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Article

Production of Bio-Oil Via Pyrolysis of Banana Peel and Tire Waste for Energy Utilization

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Abstract: The energy crisis and environmental degradation are pressing challenges, intensified by population growth and the excessive generation of solid waste. Converting waste into energy, especially through pyrolysis, is a viable and sustainable alternative. This thermal process transforms waste such as banana peels and used tires into high-value products such as gas, coal and oil. This study aims to evaluate the production of pyrolytic oil from the pyrolysis and co-pyrolysis of these materials, considering different proportions and temperatures, as well as using a decision tree to predict the composition of the bio-oils. The pyrolysis tests with 100% banana peel and 75% banana peel mixed with 25% tire showed a decrease in oil yield with increasing temperature, with a drop of around 30% when comparing 500 ºC to 400 ºC. In contrast, co-pyrolysis with 50% of each material and 100% of the tire resulted in increases in oil yield as the temperature rose. FTIR analysis of the oils showed the presence of relevant functional groups, while elemental analysis and decision tree modeling provided accurate predictions of carbon, hydrogen and nitrogen content. The results suggest that the co-pyrolysis of waste tires and banana peels is a viable alternative for the production of bio-oil.

Keywords: pyrolysis; waste; energy; banana peel; tire

1. Introduction

The energy crisis and environmental degradation represent significant challenges currently facing humanity. These issues arise from population growth and the substantial daily production of solid waste from domestic, agricultural, and industrial sources. The investigation of alternative fuels to petrochemical derivatives has been the focus of various research groups [1]. Given the fundamental need for energy, the conversion of waste into energy presents a viable method for addressing these demands sustainably [2–4].

Among the technologies employed, pyrolysis emerges as a promising strategy, as it converts waste into energy. Pyrolysis aligns with the three principles of solid waste treatment: reduction, resource recovery, and pollutant mitigation. It is a thermal degradation process capable of producing high-value products such as gas, char, and oil [5,6].

The application of resources from unconventional sources, including urban and industrial organic waste, discarded plastics, and used tires, in appropriate technologies offers an excellent alternative for both energy production and sustainability [7,8]. The agro-industrial sector generates various types of waste daily, including harvest residues, industrial waste, livestock waste, and aquaculture waste. Given that the management of these residues is often limited or inadequate, there is an urgent need to develop strategies for their utilization and valorization [9].

Among agricultural crops, banana production generates a significant amount of waste, utilizing only 20 to 30% of its mass, leaving approximately 70 to 80% as waste, which consists of rotten fruits, peels, rachis, leaves, pseudostems, and rhizomes. In light of this reality, studies have sought alternatives for utilizing these residues, with the application of banana waste as feedstock for pyrolysis proving highly promising [10–13].

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Despite recent increased attention to studies on agricultural residues, such as banana leaves, pseudostems, and peels, there are few reports in the literature regarding the pyrolysis of banana waste [14].

In addition to agro-industrial residues, another challenge in waste management involves those from tires, due to their large volume and the recycling difficulties associated with their intricate structure. Globally, nearly 1.5 billion tires are discarded annually at the end of their life cycle, with projections estimating this number will increase to 5 billion by 2030 [15]. In Brazil alone, at least 450,000 tons of tires are discarded each year [16].

The recycling of unusable tires presents significant potential for products that can be utilized in various applications, and pyrolysis provides an alternative source for fuel production. The products from the pyrolysis process of tires typically consist of 33%-39% by weight of char, 34%-42% by weight of oil, with the remainder being pyrolytic gases [6].

Given that biomass pyrolysis experiments have demonstrated promising properties as feedstock, studies have sought to apply machine learning techniques, such as decision trees, to predict the yield and composition of pyrolysis products [17]. Such models are capable of efficiently handling both continuous and categorical data while providing interpretability, which is essential for analyzing limited experimental data [18].

Therefore, this study aims to evaluate the production of pyrolytic oil obtained from the pyrolysis or co-pyrolysis of banana peel and/or tire oil, assessing the impact of feedstock ratios at temperatures of 400ºC, 450ºC, and 500ºC. Additionally, a Decision Tree modeling approach will be employed to predict the CHN composition of the bio-oils.

2. Materials and Methods

2.1. Description of the Samples

The residual material samples used in this work were banana peel and tire shavings. Tire chips were removed to obtain small, fine pieces. The banana peels were obtained pre-dried from a local factory, however, to ensure that they all had the same moisture content, they were subjected to an oven at 45ºC for 8 hours and then crushed.

To carry out the pyrolysis, 5 g of the total mass of the starting material was used in different proportions and at different temperatures, as shown in Table 1.

Table 1. Proportion of starting material (waste tire and banana peel) and pyrolysis temperature.

Starting material	Temperature
Banana peel (100%)	
Waste tire (100%)	
Banana peel: waste tire (75:25)	400, 450 and 500 ºC
Banana peel: waste tire (50:50)	
Banana peel: waste tire (25:75)	

2.2. Pyrolysis and Co-Pyrolysis Experiments:

The pyrolysis and co-pyrolysis experiments were carried out at the NUCAT (Catalysis Center) at UFRJ in a plant as shown in Figure 1. The plant has a tubular quartz reactor measuring 3 cm in diameter and 60 cm long. The plant has two cylindrical furnaces where the reactor is placed and its parts are insulated with glass wool to reduce heat loss from the ends. It also has two thermocouples which are connected to the temperature controller where the desired process temperature is programmed. At the reactor outlet is a straight condenser followed by a kitassato, with the aim of condensing the pyrolysis vapors and collecting the liquid generated. Nitrogen is the gas used to inert and drag the vapours generated. Its flow rate is set at 80 $mL.min^{-1}$ [19].

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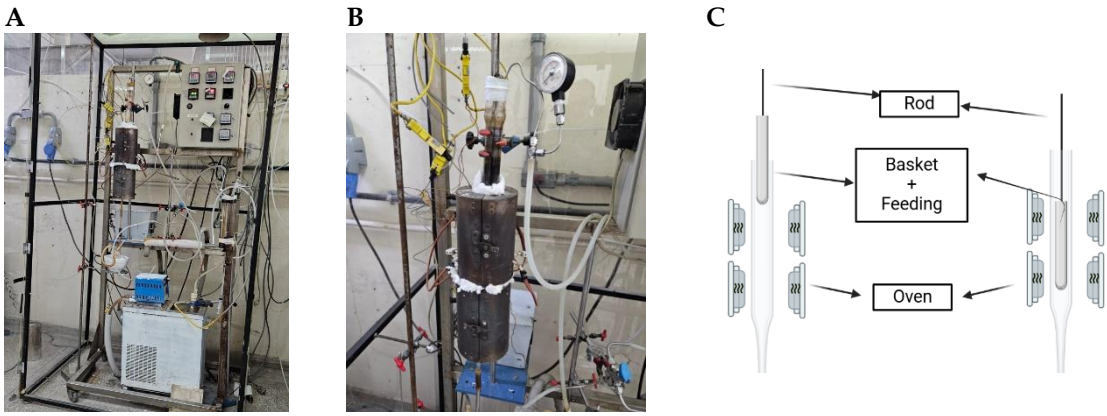

Figure 1. Pyrolysis plant (A). Furnaces and reactor (B). Diagram illustrating the reactor during the experimental procedure (C): Basket positioned above the furnaces before the start of the reaction (1C); Basket directed towards the center of the furnaces indicating the start of the reaction (2C).

The mass of waste used was 5.0 grams, varying the proportion of tire shavings and banana peel, as shown in Table 1. The material was placed inside a quartz basket with a diameter of 2 cm and a length of 12 cm. The basket was introduced into the reactor and kept above the ovens until the desired reaction temperature was reached (400ºC, 450ºC or 500ºC).

The established reaction time was 60 minutes. At the end of the reaction, the ovens were turned off and the cooling process began, with the components then being removed and weighed to determine the yields of the product fractions generated. All the reactions were carried out in triplicate and the oils obtained were stored in a freezer until analysis.

2.3. Fourier Transform Infrared Spectroscopy (FTIR) Analysis

The infrared spectroscopy analysis was carried out at the Inorganic Chemistry Department of the Chemistry Institute of the Federal University of Rio de Janeiro. For this analysis, about 15 mg of oil from the pyrolysis of tires and/or banana peels was weighed and analyzed in a Shimadzu FTIR spectrophotometer model IRAffinity-1S with an ATR-8000 accessory attached. The spectrum was obtained by horizontal attenuated total reflection with a ZnSe prism with 64 scans.

2.4. Elemental Analysis

Elemental analysis provided the percentage carbon, hydrogen and nitrogen (CHN) content of the oils obtained under the different pyrolysis conditions. This analysis was carried out at the National Institute of Technology, in the LADEQ (Laboratory for Testing and Development in Analytical Chemistry) following the parameters determined by the ASTM D5291 method.

2.5. Regression Model with Decision Tree for Predicting CHN Content in Pyrolytic Oil

The methodology adopted in this study began with the collection of experimental data, which was organized and stored in a CSV file. This data was obtained from thermal pyrolysis experiments carried out on waste tires and banana peels. The chemical parameters analyzed included the carbon (%C), hydrogen (%H) and nitrogen (%N) contents.

To ensure a robust evaluation of the model, the data was split using the train_test_split function, with 80% of the data destined for training and 20% for testing. This split ensures that the model is able to generalize well to unseen data, preventing overfitting. The regression model was developed in Python, using the collaborative environment Colab, which was chosen due to its accessibility and cloud processing capacity, making it easier to run and adjust the code. The model implemented an interface for user input, with a validation stage that ensures that the sum of the residual percentages is 100%. This validation is crucial for exploring new experimental conditions, ensuring the consistency of the input data.

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3. Results and Discussion

3.1. Effect of Temperature and Starting Material Composition on the Yield and Chemical Compounds of Pyrolytic Oil

In Figure 2, the oil yields obtained after pyrolysis with banana peels and/or tires at 400, 450 and 500ºC are shown.

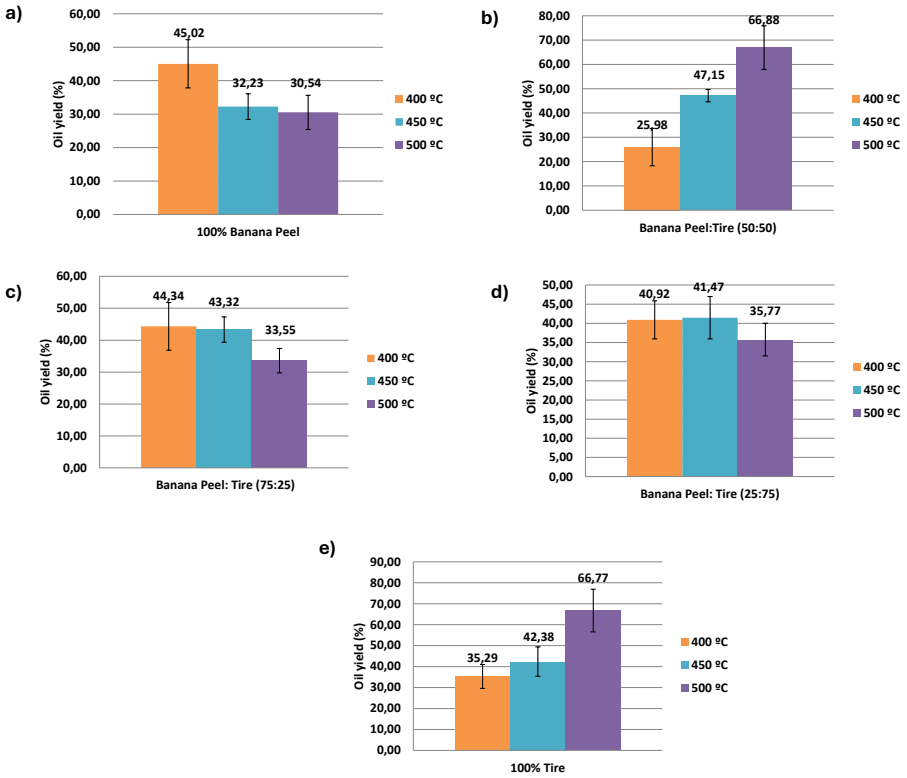

Figure 2. Oil yield (%) obtained from the pyrolysis of tires and/or banana peels at 400ºC, 450ºC and 500ºC.

The tests carried out with 100% banana peel (Figure 2a) and 75% banana peel: 25% tire (Figure 2c) showed an inversely proportional response in terms of yield as the temperature increased. At 500 ºC the oil yield fell by around 30% when compared to the yield obtained at 400 ºC. The yields observed in this study for the banana peel tests are higher than those reported in the literature, and this may be related to the properties of the raw material used in the experiment. However, the decrease in yield as the temperature increases has also been observed in other studies.

The study by Ozbay et al. (2019) investigated the thermal and catalytic pyrolysis of banana peel (400 to 700 ºC). At 400ºC the yield was 24.94%, at 550º the yield was 28.03% and at 700ºC the yield was 20.19%[14].

In the study carried out by Daimary et al. (2022), banana peel pyrolysis was carried out at temperatures of 500 ºC, 550 ºC and 600 ºC. From the tests, a yield of 22.18% was observed at 500 ºC, 24.20% at 550 ºC and 20.71 at 600 ºC [20]. Taib et al. (2021), evaluated the production of bio-oil from banana pseudostem via the fast pyrolysis process (470 ºC to 540ºC), and in their tests also observed a reduction in oil yield as the temperature increased [12].

Temperature is known as the most important factor in the pyrolysis of lignocellulosic biomass and affects the distribution of the product comprehensively. With increasing temperature, net bio-oil yields tend to decrease as a result of secondary cracking reactions of the pyrolysis vapor, reducing liquid and biochar yields while increasing gas yields [14,20].

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In the tests where 50% banana peel was used as the starting material: 50% tire (Figure 2b) and 100% tire (Figure 2e), it can be seen that as the temperature increases, the oil yield also increases. Kyari et al. (2005) pyrolyzed waste tires from seven different manufacturers and countries at a temperature of 500 ºC. The oil yield varied between 55.4 and 57.8 %, with an average of 56.6 and a standard deviation of 1.2 %. No differences were observed in the yield of the oil produced by mixing the different tires [21].

Čepić et al. (2021) evaluated the influence of temperature on the yield and composition of tire pyrolysis products, with other process parameters remaining unchanged, the temperatures evaluated were: 400, 450, 500, 550, 600, 650, 700 and 750 °C. From the results obtained, it was observed that with the increase in the final pyrolytic temperature, the oil yield increased simultaneously and reached a maximum value of 43.6% at 500 °C, after this temperature a reduction in yield was verified, at 750 °C the yield was 26.6%. In this study, the gas yield was evaluated, and by monitoring it, it was found that increasing the temperature increases the gas yield and decreases the oil yield [22].

Similar results were also observed by Cunliffe & Williams (1998), who investigated temperatures between 450ºC and 600ºC. This is due to the secondary cracking reactions that take place at high temperatures to form non-condensable gases [23].

The co-pyrolysis of tires and banana peels is still a topic that has not been widely explored in the literature. However, the results obtained in this study demonstrate the potential for using these two residues to obtain oil.

The oils obtained from the pyrolysis (400ºC, 450ºC and 550ºC) of the tire and/or banana peel were analyzed by reflectance infrared spectroscopy (FTIR) to assess the functional groups (acids, aromatics and others) present. The infrared spectra are shown in Figure A1-A3 (Appendix A).

The two most important areas for preliminary examination of the spectra are 4000-1300 cm^{-1} and 900-650 cm^{-1}. The characteristic peaks of alkanes and alkenes (1645-1500 cm^{-1}, 1475-1350 cm^{-1}) characterized in the FTIR spectra of the thermal process at 400°C were repeated for all the pyrolysis processes on the different tire and banana peel matrices, as shown in Table 2.

Table 2. Results of the FTIR spectra for the different oils with tires and banana peels.

Wavelength (cm^{-1})	Functional Groups	Components	Pyrolysis temperature														
			400 ºC					450 ºC					500 ºC				
			1	2	3	4	5	1	2	3	4	5	1	2	3	4	5
3500-3200	O-H bonded	Alcohol and phenols	-	+	+	+	-	+	+	+	+	+	-	+	+	+	+
3500-3200	O-H stretching	Water, O-H polymeric	-	+	+	+	-	+	+	+	+	+	-	+	+	+	+
3050-2800	C-H stretching	Alkanes	+	-	-	-	+	+	-	-	-	+	+	-	+	+	-
1750-1650	C=O stretching	Aldehydes, ketones, carboxylic acids, quinines	+	-	-	-	+	+	-	-	-	+	+	-	+	+	-
1645-1500	C=C stretching	Alkenes	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+
1475-1350	C-H bending	Alkanes	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+
1266-1342	C-N bending	Aromatic amines	-	-	-	-	-	+	-	-	-	+	+	-	-	-	-
1300-1150	C-O stretching	Alcohols	-	+	+	-	+	-	+	+	+	+	-	+	+	+	+
1300-1150	O=H bending	Phenols, esters, ethers	-	-	-	-	-	-	+	+	+	+	-	+	+	+	+

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1150-1000	C-H bending	Alkenes	-	-	+	+	-	+	-	-	-	+	+	-	+	-	+
650-1000	C=C stretching	Alkenes	+	-	-	-	+	+	-	-	-	+	+	-	+	-	-
900-675	O-H bending	Aromatics	+	-	-	-	+	+	-	-	-	+	+	-	+	-	-

1. 100% Tire Oil; **2.** 100% Banana Peel Oil; **3.** Tire/Banana Peel Oil, 50:50; **4.** Tire/Banana Peel Oil, 25:75, **5.** Tire Oil/Banana Peel, 75:25.

The spectra of the oils obtained from the pyrolysis of 100% tires, regardless of temperature, have a similar profile to the spectrum of commercial diesel oil analyzed by Ruschel et al. (2014) [1].

The double peaks between 2800 and 3000 cm-1 in the stretching mode were identified at all temperatures in the 100% tire and 75% tire: 25 Banana Peel samples, which indicate the presence of alkanes (C-H3, C-H2 and CH).

The peak between 1350 and 1470 cm $^{-1}$ in the bending mode due to the deformation of CH2 and CH3 denotes the presence of alkanes. The C double bond O stretching vibrations with absorbance between 1650 and 1750 cm $^{-1}$ indicate the presence of ketones or aldehydes.

Banar et al. (2012) used a fixed bed to produce pyrolytic oils derived from tires at temperatures of 350, 400, 450, 500, 550 and 600 °C and analyzed their properties as a potential fuel. Through FT-IR characterization they observed the presence of alkanes (2800 and 3000 cm $^{-1}$, 1350 and 1475 cm $^{-1}$), ketones or aldehydes (1575 and 1675 cm $^{-1}$) [24].

The samples with 100% banana peel, 25% tire: 75% banana peel and 50% tire and 50% banana peel showed a profile similar to that observed by Taib et al. (2021) who evaluated the production of bio-oil from banana pseudostem via the fast pyrolysis process [12]. The strong absorbance between 3550 and 3200 cm^{-1} represents the O- functional group, while the absorbance peak located near 3340 cm $^{-1}$ is a typical characteristic of cellulose. The absorbance peaks between 1650 and 1580 cm $^{-1}$ represent C double bond stretching vibrations which indicate the presence of alkenes. The C-H deformation vibrations between 1470 and 1350 cm -1 indicate the presence of alcohols and phenols. Finally, the peaks between 1300 and 950 cm $^{-1}$ indicating the C-O functional group are due to the presence of alcohols and phenols.

3.2. Regression Model with Decision Tree for Predicting CHN Content in Pyrolytic Oil

Elemental analysis was carried out to quantitatively determine the elements carbon, hydrogen and nitrogen in the oils obtained from pyrolysis at 400 ºC with the biomass of: Tire (T, 100%), Banana Peel (BP, 100%), T: BP (50:50), T:BP (25:75), and T:BP (75:25). The results of the elemental analysis are shown in Table 3, in terms of the percentage of Carbon (C), Hydrogen (H), Nitrogen (N) and the Hydrogen/Carbon ratio (H/C).

Table 3. Results of Elemental Analysis in oils obtained from pyrolysis at 400 ºC with Tire (T) and/or Banana Peel (BP).

Temperature (ºC)	**Type of oil**	C%*	H%*	N%*	H/C
400	T* (100%)	82,74±1,03	11,01±2,31	1,23±14,95	0,13
	BP* (100 %)	3,54±0,20	11,43±0,62	0,07±10,88	3,22
	T/ BP (50/50)	5,47±12,27	9,37±10,80	1,05±10,77	1,71
	T/ BP (25/75)	7,15±1,09	10,69±3,97	0,79±4,50	1,49
	T/ BP (75/25)	6,55±3,02	10,77±7,09	0,91±3,91	1,64
450	T (100%)	83,20±1,79	10,81±0,12	1,02±2,20	2,20
	BP (100 %)	3,30±1,43	10,72±0,84	0,46±2,02	3,25
	T/ BP (50/50)	4,30±2,59	10,78±2,19	0,34±2,31	2,51
	T/ BP (25/75)	3,75±1,06	10,75±2,47	0,15±7,28	2,87
	T/ BP (75/25)	71,50±4,33	10,63±1,89	1,64±11,65	0,15

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	T (100%)	87,47±0,50	11,97±0,50	0,05±0,01	0,14
	BP (100 %)	3,43±0,14	10,88±0,08	0,63±0,07	3,18
500	T/ BP (50/50)	6,55±0,61	11,00±0,01	0,03±0,01	1,69
	T/ BP (25/75)	4,29±0,17	10,23±0,21	0,05±0,01	2,38
	T/ BP (75/25)	85,27±0,51	11,90±0,17	0,03±0,01	0,14

* T: Tire, BP: Banana peel, C: Carbon, H: Hydrogen, N: Nitrogen.

Based on the results obtained in the CHN analysis, a regression model based on decision trees was used to predict the carbon (%C), hydrogen (%H) and nitrogen (%N) contents in bio-oils obtained from the thermal pyrolysis of waste tires and banana peels. Figure 3 shows the decision tree for predicting the chemical parameters of carbon (CHN) content. Analysis of the results revealed that variables such as banana percentage and temperature play critical roles in determining CHN levels, as illustrated in the decision tree diagram generated.

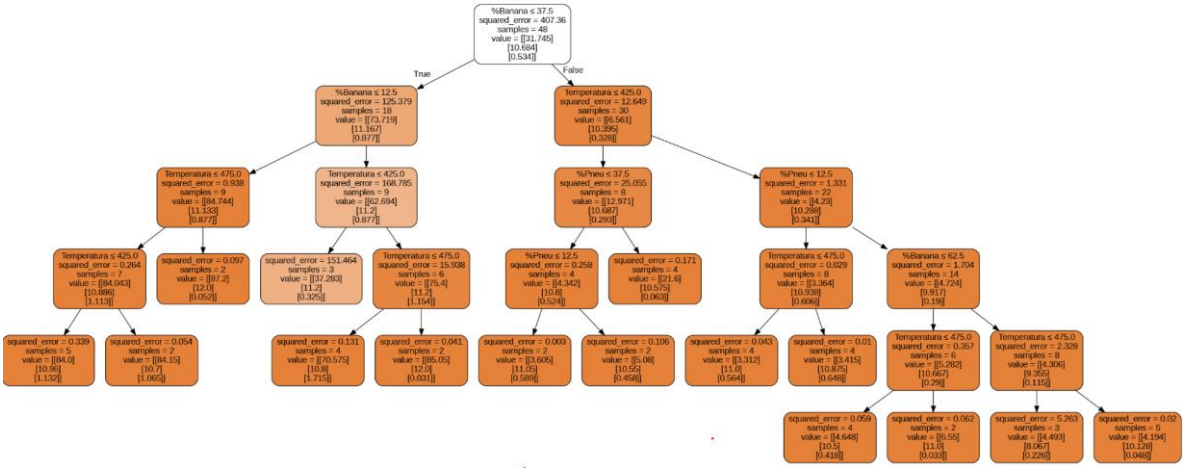

Figure 3. Decision tree generated by the model that was fed with the data from the experiments carried out containing the sample temperature values and the percentage of residue of each sample and its measured chemical parameters (%C, %H and %N).

The results of training the model and of a run with the prediction for a bio-oil produced at a temperature of 500°C and a waste mixture ratio of 40% tire and 60% banana are shown in Figure 4 below.

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61 rows × 6 columns
Erro Quadrático Médio (MSE): 7.027032398539887
    Real %C  Previsto %C  Real %H  Previsto %H  Real %N  Previsto %N
0      3.48     3.605000    11.00    11.050000   0.7440     0.589000
1      3.34     3.312500    10.90    11.000000   0.4310     0.564000
2     85.10    85.050000    11.20    12.000000   0.0246     0.030800
3      5.47     4.647500     9.40    10.500000   1.0500     0.417750
4      6.55     5.080000    10.80    10.550000   0.9100     0.458000
5     84.40    84.150000    10.60    10.700000   1.0500     1.065000
6      4.70     4.647500     9.87    10.500000   0.5500     0.417750
7     85.70    85.050000    11.70    12.000000   0.0249     0.030800
8      3.48     3.415000    10.90    10.875000   0.5580     0.647500
9     53.40    37.283333    11.50    11.200000   0.0769     0.324533
10     5.82     4.647500    10.50    10.500000   0.5540     0.417750
11    88.00    87.200000    11.90    12.000000   0.0484     0.052500
12     4.02     4.493333    10.40     8.066667   0.2690     0.226333
Digite a temperatura (em ºC): 500
Digite o percentual de pneu: 40
Digite o percentual de banana: 60
Previsão para novas entradas (500.0ºC, 40.0% Pneu, 60.0% Banana):
%C: 6.55, %H: 11.00, %N: 0.03
```

Figure 4. Prediction of the CHN content of a bio-oil produced at a temperature of 500°C, considering a waste composition of 40% tires and 60% banana peel.

The Mean Squared Error (MSE) obtained was 7.027, indicating the average level of error in the model's predictions. The predictions for %C varied in accuracy, with some predictions being very close to the actual values, as in sample 1 (Actual: 3.34, Predicted: 3.31) and others with more significant differences, as in sample 9 (Actual: 53.40, Predicted: 37.28).

In the predictions for %H there was a good match in most samples, with a few exceptions, such as sample 12 (Actual: 10.40, Predicted: 8.07), suggesting areas for potential model refinement. On the other hand, the predictions for %N are generally close to the actual values, with small variations observed, such as in sample 5 (Actual: 1.05, Predicted: 1.07).

The larger discrepancies observed, especially in relation to %C, can be attributed to variations in the input data that are not perfectly captured by the decision tree. Adjusting the maximum depth of the tree or implementing ensemble techniques, such as Random Forests, can help improve accuracy.

The results indicate that the decision tree model offers accurate predictions of the chemical parameters of bio-oils, with a significant correlation between the predicted and observed values. The structural simplicity of the model makes it easier to interpret the effects of the input variables, making it an effective tool for analyzing limited experimental data.

Simulations were carried out in the model to predict the behavior of %C, %H and N% in pyrolysis; the simulated conditions and their results are shown in Table 4.

Table 4. Elemental analysis (CHN) of the oils obtained from the pyrolysis and co-pyrolysis of tire and banana peel waste at temperatures (400, 450 and 500ºC) in different proportions of blend.

Temperature	Proportion of the base material		Elementary Analysis		
	Tire (%)	Banana Peel(%)	%C	%H	%N
400 ºC	70	30	37,28	11,20	0,32
	80	20	37,28	11,20	0,32
	60	40	21,60	10,57	0,06
	40	60	21,60	10,57	0,06
	20	80	5,08	10,55	0,46

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425 ºC	70	30	37,28	11,20	0,32
	80	20	37,28	11,20	0,32
	60	40	21,60	10,57	0,06
	40	60	21,60	10,57	0,06
	30	70	5,08	10,80	0,46
	20	80	5,08	10,80	0,46
	75	25	37,28	11,20	0,32
	25	75	5,08	10,55	0,46
	50	50	21,60	10,57	0,06
450 ºC	70	30	70,58	10,80	1,71
	80	20	70,58	10,80	1,71
	60	40	4,65	10,50	0,42
	40	60	4,65	10,50	0,42
	30	70	4,49	8,07	0,23
	20	80	4,49	8,07	0,23
475 ºC	70	30	70,58	10,80	1,71
	80	20	70,58	10,80	1,71
	60	40	4,65	10,50	0,42
	40	60	4,65	10,50	0,42
	20	80	4,49	8,07	0,23
	30	70	4,49	8,07	0,23
	75	25	70,58	10,80	1,71
	25	75	4,49	8,07	0,23
	50	50	4,65	10,50	0,42
500 ºC	70	30	85,05	12,00	0,03
	80	20	85,05	12,00	0,03
	60	40	6,55	11,00	0,03
	40	60	6,55	11,00	0,03
	30	70	4,19	10,13	0,05
	20	80	4,19	10,13	0,05

In the predictions made, the variations in the proportion of waste adopted did not show variations in the percentages of C, H and N, predicting the same values for the ranges of changes in the proportions adopted. The presence of a relatively low MSE suggests that, although the predictions are good, there is still room for improvement. Collecting more data or incorporating additional variables could help refine the model.

The production of bio-oils from the thermal pyrolysis of waste such as tires and banana peels represent a sustainable solution for waste management and energy generation. Accurately predicting the chemical parameters of bio-oils, specifically the carbon (%C), hydrogen (%H) and nitrogen (%N) contents, is essential for optimizing the production process. Several machine learning models are widely used for prediction in similar contexts. Artificial Neural Networks (ANNs), known for their ability to capture complex, non-linear relationships, are often chosen for forecasting tasks due to their flexibility [25]. However, their effectiveness depends on large volumes of data to effectively train the model's many parameters, which can lead to overfitting in small data sets.

In addition to Neural Networks, Linear Regression is one of the simplest and most interpretable models used to capture linear relationships between variables. Although useful in many contexts, it may not be suitable for data that has complex non-linear relationships, as may be the case with bio-oils. Support Vector Machines (SVM) are effective in high-dimensional spaces but can be computationally expensive and difficult to interpret.

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Decision trees, on the other hand, are ideal for smaller data sets. They segment the input space into homogeneous regions, making it easier to understand the interactions between variables and offering robust predictions with less data [18]. The use of decision trees as a predictive model was based on the need for a robust and interpretable model capable of operating efficiently with a limited data set [26]. Decision trees not only improved the accuracy of predictions, but also provided valuable insights into the interactions between variables, contributing significantly to the improvement of the thermal pyrolysis process.

The decision tree model implemented proved to be an effective tool for predicting %C, %H and %N in bio-oils, providing useful predictions that can inform improvements in the production process. Future research should consider adjustments to the model and the exploration of complementary techniques to increase the accuracy and robustness of the predictions, contributing to the improvement of the thermal pyrolysis process.

4. Conclusions

The results of this study demonstrate the effectiveness of co-pyrolysis of banana peels and tires in the production of bio-oils, showing its potential for waste recovery and energy use. The oil yield decreases with increasing temperature, confirming the literature on secondary cracking reactions that favor gas production. The banana peel yields exceeded those of previous studies, suggesting that the quality of the raw material is an important factor.

FTIR analysis revealed functional compounds, such as alkanes and ketones, relevant for applications as fuels. In addition, predictive modeling with a decision tree showed good correlation between observed and predicted data.

Although co-pyrolysis is a little explored topic, the results indicate its viability as a sustainable alternative for waste treatment. Future research should deepen the analysis of the variables, refine the predictive models and investigate different mixing ratios to optimize the products obtained.

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Appendix A

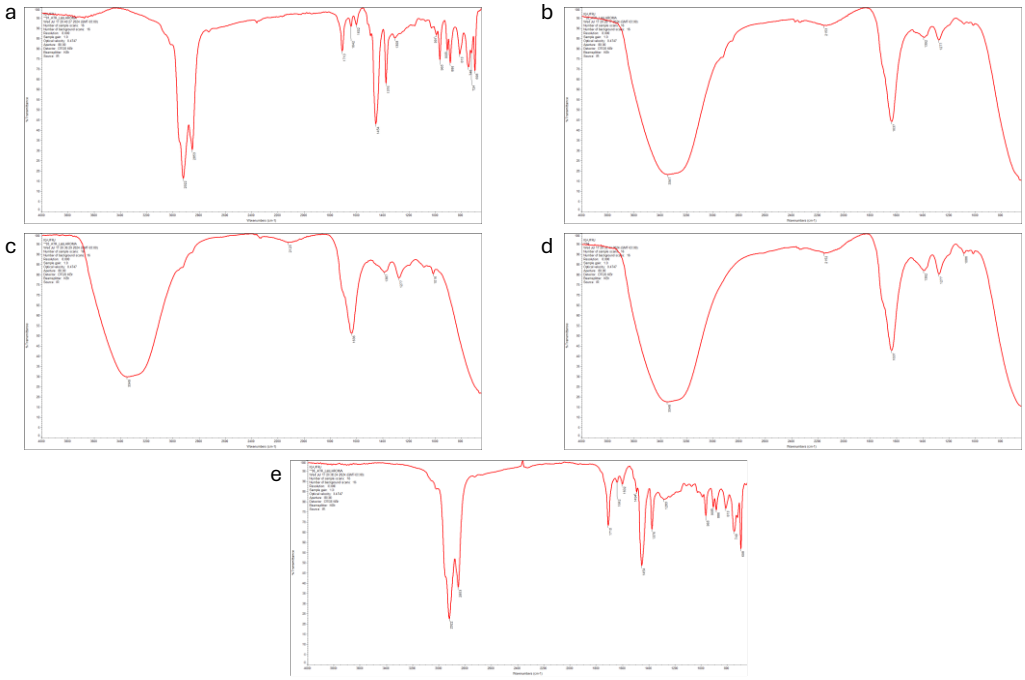

Figure A1. Infrared spectrum of 100% tire oil (a), 100% banana peel oil (b), Tire/Banana Peel Oil, 50:50 (c), Tire/Banana Peel Oil, 25:75 (d), Tire/Banana Peel Oil, 75:25 (e) at 400ºC.

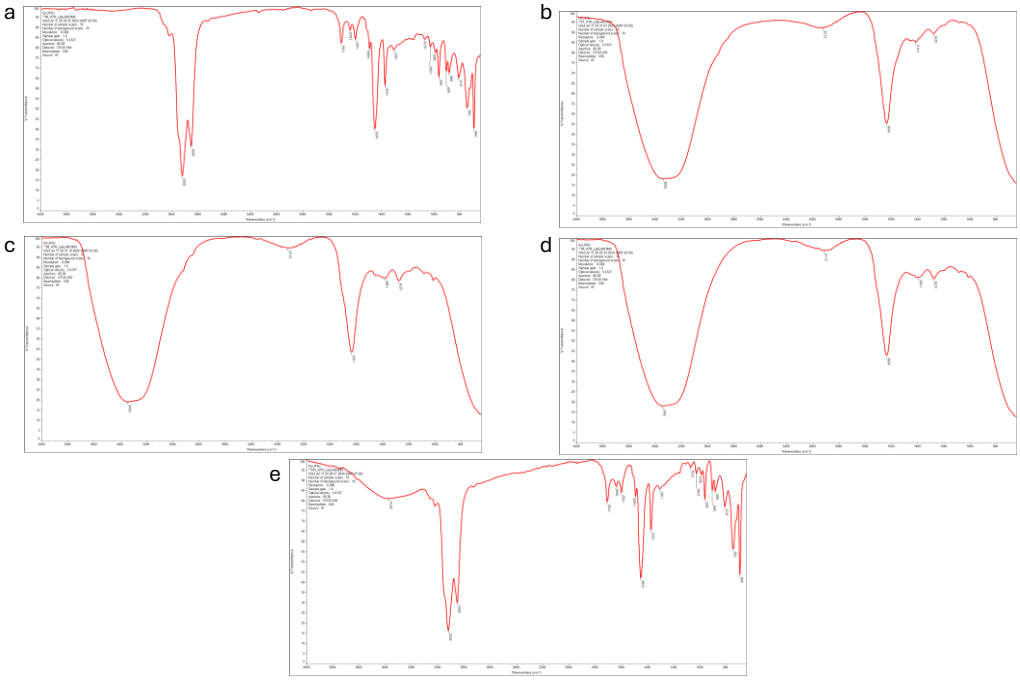

Figure A2. Infrared spectrum of 100% tire oil (a), 100% banana peel oil (b), Tire/Banana Peel Oil, 50:50 (c), Tire/Banana Peel Oil, 25:75 (d), Tire/Banana Peel Oil, 75:25 (e) at 450ºC.

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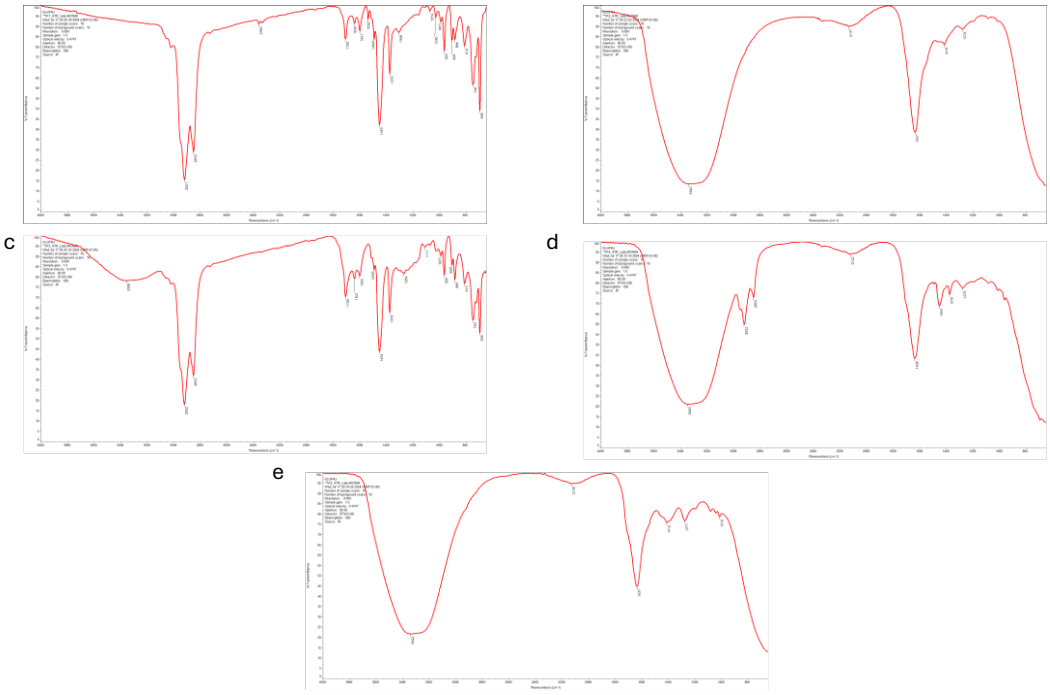

Figure A3. Infrared spectrum of 100% tire oil (a), 100% banana peel oil (b), Tire/Banana Peel Oil, 50:50 (c), Tire/Banana Peel Oil, 25:75 (d), Tire/Banana Peel Oil, 75:25 (e) at 500ºC.

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