

## Article

# Influence of $\gamma$ -Fe<sub>2</sub>O<sub>3</sub> Nanoparticles Added to Gasoline–Bio-Oil Blends Derived from Plastic Waste on Combustion and Emissions Generated in a Gasoline Engine

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**Abstract:** The environmental pressure to reduce the use of fossil fuels such as gasoline generates the need to search for new fuels that have similar characteristics to conventional fuels. In this sense, the objective of the present study is the use of commercial gasoline in mixtures with pyrolytic oil from plastic waste and the addition of  $\gamma$ -Fe<sub>2</sub>O<sub>3</sub> nanoparticles (NPs) in a spark ignition engine to analyze both the power generated in a real engine and the emissions resulting from the combustion process. The pyrolytic oil used was obtained from thermal pyrolysis at low temperatures (450 °C) of a mixture composed of 75% polystyrene (PS) and 25% polypropylene (PP), which was mixed with 87 octane commercial gasoline in 2% and 5% by volume and 40 mg of  $\gamma$ -Fe<sub>2</sub>O<sub>3</sub> NPs. A standard sample was proposed, which was only gasoline, one mixture of gasoline with bio-oil, and a gasoline, bio-oil, and NPs mixture. The bio-oil produced from the pyrolysis of PS and PP enhances the octane number of the fuel and improves the engine's power performance at low revolutions. In contrast, the addition of iron NPs significantly improves gaseous emissions with a reduction in emissions of CO (carbon monoxide), NO<sub>x</sub> (nitrogen oxide), and HCs (hydrocarbons) due to its advantages, which include its catalytic effect, presence of active oxygen, and its large surface area.

**Keywords:** waste plastic; pyrolytic oil;  $\gamma$ -Fe<sub>2</sub>O<sub>3</sub> nanoparticles; engine performance; combustion emissions



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## 1. Introduction

The exponential consumption of chemicals and commercial fuels derived from oil and natural gas has adverse effects on the environment, increasing the amount of waste and gaseous emissions, which contribute to the greenhouse effect and global warming [1]. However, these nonrenewable fuels are the primary source of supply for transport and power generation, which underpins the need for cleaner and renewable sources to achieve energy self-sufficiency in the coming decades [2]. On the other hand, plastic waste generated at the urban and industrial levels has intensified in recent years [3]. Therefore, the use of sustainable environmental technologies such as pyrolysis is being proposed to simultaneously improve the management of this waste and to obtain higher-value products, which include gas, pyrolytic oil, and biochar [4]. In this sense, the approach towards a circular economy of plastics will reduce the annual amount of plastic commonly discarded in landfills and oceans by more than 70% [5]. In addition, it is estimated that by 2040, there will be a drastic decrease in the generation of this waste (an expected production of 70 million tons without revalorization) and a more significant generation of environmentally friendly hydrocarbons [6].

Pyrolysis is a process that decomposes petroleum-derived macromolecules, such as plastic, into smaller molecules in the absence of oxygen at high temperatures, which has several advantages, including (i) minimizing the carbon footprint, (ii) reducing dependence on fossil fuels, and (iii) revalorization of different wastes that include single-use plastics, mixtures of the same, lignocellulosic biomass, tires, and sewage sludge, among others, being a sustainable and versatile alternative [7]. The composition of the compounds generated in this process depends on various factors, such as temperature, heating rate, reaction type, and raw material used. For example, the pyrolysis of polyolefins results in a complex mixture composed of alkanes, alkenes, and aromatics [8]. In contrast, the pyrolysis of plastic waste whose leading chains have aromatic rings as substituents tends to generate a higher production of these compounds due to the cleavage of the beta bond, accompanied by the relative stability of the aromatic ring, causing cracking along the main chain without affecting the aromatic ring [9]. In the case of pyrolytic oil obtained from high-density polyethylene (HDPE), pyrolysis reaches 58.4%, with a recovery of compounds up to C<sub>36</sub> and a tendency to form waxes instead of oil. These waxes consist of long chains of linear hydrocarbons (>C<sub>20</sub>) that solidify at room temperature [10]. In the other hand, polypropylene pyrolysis at temperatures above 400 °C generates a liquid fraction ranging from 42 to 55%, composed mainly of alkanes, naphthalenes, and cyclic compounds, which can even form complexes due to the randomness of the radicals produced in the reaction mechanism [11]. In the case of polystyrene (PS) residues, the production of pyrolytic oils exceeds 80% due to the presence of an aromatic ring in the side chain, with a particularly aromatic composition including styrene, benzene toluene, bibenzil, and  $\alpha$ -methyl styrene, under working conditions like polypropylene (PP) [12]. In addition, pyrolysis of plastic waste mixtures, including low-density polyethylene (LDPE), PP, and HDPE, at temperatures between 450 and 600 °C, produces a liquid fraction rich in olefin compounds, with yields close to 50% [10]. As observed, the synergistic effect of plastic waste mixtures leads to a reduction in the proportion of the liquid fraction; however, it exhibits a high calorific value ranging between 40 and 51 MJ/kg, making it a promising option to contribute to the development of today's society [13]. Studies reported in the literature [14,15] indicate that diesel–pyrolytic oil mixtures derived from plastic bags decrease the specific consumption of commercial fuel to achieve the same power. Likewise, diesel–pyrolytic oil blends derived from municipal landfill waste exhibit satisfactory yields compared to conventional diesel using 15 and 30% blends (v, v) [16]. In addition, pyrolytic oil obtained from polytetrafluoroethylene (PTFE), PP, HDPE, PS, LDPE, and polyvinyl chloride (PVC) blended with distillate oil from used tires shows an increase in the overall performance of internal combustion engines [17], which is likely due to the presence of PS that contributes to improved performance. However, the emissions generated from this process are very high for the different mixtures. In this context, this obtained biofuel cannot directly replace commercial fossil fuels due to impurities in its composition, which includes a high content of aromatic and unsaturated hydrocarbons and sulfur [18]. Therefore, the direct use of internal combustion engines is not recommended. In addition, the production and marketing of pyrolysis-derived fuels from HDPE are not profitable from a financial perspective, as the cost of production is estimated to be approximately USD 212.52 per barrel [19]. In this sense, its use is recommended as an additive for commercial gasoline, which improves its properties and quality, preventing the formation of engine deposits [20], or as a raw material in the manufacture of petrochemical products. A recent study [18] showed that using pyrolytic oil as an additive in gasoline and diesel mixtures increases the octane index and reduces exhaust emissions (NO<sub>x</sub>, CO, and CO<sub>2</sub>). In addition, several experiments in compression engines have shown improved performance and higher energy and energetic efficiencies with diesel–pyrolytic tire oil mixtures (10%, v/v) [21]. In addition, extra-commercial gasoline–biofuel blends (5%, v/v) have been used in internal combustion engines, showing optimal performance, increased power, and significantly reduced gas emissions. CO emissions were decreased to a minimum compared to the standard sample, while hydrocarbons were reduced by 61.90%, keeping CO<sub>2</sub> emissions at levels like the

normal sample [22]. In any case, these emissions negatively affect the environment, so we seek to combine these proposed methods by adding other promising materials to minimize this negative impact further.

Nowadays, metal oxide nanoparticles are used as an additive in gasoline due to the improvement in the physicochemical properties of fuels [23]. At the molecular level, these materials stand out for their exceptional specific surface and high chemical reactivity, which allows them to interact with gasoline and improve its quality. An illustrative example is iron oxide nanoparticles ( $\text{Fe}_2\text{O}_3$  NPs), successfully used as catalysts in hydrocarbon and volatile organic compound (VOC) oxidation reactions. In these reactions, the oxide acts as an active center that facilitates chemical reactions, accelerating the reaction rate and reducing the temperature needed for this to occur [24]. Studies reported in the literature have shown that  $\text{Fe}_2\text{O}_3$  NPs influence combustion and reduce fuel consumption since they reduce kinematic viscosity when suspended and dispersed in the intermolecular spaces of fuel droplets [24,25]. The studies allow adjacent layers to slide more efficiently through more precise fuel spraying and better air–fuel mixing. As a result, more complete combustion and efficient use are carried out to minimize the emissions generated [26]. Hence, nano-additives enhance the thermal efficiency of diesel engines while decreasing emissions. The level of all pollutants ( $\text{NO}_x$ , UHC, CO, and smoke) in exhaust gases is due to their catalytic effect on the fuel combustion process, particularly compared to the impact of gasoline/biodiesel blends [25].

In this way, most previous studies have focused primarily on tests involving pyrolytic oil as a substitute for diesel. However, the present work focuses on using commercial gasoline–pyrolytic oil mixtures of plastic waste with the addition of  $\text{Fe}_2\text{O}_3$  NPs to analyze the combined effect of the mixing with bio-oil and the use of NPs as additives in the power generated in a gasoline engine and the emissions from the combustion process. The pyrolytic oil was obtained from thermal pyrolysis at low temperatures ( $450\text{ }^\circ\text{C}$ ) from a 75% PS and 25% PP mixture [27]. This mixture generates liquid fractions with a relative composition ranging from C6 to C20 and a significant content of aromatic hydrocarbons and paraffin, according to previous research. Moreover, only a few works have been published combining the features mentioned above, which could be a promising alternative to minimize the consumption of fossil fuels and the emissions generated by this process.

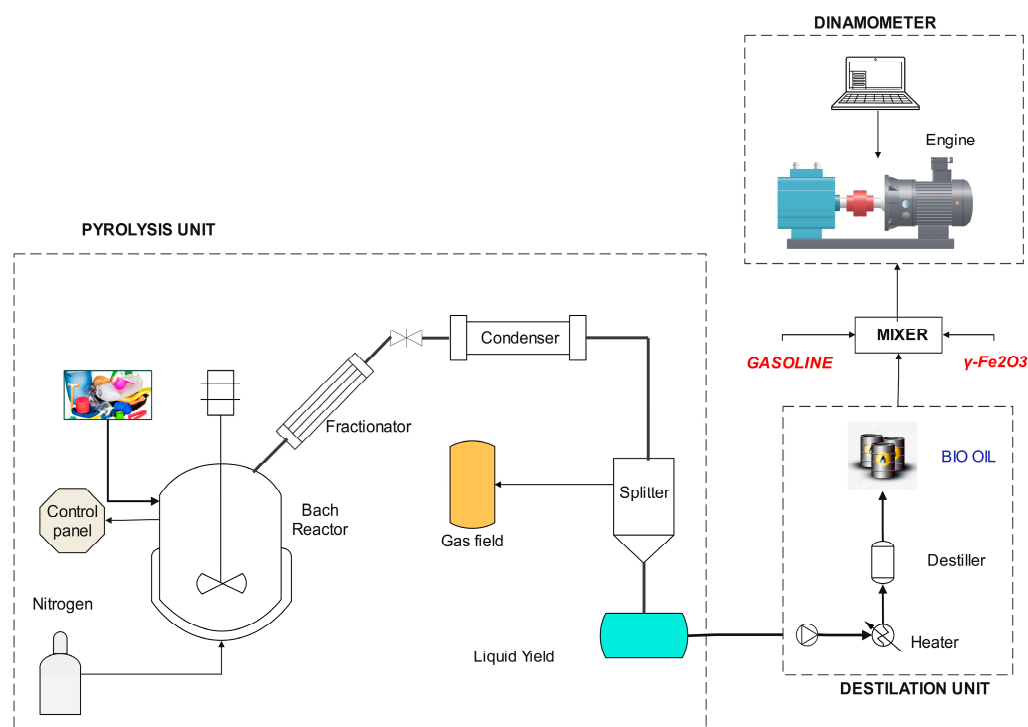
## 2. Materials and Methods

### 2.1. Materials

Municipal plastic waste was sampled from a garbage dump (Riobamba, Ecuador) at different periods for ten days over three consecutive months. They were then sorted to obtain PP and PS fractions, which were then washed and crushed to a particle size of 1 mm. These plastic residues were characterized by Fourier transform infrared spectroscopy (FTIR) using a FT/IR-4100 spectrometer (JASCO, JAPAN), working range from 4000 to  $550\text{ cm}^{-1}$  and the Spectra Analysis program for data acquisition and processing. Iron oxide nanoparticles ( $\gamma\text{-Fe}_2\text{O}_3$  NPs, 99.5%) were acquired from Luoyang Tongrun (Luoyang, China), and are reddish-brown powder in color with a particle size of 30 nm and a surface area of  $75\text{ m}^2/\text{g}$ .

### 2.2. Production of Bio-Oil

The pyrolysis process occurs in a batch reactor with an electric resistance heating system, an internal temperature control, and an agitator. The reactor was operated under a nitrogen atmosphere (5 L/min) at  $425\text{ }^\circ\text{C}$  (heating rate of  $15\text{ }^\circ\text{C}/\text{min}$ ) and 50 kPa for 1 h. The pyrolytic gases obtained circulate through a condenser ( $10\text{ }^\circ\text{C}$ ) and then pass to a simple separator where the liquid and gaseous fractions are collected, as shown in Figure 1. The experimentation was carried out in triplicate, feeding the reactor with 1000 g of a plastic waste mixture composed of 75% PS and 25% PP.



**Figure 1.** Experimental setup and scheme of the whole process.

The liquid fraction obtained was collected, weighed, and characterized under ASTM standards, while the solid fraction was received from the bottom of the reactor. As for the gaseous fraction, this was determined by the difference between the feed mass and the total liquid/solid fraction obtained previously. In order to avoid fluidization problems in the pumping systems due to the presence of waxes and gums in the hydrocarbons from pyrolysis, the pyrolytic oil was distilled at 150 °C under atmospheric pressure and subjected to a drying process with the addition of anhydrous calcium sulfate (2% *w/w*). Then, the obtained bio-oil was blended with standard gasoline and  $\gamma$ -Fe<sub>2</sub>O<sub>3</sub> NPs, as described in Section 2.3. Finally, the study samples were used to assess the engine performance (power/torque tests) and combustion gas emissions, including HC, CO, CO<sub>2</sub>, NO<sub>x</sub>, and NO<sub>2</sub>.

### 2.3. Samples

The pyrolytic oil obtained above was blended with 87 octane extra commercial gasoline and  $\gamma$ -Fe<sub>2</sub>O<sub>3</sub> NPs as follows:

- 1.- STD: Standard sample of extra commercial gasoline.
- 2.- M0: commercial gasoline + 40 mg of  $\gamma$ -Fe<sub>2</sub>O<sub>3</sub> NPs.
3. M1: commercial gasoline + 2% bio-oil (*v/v*).
4. M2: commercial gasoline + 5% bio-oil (*v/v*).
5. M3: commercial gasoline + 40 mg of  $\gamma$ -Fe<sub>2</sub>O<sub>3</sub> NPs + 2% bio-oil (*v/v*).
- 6.- M4: commercial gasoline + 40 mg of  $\gamma$ -Fe<sub>2</sub>O<sub>3</sub> NPs + 5% bio-oil (*v/v*).

All samples are characterized under commercial gasoline standards (ASTM), including density testing at 15 °C (ASTM D 1298), API density (ASTM D 287), flash point (D 93), distillation curve (ASTM D86), and octane number RON (ASTM D2699).

### 2.4. Power/Torque Tests

The power tests were carried out using a conventional automobile engine, with the following characteristics shown in Table 1. These tests were conducted using an AWD chassis dynamometer Dynocom, AWD-5000-FX (Fort Worth, TX, USA), which consists of a front unit (2WD, 5000 series) connected to a 6-link rear roller bed via a Gates Poly Chain belt. The roller bed has a tread width ranging from 36 to 86 inches and is calibrated according

to SAE Standard J1349. Data handling, processing, and all tests were performed using Quantum software under environmental conditions (pressure: 542.036 mmHg, temperature: 20.6 °C, humidity: 29%).

**Table 1.** Characteristics of the used gasoline engine.

| Parameters          | Specifications                        |
|---------------------|---------------------------------------|
| Engine Type         | Turbocharged Inline Three-Cylinder    |
| Engine Model        | T-GDi—1.0 L                           |
| Fuel                | Gasoline                              |
| Nominal power       | 120 hp or 88 kW                       |
| Maximum torque      | 200 Nm                                |
| Nominal power       | 6.000 rpm                             |
| Nominal voltage     | 48 V                                  |
| Comprehension ratio | 10, 5:1                               |
| Feeding             | Direct injection. Turbo. Intercooler. |
| Displacement        | 998 cm <sup>3</sup>                   |

The power tests were carried out as follows: (i) ABC (active body control) of the engine and fuel injection system; (ii) warm-up and stabilization time of the engine until the working temperature of 90 °C is reached; (iii) combustion gas exhaust system is checked for leaks; (iv) power/torque data collection. The test achieved the maximum engine revolutions with a start at 2500 rpm.

### 2.5. Combustion Emissions

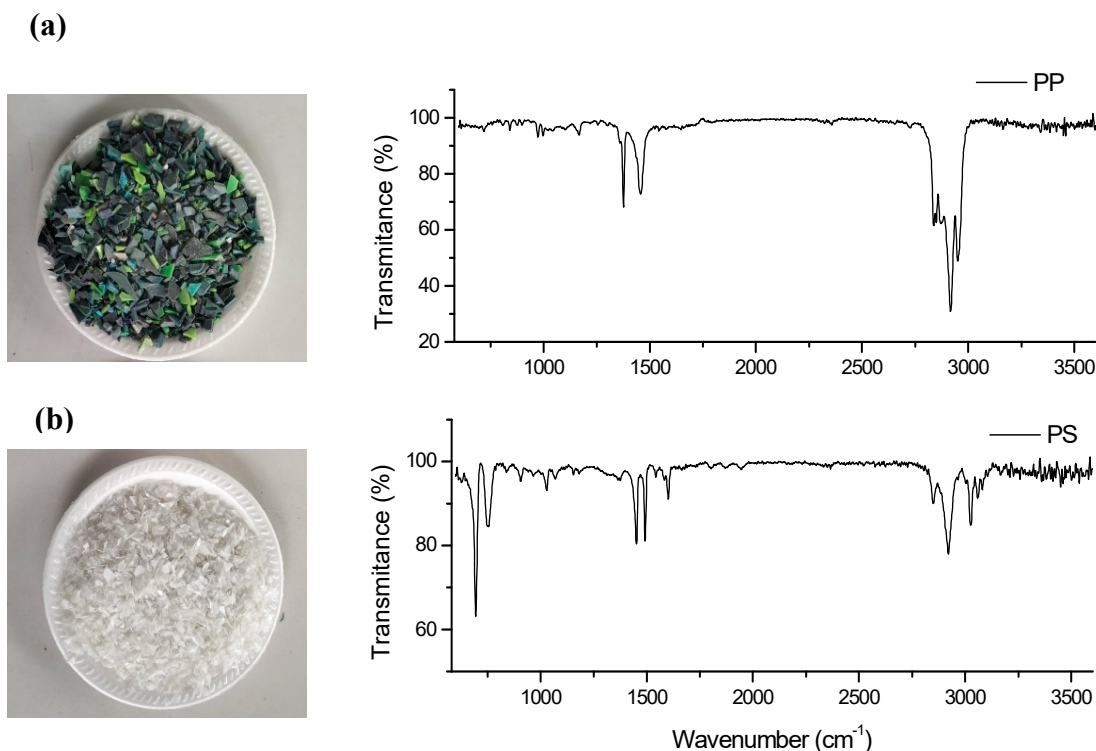
The effect of  $\gamma$ -Fe<sub>2</sub>O<sub>3</sub> NPs on the combustion reaction was studied using an exhaust gas meter for gasoline vehicles (MET 6.1, Haldenwang, Germany) by fully inserting the fixed probe into the exhaust pipe to measure the emissions generated at 4200 rpm. The components measured were HC, CO, and CO<sub>2</sub>, including the calculation of the octane number and the efficiency of the combustion process, which were obtained using a flue gas analyzer (TESTO 340, Mexico, México). This instrument has interchangeable and precalibrated sensors with temperature control and automatic CO dilution sensor protections.

The measurement of NO<sub>x</sub> employs the indirect method of Griess reactive NO<sub>x</sub> binders, which operate a solution A: sulfanilic acid plus acetic acid (5 N) and a B solution:  $\alpha$  naphthylamine plus acetic acid (5 N). First, 5 mL of solution A and 5 mL of solution B were placed in the collector tube, which was saturated with the exhaust gases at the time of the dynamometer test, and subsequently, their absorbance was determined using a UV–visible spectrophotometer at a wavelength of 541 nm. The power and emissions tests were conducted at ambient conditions of 18 °C, 60% relative humidity, and an altitude of 2754 m.a.s.l.

## 3. Results

### 3.1. Characterization of Plastic Waste

FTIR was used for the chemical characterization of plastic waste, i.e., PP and PS, as shown in Figure 2. The PP spectrum exhibits three distinct band groups at 2900 cm<sup>−1</sup> (tension movements C-H), 1350–1470 cm<sup>−1</sup> (C-C tension bonds), and 1200–1000 cm<sup>−1</sup> (−CH<sub>3</sub> bending vibrations). The PS spectrum exhibits absorption bands similar to PP, with additional bending movements of −CH<sub>2</sub> and tension vibrations due to aromatic rings between 700 and 800 cm<sup>−1</sup>. These results coincide with those reported in other studies [28], confirming the nature of the plastic waste used in this work.



**Figure 2.** FTIR of plastic waste. (a) Polypropylene (PP) and (b) polystyrene (PS).

### 3.2. Characterization of Samples

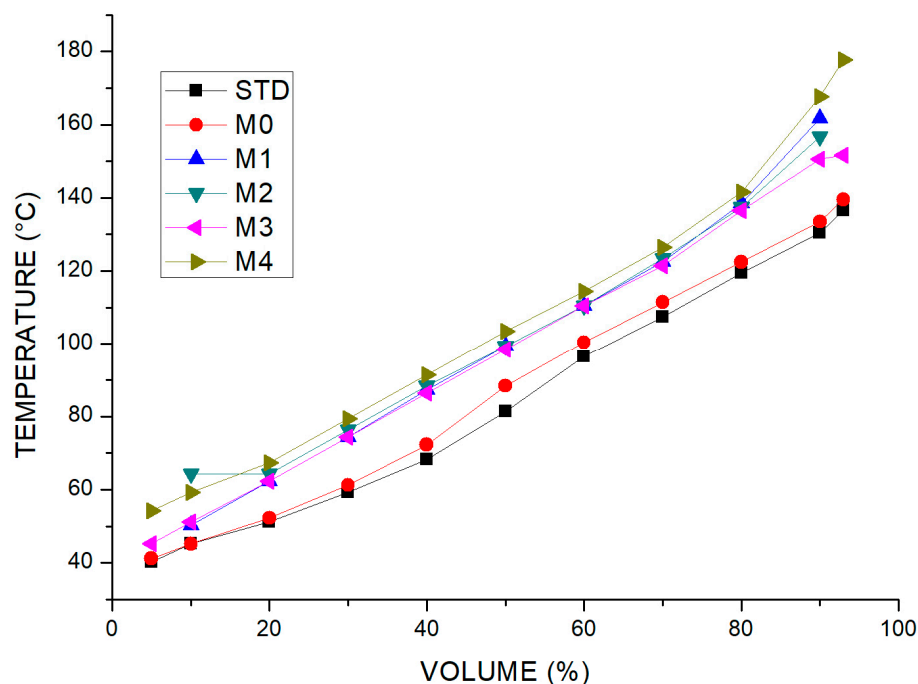
Table 2 presents the physicochemical properties of the prepared mixtures alongside the standards of commercial gasoline. As can be seen, the STD and M0 samples have similar values, which indicates that  $\gamma$ -Fe<sub>2</sub>O<sub>3</sub> NPs do not significantly influence the properties of the fuel. At the same time, the addition of bio-oil (M1 and M2) in combination with  $\gamma$ -Fe<sub>2</sub>O<sub>3</sub> NPs (M3 and M4) generates a slight decrease in API density and viscosity, which is attributed to the presence of aromatic and low-molecular-weight compounds that produce a viscosity cut with a slight increase in relative density due to the presence of additional compounds in the sample [26]. In addition, the flash point of the bio-oil was evaluated using the Pensky–Martens closed cup method. In this way, the flash point revealed similar results for each treatment, demonstrating overall remarkable properties with the pyrolytic oil and its mixture with the nanomaterial, indicating its suitability as an alternative to standard gasoline fuel [29].

**Table 2.** Physicochemical properties of standard commercial gasoline and gasoline blend with  $\gamma$ -Fe<sub>2</sub>O<sub>3</sub> NPs and bio-oil.

| Samples | API Density (°) | Relative Density | Viscosity (cSt) at 25 °C | Flash Point (°C) | Distillation (%) |                 |                 |
|---------|-----------------|------------------|--------------------------|------------------|------------------|-----------------|-----------------|
|         |                 |                  |                          |                  | T <sub>10</sub>  | T <sub>50</sub> | T <sub>90</sub> |
| STD     | 58.56           | 0.744            | 1.17                     | 18               | 45               | 81              | 130             |
| M0      | 58.56           | 0.744            | 1.17                     | 18               | 45               | 88              | 133             |
| M1      | 58.84           | 0.747            | 1.061                    | 18               | 50               | 99              | 161             |
| M2      | 57.50           | 0.752            | 1.033                    | 18               | 51               | 99              | 156             |
| M3      | 57.46           | 0.748            | 1.058                    | 18               | 51               | 98              | 150             |
| M4      | 56.46           | 0.753            | 1.025                    | 18               | 59               | 103             | 167             |

The distillation of the samples was also evaluated at different temperatures with respect to the volume of distillate recovered (Figure 3). For mixtures with bio-oil (2 and 5%, v/v), there is a more significant amount of volume at higher temperatures, which is due to

the composition of the bio-oil obtained from the random cracking of the pyrolysis process of plastic waste, ranging from C6 to C40 [30]. In addition, the presence of nanoparticles generates a slight increase in the boiling temperature of gasoline compounds. It increases at temperatures above 60 °C, attributed to the interaction of nanoparticles and molecules from bio-oil with a boiling point above that temperature. In addition, the M4 curve has a slightly more significant slope change, attributed to the high number of low-molecular-weight compounds in this pyrolytic oil. According to Torre et al. [31], the most pronounced effect of this phenomenon can be observed between 20% and 50% of the distillation curve (120), as can be seen in the behavior of mixtures with bio-oil and  $\gamma$ -Fe<sub>2</sub>O<sub>3</sub> NPs [32,33].

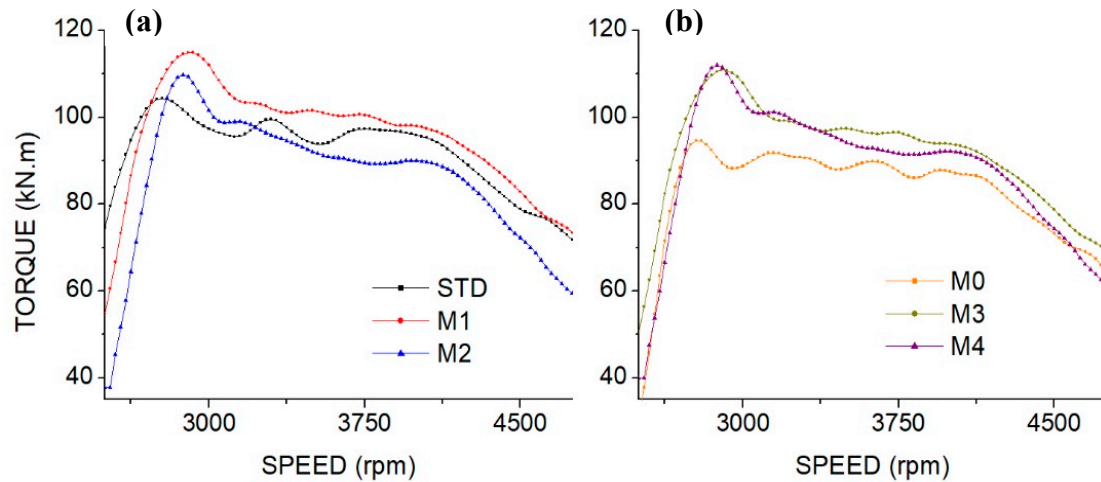


**Figure 3.** Effect of recovered distillate volume percentage for each sample versus temperature.

### 3.3. Engine Performance

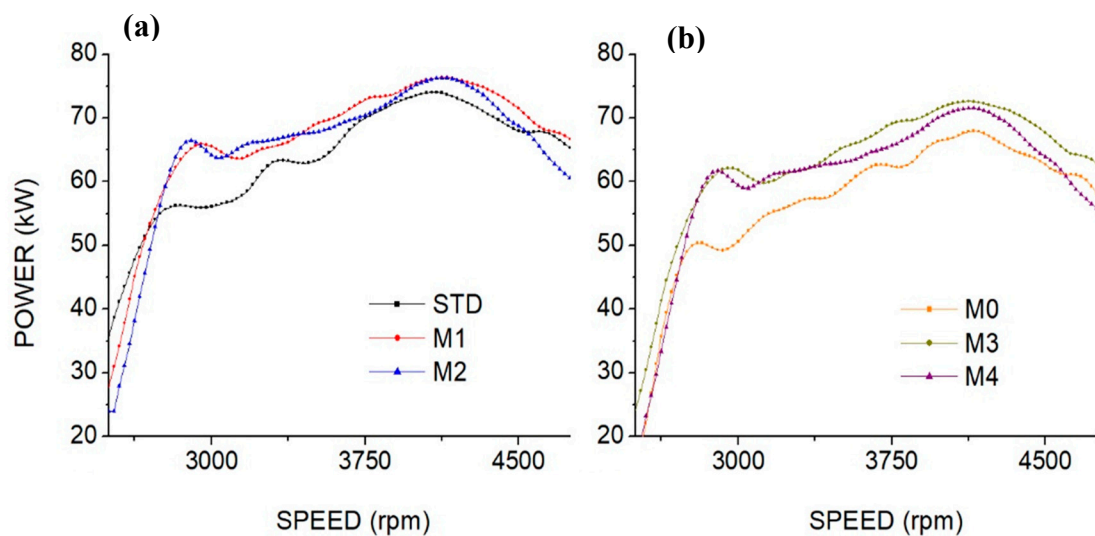
Several strategies have been reported in the literature to improve engine performance, using biodiesel as an additive in diesel or gasoline engines [34,35]. This is likely because biodiesel enhances fuel lubricity and increases the octane amount of gasoline, preventing premature wear on moving parts. In a gasoline engine, power and torque are fundamental parameters to evaluate to describe its performance, with torque essential for rotational force and power for how quickly the vehicle can complete the job. This study assessed engine power using a dynamometer that creates resistance contrary to engine rotation. The resulting dynamometer measurement represents the torque. In a gasoline engine, torque is measured at different speeds and revolutions, making it possible to determine the engine power. Figure 4a,b show the variation in motor momentum as a function of different rotational speeds for each proposed treatment (138 operating points). As shown, there is an increase in engine torque up to 2800 rpm for all fuels evaluated. However, when the engine revs at a higher number of revolutions, a decrease in torque is observed; this is likely attributed to a reduction in volumetric efficiency and increased mechanical losses [20]. Other parameters can also influence engine torque, including calorific value, viscosity, octane number, and density. In this way, the M1 fuel obtained the best results (gasoline and 2% bio-oil) and the M2 sample presents results slightly lower than M1 but both higher than the standard. The difference between M1 and M2 can be attributed to the fact that the presence of bio-oil in the mixture generates a change in the physicochemical properties of the mixture due to the presence of compounds of varied molecular weight in the bio-oil. This generates a process in which there is a good torque at the beginning;

however, when the revolutions are increased, there is a pronounced decrease. As expected, the exclusive incorporation of  $\gamma\text{-Fe}_2\text{O}_3$  NPs as an additive in the gasoline mixture (M0) does not positively impact engine torque, as it could affect its ability to atomize efficiently during fuel injection, thus decreasing process performance.



**Figure 4.** Comparison of torque–speed behavior (rpm): (a) pure gasoline (STD) and treatments of commercial gasoline with percentages of biofuel; (b) treatments of commercial gasoline with  $\gamma\text{-Fe}_2\text{O}_3$  NPs.

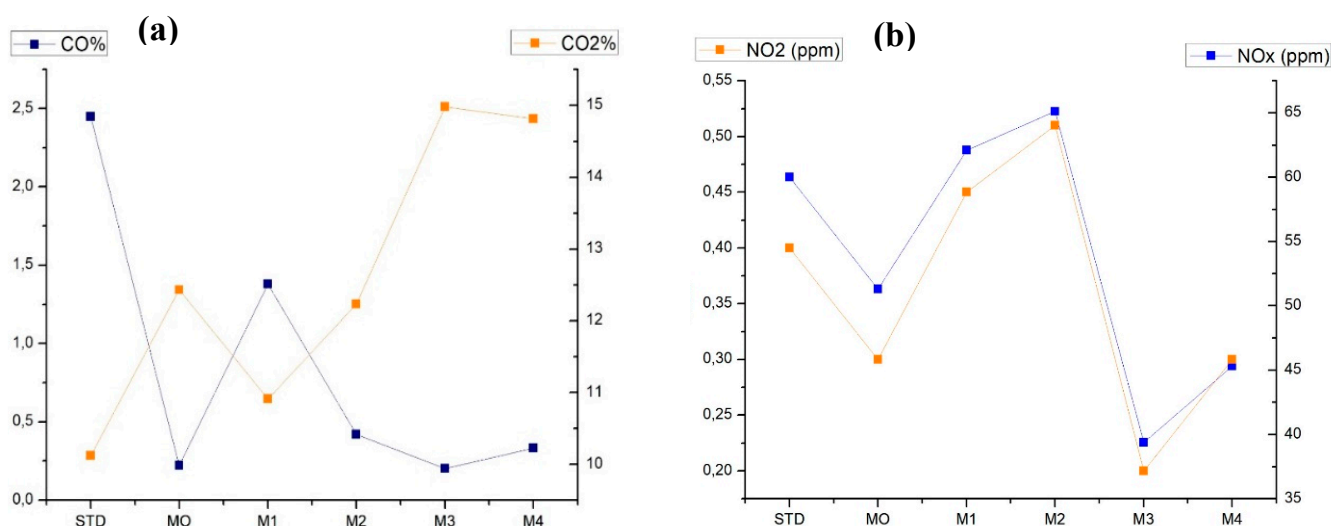
Achieving a proper balance between torque and power is essential for the efficient performance and responsiveness of a gasoline engine [36]. Figure 5a,b show the variations in engine power as a function of engine speeds (138 operating points). At 2800 rpm, the highest engine power was obtained with M1 biofuel, with a 10% increase compared to standard commercial gasoline (STD) at the same speed. On the other hand, at 4000 rpm, the engine powers of bio-oil fuels and commercial gasoline are very similar. However, with the addition of  $\gamma\text{-Fe}_2\text{O}_3$  NPs, a reduction in engine performance values, including torque and engine power, is observed, which can be attributed to a lower calorific value compared to other biofuels [37].



**Figure 5.** Comparison of power testing on engine–speed behavior (rpm): (a) pure gasoline (STD) and treatments of commercial gasoline with percentages of biofuel; (b) treatments of commercial gasoline with  $\gamma\text{-Fe}_2\text{O}_3$  NPs.

### 3.4. Evaluation of Emissions in Blended Fuels

The CO and CO<sub>2</sub> emissions generated by the engine were analyzed for each of the biofuels used, as shown in Figure 6a. Normal driving conditions were simulated, assessing the performance of a real car at 2500 rpm and under full load. The best results were obtained with the exclusive application of  $\gamma$ -Fe<sub>2</sub>O<sub>3</sub> NPs, with a 2.3% decrease in carbon monoxide emissions compared to the total production of 2.5% by standard gasoline fuel. In addition, gasoline–bio-oil blends with  $\gamma$ -Fe<sub>2</sub>O<sub>3</sub> NPs report similar results, contributing positively to gasoline engine performance and emissions reductions. Studies reported in the literature indicate that adding oxide–metal nanoparticles in gasoline–bio-oil [38] and diesel–bio-oil [37] blends leads to a reduction in atmospheric emissions from the engine and a shortened ignition time. The presence of active oxygen, its catalytic effect, and the high surface-to-volume ratio of nanoparticles improve the combustion efficiency of fuel mixtures and reduce the formation of CO (a byproduct of incomplete combustion), which is considered one of the most dangerous emissions as it generates a tremendous negative impact on human health. In addition, carbon dioxide emissions into the environment (greenhouse gas) contribute to climate change, so they must be monitored and controlled [26]. However, using gasoline blends with bio-oil and  $\gamma$ -Fe<sub>2</sub>O<sub>3</sub> NPs does not significantly change CO<sub>2</sub> production compared to standard commercial gasoline. Its effectiveness is mainly influenced by decreasing carbon monoxide production and maintaining CO<sub>2</sub> production levels.

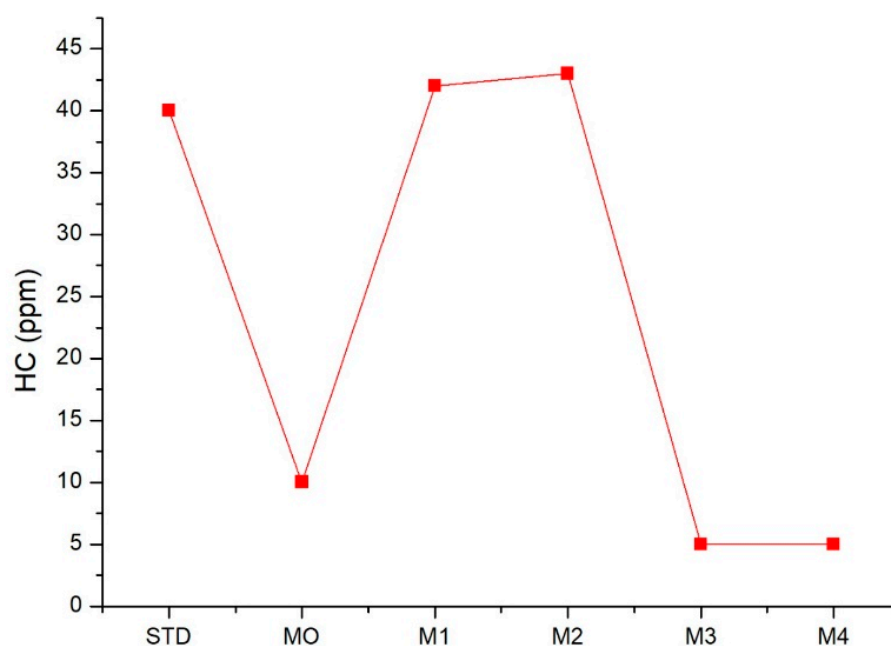


**Figure 6.** Change in emissions of (a) CO and CO<sub>2</sub> associated with each treatment; (b) NO<sub>2</sub> and NO<sub>x</sub> associated with each treatment.

On the other hand, the NO<sub>x</sub> emissions generated in the engine depend on several factors, including the percentage of oxygen in the fuel, engine temperature, and the reaction residence time [39,40]. NO<sub>x</sub> is composed mainly of nitric oxide and nitrogen dioxide, formed due to the interaction of oxygen and nitrogen at high temperatures in the cylinder. The results show that NO<sub>x</sub> emissions were significantly reduced after adding  $\gamma$ -Fe<sub>2</sub>O<sub>3</sub> NPs in gasoline–bio-oil blends (Figure 6b). This result may be due to the catalytic effect of  $\gamma$ -Fe<sub>2</sub>O<sub>3</sub> NPs improving heat transfer in the combustion chamber [41]. Furthermore, this nanomaterial has the potential to enhance the oxidation stability of gasoline, resulting in a more substantial reduction in NO<sub>x</sub> emissions.

Unburned hydrocarbons (HCs), along with the products of combustion, are pollutants emitted into the air due to incomplete combustion. Figure 7 shows that nanoparticle additive fuels act as regulating agents and improvers of complete combustion, where the size and concentration of the nanoparticles used in this work influence the combustion process, catalytic activity, oxygen content, reactivity, and calorific value [42]. In addition, studies reported in the literature indicate that using fuel–bio-oil blends in engines leads

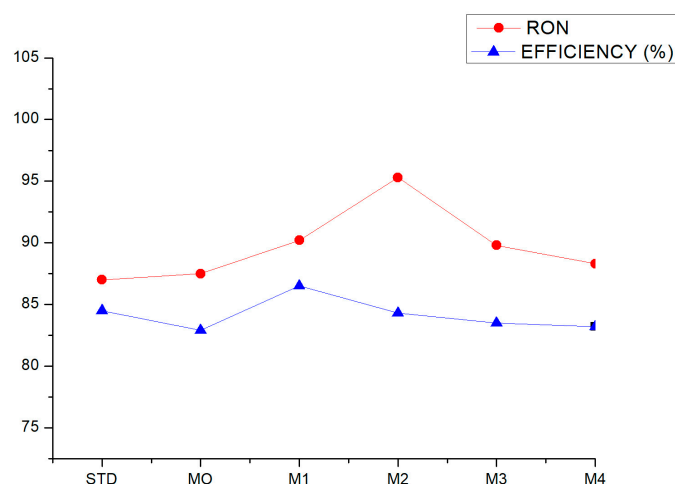
to complete combustion due to the amount of oxygen present in the composition of the biofuel, resulting in lower HC emissions [43]. In the case of the M1 and M2 samples contained in the bio-oil from pyrolysis, they have a higher concentration of HCs since the polymeric structure of the plastics used contains carbon and hydrogen in their entirety, which provides an excellent caloric value together with several hydrocarbons in the reaction process. Furthermore, as can be observed in treatments M3 and M4, mixtures of pyrolytic oil with the nanomaterial report low amounts of HCs, owing to complete combustion in the gasoline engine, attributable to the high oxygen content present in the fuel.



**Figure 7.** Variation in HC emissions related to each treatment.

### 3.5. Research Octane Number (RON) and Efficiency

The importance of the octane number lies in its significant impact on the performance of spark-ignition engines. The decrease in engine power is attributed to the effect resulting from the reduction in the octane number of the hydrocarbons in the paraffin group, especially those with a linear chain structure. In this context, using bio-oil in conjunction with nanoparticles increases the octane rating of the biofuel, as shown in Figure 8. In both cases, values higher than 88.3 were obtained compared to commercial gasoline, with similar results reported in the literature [42,43], confirming that incorporating both compounds in standard commercial gasoline positively influences fuel quality. As mentioned in the methodology, the gas emission equipment allows the combustion efficiency to be indirectly calculated, which measures theoretical efficiency based on the stoichiometry of emitted gases, as shown in Figure 8. In this way, increased efficiency signifies that the engine is utilizing fuel more effectively to produce mechanical work, potentially resulting in improved performance and greater fuel economy. The results obtained do not show significant variations among the treatments, indicating that the use of pyrolytic oil alone or mixed with the nanomaterial serves as a promising alternative additive to standard commercial gasoline, thereby reducing overall dependence on this nonrenewable fuel.



**Figure 8.** Changes in octane number and efficiency associated with each treatment.

#### 4. Conclusions

Different samples such as standard commercial gasoline, gasoline blended with bio-oil, and gasoline–bio-oil– $\gamma$ -Fe<sub>2</sub>O<sub>3</sub> NPs were studied to enhance engine performance and reduce air pollution. The benefits of biodiesel derived from plastic waste include improved fuel economy and positive economic impact, thereby enhancing air quality and engine performance. Additionally, when using  $\gamma$ -Fe<sub>2</sub>O<sub>3</sub> NPs in gasoline engines as a nano-additive, reductions in CO (carbon monoxide), NO<sub>x</sub> (nitrogen oxide), and HC (hydrocarbon) emissions were observed due to their advantages, including their catalytic effect, presence of active oxygen, and large surface area.

On the other hand, the addition of bio-oil in combination with  $\gamma$ -Fe<sub>2</sub>O<sub>3</sub> NPs generates a slight decrease in API density and viscosity, which is attributed to the presence of aromatic and low-molecular-weight compounds that produce a viscosity cut with a slight increase in relative density due to the presence of additional compounds in the sample.

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