Research Article

Co-pyrolysis Characteristics and Synergistic Interaction of Waste Polyethylene Terephthalate and Woody Biomass towards Bio-Oil Production

Harishchander Anandaram,[1] Bipin Kumar Srivastava,[2] B. Vijayakumar,[3] P. Madhu ⓘ,[4] Melvin Victor Depoures ⓘ,[5] Pravin P. Patil,[6] Sarika Chhabria,[7] Praveen Bhai Patel ⓘ,[8] and S. Prabhakar ⓘ[9]

[1]Centre for Excellence in Computational Engineering and Networking, Amrita Vishwa Vidyapeetham, Coimbatore, Tamil Nadu 641112, India
[2]Department of Applied Sciences, Galgotias College of Engineering and Technology, Greater Noida, Uttar Pradesh 201306, India
[3]Department of Chemistry, Panimalar Engineering College, Chennai, Tamil Nadu 600123, India
[4]Department of Mechanical Engineering, Karpagam College of Engineering, Coimbatore, Tamil Nadu 641032, India
[5]Department of Thermal Engineering, Saveetha School of Engineering, Saveetha Institute of Medical and Technical Sciences, Chennai, Tamil Nadu 600124, India
[6]Department of Mechanical Engineering, Graphic Era Deemed To Be University, Clement Town, Dehradun, Uttarakhand 248002, India
[7]Department of Chemistry, Smt. Chandibai Himathmal Mansukhani College, Thane, Maharashtra 421003, India
[8]Department of Chemical Engineering, University Institute of Engineering and Technology, C S J M University, Kanpur, Uttar Pradesh 208024, India
[9]Department of Mechanical Engineering, Automotive Engineering Stream, Wollo University-KIOT, Kombolcha 208, Ethiopia

Correspondence should be addressed to Melvin Victor Depoures; melvin.mech02@gmail.com and S. Prabhakar; prabhakar@kiot.edu.et

In this study, the impacts of co-pyrolyzing wood-based biomass from *Ficus benghalensis* with PET on liquid oil output, reactivity, and heating values were investigated. The effects of temperature on the product distribution of individual pyrolysis and the biomass-plastic ratio on co-pyrolysis were investigated. For individual pyrolysis, a maximum amount of 40.8 wt (%) liquid oil was obtained from biomass at 450°C. On the other hand, a maximum of 59.5 wt (%) liquid oil was obtained from PET at 500°C. The co-pyrolysis experiments were conducted by blending PET with biomass at different percentages, such as 20%, 40%, 60%, and 80%. At 60% addition of PET, a more positive synergistic effect was identified due to radical secondary reactions. In addition, the physical and chemical characterization studies conducted on pyrolysis oil showed that biomass and plastic materials could be used to make valuable chemicals.

1. Introduction

Due to increased population and industrialization, energy from biomass is rapidly being evaluated as a crucial option for conventional fuels [1]. According to the International Energy Agency (IEA), it is expected that biomass will account for 10% of the total global energy production by 2035 [2]. Renewability, CO_2 neutrality, and availability are the major driving forces for the utilization of biomass materials for energy extraction [3]. The world's total biomass availability is assessed to be around 100 billion tonnes per year [4]. Biomass has the ability to produce heat, power, fuel, and value-added chemicals [5].

Through biochemical and thermochemical conversion techniques, biomass can be transformed into biofuels and chemicals. Higher biofuel production and compatibility are the main advantages of the thermochemical conversion process over biochemical conversion techniques [6]. Pyrolysis, gasification, combustion, hydrothermal liquefaction, and hydrothermal carbonization are the various thermochemical conversion techniques [7]. In the absence of air, pyrolysis is an efficient conversion process that converts biomass materials into valuable biofuels. It is a viable platform for producing fuels and chemicals from a variety of biomass. Char, oil, and gas are the three types of yields, and their energy content and yield are highly dependent on the reaction conditions.

Since 1990, the use of plastic has increased at a pace of 5% per year [8]. The increased use of various forms of plastics combined with inadequate recycling has resulted in global plastic waste management issues. In underdeveloped countries, most plastics constitute long-term economic, environmental, and health risks [9]. Urbanisation and population growth are the two important factors for the accumulation of a massive amount of plastic waste. The waste accumulation in nature severely affects economic activities and living standards [10]. Plastics are mostly produced from petroleum hydrocarbons. They are not an easily decomposable material which can endure in the environment for more than two decades. The continuous accumulation of waste plastics in landfills causes severe environmental problems for future generations [11]. Plastics come to the market in different forms and accomplish our daily needs in various domains. The production rate of plastic has improved by almost 20 times in the last six decades [12]. Polyethylene terephthalate (PET) is the most commonly used plastic for a variety of purposes, including garment fibres and liquid and food containers. Polyethylene (PE) and PET account for over half of the worldwide plastic market (40%). Due to significant advantages over other plastics, PET $(C_{10}H_8O_4)n$ is the most common plastic and comes in a variety of shapes and sizes [13]. After polypropylene (PP) and low-density polyethylene (LDPE), it is the third most popular plastic material broadly used for the packaging industry [14, 15]. Recycling of used plastics considerably benefits the environment. This process reduces the demand for raw materials as a new product can be replaced by a recycled product. Furthermore, it reduces the quantity of plastic disposed of through landfill. Like biomass pyrolysis, pyrolysis of waste plastics is a significant approach for recycling plastic wastes. Rather than mechanical and chemical processing, pyrolysis of plastic materials is a flexible approach that can produce value-added chemicals and energy-rich liquid fuel along with municipal wastes, biomass, and electronic wastes [16]. Among a variety of plastics, PET plastics are widely used in everyday life. The polymer has a wide range of industrial uses, including those in electronics, packaging, and textiles. Every year, millions of tonnes of PET materials are collected across the globe. The recyclable PET materials can be further processed and sent to the market. The nonrecyclable plastics end up in land fill, where they could take up to 500 years to degrade and might seep contaminants into the soil and water.

Due to the simplicity of the technique, energy production from biomass via thermochemical conversion could be

accomplished [17–19]. Pyrolysis of giant mullein was carried out by Aysu and Durak [20]. The authors conducted the experiment in order to get more pyrolysis oil through catalytic and noncatalytic processes. In this study, at 500°C, a 10% zinc oxide catalyst produced a maximum liquid yield of 40.43 wt (%). The study suggested that giant mullein was a good candidate for the production of pyrolysis oil. In another study, Alayont et al. [21] utilized *Sinapis arvensis* biomass for the production of pyrolysis oil. The authors pretreated the biomass and processed it for pyrolysis using acidic, alkaline, and high-temperature water. The study determined that the alkaline and acidic pretreatment had influenced higher oil production. Through a characterization study, it can be understood that high temperature water and alkaline pretreatments produce mono-aromatic compounds. Biomass co-pyrolysis with waste plastics is an effective solution for plastic waste disposal [22]. The combination of biomass with plastic materials during pyrolysis produces synergistic effects that increase the value of the end products by altering hydrogen and oxygen concentrations [23]. Recently, many literatures focused on the production of high-quality bio-oil by co-pyrolysis [24, 25]. Nardella et al. [26] carried out co-pyrolysis experiments and analysed synergistic effects on product yields by utilizing fir and chestnut as softwood and hardwood biomass materials combined with the collection of PE and PS. In this study, secondary pyrolysis reactions of holocellulose biomass material were encouraged by the addition of polymeric material. Xu et al. [27] looked into the synergistic effects on co-pyrolysis of combined microalgae and plastics with the presence of zeolite. The study produced liquid with a reduced level of acids and oxygenated chemicals due to radical reactions that have also been studied in the literature [28–30]. Brebu et al. [31] investigated the synergistic effects on the production of pyrolysis oil and biochar during co-pyrolysis of pinecones and mixed plastic wastes and showed positive results with more bio-oil yield and energy-rich biochar. The synergistic effect on gas yield with tobacco straw and polypropylene was experimentally tested by Chen et al. [32]. The results also showed higher biogas production with reduced char components.

Ficus benghalensis is commonly known as the Indian banyan. It is the largest tree native to the Indian subcontinent, and it appears throughout the country in all the states and tertiary units. It is the fastest growing tree that can reach a height of 70 feet. The availability of this tree in India is plenty. The tree can grow in almost all parts of the country. Different parts of the tree, including leaves, are used for a variety of purposes [33, 34]. The wood obtained from this tree cannot be used for construction work or firewood, but it is used for making paper pulp. The hardest heartwood can be used for making small furniture. But the thin wood, stalks, and bark have no utility in terms of industry and medicine. The wood and wood bark of *Ficus benghalensis* have not been thoroughly researched in terms of biofuel production. One of the families of the tree *Ficus religiosa* was previously utilized by Rao et al. [35] for yielding bio-oil through a pyrolysis reaction. Ganeshan et al. [36] showed a degradation study of mango seed wastes with PET through a

thermal and co-pyrolysis process. In this study, compared to mango seed kernel, the degradation of mango seed shell takes place at a higher temperature due to the higher cellulose in the shell. During co-pyrolysis, the rate of degradation of biomass was increased with the addition of PET.

In this study, experiments on the co-pyrolysis of *Ficus benghalensis* wood and waste PET were performed in a lab-scale fixed bed reactor. Thermal and co-pyrolysis characteristics of wood-based materials and PET polymers were conducted to analyse the influence of reaction temperature and biomass-to-plastic ratio on getting maximum bio-oil with improved quality. Initially, *Ficus benghalensis* and PET were pyrolyzed separately, and then, the blend was co-pyrolyzed with the addition of LDPE with the biomass at 20%, 40%, 60%, and 80% by weight to investigate the interaction during pyrolysis product yields. This study is novel in terms of feed selection. To the best of our knowledge, no study has focused on the co-pyrolysis of *Ficus benghalensis* and PET. The study ends with the physical characterization of the obtained bio-oil to determine its suitability for various applications.

2. Materials and Methods

2.1. Feedstock Preparation. The waste PET bottles were obtained from local vendors in Coimbatore, India. In order to avoid the blend of other plastic polymers, the PET bottles were carefully screened and crushed. The wood of *Ficus benghalensis* as the representative biomass was collected from the tree available at a local residence in Coimbatore, India. The collected PET bottles were smashed into a powder form. Before being utilized for experimentation and characterization studies, the biomass and plastic materials were crushed and sieved to get a uniform size of <0.5 mm and then dried in a furnace kept at 100°C for 2 hours.

2.2. Material and Product Characterization. The proximate analysis of both biomass and plastic materials was carried out by following the ASTM standards, and the results are displayed in Table 1. The facilities used by SiTarc, Coimbatore, were used for testing the samples. The ultimate analysis of the feedstocks was carried out 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.

2.3. Pyrolysis Experiment. The pyrolysis tests were performed in a fixed bed reactor that included a reactor, heater, condenser, and liquid collector. The reactor can be heated up to 900°C, and the experiments in this study are conducted to a maximum temperature of 600°C. For each run, 30 g of biomass and biomass-plastic mixture was placed inside the reactor, and they were pyrolyzed by keeping the reactor at the fixed temperature. The reactor was ensured to keep the reaction going in the absence of air and continued till no vapour was visually released. The reactor has a diameter of 100 mm and a length of 150 mm. The outlet of the reactor is connected to a water-cooled condenser, which is connected

TABLE 1: Characterization of the feedstocks.

Parameters	*Ficus benghalensis*	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

[a]Estimated by difference.

to a surplus amount of water kept at 0°C. Finally, the condensed bio-oil is gathered in a bottle and analysed for various physical characteristics. The amounts of liquid oil and char were calculated by weighing directly. By subtracting the liquid and solid product yields from the total, the gas yield was calculated.

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

$$\text{Predicted yield} = (X1 * Y1 + X2 * Y2), \tag{1}$$

where X_1 and X_2 are the mass ratios of biomass and plastic. Y_1 and Y_2 are the individual pyrolysis reactions from biomass and plastic.

3. Results and Discussion

3.1. Thermogravimetric Study. Typical TG and DTG analyses of *Ficus benghalensis* and waste PET pellets were carried out under a nitrogen environment to analyse their pyrolysis and combustion characteristics. The materials were heated from the atmospheric temperature to 700°C for biomass and 900°C for plastic material at a heating rate of 15°C/min. For biomass, the preliminary weight loss that appears at 30–100°C represents the release of moisture [37]. The sudden weight loss of the biomass was caused by the release of volatile matters after 240°C. This is also confirmed by the results obtained through the DTG curve. At around 500°C, *Ficus benghalensis* was completely pyrolyzed, and there was a progressive decline in weight loss after this temperature till 620°C. This was ascribed to the burning of biomass particles or char that remained [38]. Figure 1 represents the report of TG and DTG analyses of *Ficus benghalensis*. The unburned char is estimated as 18%, which means that the biomass is a source for the production of char up to 20 wt (%). The TG and DTG weight loss curve of PET in a nitrogen environment is shown in Figure 2. The figure shows that, unlike biomass materials, PET polymer exhibits single-step decomposition due to its homogenous structure. The degradation of polymers
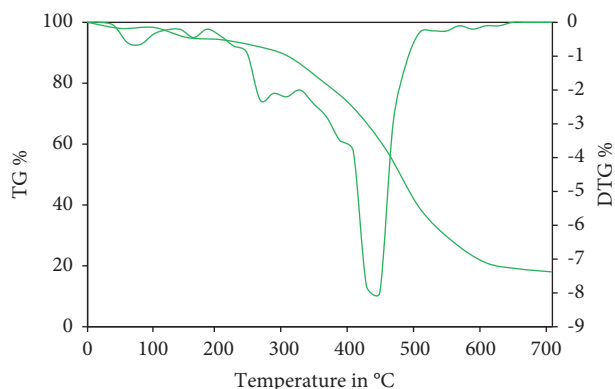
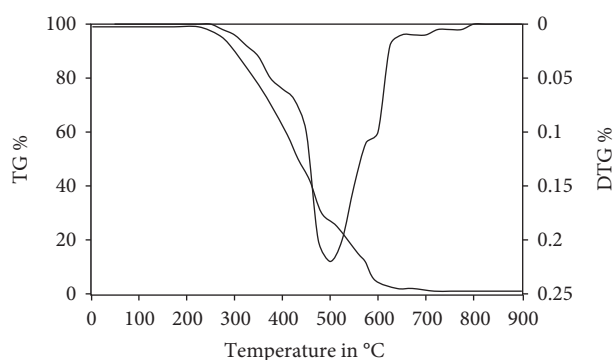FIGURE 1: TG and DTG analyses of *Ficus benghalensis*.

FIGURE 2: TG and DTG analyses of waste PET polymer.

is mainly due to the end group-initiated process and degradation of yields produced during the polymer chain degradation [39]. PET lost 80% of its total mass between 325 and 575°C, and after 625°C, there was no degradation. The aforementioned thermal decomposition data are used for the selection of the pyrolysis temperature for maximum decomposition.

3.2. Biomass Thermal Pyrolysis. Thermal pyrolysis of biomass can be conducted under various reaction temperatures to control the quality of the bio-oil and fulfil the needs of individuals. The relationship between the yield qualities and its compositions are not always easy to predict [40]. It generally depends on the various operating factors. Among the various operating parameters, the pyrolysis temperature is the one that determines the quality as well as the quantity of the yield [41, 42]. During biomass pyrolysis, the liquid oil is formed due to the immediate destruction and depolymerization of the lignocellulosic content of the biomass material. In this study, the yield of oil enhanced with increasing bed temperature. The yield of oil has reached a maximum value of 40.8 wt (%) at a temperature of 450°C. Further increments of the temperature reduce the yield of oil to 37.0 wt (%). The yield of this gas fraction increases continuously with increasing bed temperature. The gas yield varies from 29.3 wt (%) to 40.5 wt (%) when the temperature is increased from 350°C to 550°C. In Figure 3, the variation in different product yields based on process temperature is
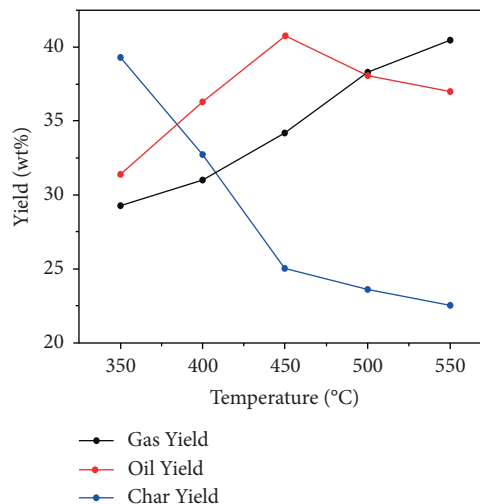

FIGURE 3: Effect of temperature on pyrolysis of *Ficus benghalensis*.

displayed. From the figure, it can be noticed that there is a steep decrement in the production of char. At 350°C, the yield of char was 39.3 wt (%), and the value was lowered to 22.5 wt (%) when the reactor temperature was increased to 550°C. The decreased char yield with higher temperatures is prominently due to the increased conversion of lignin in the biomass material [43]. The increased gas production with increased temperatures can be elucidated by increased biomass conversion. The secondary reactions of vapours to gases become more prominent at increasing temperatures.

3.3. PET Thermal Pyrolysis. PET material was employed in this study. It was pyrolyzed separately by changing the reaction temperature to get the suitable reaction conditions. In this case, the maximum conversion of bio-oil was found at 500°C. At 350°C, the production of oil is as low as 48.6 wt (%). At that point, the yield of char was a maximum of 26.3 wt (%). The yield of char reduced drastically from 26.3 wt (%) to 6.3 wt (%) with the increase in temperature from 350°C to 550°C. The production of gas increased steadily as the temperature rose. At 350°C, the gas yield was 25.1 wt (%), with a maximum of 35.2 wt (%) at 550°C. The difference in the thermal stability of the PET increases the yield of liquid oil and gas. According to Garba et al. [44], when the polymeric material was subjected to higher temperatures, there was a chance to break the stability by flouting C=C bonds, which increases the release of the gas fractions. Figure 4 shows the effect of temperature on pyrolysis of PET.

3.4. Co-pyrolysis Characteristics. Co-pyrolysis characteristics of *Ficus benghalensis* and PET mixture are illustrated in Figure 5. The experiments for this phase were performed at a constant temperature of 500°C with the addition of PET with biomass. The addition of PET with biomass increased from 20% to 80% with an interval of 20%. From the figure, it can be understood that the char decreased with an increased PET component, which was comparable to that of individual
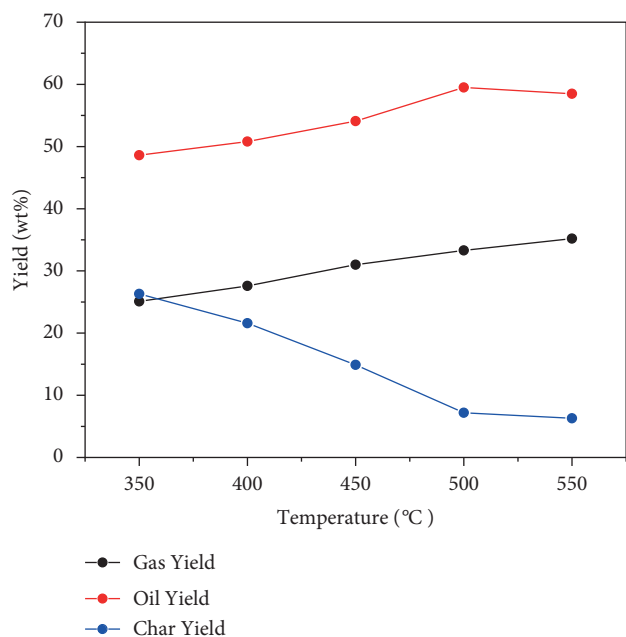
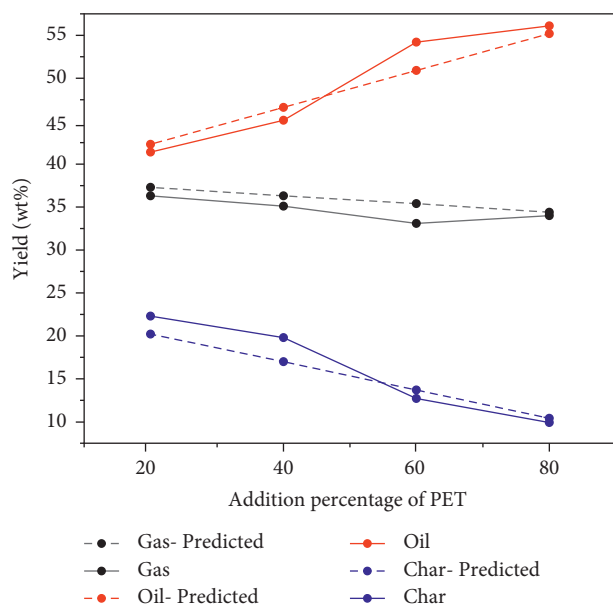FIGURE 4: Effect of temperature on pyrolysis of PET.

FIGURE 5: Effect of PET on biomass pyrolysis.

pyrolysis. The value of char decreased from 22.3 wt (%) to 9.9 wt (%) with the increment of PET from 20% to 80% of the biomass. The oil production through individual pyrolysis of PET was higher than biomass pyrolysis, which is also reflected in the co-pyrolysis reaction. In this process, the yield of oil is changed from 41.4 wt (%) to 56.1 wt (%). The oil yield enhanced with respect to the higher addition percentage of PET. The yield of oil was only 41.4 wt (%) at a 20% addition of PET. The value increased to 56.1 wt (%) with the addition of 80% PET. The increased oil yield with respect to the addition of PET is due to the existence of maximum volatiles in PET rather than biomass. According to Guo and Lua [45]

and Zhou et al. [46], polyolefin polymers during pyrolysis will act as a perfect hydrogen donor and create the radical interaction to form maximum bio-oil.

3.5. Degree of Synergistic Effects. The synergistic effect on product yields during co-pyrolysis was assessed with the help of experimental and predicted yields, which are also shown in Figure 5. The experimental yield of gas throughout the co-pyrolysis process was less than the predicted value. With up to 40% addition of PET, the production of oil was lower than the predicted value and the yield of char was higher than the predicted value. For oil yield, the positive synergistic effect was identified when more than 40% of PET was added along with biomass. At 60% addition of PET, a more positive synergistic effect was identified. At that point, the liquid yield is 6.48% higher than the predicted yield. The positive synergetic effect on oil yield was attributed to radical secondary reactions, which are responsible for the condensation of noncondensable elements [47]. Furthermore, PET in the mixture acts as a biomass hydrogenation medium, potentially inhibiting polymerization and cross-linking reactions, enhancing the biomass decomposition reaction [48]. Previously, the literature [49–51] reported the synergistic effect on co-pyrolysis of various biomaterials with PET. Çepelioğullar and Pütün [52] investigated the synergistic effects of three different biomass materials combined with PET. The study produced more bio-oil and char with less gas compared to the cumulative yields obtained from individual pyrolysis. The synergistic effect of co-pyrolysis of municipal solid waste and PET was examined by Ansah et al. [53] and showed a higher synergistic effect on bio-oil yield at a 70 : 30 blend of biomass to plastic ratio. The study also concluded that when the biomass fraction was prominent in the mixture, significant interaction between biomass and PET was detected.

3.6. Physical Characterization. The physical, elemental composition, and heating value of the liquid oils acquired through individual and co-pyrolysis processes are listed in Table 2. 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 were 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 a higher heating value.

3.7. Chemical Analysis. For the analysis of various chemical elements in the oil, GC–MS is an important and quick technique. During pyrolysis, the three primary components of biomass, such as cellulose, hemicellulose, and lignin, were decomposed into various chemical elements such as alcohol, alkanes, alkenes, and phenolic components [54, 55]. Table 3 represents a list of chemical components determined by GC–MS. As illustrated in the table, the biomass is typically broken down into phenolic compounds. Phenols, alkyl phenols, and methoxy phenols are identified from biomass pyrolysis oil

TABLE 2: Physical properties of the oils.

Properties	Ficus benghalensis	Ficus benghalensis-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 (%))
Sulfur	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)

[a]By difference.

TABLE 3: List of chemical elements identified in liquid oils through GC–MS.

Compound name	Molecular formula	A	B	C	D	E	F
2-Isopropyl-2,5-dihydrofuran	$C_7H_{12}O$	0.92	0.40	0.22			
Phenol, 2-methoxy-	$C_7H_8O_2$	1.26	1.05	0.88	0.40		
1,2-Benzendiol	$C_6H_6O_2$	2.01	1.89	1.74	0.42	0.22	
2-Furancarboxaldehyde,-5-methyl	$C_6H_6O_2$	0.91	0.25				
3-Undecene, (Z)-	$C_{11}H_{22}$					1.95	2.62
Phenol	C_6H_6O	9.12	9.01	8.24	4.20	2.11	
Furfural	$C_5H_4O_2$	0.74	0.55	0.12			
Ethisterone	$C_{21}H_{28}O_2$	0.24					
Trimethylamine	C_3H_9N					0.25	0.74
Phenol, 2-methyl-	C_7H_8O	3.44				0.11	0.19
4,5-Dimethoxy-2-methylpheno	$C_9H_{12}O_3$	1.25	1.01	0.82	0.31		
Phenol, 2-ethyl-6-methyl-	$C_9H_{12}O$	5.84	5.04	3.77	3.09	2.01	
Naphthalene, 1-methyl-	$C_{11}H_{10}$						5.22
Benzoic acid	$C_7H_6O_2$			2.55	19.81	25.14	31.24
Tridecane	$C_{13}H_{28}$			0.22	0.85	0.90	0.97
4-Ethylbenzoic acid	$C_9H_{10}O_2$	0.84	0.54	0.14			
2,4 Dimethyl pentone	C_9H_{16}			0.19	3.18	5.70	7.92
2-Methoxy phenol	$C_7H_8O_2$	5.42	3.26	1.22	0.94	0.42	
2-Acetyl furan	$C_6H_6O_2$				0.71	1.94	2.21
Phenol, 4-methyl-	$C_{21}H_{28}O$	6.01	4.10	1.25			
Tetradecane	$C_{14}H_{30}$						2.04
Benzoic acid, methyl ester	$C_8H_8O_2$	0.94	0.90	0.42	0.18		
4-Methoxy-2-methyl-1-benzene	$C_9H_{12}OS$	1.22	1.20				
Benzoic acid	$C_7H_6O_2$	1.20	1.11	0.84			
Oxirane	C_2H_4O					0.21	0.87
Pyridine 2-methyl	C_6H_7N				1.25	2.14	3.54
Cyclopentanone	C_5H_8O	1.75	0.92				
2-Phenyl-1-p-tolylethanol	$C_{14}H_{16}O$	1.25	1.05	0.81			
Naphthalene	$C_{10}H_8$	0.11					
Cyclopent-2-enethione	C_5H_6S				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	$C_8H_{10}O_2$	2.28	1.24	0.28			
trans-1,4-Hexadiene	C_6H_{10}			0.21	1.75	2.48	4.41
Phenol, 2,6-dimethoxy	$C_8H_{10}O_3$	1.58					
Thiophene, 2,5-dimethyl	C_6H_8S						0.94
Benzenemethanol, 4-hydroxy	$C_7H_8O_2$	1.72	0.84				
3-Methoxy-2-methylphenol	$C_8H_{10}O_2$	1.88	1.55	1.31	0.74	0.14	0.10
Palustrol	$C_{15}H_{26}O$						0.45
2-Acetylcycloheptaneone	$C_9H_{14}O_2$					0.21	0.94
2,4-Dihydroxy-6-methoxyacetophenone	$C_9H_{10}O_4$	1.85	1.22	0.73			
2-Methyl-5-methoxy-6-hydroxybenzofuran	$C_{11}H_{14}O_3$	1.79					
2-Furanmethanol	$C_5H_6O_2$	2.56	2.12	1.84	1.02	0.74	

TABLE 3: Continued.

Compound name	Molecular formula	A	B	C	D	E	F
Vanillin	$C_8H_8O_3$	2.40	1.26				
1-Methyl-1,3,3-triphenylindan-2-one	$C_{28}H_{22}O$	0.97					
10-Chlorodanuphylline	$C_{24}H_{25}ClN_2O_8$					0.12	0.78
3,4-Dimethylthiophene	C_6H_8S					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	$C_9H_{12}O_2$	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_6H_7NO	1.25	0.82	0.11			
Pyridine, 2-propyl-	$C_8H_{11}N$			0.54	0.99	1.25	2.41

A, biomass; B, 80 : 20; C, 60 : 40; D, 40 : 60; E, 20 : 80; F, PET.

under various proportions. The amount of these chemicals varies depending upon the amount of biomass material in the feedstock. The components identified in PET pyrolysis oil, on the other side, are completely different from biomass pyrolysis oil. The chemical components identified in PET oil are mostly hydrocarbon elements with some oxygenated elements. In contrast to the biomass pyrolysis, half of PET was decomposed into a majority of benzoic acid (31.24%). It is well known that pyrolysis oils with an acidic nature can cause corrosion difficulties in reactors and handling devices. In addition to that, the acidic properties may cause environmental issues during its natural degradation. Apart from these drawbacks, it is well recognised that benzoic acid can be utilized as a significant feedstock for a variety of chemical industries. From this perspective, pyrolysis of PET can be used to transform PET into valuable chemical feedstocks for industrial applications.

4. Conclusion

Fixed-bed pyrolysis of wood-based biomass obtained from *Ficus benghalensis* and waste PET was used in this study for the production of liquid oil. The maximum yield of pyrolysis oil was obtained from biomass and PET at 450°C and 500°C, respectively. The co-pyrolysis of biomass and PET was performed in four stages. Among different blends, the highest positive synergy for liquid oil production was obtained at a 60% addition of PET. In parallel with these results, the physical and chemical properties of the obtained liquid oil were determined to find the basic characteristics. Physical characterization demonstrates that the amount of plastic in the feedstock has a direct correlation with the heating value of the oil. The hydrogen and carbon-rich compositions were found in co-pyrolysis due to the interaction of plastics. In conclusion, it can be inferred that co-pyrolysis of *Ficus benghalensis* and waste PET could be an environmentally benign approach of converting biomass-plastic mixtures into useful products for a variety of applications.

Data Availability

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

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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