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Production of Bio-Oil by Co-Pyrolysis of the Coffee and Tire Wastes

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Abstract **–**The escalating energy consumption has underscored the urgent need for viable alternative sources that are renewable and sustainable. Among various industrial processes, pyrolysis has emerged as a prominent method for generating bio-oil, biochar, and syngas. The temperature during pyrolysis assumes a critical role in these processes. Co-pyrolysis, on the other hand, involves utilizing different types of waste as feedstock. The proliferation of coffee waste can be attributed to its high consumption rate, while tire waste represents a plentiful polymeric waste stream. Combining coffee and tire wastes can offer a promising approach for bio-oil production. To attain optimal results, certain conditions must be met. The ideal temperature for bio-oil production is 361.263 °C, accompanied by a duration of 15 minutes. Furthermore, it is essential to maintain a plastic content of 78% in the feedstock. By adhering to these specific parameters, the co-pyrolysis process can efficiently convert the mixture of coffee and tire waste into bio-oil, which holds great potential as a renewable energy source. The surge in energy consumption has necessitated the exploration of alternative, sustainable energy sources. Pyrolysis, particularly co-pyrolysis involving coffee and tire wastes, presents a viable solution for generating bio-oil. This approach not only addresses the growing need for renewable energy but also offers a sustainable solution for managing coffee and tire waste.

Keywords**:** Energy consumption; Renewable sources; Pyrolysis; Co-pyrolysis; Bio-oil production; Coffee waste; tire waste

1. Introduction

Increasing global consumption has coincided with the consumption of fossil fuel-based energy resources [1]. This expansion increases the need to find alternative energy resources that are completely free from all negative impacts on the Earth, such as greenhouse gas (GHG) emissions. The evaluation of carbonaceous wastes such as biomass is considered a reliable clean energy source [2]. Industrial wastes, agricultural wastes, food wastes, and wastewater represent different types of biomasses. Conversion of these carbonaceous wastes into clean energy through processes such as pyrolysis, gasification, thermal cracking, anaerobic digestion, etc., has not only been considered in laboratory-scale research work, but has been used industrially in various fields for years [3]. In pyrolysis, there is no combustion reaction because there is no oxygen, which makes this process more favorable in industry, and the temperature of the process (350−650 ºC) can be lower than gasification (>900 ºC). These two principles are the main differences between gasification and pyrolysis [4]. In many industrial applications, pyrolysis is a considerable reaction economically, and it has no negative impact on the environment [5]. Depending on the temperature applied, the components of the product can be divided into three categories: Bio-oil, biochar and syngas [6].

Wang et al. [7] investigated the co-pyrolysis of tire waste and bamboo sawdust using a zeolite catalyst. The optimum design was defined in terms of temperature, yield, and various parameters. It was found that 550 ºC is the optimum operating condition. The ratio (tire waste: bamboo sawdust) was 1:1 when the ratio of catalyst to feed rate was 1:2. It was found that the bio-oil content increased with the increase of temperature from 19.56% at 450 oC to 30.23% at 550 ºC. Ucar et al. [8] studied different ratios of co-pyrolysis of pine nut shells and waste tires without catalyst in experiment. The increase in bio-oil content is directly proportional to the increase in waste tire content in the mixture. The experiment on co-pyrolysis of soap stock and waste tire was studied by Dai et. al. [9]. The zeolite catalyst was used in this experiment with a 1:2 ratio of catalyst to feedstock. The helium gas stream was fed to the reactor as a carrier gas, and the temperature range was 450-650 °C. The optimum temperature for the highest bio-oil yield was reached at 550 ºC. In another study, Cao et. al. [10] investigated the co-pyrolysis of sawdust and waste tires at 500 ºC. Nitrogen was the selected gas to sustain the pyrolysis reaction. In the experiment, different ratios between biomass and waste tire were investigated. Different types of catalysts were used in the experiments: SBA-15, MCM-41, and HZSM-5. It was found that SBA-15 had a higher performance either by reducing the values of density and viscosity or by degrading rather large molecules. Martinez et al. [11] analyzed a different type of biomass (pine wood French fries) with waste tires. No catalyst was used while the reaction proceeded at 500 ºC. Nitrogen was used as a carrier gas for the reaction. When the ratio of biomass and tire was studied, it was found that 90/10 (WT /biomass) favored the properties of bio-oil. Another co-pyrolysis experiment was conducted by Wang et al. [11] using tire waste and biomass such as rice straw or polar wood. The products studied were mainly three different types of hydrocarbons, oxygenated compounds, and the undesirable residues of nitrogen and sulfur compounds. The research group found that increasing the plastic weight fraction significantly increases the ratio of hydrocarbon groups. Table 1 gives an overview of the previous studies on the co-pyrolysis of waste tires.

Table 1: Literature survey on pyrolysis reaction conditions for tire wastes and other wastes.

Wastes type	**Temperature**	**Wastes ratio Biomass: plastic**	**Catalyst**	**Catalyst /feed ratio**	**Ref**
Bamboo sawdust tire wastes	450-650 ºC	1:1	HZSM-5	1:2	[7]
Pine nut shells and scrap tire	500 ºC	1:1, 2:1, 4:1, and1:2	-	-	[8]
Soap stock and waste tire	450-650 ºC	1:1	HZSM-5 zeolite	1;2	[9]
Sawdust and waste tire	500 ºC	-	SBA-15, MCM-41 HZSM-5	10 g	[10]
Pine woodchips and waste-tire scraps	500 ºC	Too many different ratios had been tested	-	-	[11]
Waste tire and biomass (Rice straw or polar wood)	500 ºC	8:2, 6:4, 4:6 and 2:8	-	-	[11]
Individually coffee tea	400 ºC	-	Uncatalyzed CaCO3 Na2CO3	20%	[12]
Spent coffee grounds	429-550 ºC	-	-	-	[13]
Tire wastes rice husk	350-450 ºC	1:1	-	-	[14]
Coffee grounds and polypropylene	360- 420 ºC	Too many different ratios had been tested	-	-	[15]

2. Materials and methods

2.1. Materials

The co-pyrolysis process was carried out in a stainless-steel reactor manufactured by Weihai Borui Chemical Machinery Mfg. Ltd, China, model number BFK-1L/12.5. The coffee waste was from the espresso waste in the cafeteria of the University of Sharjah and the tire waste was provided by a nearby auto repair shop from the industrial area.

2.2. Experimental procedure

The process starts with drying the coffee at 110 °C. The drying time is about 8-12 minutes, which depends on the thickness of the layer in the oven. The tire waste was chopped into small pieces that fit into the reactor. After placing the materials in the reactor, the first thing was to check if it was perfectly sealed. The importance of sealing is based on two main reasons: Prevention of possible mass loss and release of gasses during the process that could be toxic in the laboratory environment. The carrier gas of the reaction was nitrogen. The temperature had to be adjusted to the desired level after preparation. As indicated in Table 2, the reaction sequences were optimized using Response Surface Methodology (RSM). Table 3 shows changes parameters in pyrolysis reaction.

Table 2: Co-pyrolysis reaction run conditions.

Run	Reaction temperature (°C)	Plastic ratio (wt. %)	Reaction time (mins)
1.	400	50%	10
2.	400	50%	20
3.	400	50%	30
4.	350	50%	20
5.	450	50%	20
6.	400	0%	20
7.	400	100%	20

Table 3: Changing parameters in pyrolysis reaction.

Experimental variables	-1	0	1
Reaction temperature (°C)	350	400	450
Reaction time (min)	10	20	30
Plastic ratio (%)	0	50	100

Coffee and tire analysis had done previously in other papers by Abrar et. al. and Al-Balushi et. al. respectively. The results are indicated in table 4 and table 5.

Table 4: Proximate analysis of waste tires and coffee wastes.

Property	Waste tires	Coffee wastes
Volatile matter	62.51%	78.3%
Fixed Carbon	27.88%	8.12%
Ash	8.92%	13.6%
Moisture	0.69%	6.09%

Table 5: Ultimate analysis of waste tires and coffee wastes.

Property	Tire waste	Coffee wastes
C %	81.85%	54.5%
H %	6.66%	7.3%
N %	1.70%	2.2%
S %	1.37%	0.2%
O %	9.80%	34.1%

3. Results and Discussion

3.1 Bio-oil analysis

Fig. 1 shows the variation of bio-oil yield as a function of reaction time. The other parameters are constant, with the applied temperature being 400 °C and the plastic content being 50%. Too long or insufficient reaction time would reduce the yield of bio-oil. From the Fig. 2, it is shown that overloading the temperature reduces the bio-oil production when the run time is constant at 20 minutes and the plastic fraction is 50%. The increase in plastic fraction parallels the increase in bio-oil yield (Fig. 3). These three different results were observed at 400 °C and 20 minutes run time.

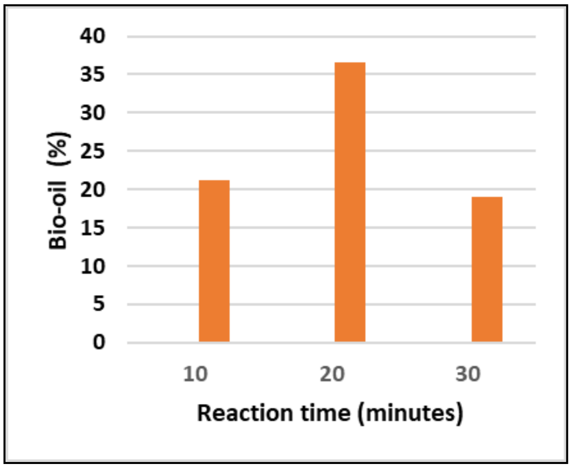

Figure 1: Effect of reaction time on bio-oil.

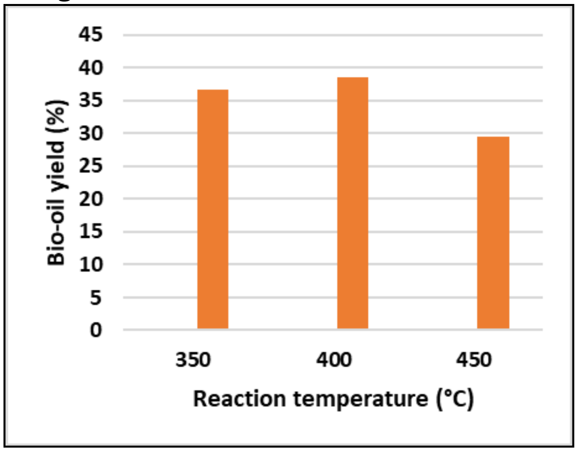

Figure 2: Effect of reaction temperature in bio-oil yield.

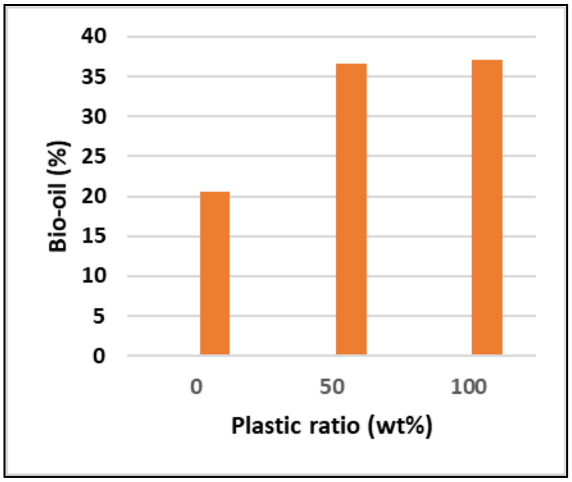

Figure 3: Effect of plastic ration on bio-oil yield.

Fig. 4 shows the effects of different parameters on the yield of bio-oils. Fig. 4a shows the effect of reaction temperature and time. The red area indicates the richest and most suitable range for this synthesis process. The blue area indicates the poorest range of bio-oil. The increased application of temperature over time limits the bio-oil yield. Fig. 4b illustrates the importance of the plastic ratio in this process. The comparison between (b) and (c) illustrates the potential losses that can occur by changing one parameter even though the required plastic ratio is present.

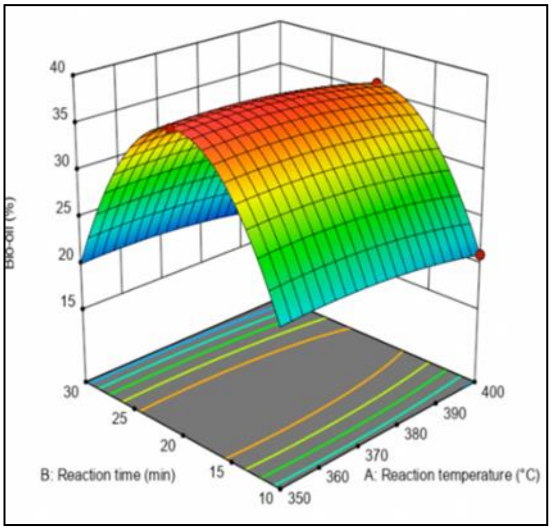

Figure 4a: Effect of reaction temperature and time.

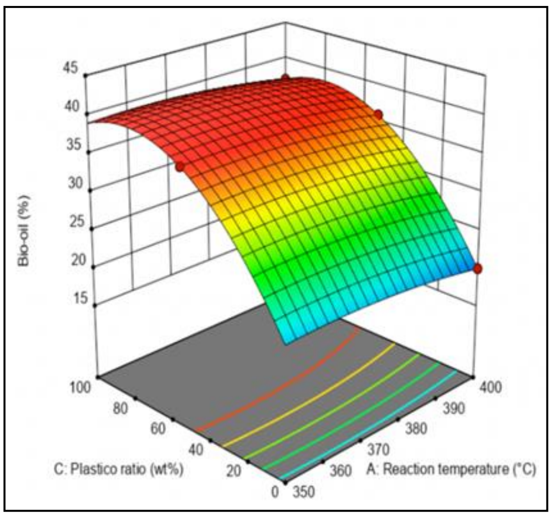

Figure 4b: Effect of reaction temperature and plastic ratio.

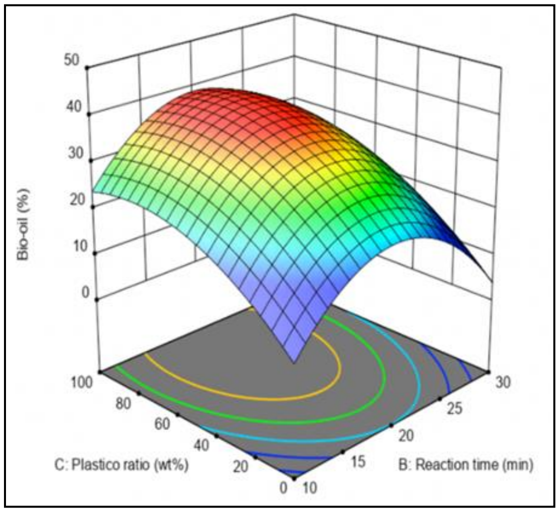

Figure 4c: Effect of reaction time and plastic ratio.

Perturbation diagrams show how important each factor is to the response. The slope of a curve can describe the sensitivity of the influence of the parameters on the product. Fig. 5a. and Fig.5b. refer to a temperature of 375 °C, a plastic content of 50 wt% and a reaction time of 20 and 30 minutes, respectively. A represents the reaction temperature, B the reaction time and C the plastic content. It was found that the time and the plastic content have the greatest influence on the product compared to the temperature.

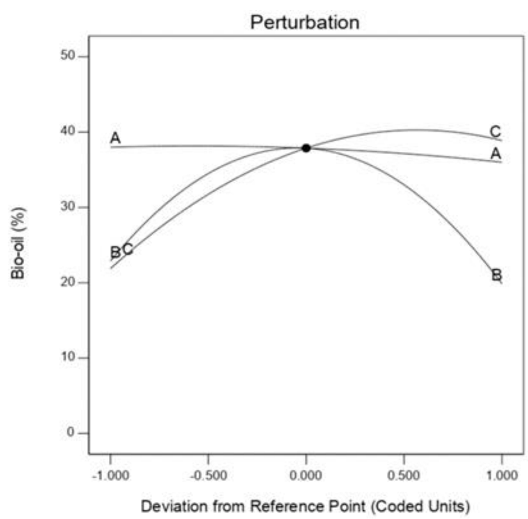

Figure 5a: Default perturbation graph for bio-oil results based on actual factors.

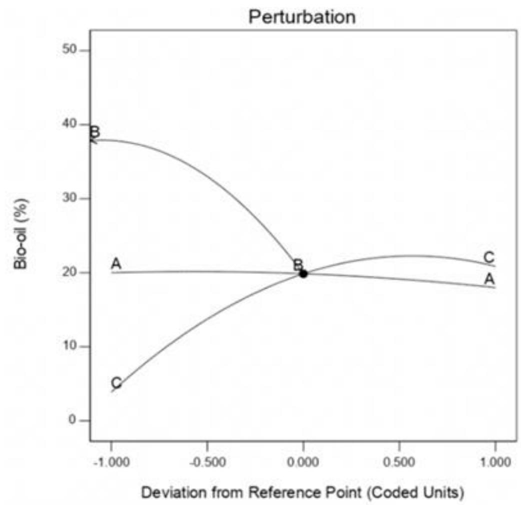

Figure 5b: Default perturbation graph for bio-oil results based on actual factors.

The scatter between the predicted value and the actual value, shown in Fig. 6, ensures that the model created has a high degree of reliability. As discussed in the previous sections and shown in the above Figures, the use of Response Surface Methodology (RSM) presents the optimized values of bio-oil production from tire waste and coffee as follows: Temperature 361.263 °C, duration 15.4204 minutes, 78.0609 wt% plastic. At the end of the above points, 37.79 wt% bio-oil was produced.

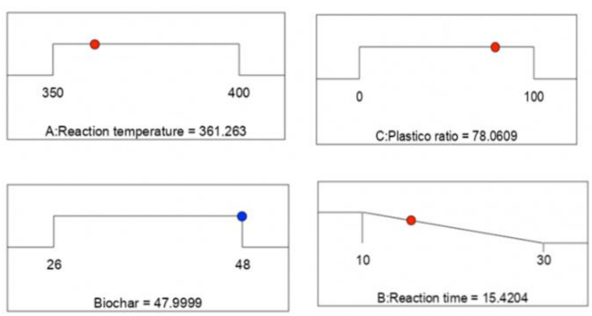

Figure 6: Optimized values of Bio-oil/ Desirability = 0.849, solution 1 out of 4.

4. Conclusion

Coffee and tire waste have become promising feedstocks for bio-oil production. The reaction temperature was tested between 350 and 450 °C. The highest amount of bio-oil was measured at 20 minutes. No variation in the amount of bio-oil was observed after 400 °C. It was found that the lower range conditions were the best for bio-oil production. The optimized plastic ratio, temperature and time were determined by the RSM method as 78.0609%, 361.263 °C and 15.42 minutes, respectively.

Acknowledgements

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