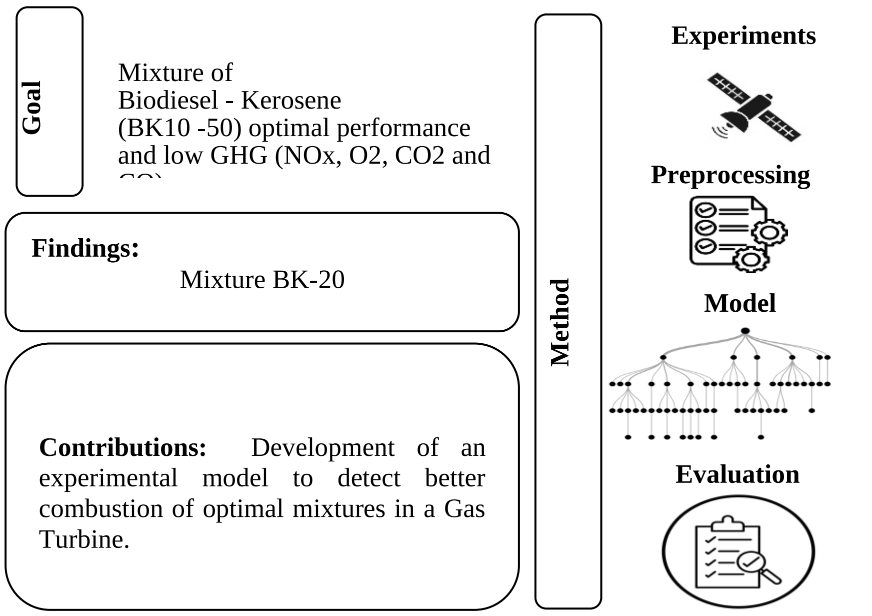
Abstract

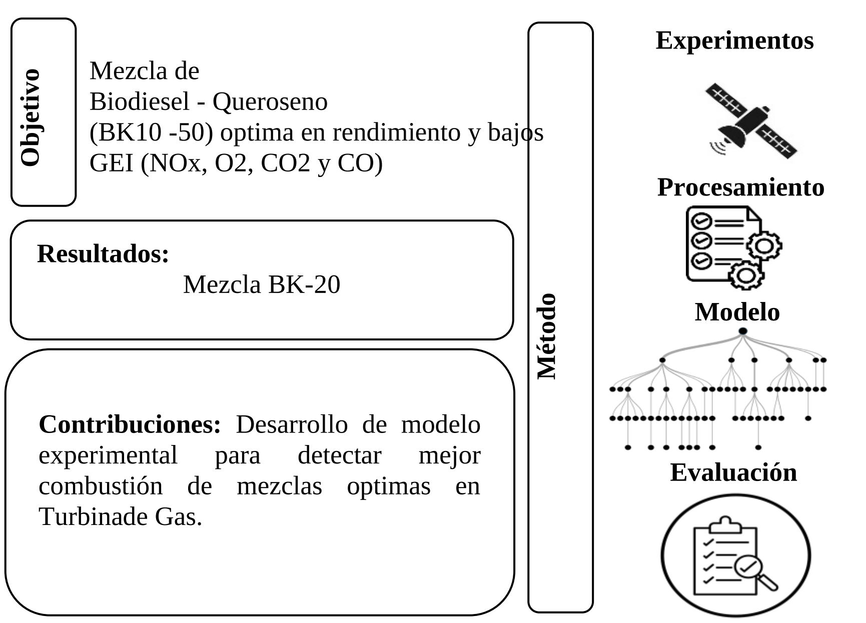
This work seeks to analyze and reduce the percentage in gram/gram of exhaust gases that cause the greenhouse effect using an aeronautical miniturbine. For this research, mixtures of biodiesel (own) and commercial aviation kerosene are used in a BEE-80 model miniturbine. A test bench was implemented which has the microturbine installed, it is monitored telemetrically using an Arduino system and a combustion gas analyzer (CO_2, CH_4, SO_x), the turbine parameters allow experimenting with the different mixtures to find the optimal one. It is operated with mixtures varying the percentage of biodiesel from 10%, 20%, 30%, 40% to 50% (B10-B50), to observe the changes in power, consumption, lubricity and mainly the emissions released to the atmosphere. The mixture that showed the best efficiency, an acceptable reduction in greenhouse gases and better lubrication, was B20, in addition to acceptable consumption compared to the other mixtures.



Biodiesel, Transesterification, pollution

Resumen

En este trabajo se busca analizar y disminuir el porcentaje en gramo/gramo de gases de escape causantes del efecto invernadero empleando una miniturbina aeronáutica. Para esta investigación se utilizan mezclas de biodiesel (propio) y queroseno de aviación comercial, en una miniturbina modelo BEE-80. Se implementó un banco de pruebas el cual tiene instalada la microturbina, se monitorea telemétricamente mediante un sistema Arduino y un analizador de gases de combustión (CO_2, CH_4, SOx,) los parámetros de la turbina permiten experimentar las diferentes mezclas para encontrar la óptima. Se hace funcionar con mezclas variando el porcentaje de biodiesel desde 10%, 20%, 30%, 40% hasta 50% (B10-B50), para observar los cambios en la potencia, consumo, lubricidad y principalmente las emisiones que libera a la atmósfera. La mezcla que mostró mejor eficiencia, una disminución aceptable de gases de efecto invernadero y mejor lubricación, fue B20, además de un consumo aceptable respecto a las otras mezclas.



Biodiesel, Transesterificación, Contaminación

Introduction

One of humanity's greatest problems is its dependence on fossil fuels, which are not only a non-renewable resource, but are also limited and cause a strong environmental impact with a constant variation in their prices.

One fifth of greenhouse gas emissions are produced by the transport sector, which is the main generator of pollutants worldwide; it is known that these emissions contain polluting compounds such as: carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs) and sulphur hexafluoride (SF_6), generated by the transport sector. Air transport is the second most polluting sector with a global consumption of 800 million litres of turbofuel per day and rising, accounting for about 10% of global energy used for transport.

The challenge is to ensure that renewable energy sources gradually replace these fuels; one alternative could be liquid biomass, especially that which can be converted into biofuel-producing sources. Biofuels currently represent a potential source of renewable energy and could also generate large new markets for agricultural producers.

This work shows how by experimenting with different Biodiesel-Turbosine blends an ideal blend can be found that maintains the ideal power and fuel consumption, while providing the lowest greenhouse gas emissions to the atmosphere, biofuels can offer savings in greenhouse gas emissions of at least 50% compared to fossil fuels such as diesel or gasoline.

Objective

To find the biodiesel-kerosene blend that generates the lowest percentage of greenhouse gases and maintains the best efficiency in terms of power, consumption and lubricity (noise and vibration).

- To produce biodiesel through the transesterification process, ensuring a high degree of purity and yield.
- Examine the properties of biodiesel (density, viscosity, volatility and calorific value) in accordance with ASTM 6761-A, for use in a scale Brayton cycle turbine.
- Determine the best biodiesel-kerosene blends that optimise power, fuel consumption and lubricity in the turbine.
- Determine the positive impact on the environment in terms of greenhouse gas reduction percentages (NOx, O_2, CO_2 and CO) by implementing a percentage of biodiesel in the aeronautical fuel (paraffin).

Open Brayton cycle

The Brayton cycle describes the operation of a constant pressure heat engine. Most gas turbines are based on the open Brayton cycle with internal combustion. In this cycle, air from the atmosphere is compressed to the higher pressure and temperature of the compressor. In the combustion chamber, the air is further heated by burning the fuel-air mixture in the air flow. The products and gases of combustion are expanded in the turbine to near atmospheric pressure (engines producing mechanical power or electrical power) or to the pressure required by jet engines. The open Brayton cycle means that the gases are discharged directly into the atmosphere.

Figure 1 shows the P-V (pressure-volume) and T-S (temperature-entropy) diagrams of the Brayton cycle, showing the effect of thermal and pressure levels on the four Brayton cycle processes:

- 1-2 Isentropic compression (in a compressor).
- 2-3 Heat addition at constant pressure.
- 3-4 Isentropic expansion (in a turbine).

- 4-1 Heat rejection at constant pressure.

Box 1

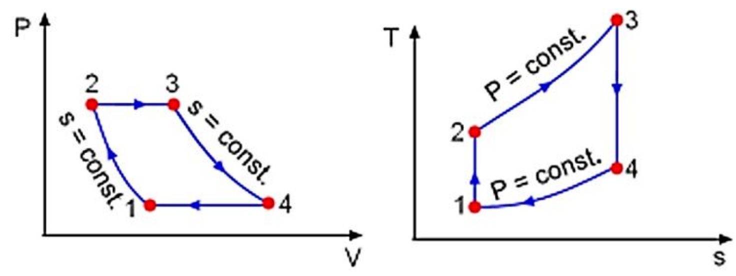


Figure 1
P-V and T-S diagram of the Brayton cycle
Source [*Nuclear power, 2022*]

Gas turbines

Gas turbines generally operate in an open cycle, as shown in Figure 2. In step 1, fresh air at ambient conditions is introduced into the compressor where its temperature and pressure rises, then at point 2, the high-pressure air goes into the combustion chamber where the fuel is burned at constant pressure. At point 3, the resulting high-temperature gases enter the reaction turbine, where they expand to atmospheric pressure, thereby producing power. Finally, at point 4, the exhaust gases leaving the turbine are expelled to the outside (not recirculated), thus the cycle is classified as an open cycle (Emilio Rivera Chávez, 2020).

Box 2

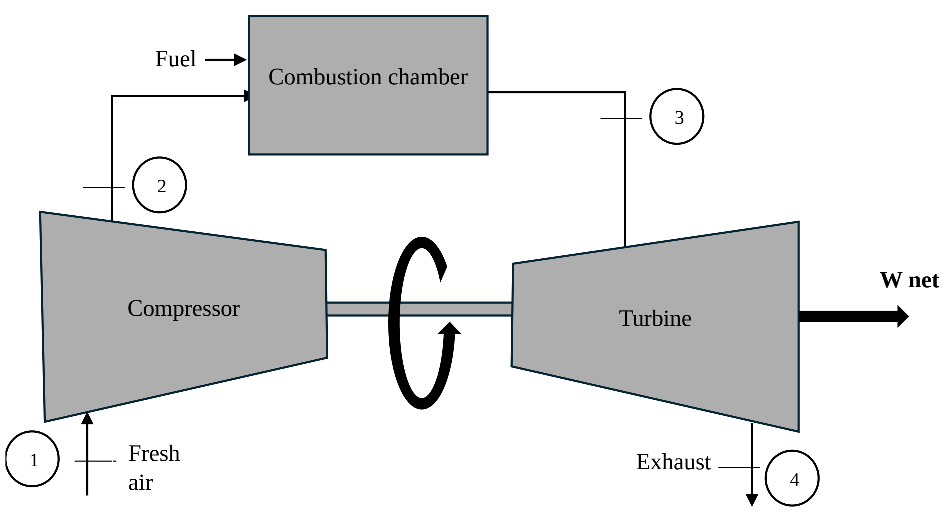


Figure 2
Open cycle gas turbine engine
Source [*Emilio Rivera Chávez, 2020*]

Basic components of the gas turbine:

- Compressor (also called action turbine): draws in external air and compresses it.
- Combustion chamber: fuel is added to the pressurised air and ignited.
- Reaction turbine: converts high-speed gas energy into rotational energy through expansion.
- Output shaft and gearbox: delivers rotational energy to the driven equipment.
- Exhaust: extracts the low-emission gas used from the turbine section.

Biofuels

Biofuels are fuels obtained from biomass. The term biomass, in the broad sense, refers to any type of organic matter that has had its immediate origin in the biological process of recently living organisms, such as plants, or their metabolic waste (manure); the concept of biomass includes products of both plant and animal origin. In order to better understand the concept of biomass, we can see in Table 1 the different types of biomass into which it is divided.

Box 3

Table 1
Classification of biomass

Type of biomass	Definition
Primary biomass	Organic matter formed directly from photosynthetic organisms. This group includes plant biomass, including agricultural and forestry residues.
Secondary biomass	It is produced by heterotrophic organisms using primary biomass in their nutrition. It is the faecal matter or meat of animals.
Tertiary biomass	It is produced by organisms that feed on secondary biomass, e.g. the remains and excrements of carnivorous animals that feed on herbivores.
Natural biomass	It is produced by wild ecosystems; 40% of the biomass produced on land comes from the oceans.
Residual biomass	It can be extracted from agricultural and forestry residues, and from human activities.
Energy crops	Any agricultural crop whose purpose is to supply biomass for biofuel production.

Source: *[Salinas Edmar & Gasca Víctor, 2009]*

Biofuels are considered clean energy because they release only 20% of carbon emissions during combustion compared to fossil fuels. The use of biofuels as an alternative source of energy to hydrocarbons and the reduction of environmental impact is new work, but their use has been done for a long time. For example, in underdeveloped countries (especially in rural areas), and in developed countries, wood is used to generate electricity. Various types of biofuels are currently being developed, but the best known are classified into three groups: first, second and third generation, each of which is described below.

ASTM D6751A Standard

The ASTM D6751A biodiesel standard covers B100 biodiesel for use as a component of a blend with middle distillate fuels. The standard takes into consideration important minimum properties that biodiesel must have: flash point, methanol, kinematic viscosity, sulphated ash, oxidation stability, sulphur, copper strip corrosion, cetane number, cloud point, acid number, carbon residue, total and free glycerol, phosphorus, and water sediment; these depend on the refining practices employed and the nature of the renewable lipids from which they are produced as they can generate similar characteristic volatilities and combustion emissions with different cold flow properties.

Methodology

Fifty samples of residual vegetable oil (150 ml each) are subjected to a transesterification process, i.e. the oil is mixed with methanol in the presence of a basic catalyst and sodium methoxide at 65 °C, yielding quantitatively a methyl ester and glycerol. After this process, an average of 30 ml of glycerine and 150 ml of residual oil biodiesel was obtained (ASTM D 6751 standard is reached), whose density is 0.867 g/ml, therefore: 150 ml x 0.867 g/ml = 130.05 g of residual oil biodiesel.

Mixtures made

1. Ten samples of B10 + aviation paraffin: 10% biodiesel + 90% aviation paraffin.
2. Ten samples of B20 + aviation paraffin: 20% Biodiesel + 80% aviation paraffin.
3. Ten samples of B30 + aviation paraffin: 30% Biodiesel + 70% aviation paraffin.
4. Ten samples of B40 + aviation paraffin: 40% Biodiesel + 60% aviation paraffin.
5. Ten samples of B50 + aviation paraffin: 50% Biodiesel + 50% aviation paraffin.

Characterisation with gas chromatography

To characterise the methyl esters (biodiesel) obtained, they were determined by gas chromatography-mass spectrometry according to the technique used by the researcher Warawut in order to observe the whole range of elements.

Calibration standards supplied by Supelco, Sigma - Aldrich, Glycerine, 1 ml, 500 mg / ml in pyridine, Monoolein, 3 ml, 5,000 g / ml in pyridine, Diolein solution, 2 ml, 5,000 g / mL in pyridine, Triolein, 2 ml, 5,000 g / ml in pyridine, Butanotriol internal standard no. 1, 5 ml, 1,000 g / ml in pyridine, Butanotriol internal standard no. 1, 5 ml, 1,000 g/mL in pyridine, Tricaprin internal standard #2, 5 ml, 8,000 g/mL in pyridine, ASTM D6584 Standard Solution 1,2,3,4 and 5, 1 ml, in pyridine (varied), 1000 ml anhydrous tetrahydrofuran (the standard standards were used exclusively for curve comparison). The technique consisted in extracting 100 µl of biodiesel (from the chosen sample) and diluting it in 0.8 ml of tetrahydrofuran (THF). The syringe was rinsed three times with the solution and 1 µl of diluted biodiesel was injected into the chromatograph with a 10 µl hypodermic syringe.

The gas chromatograph used is a Trace CG ultra from Thermo Finigan Corporation with a capillary column (30 m × 0.25 mm ID × 0.25 µm) and a mass spectrometry detector, which can be seen in Figure 3. The equipment conditions are as follows: injection temperature 280 °C (injector) and detector temperature 200 °C (MS). The oven temperature programme was 140 ºC for 4 min, followed by a ramp of 15ºC/min to reach 280ºC in 7 min, and a second ramp of 10ºC/min to reach 340ºC, maintaining this temperature for 6 min until the end of the programme. The carrier gas was 99.998% chromatographic grade helium at a constant flow rate of 1 ml/min. These analyses were carried out in the Hydrogen and Biofuels Laboratory of the Institute of Renewable Energies of the Universidad Autónoma de México.

Test bench system

A test bench previously developed by M.I Carlos Gallardo Martínez for his thesis work was used, which has been modified for this new project, whose design is presented in Figure 4. This test bench is equipped with a JetCentral Bee 80 Se microturbine that is telemetrically monitored by an Arduino system and a flue gas analyser that measures parameters such as O,$_{CO2}$, $_{CH4}$, $_{SOx}$, among others. This comprehensive approach allows the analysis and comparison of various aspects of performance, such as power output, fuel consumption, greenhouse gas emissions, lubricity (related to mechanical noise and vibration), and thermal stability during operation. The test bench facilitates the evaluation of the microturbine with different fuel blends, in this case biodiesel and paraffin, with the aim of identifying the combination that offers the best overall performance.

Box 4

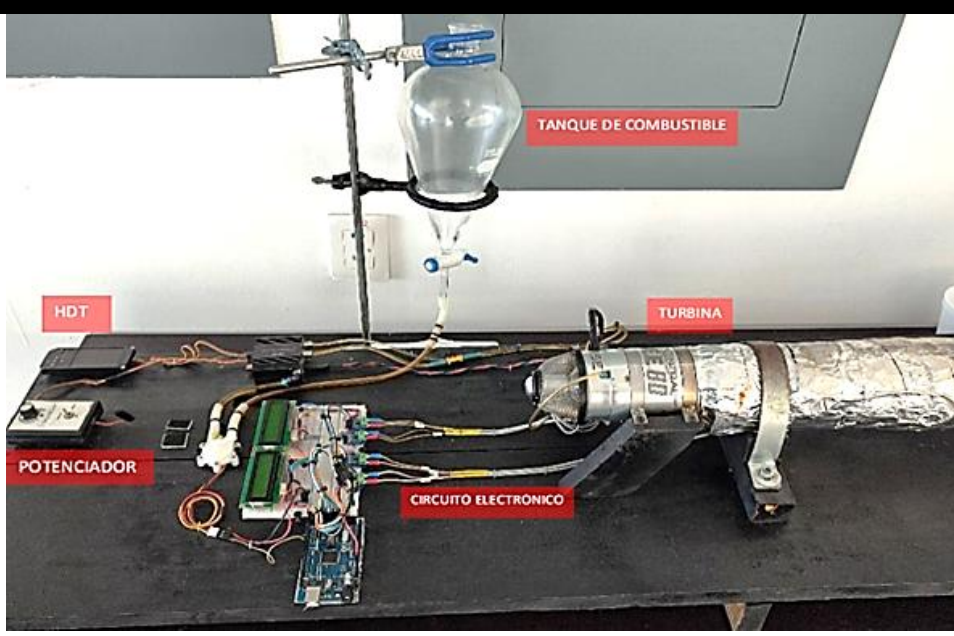


Figure 3
Test bench

Source: [*Own elaboration*]

The mini-turbine used is an open Brayton cycle gas turbine, with all the characteristics of a large turbine, but on a much smaller scale (250-1), reducing the logistics of operation, consumption, safety, unit cost and testing.

Programming

This project uses an Arduino embedded system, which is an open source platform with easily accessible hardware and software. Two programs were made for the test bench, one in Arduino and one in LabVIEW.

Turbine exhaust gas measurement process

To carry out the process of measuring exhaust gases at the turbine outlet, the combustion gas analyser (E Instruments E4500) is used, which is a practical tool for its rapid analysis and with a minimum error of 5% in the data obtained on site, or for graphing with the interface to the computer, which can be seen in Figure 4.

Box 5

Figure 4

Gas analyser

Source: [*CICSA, 2023*]

Results

Gas chromatography

Box 6

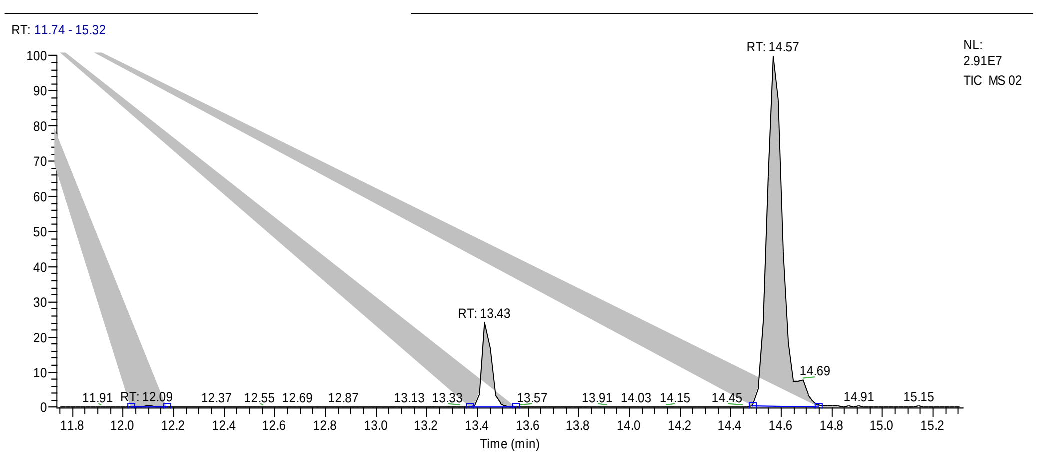


Figure 5

Chromatography of the elements detected in sample 1

Source: [*Own elaboration*]

Box 7

Table 2

Name of elements and percentage of sample 1

01.RAW								
RT: 11.74 - 15.32								
Number of detected peaks: 3								
Apex RT	**Start RT**	**End RT**	**Area**	**%Area**	**Height**	**%Height**	**Name**	**Formula**
12.09	12.03	12.17	276685.9	0.19	134119	0.37	Glycerine propanetriol	$C_3H_8O_3$
13.43	13.37	13.55	16994521	11.66	6951370	19.28	Pentadecanoic acid, 14-methyl-, methylester (pentadecílico)	$C_{17}H_{34}O_2$
14.57	14.49	14.75	1.28E+08	86.77	28964416	80.35	6- Octadecenoic acid, Methylester (Z), (Oleico)	$C_{19}H_{36}O_2$

Source [*Own elaboration*]

Box 8

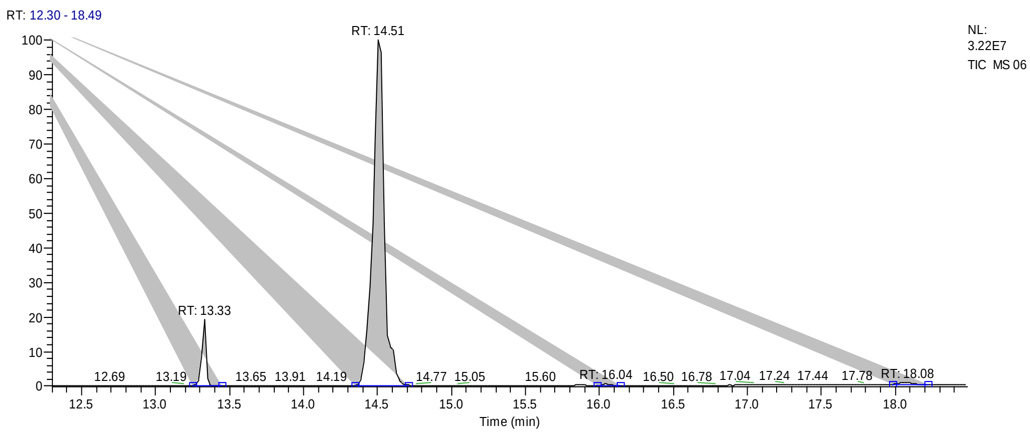


Figure 6

Chromatography of the elements detected in sample 2

Source [Own elaboration]

Box 9

Table 3

Name of elements and percentage of sample 2

02.RAW								
RT: 13.14 - 15.51								
Number of detected peaks: 3								
Apex RT	**Start RT**	**End RT**	**Area**	**%Area**	**Height**	**%Height**	**Name**	**Formula**
13.33	13.25	13.45	12798456	6.63	6234587	16.08	Pentadecanoic acid, 14- methyl-, methylester (pentadecílico)	$C_{17}H_{34}O_2$
14.51	14.35	14.71	1.78E+08	92.1	32194767	83.57	6- Octadecenoic acid, methylester, (Z) (oleico)	$C_{19}H_{36}O_2$
16.04	15.98	16.14	577442.1	0.3	137621	0.35	Docosanoic acid, Methylester (Behenico)	$C_{23}H_{46}O_2$

Source [*Own elaboration*]

Box 10

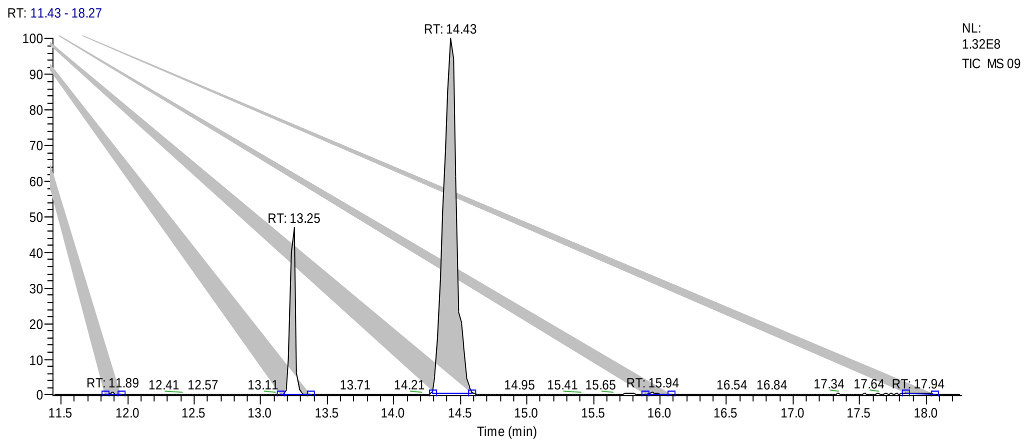


Figure 7

Chromatography of the elements detected in sample 3

Source: [*Own elaboration*]

Box 11

Table 4

Name of elements and percentage of sample 3

03.RAW								
RT: 11.43 - 18.27								
Number of detected peaks: 5								
Apex RT	**Start RT**	**End RT**	**Area**	**%Area**	**Height**	**%Height**	**Name**	**Formula**
11.89	11.83	11.95	1868876	0.17	789925.2	0.4	Tetradecanoic acid, Methylester (Miristico)	C15H30O2
13.25	13.15	13.37	1.7E+08	15.64	62086183	31.75	Nonanoic acid, Methylester(Pelargonico)	C10H20O2
14.43	14.29	14.59	9.11E+08	83.6	1.32E+08	67.34	6- Octadecenoic acid, methylester, (Z) (oleico)	C19H36O2
15.94	15.88	16.08	2787976	0.26	659117.1	0.34	Tetradecanoic acid, Methylester (Miristico)	C15H30O2
17.94	17.84	18.06	2044937	0.19	335358	0.17	Cyclopentaneundecanoic acid, methylester	C17H32O2

Source: [*Own elaboration*]

The three analyses show on average more than 99% of different types of methyl ester (biodiesel) and only in the first sample a percentage of 0.19% of glycerine can be seen, therefore, it is assured that these samples easily exceed the ASTM 6751-A standard.

O_2 increase in the blends

Box 12

Table 5

Molar percentage of O_2 at the outlet of the nozzle

% Biodiesel blended with paraffin	**% O_2 molar gases at the nozzle outlet**	
	Average	**Desv. Standard**
B10	6.09	0.23
B20	6.50	0.06
B30	7.15	0.24
B40	8.1	0.10
B50	9.00	0.00

Source: [*Own elaboration*]

Box 13

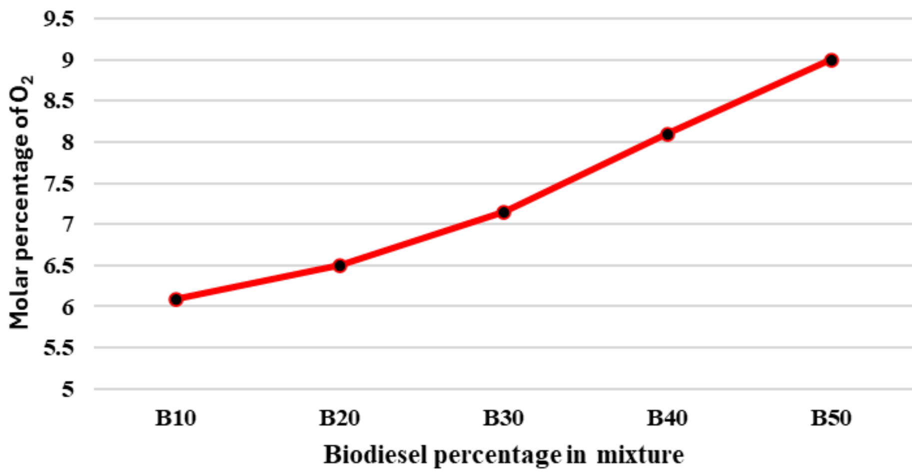


Figure 8

Average % molar O_2 of gases at nozzle outlet

Source [*own elaboration*]

Decrease of CO_2 in the mixtures

Box 14

Table 6

Molar percentage of CO_2 at the nozzle outlet

% Biodiesel blended with paraffin	% CO_2 molar of gases at the nozzle outlet Average
B10	10.7
B20	8
B30	6.7
B40	5
B50	4.3

Source [*own elaboration*]

Box 15

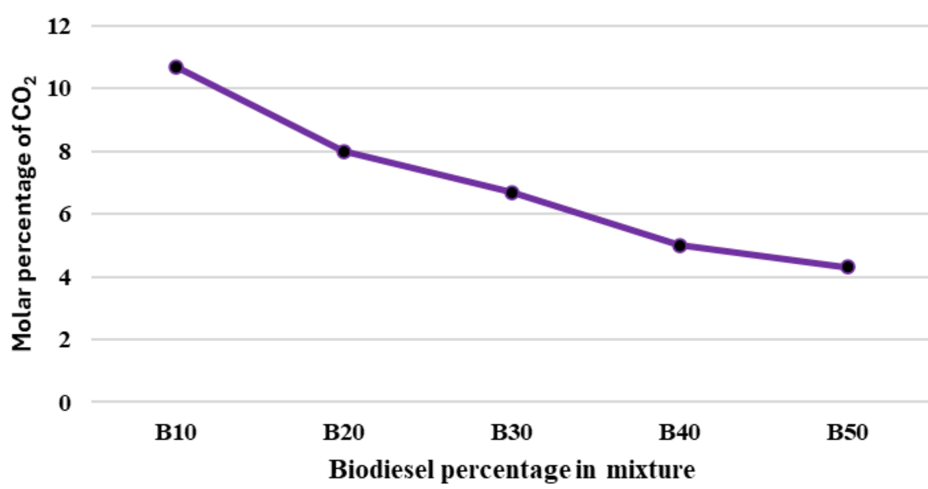


Figure 9

Average % CO_2 molar gases at nozzle outlet

Source: [*Own elaboration*]

Box 16

Table 7
PPM of contaminants in mixtures

% Biodiesel in blend with paraffin	Particles per million		
	NO_2	NO	CO
B10	20	50	270
B20	32	55	250
B30	38	64	230
B40	50	68	220
B50	35	75	210

Source: [*Own elaboration*]

Box 17

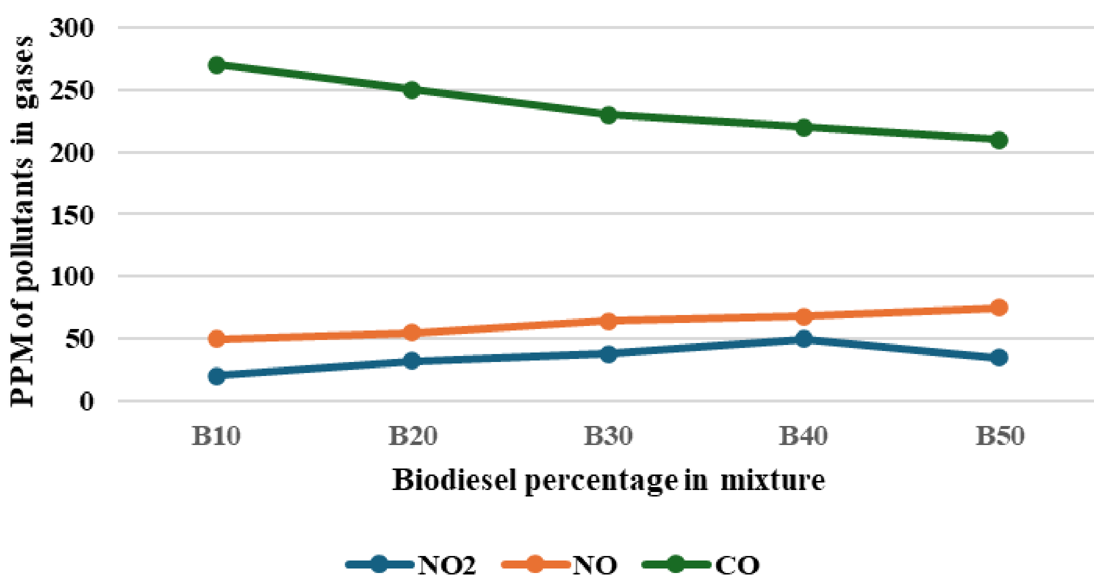


Figure 10
Contaminants in PPM by biodiesel/kerosene blend
Source: [*Own elaboration*]

Conclusions

With the results obtained from the experiments we can observe that the most environmentally friendly blends are the BK20 and BK30 blends, as they show higher levels of O_2 and lower levels of CO_2 and NO_2; we must consider that the higher levels of O_2 could$_{not}$ precisely indicate a bad combustion, but rather that there is good combustion, only that the input increases the proportion of oxygen as the amount of biodiesel in the blend increases. NO_x tends to increase naturally in blends by about 10%, but in contrast to fossil fuels it is about 70% lower. Taking into consideration the power, the consumption of a previous work and the lower amount of pollutant gases in this work we can conclude that the optimal blend for the target is BK20.

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Support

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