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*Research Article*

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

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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 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.

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.

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.

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

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

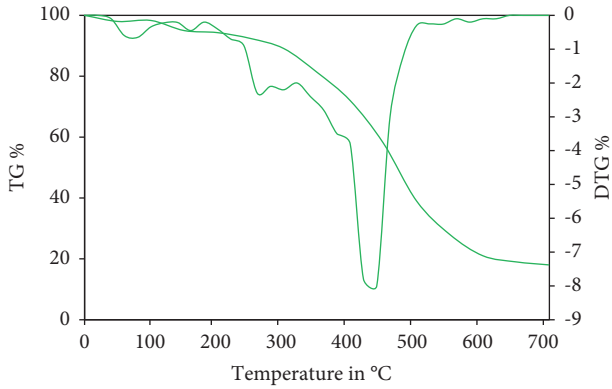



Figure 1: TG and DTG analyses of *Ficus benghalensis*.

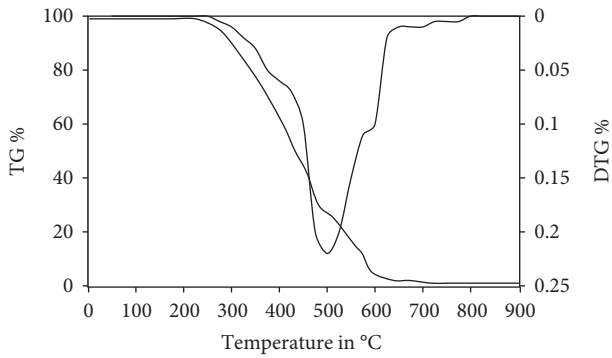



Figure 2: TG and DTG analyses of waste PET polymer.

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

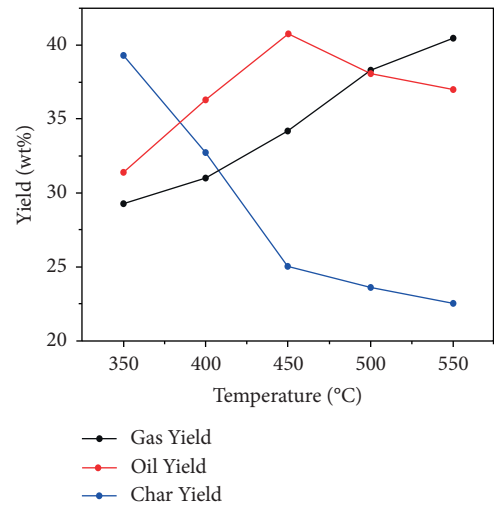



Figure 3: Effect of temperature on pyrolysis of *Ficus benghalensis*.

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

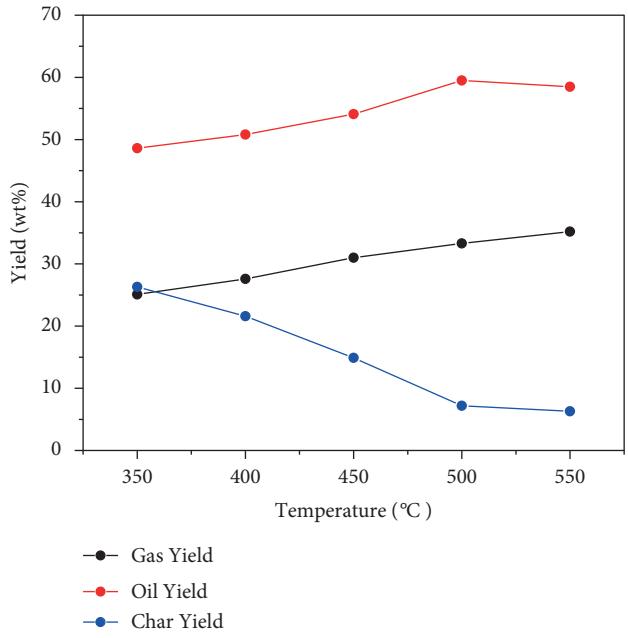



Figure 4: Effect of temperature on pyrolysis of PET.

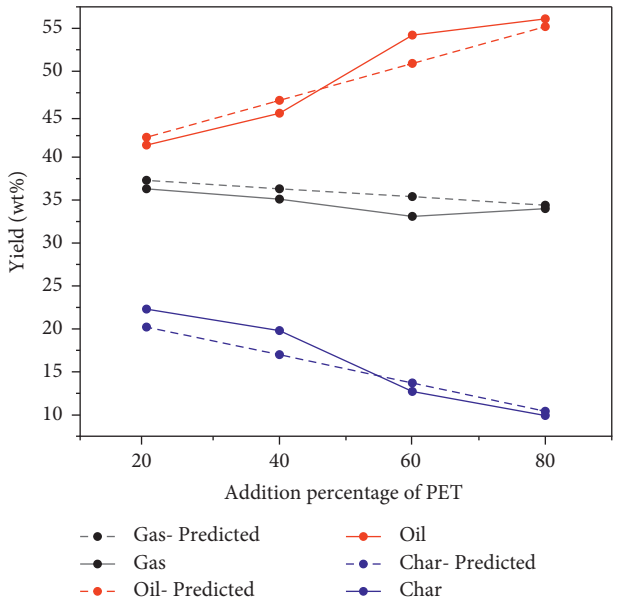



Figure 5: Effect of PET on biomass pyrolysis.

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.

## References

[1] T. Kan, V. Strezov, and T. J. Evans, "Lignocellulosic biomass pyrolysis: a review of product properties and effects of pyrolysis parameters," *Renewable and Sustainable Energy Reviews*, vol. 57, pp. 1126–1140, 2016.

[2] https://www.iea.org/topics/renewables/subtopics/bioenergy/.

[3] S. Wang, G. Dai, H. Yang, and Z. Luo, "Lignocellulosic biomass pyrolysis mechanism: a state-of-the-art review," *Progress in Energy and Combustion Science*, vol. 62, pp. 33–86, 2017.

[4] R. A. Sheldon, "Green and sustainable manufacture of chemicals from biomass: state of the art," *Green Chemistry*, vol. 16, no. 3, pp. 950–963, 2014.

[5] H. B. Goyal, D. Seal, and R. C. Saxena, "Bio-fuels from thermochemical conversion of renewable resources: a review," *Renewable and Sustainable Energy Reviews*, vol. 12, no. 2, pp. 504–517, 2008.

[6] M. Verma, S. Godbout, S. K. Brar, O. Solomatnikova, S. P. Lemay, and J. P. Larouche, "Biofuels production from biomass by thermochemical conversion technologies," *International Journal of Chemical Engineering*, vol. 2012, Article ID 542426, 18 pages, 2012.

[7] B. M. Lakshmi, M. Mathew, A. M. J. Kinol et al., "An integrated CRITIC-TOPSIS-and entropy-TOPSIS-based informative weighting and ranking approach for evaluating green energy sources and its experimental analysis on pyrolysis," *Environmental Science and Pollution Research*, vol. 29, no. 40, pp. 61370–61382, 2022.

[8] B. Kunwar, H. N. Cheng, S. R. Chandrashekaran, and B. K. Sharma, "Plastics to fuel: a review," *Renewable and Sustainable Energy Reviews*, vol. 54, pp. 421–428, 2016.

[9] A. S. Nizami, K. Shahzad, M. Rehan et al., "Developing waste biorefinery in Makkah: a way forward to convert urban waste into renewable energy," *Applied Energy*, vol. 186, pp. 189–196, 2017.

[10] S. N. M. Menikpura, J. Sang-Arun, and M. Bengtsson, "Assessment of environmental and economic performance of waste-to-energy facilities in Thai cities," *Renewable Energy*, vol. 86, pp. 576–584, 2016.

[11] M. I. Jahirul, M. G. Rasul, D. Schaller, M. M. K. Khan, M. M. Hasan, and M. A. Hazrat, "Transport fuel from waste

plastics pyrolysis–a review on technologies, challenges and opportunities," *Energy Conversion and Management*, vol. 258, Article ID 115451, 2022.

[12] D. Raguraman, A. Kumar, S. Prasanna Raj Yadav et al., "Performance and emission characteristics of pyrolysis oil obtained from neem de oiled cake and waste polystyrene in a compression ignition engine," *Advances in Materials Science and Engineering*, vol. 2021, Article ID 3728852, 10 pages, 2021.

[13] P. Das and P. Tiwari, "Thermal degradation study of waste polyethylene terephthalate (PET) under inert and oxidative environments," *Thermochimica Acta*, vol. 679, Article ID 178340, 2019.

[14] A. Dhahak, C. Grimmer, A. Neumann et al., "Real time monitoring of slow pyrolysis of polyethylene terephthalate (PET) by different mass spectrometric techniques," *Waste Management*, vol. 106, pp. 226–239, 2020.

[15] D. Kawecki, P. R. W. Scheeder, and B. Nowack, "Probabilistic material flow analysis of seven commodity plastics in Europe," *Environmental Science and Technology*, vol. 52, no. 17, pp. 9874–9888, 2018.

[16] S. O. Ayodeji and T. O. Oni, "Thermal pyrolysis production of liquid fuel from a mixture of polyethylene terephthalate and polystyrene," *Heat Transfer - Asian Research*, vol. 48, no. 5, pp. 1648–1662, 2019.

[17] T. Aysu and H. Durak, "Thermochemical conversion of *Datura stramonium* L. by supercritical liquefaction and pyrolysis processes," *The Journal of Supercritical Fluids*, vol. 102, pp. 98–114, 2015.

[18] H. Durak, "Hydrothermal liquefaction of *Glycyrrhiza glabra* L. (Liquorice): effects of catalyst on variety compounds and chromatographic characterization," *Energy Sources, Part A: Recovery, Utilization, and Environmental Effects*, vol. 42, no. 20, pp. 2471–2484, 2020.

[19] H. Durak and S. Genel, "Characterization of bio-oil and biochar obtained from black cumin seed by hydrothermal liquefaction: investigation of potential as an energy source," *Energy Sources, Part A: Recovery, Utilization, and Environmental Effects*, pp. 1–11, 2020.

[20] T. Aysu and H. Durak, "Pyrolysis of giant mullein (*Verbascum thapsus* L.) in a fixed-bed reactor: effects of pyrolysis parameters on product yields and character," *Energy Sources, Part A: Recovery, Utilization, and Environmental Effects*, vol. 38, no. 5, pp. 661–669, 2016.

[21] Ş. Alayont, D. B. Kayan, H. Durak, E. K. Alayont, and S. Genel, "The role of acidic, alkaline and hydrothermal pre-treatment on pyrolysis of wild mustard (*Sinapis arvensis*) on the properties of bio-oil and bio-char," *Bioresource Technology Reports*, vol. 17, Article ID 100980, 2022.

[22] C. Vibhakar, R. S. Sabeenian, S. Kaliappan et al., "Production and optimization of energy rich biofuel through co-pyrolysis by utilizing mixed agricultural residues and mixed waste plastics," *Advances in Materials Science and Engineering*, vol. 20229 pages, Article ID 8175552, 2022.

[23] H. Hassan, B. H. Hameed, and J. K. Lim, "Co-pyrolysis of sugarcane bagasse and waste high-density polyethylene: synergistic effect and product distributions," *Energy*, vol. 191, Article ID 116545, 2020.

[24] V. S. Kaushik, C. S. Dhanalakshmi, P. Madhu, and P. Tamilselvam, "Co-pyrolysis of neem wood bark and low-density polyethylene: influence of plastic on pyrolysis product distribution and bio-oil characterization," *Environmental Science and Pollution Research International*, pp. 1–11, 2022.

[25] P. Madhu, L. Vidhya, S. Vinodha et al., "Co-Pyrolysis of hardwood combined with industrial pressed oil cake and agricultural residues for enhanced bio-oil production," *Journal of Chemistry*, vol. 2022, Article ID 9884766, 18 pages, 2022.

[26] F. Nardella, S. Bellavia, M. Mattonai, and E. Ribechini, "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*, vol. 354, Article ID 127170, 2022.

[27] S. Xu, B. Cao, B. B. Uzoejinwa et al., "Synergistic effects of catalytic co-pyrolysis of macroalgae with waste plastics," *Process Safety and Environmental Protection*, vol. 137, pp. 34–48, 2020.

[28] E. Önal, B. B. Uzun, and A. E. Pütün, "Bio-oil production via co-pyrolysis of almond shell as biomass and high density polyethylene," *Energy Conversion and Management*, vol. 78, pp. 704–710, 2014.

[29] W. Chen, S. Shi, M. Chen, and X. Zhou, "Fast co-pyrolysis of waste newspaper with high-density polyethylene for high yields of alcohols and hydrocarbons," *Waste Management*, vol. 67, pp. 155–162, 2017.

[30] Z. Wang, K. G. Burra, T. Lei, and A. K. Gupta, "Co-pyrolysis of waste plastic and solid biomass for synergistic production of biofuels and chemicals-A review," *Progress in Energy and Combustion Science*, vol. 84, Article ID 100899, 2021.

[31] M. Brebu, S. Ucar, C. Vasile, and J. Yanik, "Co-pyrolysis of pine cone with synthetic polymers," *Fuel*, vol. 89, no. 8, pp. 1911–1918, 2010.

[32] R. Chen, J. Zhang, L. Lun, Q. Li, and Y. Zhang, "Comparative study on synergistic effects in co-pyrolysis of tobacco stalk with polymer wastes: thermal behavior, gas formation, and kinetics," *Bioresource Technology*, vol. 292, Article ID 121970, 2019.

[33] S. K. Prajapati and B. D. Tripathi, "Biomonitoring seasonal variation of urban air polycyclic aromatic hydrocarbons (PAHs) using *Ficus benghalensis* leaves," *Environmental Pollution*, vol. 151, no. 3, pp. 543–548, 2008.

[34] B. Viswanathan, A. Ariharan, and V. Nandhakumar, "Phosphorous-doped porous carbon derived from paste of newly growing *Ficus benghalensis* as hydrogen storage material," *Indian Journal of Chemistry, Section A*, vol. 55, no. 6, pp. 649–656, 2020.

[35] Y. K. S. S. Rao, C. S. Dhanalakshmi, D. K. Vairavel et al., "Investigation on forestry wood wastes: pyrolysis and thermal characteristics of *Ficus religiosa* for energy recovery system," *Advances in Materials Science and Engineering*, vol. 2022, Article ID 3314606, 9 pages, 2022.

[36] G. Ganeshan, K. P. Shadangi, and K. Mohanty, "Degradation kinetic study of pyrolysis and co-pyrolysis of biomass with polyethylene terephthalate (PET) using coats–redfern method," *Journal of Thermal Analysis and Calorimetry*, vol. 131, no. 2, pp. 1803–1816, 2018.

[37] I. Kathir, K. Haribabu, A. Kumar et al., "Utilization of tea industrial waste for low-grade energy recovery: optimization of liquid oil production and its characterization," *Advances in Materials Science and Engineering*, vol. 2022, Article ID 7852046, 9 pages, 2022.

[38] A. Dewangan, D. Pradhan, and R. K. Singh, "Co-pyrolysis of sugarcane bagasse and low-density polyethylene: influence of plastic on pyrolysis product yield," *Fuel*, vol. 185, pp. 508–516, 2016.

[39] R. R. Chowreddy, K. Nord-Varhaug, and F. Rapp, "Recycled polyethylene terephthalate/carbon nanotube composites with improved processability and performance," *Journal of Materials Science*, vol. 53, no. 9, pp. 7017–7029, 2018.

[40] R. J. M. Westerhof, D. W. F. W. Brilman, W. P. M. van Swaaij, and S. R. A. Kersten, "Effect of temperature in fluidized bed fast pyrolysis of biomass: oil quality assessment in test units," *Industrial & Engineering Chemistry Research*, vol. 49, no. 3, pp. 1160–1168, 2010.

[41] Y. Ke, S. Cui, Q. Fu, R. Hough, Z. Zhang, and Y. F. Li, "Effects of pyrolysis temperature and aging treatment on the adsorption of Cd2+ and Zn2+ by coffee grounds biochar," *Chemosphere*, vol. 296, Article ID 134051, 2022.

[42] C. S. Dhanalakshmi and P. Madhu, "Recycling of wood bark of azadirachtaindica for bio-oil and chemicals by flash pyrolysis," *Indian Journal of Ecology*, vol. 46, no. 2, pp. 347–353, 2019.

[43] Q. Shen, S. B. Liaw, M. Costa, and H. Wu, "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 and Fuels*, vol. 34, no. 6, pp. 7140–7148, 2020.

[44] M. U. Garba, U. Musa, A. G. Olugbenga, Y. S. Mohammad, M. Yahaya, and A. A. Ibrahim, "Catalytic upgrading of bio-oil from bagasse: thermogravimetric analysis and fixed bed pyrolysis," *Beni-Suef University Journal of Basic and Applied Sciences*, vol. 7, no. 4, pp. 776–781, 2018.

[45] J. Guo and A. C. Lua, "Kinetic study on pyrolytic process of oil-palm solid waste using two-step consecutive reaction model," *Biomass and Bioenergy*, vol. 20, no. 3, pp. 223–233, 2001.

[46] L. Zhou, Y. Wang, Q. Huang, and J. Cai, "Thermogravimetric characteristics and kinetic of plastic and biomass blends co-pyrolysis," *Fuel Processing Technology*, vol. 87, no. 11, pp. 963–969, 2006.

[47] G. Özsin and A. E. Pütün, "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*, vol. 205, pp. 1127–1138, 2018.

[48] H. Yuan, H. Fan, R. Shan, M. He, J. Gu, and Y. Chen, "Study of synergistic effects during co-pyrolysis of cellulose and high-density polyethylene at various ratios," *Energy Conversion and Management*, vol. 157, pp. 517–526, 2018.

[49] L. Chen, S. Wang, H. Meng, Z. Wu, and J. Zhao, "Synergistic effect on thermal behavior and char morphology analysis during co-pyrolysis of paulownia wood blended with different plastics waste," *Applied Thermal Engineering*, vol. 111, pp. 834–846, 2017.

[50] K. H. Ko, A. Rawal, and V. Sahajwalla, "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*, vol. 86, pp. 154–164, 2014.

[51] K. H. Ko, V. Sahajwalla, and A. Rawal, "Specific molecular structure changes and radical evolution during biomass–polyethylene terephthalate co-pyrolysis detected by 13C and 1H solid-state NMR," *Bioresource Technology*, vol. 170, pp. 248–255, 2014.

[52] Ö. Çepelioğullar and A. E. Pütün, "Products characterization study of a slow pyrolysis of biomass-plastic mixtures in a fixed-bed reactor," *Journal of Analytical and Applied Pyrolysis*, vol. 110, pp. 363–374, 2014.

[53] E. Ansah, L. Wang, and A. Shahbazi, "Thermogravimetric and calorimetric characteristics during co-pyrolysis of municipal solid waste components," *Waste Management*, vol. 56, pp. 196–206, 2016.

[54] S. Kaliappan, M. Karthick, P. P. Patil et al., "Utilization of eco-friendly waste eggshell catalysts for enhancing liquid product yields through pyrolysis of forestry residues," *Journal of Nanomaterials*, vol. 2022, Article ID 3445485, 10 pages, 2022.

[55] C. Sowmya Dhanalakshmi, S. Kaliappan, H. Mohammed Ali et al., "Flash pyrolysis experiment on albizia odoratissima biomass under different operating conditions: a comparative study on bio-oil, biochar, and noncondensable gas products," *Journal of Chemistry*, vol. 2022, Article ID 9084029, 9 pages, 2022.