

WASTE POLYETHYLENE TEREPHTHALATE AND WOODY BIOMASS SYNERGISTIC INTERACTION FOR BIO-OIL PRODUCTION

Dr. Mohammed Saleh Al Ansari

Associate Professor, College of Engineering-Department of Chemical Engineering,
University of Bahrain, Bahrain
malansari.uob@gmail.com

Abstract

Pyrolysis oil is a valuable liquid substance obtained by the process of pyrolyzing biomass and plastic waste. This study investigates the impact of co-pyrolysis of Ficus benghalensis wood biomass and polyethylene terephthalate (PET) on the production of liquid oil, reactivity, and heating value. At first, thermogravimetric analysis was performed on wood and plastic feedstocks to ascertain the stability and proportion of volatile components during pyrolysis. An investigation was conducted to examine the impact of temperature on the distribution of products in individual pyrolysis, as well as the influence of the biomass-plastic ratio on co-pyrolysis. The pyrolysis of biomass at 450 °C yielded a maximum of 40.8 wt% liquid oil on an individual basis. Conversely, PET yielded a high of 59.5 wt% liquid oil when heated to 500 °C. The co-pyrolysis tests involved combining PET and biomass in varying proportions, specifically 20%, 40%, 60%, and 80%. A greater synergistic impact was observed when PET was added at a concentration of 60%, attributed to radical secondary reactions. Furthermore, the performed research on pyrolysis oil revealed that biomass and plastic materials has the potential to be utilized in the production of important compounds, as evidenced by their physical and chemical characterisation.

Keywords: Co-pyrolysis, synergistic effect, biomass to plastic blend, pyrolysis oil, characterization

1. Introduction

As a result of the growing population and industrialization, the use of biomass as an alternative to conventional fuels is being extensively examined [1]. The International Energy Agency (IEA) predicts that biomass will contribute 10% of the world's total energy production by 2035 [2]. The employment of biomass resources for energy extraction is primarily driven by their renewability, CO₂ neutrality, and availability [3]. The global biomass supply is estimated to be approximately 100 billion metric tons annually [4]. Biomass possesses the capacity to generate heat, power, fuel, and value-added compounds [5]. Biomass can be converted into biofuels and chemicals using biochemical and thermochemical conversion methods. The thermochemical conversion

process offers significant advantages over biological conversion strategies, primarily in terms of increased biofuel production and improved compatibility [6]. Pyrolysis, gasification, combustion, hydrothermal liquefaction, and hydrothermal carbonization are several methods of converting substances using heat and chemical reactions [7]. Pyrolysis is a highly efficient conversion process that transforms biomass resources into valuable biofuels in the absence of oxygen. This platform is capable of efficiently generating fuels and chemicals from diverse biomass sources. Char, oil, and gas are the three forms of yields in which their energy content and yield are greatly influenced by the reaction conditions.

Since 1990, the utilization of plastic has been growing steadily at a rate of 5% annually [8]. The escalating use of diverse plastic materials, along with insufficient recycling practices, has led to worldwide challenges in managing plastic trash. In less developed nations, the majority of plastics pose significant long-term economic, environmental, and health hazards [9]. The accumulation of a substantial quantity of plastic waste is mostly driven by urbanization and population expansion. The accumulation of garbage in the environment has a significant impact on economic operations and living conditions [10]. Plastics are mostly derived from petroleum hydrocarbons. They are a non-biodegradable substance that can persist in the environment for over twenty years. The persistent accumulation of plastic garbage in landfills poses significant environmental challenges for future generations [11]. Plastics are available in numerous forms and serve a wide range of purposes in diverse areas of our everyday lives. The plastic production rate has increased nearly twentyfold over the past sixty years [12]. Polyethylene terephthalate (PET) is a widely utilized type of plastic that is commonly employed in many applications, such as textile fibers for clothing and containers for storing liquids and food. Polyethylene (PE) and PET collectively constitute more than 50% of the global plastic market, representing 40% of the total market share. Polyethylene terephthalate (PET) is the most prevalent plastic because of its notable superiority over other plastics. It is available in various forms and dimensions [13]. Following polypropylene (PP) and low density polyethylene (LDPE), this plastic substance is widely utilized in the packaging business, making it the third most often used plastic material [14, 15]. The recycling of used plastics significantly improves the environment. This method diminishes the need for raw materials since a recycled product can substitute for a new product. Moreover, it decreases the amount of plastic that is discarded in landfills. Similar to biomass pyrolysis, the pyrolysis of waste plastics is a notable method for recycling plastic waste. Pyrolysis of plastic materials offers a versatile method for generating value-added chemicals and energy-rich liquid fuel. This process can be used for municipal wastes, biomass, and electronic wastes, providing an alternative to mechanical and chemical processing [16].

Energy derived from biomass is fast being regarded as a vital alternative to conventional fuels [1]. This is due to the fact that the population is growing and that industrialization is occurring. According to the International Energy Agency (IEA), it is anticipated that by the year 2035, biomass would account for ten percent of the entire energy generation that occurs across the globe [2]. The exploitation of biomass materials for the extraction of energy is primarily driven by the fact that it is replenishable, does not produce carbon dioxide, and is readily available [3]. It is estimated that the entire amount of biomass that is available on the planet is somewhere around 100 billion tons every year [4]. Among the many things that can be produced from biomass are heat, power, fuel, and compounds with added value [5]. The transformation of biomass into biofuels and chemicals can be accomplished through the utilization of biochemical and thermochemical conversion processes. There are a number of

advantages that the thermochemical conversion method has over the biochemical conversion approaches [6]. The most important advantages are compatibility and increased biofuel production. There are a number of different thermochemical conversion processes, including pyrolysis, gasification, combustion, hydrothermal liquefaction, and hydrothermal carbonization [7]. The absence of air during the pyrolysis process results in the production of useful biofuels from biomass materials. Pyrolysis is an efficient technology. When it comes to the production of fuels and chemicals from a wide range of biomass, this platform is a viable option. The three forms of yields are char, oil, and gas, and the parameters of the reaction have a significant impact on the amount of energy contained in each of these three types of yields.

The disposal of waste plastics can be accomplished through the utilization of biomass co-pyrolysis in conjunction with waste plastics [17]. Synergistic effects are produced during the pyrolysis process when plastic materials are combined with biomass. These effects include a rise in the value of the end products through the modification of the concentrations of hydrogen and oxygen [18]. Co-pyrolysis has been the subject of a significant amount of research in recent years [19, 20], with the goal of producing bio-oil of superior quality. By utilizing fir and chestnut as softwood and hardwood biomass materials in conjunction with the collection of PE and PS, Nardella et al. [21] conducted co-pyrolysis studies and analyzed the synergistic impacts on product yields. These tests were carried out in order to determine the effects of the combination. During the course of this investigation, the incorporation of polymeric material served to stimulate secondary pyrolysis processes of holocellulose biomass material. A study conducted by Xu and colleagues [22] investigated the synergistic effects that the presence of zeolite has on the co-pyrolysis of mixed microalgae and polymers. Through the use of radical reactions that have also been investigated in the literature [23-25], the research resulted in the production of liquid that included a lower concentration of oxygenated compounds and acids. An investigation into the synergistic influence on the production of pyrolysis oil and biochar during the co-pyrolysis of pinecones and mixed plastic wastes was carried out by Brebu et al. [26]. The findings of this study revealed favorable outcomes, including an increased yield of bio-oil and biochar that was rich in energy. Experimental research conducted by Chen et al. [27] investigated the synergistic effect that polypropylene and tobacco straw had on the amount of gas produced. As a result of the findings, the production of biogas was increased while the components of char were decreased.

In common parlance, the Indian banyan is referred to as the *Ficus benghalensis*. In addition to being the largest tree that is indigenous to the Indian Subcontinent, it can be found in every state and administrative unit of the country. It is the tree that grows the quickest and has the potential to reach a height of seventy feet. According to [28, 29], various parts of the tree, especially the leaves, are utilized for a number of specific functions. The wood is utilized in the production of paper pulp, despite the fact that it is not generally advised for use as firewood or in carpentry work. The wood and wood bark of the *Ficus benghalensis* tree have not been subjected to a significant amount of research in relation to the production of biofuels. One of the families of the tree known as *Ficus religiosa* was previously exploited by Rao et al. [30] for the purpose of producing bio-oil through a pyrolysis reaction. Ganeshan et al. [31] presented the results of a study that investigated the degradation of waste mango seeds composed of PET by a thermal and co-pyrolysis process. In this particular investigation, the degradation of mango seed shell occurs at a higher temperature than that of mango seed kernel. This is because the shell contains a

greater quantity of cellulose than the kernel does. During the process of co-pyrolysis, the incorporation of PET resulted in an increase in the progression of the breakdown of biomass.

Experiments on the co-pyrolysis of waste PET and wood from the Ficus Bengalese's tree were carried out in a fixed bed reactor that was carried out on a laboratory scale for this investigation. Thermal and co-pyrolysis characteristics of wood-based material and PET polymers were investigated in order to better understand the impact of reaction temperature and the ratio of biomass to plastic on the production of the highest possible amount of bio-oil while simultaneously enhancing its quality. Twenty percent, forty percent, sixty percent, and eighty percent of the PET material consisted of biomass in the co-pyrolysis tests. At the conclusion of the study, the resulting bio is subjected to physical characterization in order to ascertain whether or not it is suitable for a variety of uses.

2. Materials and Methods

2.1 Feedstock preparation

It was from local traders in Coimbatore, India, that the waste PET bottles were acquired. The PET bottles were crushed and screened with great care in order to separate them from the mixture of other plastic polymers. The tree that was available at a local residence in Coimbatore, India, was used to collect the wood of the Ficus Bengalese's tree, which served as the representative biomass. A powder was created by crushing the PET bottles that were gathered. Initially, the biomass and plastic materials were subjected to crushing and sieving in order to achieve a homogeneous size of less than 0.5 millimetres. Following this, they were dried in a furnace maintained at a temperature of 100 degrees Celsius for a duration of two hours.

2.1. Material and product characterization

The proximate analysis of both biomass and plastic materials was done by following ASTM standards and the results are displayed in Table 1. The facilities used with Si'Tarc Coimbatore were used for testing the samples. The ultimate analysis of the feedstocks was done by an element analyzer (Elementar Vario EL-III). The various chemical elements of the liquid oil were determined with the help of Thermo GC-Trace Version: 5.0, Thermo MS DSQ II spectroscopy.

Table 1 Characterization of the feedstocks

Parameters	<i>Ficus benghalensis</i>	PET
Proximate analysis (wt%)		
Volatile matter	70.3	83.9
Fixed carbon ^a	17.4	16.1
Moisture content	6.9	-
Ash	5.4	-
Ultimate analysis (wt%)		

Carbon	50.1	64.2
Hydrogen	6.2	3.9
Nitrogen	1.8	0.32
Sulfur	0.3	0.09
Oxygen ^a	41.6	31.49
H/C molar ratio	1.474	0.723
O/C molar ratio	0.623	0.368
Heating value (MJ/kg)	18.1	23.4

^aEstimated by difference

2.2. Pyrolysis experiment

A fixed bed reactor, which consisted of a reactor, heater, condenser, and liquid collection, was utilized for the pyrolysis experiments. During the course of this investigation, the reactor is heated to a maximum temperature of 600 degrees Celsius, and it is capable of reaching temperatures as high as 900 degrees Celsius. The reactor was kept at a constant temperature during each run, and thirty grams of biomass and a mixture of biomass and plastic were introduced inside. The mixture was then pyrolyzed. Until there was no visible emission of vapour, the reactor was maintained in such a way that it kept the reaction going in the absence of air. The reactor is 150 millimeters in length and has a diameter of one hundred millimeters. The outflow of the reactor is connected to a water-cooled condenser, which is associated with an increase in the volume of water that is maintained at a temperature of 0 degrees Celsius. After everything is said and done, the bio-oil that has been condensed is collected in a bottle and examined for a variety of tangible qualities. The determination of the quantities of liquid oil and char was accomplished by the use of direct weighing. In order to get the gas yield, the total yield of the liquid and solid products was subtracted from the total.

The synergistic effect on product distributions due to the co-pyrolysis process was calculated using the below equation based on the yields achieved from individual thermal pyrolysis of *Ficus benghalensis* and PET.

$$\text{Predicted Yield} = (X_1 * Y_1 + X_2 * Y_2)$$

Where X_1 and X_2 are mass ratio of biomass and plastic

Y_1 and Y_2 are individual pyrolysis from biomass and plastic.

3. Results and discussion

3.1. Thermogravimetric study

Typical TG and DTG analyses of waste PET pellets and *Ficus benghalensis* were carried out in a nitrogen atmosphere in order to investigate the pyrolysis and combustion characteristics of the materials. At a rate of 15 degrees Celsius per minute, the materials were heated from the temperature of the atmosphere to 900 degrees Celsius for the plastic material and 700 degrees Celsius for the biomass. When it comes to biomass, the release of moisture is represented by the preliminary weight loss that occurs between 30 and 100 degrees Celsius [32]. After

240 degrees Celsius, the release of volatile substances was the reason of the dramatic decrease in the biomass's weight. Additionally, this is supported by the findings that were acquired by the utilization of the DTG curve. *Ficus benghalensis* was entirely pyrolyzed at a temperature of around 500 degrees Celsius, and beyond this temperature, there was a gradual decrease in weight loss that continued until 620 degrees Celsius. The burning of biomass particles or char that was left over was attributed to this phenomenon [33]. The report of the TG and DTG analysis of *Ficus benghalensis* is depicted in Figure 1. The unburned char is estimated to be 18 percent, which indicates that the biomass can serve as a source for the manufacture of char up to 20 weight percent. The weight loss curves of TG and DTG for PET in an environment containing nitrogen are depicted in Figure 2. It is seen in the figure that, in contrast to materials derived from biomass, PET polymer undergoes degradation in a single step due to its uniform structure. Degradation of polymers is mostly caused by the end group-initiated process as well as the degradation of yields that are formed during the process of polymer chain breakdown [34]. PET saw a loss of eighty percent of its total mass between the temperatures of 325 and 575 degrees Celsius, and after 625 degrees Celsius, there was no degradation that took place. The pyrolysis temperature that will result in the greatest amount of decomposition is determined by using the data on thermal decomposition that was previously provided.

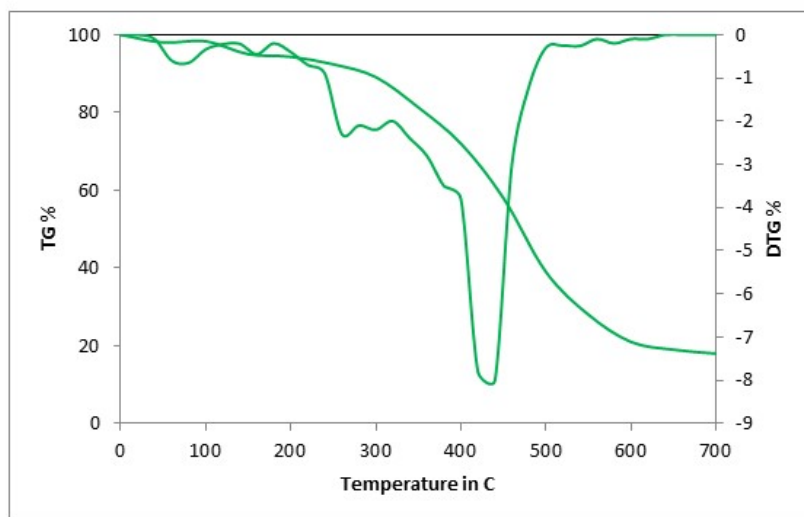


Figure 1 TG and DTG analysis of *Ficus benghalensis*

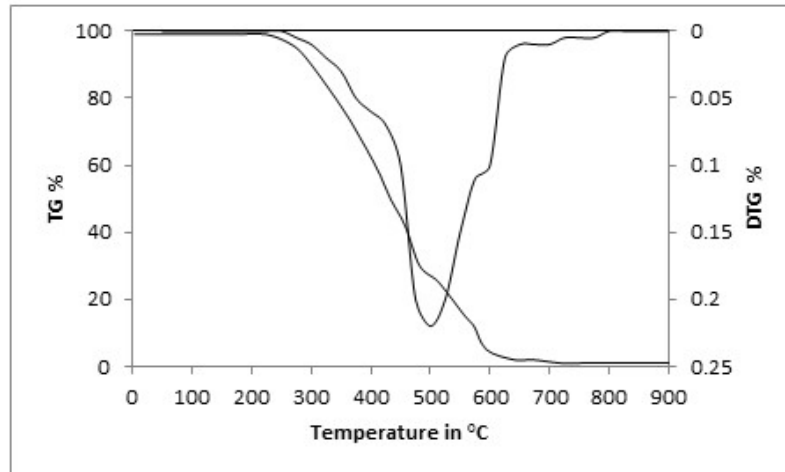


Figure 2 TG and DTG analysis of waste PET polymer

3.2. Biomass thermal pyrolysis

In order to manipulate the quality of the bio-oil and satisfy the requirements of individuals, thermal pyrolysis of biomass can be carried out at a range of reaction temperatures. According to [35], it is not always simple to make accurate predictions regarding the relationship between the yield quality and its components. In most cases, it is contingent upon the many different functional elements. The pyrolysis temperature is the operation parameter that is responsible for determining both the quality and the quantity of the yield [36, 37]. This is the case among the numerous operating parameters. Since the lignocellulosic content of the biomass material is immediately destroyed and depolymerized during the process of biomass pyrolysis, the liquid oil that is produced is the result of this process. In this particular investigation, the amount of oil produced increased as the temperature of the bed increased. At a temperature of 450 degrees Celsius, the amount of oil that was produced reached its highest possible value of 40.8% by weight. When the temperature is raised even further, the amount of oil that is produced drops to 37.0% by weight. When the temperature of the bed is raised, there is a constant increase in the amount of gas fraction that occurs. The gas yield ranges from 29.3 weight percent to 40.5 weight percent when the temperature is raised from 350 degrees Celsius to 550 degrees Celsius. The various product yields that vary depending on the temperature of the process are depicted in Figure 3. There is a significant decrease in the amount of char that is produced, as can be seen from the figure. At a temperature of 350 degrees Celsius, the yield of char was 39.3 weight percent, but when the temperature of the reactor was raised to 550 degrees Celsius, the figure dropped to 22.5 weight percent. Due to the increasing conversion of lignin in the biomass material, the char yield decreases with higher temperatures [38]. This is the primary reason for the decline. A greater conversion of biomass can shed light on the increased gas production that occurs in conjunction with higher temperatures. When the temperature rises, the secondary processes that occur when vapours are converted into gases become more noticeable.

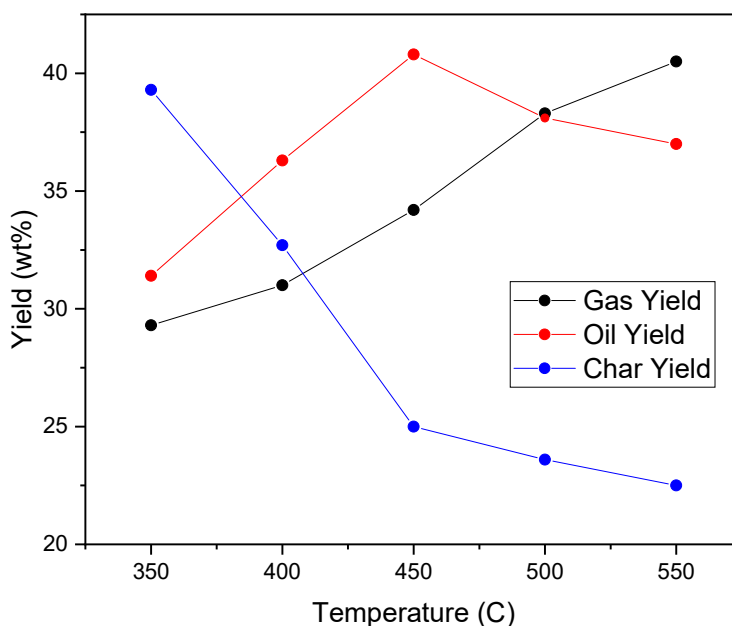
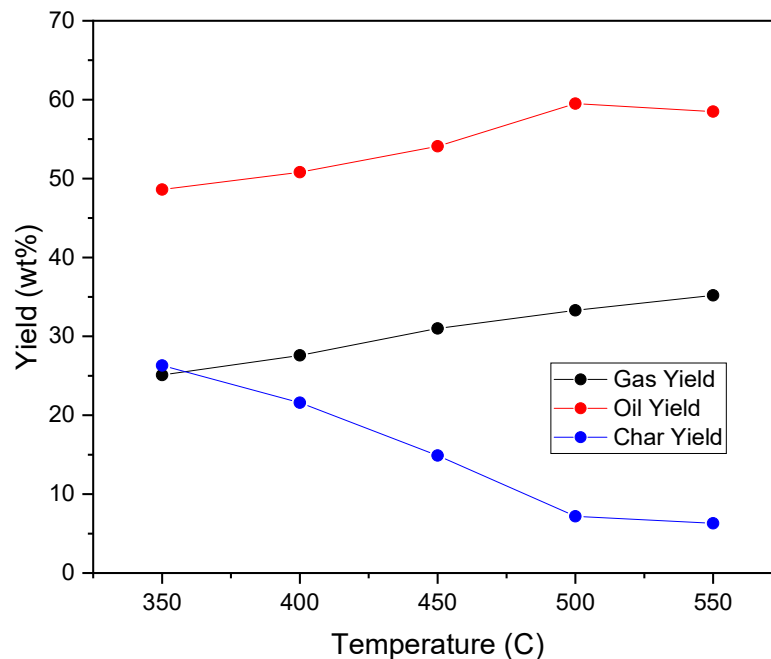


Figure 1 Effect of temperature on pyrolysis of *Ficus benghalensis*

3.3. PET thermal pyrolysis

In the course of this investigation, PET material was utilized. Changing the temperature of the reaction in order to achieve the appropriate reaction conditions allowed for its pyrolysis to be performed independently. At a temperature of 500 degrees Celsius, the highest possible conversion of bio-oil was discovered. As low as 48.6 weight percent of oil is produced at temperatures around 350 degrees Celsius. It was at that point that the yield of char reached its highest point of 26.3 weight percent. Increases in temperature from 350 degrees Celsius to 550 degrees Celsius resulted in a significant decrease in the amount of char produced, which went from 26.3 weight percent to 6.3 weight percent. When the temperature was raised, there was a consistent increase in the amount of gas that was produced. With a maximum of 35.2 weight percent at 550 degrees Celsius, the gas yield was 25.1 weight percent while it was at 350 degrees Celsius. The PET has a different thermal stability than other materials, which results in an increase in the amount of liquid oil and gas released. There was a possibility of breaking the stability of the polymeric material by flouting C=C bonds, which results in an increase in the release of gas

fractions, as stated by Garbaet al [39]. This occurred when the polymeric material was subjected to higher



temperatures.

Figure 1 Effect of temperature on pyrolysis of PET

3.4. Co-pyrolysis characteristics

Figure 3 presents an illustration of the co-pyrolysis properties of the *Ficus benghalensis* and PET mixture. The trials for this phase were carried out at a temperature of 500 degrees Celsius throughout the entire process, with the addition of PET along with biomass. At intervals of twenty percent, the percentage of PET that was combined with biomass was raised from twenty percent to eighty percent. The char decreased with increased PET component, which was comparable to those of individual pyrolysis, as shown in Figure. This can be understood by looking at the figure. As a result of increasing the percentage of PET from 20% to 80% of the biomass, the value of char dropped from 22.3 weight percent to 9.9 weight percent. When compared to the generation of oil by biomass pyrolysis, the oil production through individual pyrolysis of PET was significantly higher. This is also reflected in the co-pyrolysis reaction. The yield of oil is increased from 41.4 weight percent to 56.1 weight percent as a result of this method. Because of the increased proportion of PET that was added, the amount of oil that was extracted was increased. A 20% addition of PET resulted in a production of oil that was only 41.4 weight percent. As a result of the incorporation of 80% PET, the value was raised to 56.1 weight percent. The presence of a greater quantity of volatiles in PET than in biomass is the reason for the improvement in oil yield that may be attributed to the incorporation of PET. During the process of pyrolysis, polyolefin polymers will function as an ideal hydrogen donor and generate the radical interaction that will result in the formation of the greatest amount of bio-oil, as stated by Guo et al [40] and Zhou et al [41].

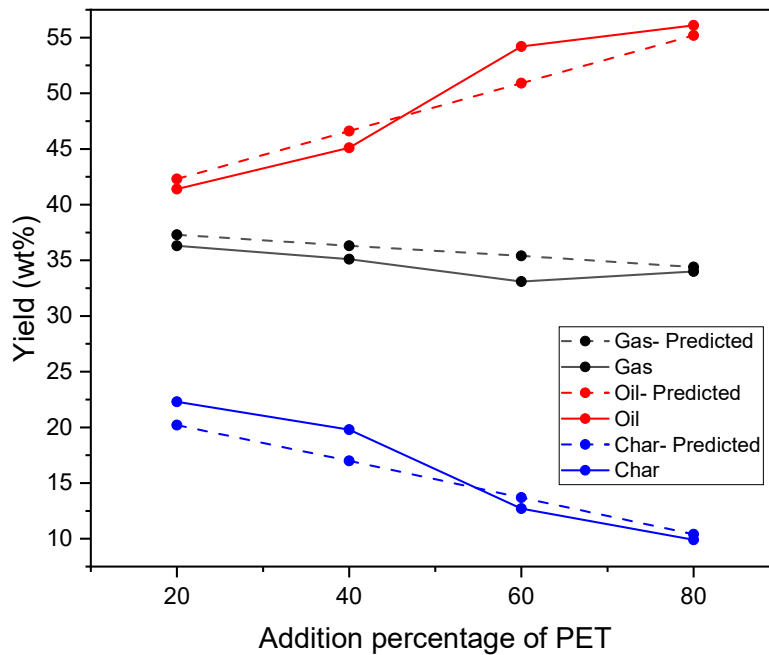


Figure 1 Effect of PET on biomass pyrolysis

3.5. Degree of synergistic effects

3.6. By utilizing both experimental and anticipated yields, which are also displayed in Figure 2, we were able to evaluate the synergistic effect that co-pyrolysis had on product yields. During the course of the co-pyrolysis process, the experimental yield of gas was substantially lower than the value that was projected. Even with the addition of up to forty percent of PET, the amount of oil produced was lower than the value that was projected, while the amount of char that was produced was larger than the value that was predicted. When more than forty percent of PET was applied in addition to biomass, a good synergistic impact was found to happen in terms of oil yield. An even more favorable synergistic effect was discovered when PET was added at a percentage of sixty percent. This indicates that the liquid yield is 6.48 percent more than what was anticipated at that moment. Radical secondary reactions, which are responsible for the condensation of non-condensable components, were found to be the cause of the beneficial synergistic impact with regard to oil production [42]. In addition, the presence of PET in the mixture serves as a medium for the hydrogenation of biomass, which has the ability to limit polymerization and cross-linking events, hence boosting the hydrogenation of biomass [43]. Synergistic effects on the co-pyrolysis of a variety of biomaterials with PET have been documented in the literature [44-46] in the past. One study conducted by Çepelioğullar and Pütün [47] looked into the synergistic effects of combining three distinct types of biomass materials with PET. The cumulative yields obtained from individual pyrolysis were compared to the results of the study, which showed that the study produced more bio-oil and char while producing less gas. Ansah et al. [48] investigated the synergistic effect of co-pyrolysis of municipal solid waste and PET. They found that the ratio of biomass to plastic in the mixture was 70:30, which resulted in a larger synergistic effect on their bio-oil production.

According to the findings of the study, a strong interaction between PET and biomass was observed when the biomass fraction was present in the mixture to a significant degree.

3.7. Physical characterization

The physical, elemental composition and heating value of the liquid oils acquired through individual and co-pyrolysis processes are listed in Table 1. It is noticed that the fraction of carbon and hydrogen increases with the addition of PET with biomass. The oxygen components in the bio-oil reduced gradually from 48.45 wt% to 27.82 wt%. At the same temperature, lowering the oxygen level enhanced the heating value to 28.64 MJ/kg. The findings suggest that co-pyrolysis of wood based biomass with PET is an effective method for producing liquid oil with higher heating value.

Table 2 Physical properties of the oils

Properties	<i>Ficus benghalensis</i>	<i>Ficus benghalensis</i> -to-PET ratio				PET	Unit
		80:20	60:40	40:60	20:80		
Density	1010	995	965	930	915	910	kg/m ³
Viscosity	7.1	6.9	6.4	5.8	5.0	4.1	cSt
Flash point	135	130	110	92	73	58	°C
Carbon	43.52	46.33	50.14	54.89	59.20	63.50	wt%
Hydrogen	7.10	7.10	7.31	7.72	7.90	8.10	wt%
Nitrogen	0.74	0.72	0.70	0.66	0.59	0.54	wt%
Sulphur	0.21	0.19	0.15	0.11	0.07	0.04	wt%
Oxygen ^a	48.45	46.12	41.02	35.30	32.41	27.82	wt%
H/C molar ratio	1.943	1.826	1.734	1.671	1.590	1.519	-
O/C molar ratio	0.835	0.739	0.624	0.501	0.408	0.328	-
Heating value	17.91	18.92	21.36	23.90	26.83	28.64	MJ/kg

^aBy difference

3.8. Chemical analysis

GC-MS is a technology that is both vital and quick, and it is used for the examination of numerous chemical elements that are present in oil. During the process of pyrolysis, the three basic components of biomass, namely cellulose, hemicellulose, and lignin, were broken down into a variety of chemical constituents, including alcohol, alkanes, alkenes, and phenolic components, amongst others [47]. An inventory of the chemical components that were identified by GC-MS is presented in Table 4. As can be seen in the table, the biomass is often broken down into compounds that contain phenolic aromatic chemicals. It is possible to identify phenols, alkyl phenols, and methoxy phenols from the oil that is produced from the pyrolysis of biomass in a variety of quantities. The amount of these compounds fluctuates according to the amount of biomass material that is present in the feedstock during the production process. On the other hand, the components that were found in PET pyrolysis oil are entirely distinct from those found in biomass pyrolysis oil. There are a few oxygenated elements among the chemical

components that have been found in PET oil. The majority of the components are hydrocarbons. In contrast to the pyrolysis of biomass, the majority of the PET was broken down into benzoic acid, which accounted for 31.24% of the total. It is common knowledge that pyrolysis oils that have an acidic composition can lead to corrosion problems in handling equipment and reactors. In addition to that, the acidic qualities may result in environmental problems throughout the natural degradation process. In addition to these difficulties, it is well knowledge that benzoic acid has the potential to serve as a substantial feedstock for a wide range of chemical businesses. According to this point of view, the pyrolysis of PET can be utilized to achieve the transformation of PET into valuable chemical feedstocks that can be utilized in industrial applications.

Table 3 List of chemical elements identified in liquid oils through GC–MS (Biomass^A, 80:20^B, 60:40^C, 40:60^D, 20:80^E and PET^F)

Compound name	Molecular formula	A	B	C	D	E	F
2-Isopropyl-2,5-dihydrofuran	C ₇ H ₁₂ O	0.92	0.40	0.22			
Phenol, 2-methoxy-1,2-benzendiol	C ₇ H ₈ O ₂	1.26	1.05	0.88	0.40		
2-Furancarboxaldehyde,-5-Methyl	C ₆ H ₆ O ₂	2.01	1.89	1.74	0.42	0.22	
3-Undecene, (Z)-	C ₁₁ H ₂₂					1.95	2.62
Phenol	C ₆ H ₆ O	9.12	9.01	8.24	4.20	2.11	
Furfural	C ₅ H ₄ O ₂	0.74	0.55	0.12			
Ethisterone	C ₂₁ H ₂₈ O ₂	0.24					
Trimethylamine	C ₃ H ₉ N					0.25	0.74
Phenol, 2-methyl-4,5-Dimethoxy-2-methylpheno	C ₇ H ₈ O	3.44				0.11	0.19
Phenol, 2-ethyl-6-methyl-Naphthalene, 1-methyl-	C ₉ H ₁₂ O ₃	1.25	1.01	0.82	0.31		
Benzoic acid	C ₉ H ₁₂ O	5.84	5.04	3.77	3.09	2.01	
Tridecane	C ₁₁ H ₁₀						5.22
4-Ethylbenzoic acid	C ₇ H ₆ O ₂			2.55	19.81	25.14	31.24
2,4 dimethyl pentone	C ₁₃ H ₂₈			0.22	0.85	0.90	0.97
2-methoxy phenol	C ₉ H ₁₀ O ₂	0.84	0.54	0.14			
2-Acetyl furan	C ₉ H ₁₆			0.19	3.18	5.70	7.92
Phenol, 4-methyl-Tetradecane	C ₇ H ₈ O ₂	5.42	3.26	1.22	0.94	0.42	
Benzoic acid, methyl ester	C ₆ H ₆ O ₂				0.71	1.94	2.21
4-Methoxy-2-methyl-1-benzene	C ₂₁ H ₂₈ O	6.01	4.10	1.25			
Benzoic acid	C ₁₄ H ₃₀						2.04
Oxirane	C ₈ H ₈ O ₂	0.94	0.90	0.42	0.18		
Pyridine 2-methyl	C ₉ H ₁₂ OS	1.22	1.20				
	C ₇ H ₆ O ₂	1.20	1.11	0.84			
	C ₂ H ₄ O					0.21	0.87
	C ₆ H ₇ N				1.25	2.14	3.54

Cyclopentanone	C ₅ H ₈ O	1.75	0.92				
2-Phenyl-1-p-tolyethanol	C ₁₄ H ₁₆ O	1.25	1.05	0.81			
Naphthalene	C ₁₀ H ₈	0.11					
Cyclopent-2-enethione	C ₅ H ₆ S				1.40	3.10	5.14
Butane-1,1-D2, 1-iodo	C ₁₀ H ₁₆ O ₃	0.75	0.20				
2-Methoxy-4-methylphenol	C ₈ H ₁₀ O ₂	2.28	1.24	0.28			
trans-1,4-Hexadiene	C ₆ H ₁₀			0.21	1.75	2.48	4.41
Phenol, 2,6-dimethoxy	C ₈ H ₁₀ O ₃	1.58					
Thiophene, 2,5-dimethyl	C ₆ H ₈ S						0.94
Benzenemethanol, 4-hydroxy	C ₇ H ₈ O ₂	1.72	0.84				
3-Methoxy-2-methylphenol	C ₈ H ₁₀ O ₂	1.88	1.55	1.31	0.74	0.14	0.10
Palustrol	C ₁₅ H ₂₆ O						0.45
2-Acetylcycloheptaneone	C ₉ H ₁₄ O ₂					0.21	0.94
2,4-Dihydroxy-6-methoxyacetophenone	C ₉ H ₁₀ O ₄	1.85	1.22	0.73			
2-Methyl-5-methoxy-6-hydroxybenzofuran	C ₁₁ H ₁₄ O ₃	1.79					
2-furanmethanol	C ₅ H ₆ O ₂	2.56	2.12	1.84	1.02	0.74	
Vanillin	C ₈ H ₈ O ₃	2.40	1.26				
1-Methyl-1,3,3-triphenylindan-2-one	C ₂₈ H ₂₂ O	0.97					
10-Chlorodanaphylline	C ₂₄ H ₂₅ ClN ₂ O ₈					0.12	0.78
3,4-Dimethylthiophene	C ₆ H ₈ S					0.85	2.47
9-Octadecenamide	C ₁₈ H ₃₅ NO	0.82	0.24				
Benzhydryl vinyl ether	C ₁₅ H ₁₄ O	0.86	0.25				
oleic acid	C ₁₈ H ₃₄ O ₂	1.25	1.02	1.00	0.78	0.54	0.24
4-ethyl-2 methoxy-phenol	C ₉ H ₁₂ O ₂	5.62	5.04	4.44	1.87	0.97	
Dibenzo[a,e]cyclooctene	C ₁₆ H ₁₂			0.97	2.47	3.22	5.41
2-(2,4,6-Trimethylphenyl)butylamine	C ₁₃ H ₂₁ N					2.14	3.05
Phenol, 3-amino	C ₆ H ₇ NO	1.25	0.82	0.11			
Pyridine, 2-propyl-	C ₈ H ₁₁ N			0.54	0.99	1.25	2.41

4. Conclusion

In this study, the synthesis of liquid oil was accomplished through the utilization of fixed-bed pyrolysis of wood-based biomass with *Ficus benghalensis* and waste PET. The thermogravimetric analysis was utilized in the initial stage of the experimental effort, which was devoted to analyzing the decomposition behavior of the raw materials that were chosen. Using the information gained from TGA, the temperature range that was found to be appropriate for pyrolysis studies was determined. At temperatures of 450 degrees Celsius and 500 degrees Celsius, respectively, the highest possible yield of pyrolysis oil was obtained from biomass and PET. Four distinct phases were involved in the process of co-pyrolysis of biomass and PET. In comparison to other mixtures, the inclusion of PET at a percentage of sixty percent resulted in the strongest favorable synergy for the processing of liquid oil. The physical and chemical properties of the liquid oil that was obtained were investigated in tandem with these results in order to determine the fundamental qualities. When the amount of plastic in the feedstock is raised, it is possible to determine, through the use of physical characterization, that the heating value of the oil is increased as well. GC-MS analysis revealed that the co-pyrolysis process resulted in the presence of hydrogen and carbon-rich compositions. This was owing to the interaction of polymers. In light of the findings, it is possible to draw

the conclusion that co-pyrolysis as a method of converting biomass-plastic mixtures into valuable products for a variety of uses could be an environmentally friendly strategy.

Data Availability

The data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare that there is no conflict of interest regarding the publication of this article.

Funding

There is no funding to report for this article.

References

1. Kan, T., Strezov, V., & Evans, T. J. (2016). Lignocellulosic biomass pyrolysis: A review of product properties and effects of pyrolysis parameters. *Renewable and sustainable energy reviews*, 57, 1126-1140.
2. <https://www.iea.org/topics/renewables/subtopics/bioenergy/>
3. Wang, S., Dai, G., Yang, H., & Luo, Z. (2017). Lignocellulosic biomass pyrolysis mechanism: a state-of-the-art review. *Progress in energy and combustion science*, 62, 33-86.
4. Sheldon, R. A. (2014). Green and sustainable manufacture of chemicals from biomass: state of the art. *Green Chemistry*, 16(3), 950-963.
5. Goyal, H. B., Seal, D., & Saxena, R. C. (2008). Bio-fuels from thermochemical conversion of renewable resources: a review. *Renewable and sustainable energy reviews*, 12(2), 504-517.
6. Verma, M., Godbout, S., Brar, S. K., Solomatnikova, O., Lemay, S. P., & Larouche, J. P. (2012). Biofuels production from biomass by thermochemical conversion technologies. *International Journal of Chemical Engineering*, 2012.
7. Brindhadevi, K., Anto, S., Rene, E. R., Sekar, M., Mathimani, T., Chi, N. T. L., & Pugazhendhi, A. (2021). Effect of reaction temperature on the conversion of algal biomass to bio-oil and biochar through pyrolysis and hydrothermal liquefaction. *Fuel*, 285, 119106.
8. Kunwar, B., Cheng, H. N., Chandrashekar, S. R., & Sharma, B. K. (2016). Plastics to fuel: a review. *Renewable and Sustainable Energy Reviews*, 54, 421-428.
9. Nizami, A. S., Shahzad, K., Rehan, M., Ouda, O. K. M., Khan, M. Z., Ismail, I. M. I., ...& Demirbas, A. (2017). Developing waste biorefinery in Makkah: a way forward to convert urban waste into renewable energy. *Applied Energy*, 186, 189-196.
10. Menikpura, S. N. M., Sang-Arun, J., & Bengtsson, M. (2016). Assessment of environmental and economic performance of Waste-to-Energy facilities in Thai cities. *Renewable Energy*, 86, 576-584.
11. Jahirul, M. I., Rasul, M. G., Schaller, D., Khan, M. M. K., Hasan, M. M., & Hazrat, M. A. (2022). Transport fuel from waste plastics pyrolysis—A review on technologies, challenges and opportunities. *Energy Conversion and Management*, 258, 115451.

12. Osman, A. I., Farrell, C., Al-Muhtaseb, A. H., Al-Fatesh, A. S., Harrison, J., & Rooney, D. W. (2020). Pyrolysis kinetic modelling of abundant plastic waste (PET) and in-situ emission monitoring. *Environmental Sciences Europe*, 32(1), 1-12.
13. Das, P., & Tiwari, P. (2019). Thermal degradation study of waste polyethylene terephthalate (PET) under inert and oxidative environments. *ThermochimicaActa*, 679, 178340.
14. Dhahak, A., Grimmer, C., Neumann, A., Rüger, C., Sklorz, M., Streibel, T., ...& Burkle-Vitzthum, V. (2020). Real time monitoring of slow pyrolysis of polyethylene terephthalate (PET) by different mass spectrometric techniques. *Waste Management*, 106, 226-239.
15. Kawecki, D., Scheeder, P. R., & Nowack, B. (2018). Probabilistic material flow analysis of seven commodity plastics in Europe. *Environmental science & technology*, 52(17), 9874-9888.
16. Ayodeji, S. O., & Oni, T. O. (2019). Thermal pyrolysis production of liquid fuel from a mixture of polyethylene terephthalate and polystyrene. *Heat Transfer—Asian Research*, 48(5), 1648-1662.
17. Brebu, M., Ucar, S., Vasile, C., & Yanik, J. (2010). Co-pyrolysis of pine cone with synthetic polymers. *Fuel*, 89(8), 1911-1918.
18. Hassan, H., Hameed, B. H., & Lim, J. K. (2020). Co-pyrolysis of sugarcane bagasse and waste high-density polyethylene: Synergistic effect and product distributions. *Energy*, 191, 116545.
19. Oh, S. Y., & Seo, T. C. (2019). Upgrading biochar via co-pyrolyzation of agricultural biomass and polyethylene terephthalate wastes. *RSC advances*, 9(48), 28284-28290.
20. Vo, T. A., Tran, Q. K., Ly, H. V., Kwon, B., Hwang, H. T., Kim, J., & Kim, S. S. (2022). Co-pyrolysis of lignocellulosic biomass and plastics: A comprehensive study on pyrolysis kinetics and characteristics. *Journal of Analytical and Applied Pyrolysis*, 163, 105464.
21. Nardella, F., Bellavia, S., Mattonai, M., & Ribechini, E. (2022). Co-pyrolysis of biomass and plastic: synergistic effects and estimation of elemental composition of pyrolysis oil by analytical pyrolysis-gas chromatography/mass spectrometry. *Bioresource Technology*, 127170.
22. Xu, S., Cao, B., Uzoejinwa, B. B., Odey, E. A., Wang, S., Shang, H., ...& Nwakaire, J. N. (2020). Synergistic effects of catalytic co-pyrolysis of macroalgae with waste plastics. *Process Safety and Environmental Protection*, 137, 34-48.
23. Önal, E., Uzun, B. B., & Pütün, A. E. (2014). Bio-oil production via co-pyrolysis of almond shell as biomass and high density polyethylene. *Energy conversion and management*, 78, 704-710.
24. Chen, W., Shi, S., Chen, M., & Zhou, X. (2017). Fast co-pyrolysis of waste newspaper with high-density polyethylene for high yields of alcohols and hydrocarbons. *Waste Management*, 67, 155-162.
25. Wang, Z., Burra, K. G., Lei, T., & Gupta, A. K. (2021). Co-pyrolysis of waste plastic and solid biomass for synergistic production of biofuels and chemicals-A review. *Progress in Energy and Combustion Science*, 84, 100899.
26. Brebu, M., Ucar, S., Vasile, C., & Yanik, J. (2010). Co-pyrolysis of pine cone with synthetic polymers. *Fuel*, 89(8), 1911-1918.
27. Chen, R., Zhang, J., Lun, L., Li, Q., & Zhang, Y. (2019). Comparative study on synergistic effects in co-pyrolysis of tobacco stalk with polymer wastes: Thermal behavior, gas formation, and kinetics. *Bioresource Technology*, 292, 121970.

28. Prajapati, S. K., & Tripathi, B. D. (2008). Biomonitoring seasonal variation of urban air polycyclic aromatic hydrocarbons (PAHs) using *Ficus benghalensis* leaves. *Environmental Pollution*, 151(3), 543-548.
29. Viswanathan, B., Ariharan, A., & Nandhakumar, V. (2020). Phosphorous-doped porous carbon derived from paste of newly growing *Ficus benghalensis* as hydrogen storage material. *Indian Journal of Chemistry-Section A (IJCA)*, 55(6), 649-656.
30. Rao, Y. K., Dhanalakshmi, C. S., Vairavel, D. K., Surakasi, R., Kaliappan, S., Patil, P. P., ...& Lalvani, J. (2022). Investigation on Forestry Wood Wastes: Pyrolysis and Thermal Characteristics of *Ficus religiosa* for Energy Recovery System. *Advances in Materials Science and Engineering*, 2022.
31. Ganeshan, G., Shadangi, K. P., & Mohanty, K. (2018). Degradation kinetic study of pyrolysis and co-pyrolysis of biomass with polyethylene terephthalate (PET) using Coats–Redfern method. *Journal of Thermal Analysis and Calorimetry*, 131(2), 1803-1816.
32. Kathir, I., Haribabu, K., Kumar, A., Kaliappan, S., Patil, P. P., Dhanalakshmi, C. S., ...& Birhanu, H. A. (2022). Utilization of Tea Industrial Waste for Low-Grade Energy Recovery: Optimization of Liquid Oil Production and Its Characterization. *Advances in Materials Science and Engineering*, 2022.
33. Dewangan, A., Pradhan, D., & Singh, R. K. (2016). Co-pyrolysis of sugarcane bagasse and low-density polyethylene: influence of plastic on pyrolysis product yield. *Fuel*, 185, 508-516.
34. Chowreddy, R. R., Nord-Varhaug, K., & Rapp, F. (2018). Recycled polyethylene terephthalate/carbon nanotube composites with improved processability and performance. *Journal of materials science*, 53(9), 7017-7029.
35. Westerhof, R. J., Brilman, D. W., Van Swaaij, W. P., & Kersten, S. R. (2010). Effect of temperature in fluidized bed fast pyrolysis of biomass: oil quality assessment in test units. *Industrial & engineering chemistry research*, 49(3), 1160-1168.
36. Ke, Y., Cui, S., Fu, Q., Hough, R., Zhang, Z., & Li, Y. F. (2022). Effects of pyrolysis temperature and aging treatment on the adsorption of Cd²⁺ and Zn²⁺ by coffee grounds biochar. *Chemosphere*, 296, 134051.
37. Dhanalakshmi, C. S., & Madhu, P. (2019). Recycling of wood bark of *Azadirachta indica* for bio-oil and chemicals by flash pyrolysis. *Indian Journal of Ecology*, 46(2), 347-353.
38. Shen, Q., Liaw, S. B., Costa, M., & Wu, H. (2020). Rapid pyrolysis of pulverized biomass at a high temperature: the effect of particle size on char yield, retentions of alkali and alkaline earth metallic species, and char particle shape. *Energy & Fuels*, 34(6), 7140-7148.
39. Garba, M. U., Musa, U., Olugbenga, A. G., Mohammad, Y. S., Yahaya, M., & Ibrahim, A. A. (2018). Catalytic upgrading of bio-oil from bagasse: Thermogravimetric analysis and fixed bed pyrolysis. *Beni-Suef University journal of basic and applied sciences*, 7(4), 776-781.
40. Guo, J., & Lua, A. C. (2001). Kinetic study on pyrolytic process of oil-palm solid waste using two-step consecutive reaction model. *Biomass and Bioenergy*, 20(3), 223-233.
41. Zhou, L., Wang, Y., Huang, Q., & Cai, J. (2006). Thermogravimetric characteristics and kinetic of plastic and biomass blends co-pyrolysis. *Fuel processing technology*, 87(11), 963-969.

42. Özsin, G., & Pütün, A. E. (2018). A comparative study on co-pyrolysis of lignocellulosic biomass with polyethylene terephthalate, polystyrene, and polyvinyl chloride: Synergistic effects and product characteristics. *Journal of Cleaner Production*, 205, 1127-1138.
43. Yuan, H., Fan, H., Shan, R., He, M., Gu, J., & Chen, Y. (2018). Study of synergistic effects during co-pyrolysis of cellulose and high-density polyethylene at various ratios. *Energy conversion and management*, 157, 517-526.
44. Chen, L., Wang, S., Meng, H., Wu, Z., & Zhao, J. (2017). Synergistic effect on thermal behavior and char morphology analysis during co-pyrolysis of paulownia wood blended with different plastics waste. *Applied Thermal Engineering*, 111, 834-846.
45. Ko, K. H., Rawal, A., & Sahajwalla, V. (2014). Analysis of thermal degradation kinetics and carbon structure changes of co-pyrolysis between macadamia nut shell and PET using thermogravimetric analysis and ¹³C solid state nuclear magnetic resonance. *Energy conversion and management*, 86, 154-164.
46. Ko, K. H., Sahajwalla, V., & Rawal, A. (2014). Specific molecular structure changes and radical evolution during biomass–polyethylene terephthalate co-pyrolysis detected by ¹³C and ¹H solid-state NMR. *Bioresource technology*, 170, 248-255.
47. Çepelioğullar, Ö., & Pütün, A. E. (2014). Products characterization study of a slow pyrolysis of biomass-plastic mixtures in a fixed-bed reactor. *Journal of Analytical and Applied Pyrolysis*, 110, 363-374.
48. Ansah, E., Wang, L., & Shahbazi, A. (2016). Thermogravimetric and calorimetric characteristics during co-pyrolysis of municipal solid waste components. *Waste management*, 56, 196-206.