



Research Article

In-sito co-pyrolysis of tea waste and polypropylene using microwave-assisted pyrolysis: Products analysis, energy consumption, and synergy effect

Husam Talib HAMZAH^{1,*}, Sridevi VELURU¹, Suhair Abdulhadi MAHDI²,
Thamer Adnan ABDULLAH³, M. TUKARAMBAI¹, Venkata Rao POIBA¹

¹Department of Chemical Engineering, College of Engineering, Andhra University, Visakhapatnam, 530003, India

²Department of Chemistry, College of Science, Mustansiriyah University, Baghdad, 10052, Iraq

³Applied Science Department, University of Technology, Baghdad, 10066, Iraq

ARTICLE INFO

Article history

Received: 05 May 2024

Revised: 02 July 2024

Accepted: 10 October 2024

Keywords:

Microwave Co-Pyrolysis;
Pyrolysis Index; Synergy Effect;
Polypropylene; Tea Waste

ABSTRACT

This study focuses on the microwave-assisted co-pyrolysis method, which recycles polypropylene (PP) and tea residues (TW). When utilising a KOH catalyst for co-pyrolyzing (PP: TW), the gaseous product yield dropped to 33.6%, but the oil and char yields rose to 34.8% and 31.6%, respectively. The maximum gas yield achieved by microwave co-pyrolysis without a KOH catalyst was 41.67 weight percent. In MACP of (PP: TW), 459 kJ of energy was consumed. Compared to co-pyrolysis without a catalyst, which had a synergistic impact on oil yield (-17.0) and char yield (-5.02), co-pyrolysis with a KOH catalyst has a synergistic effect that improves oil yield. While the maximal pyrolysis index (PI) without a catalyst is 88.12, it drops to 86.58 with the KOH catalyst. It shows how the KOH catalyst contributed to the pyrolysis process during the co-pyrolysis of polypropylene and tea waste. Uncatalyzed co-pyrolysis has more internal pore area. Finally, PP: TW char (123-196 m²/g) is created. The gasses created during co-pyrolysis would have affected the char "pore area." Aromatic hydrocarbon selectivity was 93.6 %. CO-pyrolysis oil was 27% cycloalkanes and alkenes. In co-pyrolysis, cyclic aliphatic molecules and benzene derivatives generated dispersion of carbon. Most compounds were C8 (31.5%), C15-C24 (22.4%), and C9 (14.4%).

Cite this article as: Hamzah HT, Velurus, Mahdi SA, Abdullah TA, Tukarambai M, Poiba VR. In-sito co-pyrolysis of tea waste and polypropylene using microwave-assisted pyrolysis: Products analysis, energy consumption, and synergy effect. Sigma J Eng Nat Sci 2025;43(5):1653–1662.

INTRODUCTION

There has been a correlation between rising global consumption and the usage of energy resources

dependent on fossil fuel utilization [1]. Because of this expansion, there is a greater demand for the discovery of alternative energy supplies that are devoid of any adverse effects on the planet, such as emissions of greenhouse

*Corresponding author.

*E-mail address: alwatanaliraqi@gmail.com

*This paper was recommended for publication in revised form by
Editor-in-Chief Ahmet Selim Dalkilic*



gases (GHG). One of the most dependable and environmentally friendly energy sources is carbon-based waste, such as biomass [2]. Wastes from industries such as manufacturing, agriculture, food production, and wastewater are all examples of diverse types of biomasses. There has been extensive industrial use of this technology for years, and it has also been the subject of laboratory-scale study into the potential for converting carbonaceous wastes towards clean energy. Some techniques include pyrolysis, gasification, thermal cracking, and anaerobic digestion [3]. Polypropylene (PP), a ubiquitous material used in packaging, automotive parts, and other products, accounts for over 30% of the world's plastic manufacturing. Based on current estimations, the global production of polypropylene (PP) exceeds 85 million tons per year, of which less than 10% is recycled. The remainder enters ecosystems as pollution. Tea waste is among the many organic wastes produced in large numbers. Tea trash is a significant by-product of the approximately 6 million tons of tea produced worldwide each year, the majority of which is either discarded or ends up polluting the environment. Environmental issues include greenhouse gas emissions, hazardous chemical leaching, and soil pollution are caused by both polypropylene products and tea waste [4,5]. Specifically, co-pyrolysis of PP and tea waste has been demonstrated to improve bio-oil production; studies have reported as much as a 25% increase in oil yield when compared to the pyrolysis of tea waste alone; the tea waste also improves plastic decomposition, leading to higher-quality bio-oil and as much as a 30% reduction in solid residue; microwave heating has also been shown to reduce energy consumption; reports have indicated that it can reduce energy use by 20-50% when compared to traditional heating methods [6]. The absence of oxygen in pyrolysis eliminates the need for a reaction, making this process more advantageous for industrial applications. Additionally, the temperature of the process, which ranges from 350 to 650 °C, can be lower than the temperature at which gasification occurs, which is greater than 900 °C. The most significant distinctions between gasification and pyrolysis can be found in these two fundamental ideas [7]. In various industrial applications, pyrolysis is an essential economic reaction without adverse environmental effects. The product's constituent parts can be classified into one of three groups, depending on the temperature at which they are implemented: Bio-oil, charcoal, and syngas [8]. Reported that the wastes of polystyrene (PS) and tea powder (WTP) were converted into far more valuable products through catalytic co-pyrolysis using a KOH catalyst. The production of the product and the heating rates (17–75 °C/min) were correlated. WTP was in charge of generating char, whereas PS was in charge of producing oil. According to (Erkus & Calhan 2022) [9], activated carbon (AC) with a large surface area is produced using microwave-assisted pyrolysis (MAP), a two-stage chemical activation process. For

this aim, a special precursor material made of Tangerine peel (TP) and spent tea waste (STW) is combined. TP and STW were combined to create AC through the first step of the process, which involved impregnating samples with alkali metal hydroxide. ZnCl_2 , H_3PO_4 , and KOH were then used as catalysts after this stage. Every experiment was run for twenty to thirty minutes, using a microwave power of between 600 and 700 watts.

Fu et al. [10] reported that to evaluate how the HZSM-5 and HY catalysts affected the co-pyrolysis performance and product distribution of polyethylene (CP73) and coffee grounds, a thermogravimetric analyzer equipped with Fourier transform infrared spectroscopy and pyrolysis-gas-chromatography-mass spectrometry was used. The incorporation of HZSM-5 and HY made the disintegration of CP73 easier and resulted in a decrease in the amount of leftover material it contained. Compared to CP73, HY-catalyzed CP73 (CP73/HY) has displayed a reduced residual content, with a reduction of 9.09%, eliminating the influence of the mixing ratio [10]. Ben Abdallah et al. [11] reported that a two-stage thermochemical method was studied for discarded green tea waste (GTW), with the first step being pyrolysis and the second being thermal or catalytic cracking. Two bench-scale reactors, one with a fixed bed and the other with a tubular design, were linked in parallel to execute this procedure. When applied to a fixed temperature at which pyrolysis occurs of GTW (550 °C), high cracking temperatures (700 and 800 °C) improved the gas product's yield and composition. Because of this, it might find numerous applications in the biofuel and chemical production processes, and it could even be partially recycled to improve efficiency further [11]. Waste is transformed into valuable resources through this process, which includes the production of chemicals and materials that absorb pollutants. To accurately anticipate product yields, it is essential to take into consideration the characteristics of the feedstock as well as the circumstances of the pyrolysis process. The pyro-product yields from the co-pyrolysis of biomass and polymers assisted by microwaves were predicted using a support vector machine (SVM). Following the training and validation of SVM models, they were applied to new data [12]. On the other hand, co-pyrolysis is a process that uses various waste materials as feedstock. In contrast to the abundant polymeric waste stream represented by tire debris, there is a correlation between the high consumption rate of coffee generally and the expansion of coffee waste material. Coffee and tire wastes can be combined to create a bio-oil manufacturing method that has the potential to be very successful. Specific conditions must be fulfilled to achieve the best possible outcomes [13]. MW-assisted pyrolysis is an efficient solid waste management approach. Hamzah et al. [6] reported that, converted Paraffin wax (PW) and rice straw (RS) into char, gas, and oil using MW-assisted catalytic co-pyrolysis. The catalyst and susceptor were KOH and graphite. RS and PW (0–10

g combination) were the feedstock. RS: PW co-pyrolysis yields varied in char content (9.8%–22.6% by wt.), oil production (34.1%–76.9%), and gas creation (13.2%–47.5%). Researchers also examined how different RS: PW ratios affected product yields, average heating rate, and feedstock conversion [6].

This work aims to study the effect of co-pyrolysis of tea waste and polypropylene using microwave-assisted co-pyrolysis on product yield, energy consumption, synergy effect, and pyrolysis index. Examining the effects of KOH catalyst on MW-assisted co-pyrolysis of tea waste and polypropylene, including the pyrolysis index, yields, composition, average heating rate, high heating value, energy consumption, and pyrolysis reaction time, is the main objective of this research.

MATERIALS AND METHODS

Materials

During this research, co-pyrolysis was carried out using two distinct feedstocks. These feedstocks were biomasses (tea waste) and heavy hydrocarbons (polypropylene) of Indian origin. The result was the production of high-quality oil, char, and syngas. Because microwave co-pyrolysis requires the identification of types of heavy hydrocarbons and biomass that can be utilized, the significance of this discovery becomes readily evident. When considering solid waste management, the selected feedstocks are of the utmost importance [5]. After the pyrolysis and co-pyrolysis of tea waste and polypropylene, the graphite employed as a susceptor in our studies, we examined the production of bio-oil, char, and gases and the quality of these products. 10 g each of tea waste and polypropylene were used in the laboratory experiments, 2 g KOH was used as catalyst, graphite was used as susceptor and the microwave power setting was 450 W. Our research aims to provide insight into the potential of microwave-assisted pyrolysis and co-pyrolysis for recovering energy and resources from recyclable biomass and heavy hydrocarbon polymers. The temperature was recorded every 30 seconds for the study of temperature and heating rate profile. The microwave energy has been calculated to be necessary for pyrolysis. To find out how much microwave power is needed, one uses the following equation 1[4]:

$$\text{Microwave energy} = \text{MW Power (450 W)} \times 60 \times \text{Total pyrolysis time (min)} \quad (1)$$

To find out how much of an impact synergistic effect, or the degree to which various biomass mixtures interacted during co-pyrolysis, we used the following equation 2:

$$\Delta X = X_{EXP} - X_{CAL} \quad (2)$$

X_{CAL} was calculated by using the Equation 3:

$$X_{CAL} = A1B1 + A2B2 \quad (3)$$

A1 and A2 represent the TW and PP weight percentages, respectively, whereas B1 and B2 denote the mixture's TW and PP mass fractions. If the ΔX value is more than 0, it indicates that the synergistic impact is negative. When the ΔX value is less than zero, the synergistic impact is positive [4]. It has been determined that the following equation Can be used to compute the pyrolysis index:

$$\text{Pyrolysis index (PI)} = F_m * F_{HHV} * F_X / P_{EC} * P_t \quad (4)$$

Where P_t , P_{EC} , F_m , F_X , F_{HHV} are pyrolysis time (s), pyrolysis energy consumption (J/s), the mass, of feedstock (g), conversion of feedstock (%), and the higher heating value of feedstock (J/g), respectively [4].

Analysis of Proximate and Elements for the Characterization of TW and PP

Elements and proxy Analysis are performed on dry samples of feedstocks, namely tea waste powder (TWP). The chemical composition of TWP is as follows: 79.3% carbon, 1.7% hydrogen, 3.4% nitrogen, 0.2% sulfur, and 15.2% oxygen, as stated in Table 1. The TWP has significant volatile matter (71.0%) and fixed carbon (15.57%). Meanwhile, TWP has little ash content and can work as a susceptor. The PP comprises 90.8 weight percent carbon, 7.1% hydrogen, 0.1 weight percent nitrogen, and 0.0 weight percent sulfur, while 2 weight percent oxygen makes up the compound. Its thermal value is high because of the low concentration of oxygen and ash in it. The PP's volatile matter and fixed carbon percentages are 93.7% and 6.3%, respectively. However, PP does not include a significant amount of ash. Ash, which is present in, permits this change in available products by acting as a susceptor. Table 1 shows the results of the elements and proximity analyses of TW and PP, respectively [4].

Table 1. Proximate and elemental analysis of (TW, PP)

Feedstock	Proximate Analysis (wt%)			Elemental Analysis (wt%)				
	VM	FC	Ash	C	H	N	S	O
Tea Waste Powder (TW)	19.8	71	9.2	79.3	1.7	3.4	0.2	15.3
Polypropylene (PP)	93.7	6.3	0.0	90.8	7.1	0.1	0.0	2.0

GC-MS Analysis

The organic composition of the bio-oil byproduct of MW-pyrolysis was examined employing gas chromatography/mass spectrometry (Agilent 7890, 5975C). With an internal diameter of 0.25 millimeters and a film thickness of 0.25 micrometers, the HP-5MS column, which is 30 meters long, was designed. In 69 steps, it separated the gaseous products of pyrolysis. To serve as the carrier gas, 0.8 millimeters per minute of ultra-high-grade helium, 99.9995%, was utilized. Peak mass spectra were compared to the NIST library, which allowed for the identification of the chemical components of bio-oil components. Other categories have been developed for organic compounds with at least 85 percent match factors. To achieve the mass balance, substances that were either unidentifiable or poorly matched were added to the range of already present compounds. Standardization was performed on the fraction of peak area for each chemical concerning bio-oil production. The peak area percentage is sometimes displayed as the relative selectivity [14,15].

Calorific Value

Feedstocks and products have calorific values, which is the energy produced when burned under standard conditions. The higher and lower heating values (HHV and LHV, respectively) indicate calorific values, and this reflects the energy of the feedstock or product. When water's latent heat of vaporization is considered, HHV represents the most significant heat extracted from fuel after burning. LHV does not consider the latent heat of vaporization. Due to the cooling process that occurs before testing, LHV is consistently lower than HHV. This method calculated hydrocarbon polymers, oil, biomass, and other components' HHVs [6].

Table 2. High heating value of feedstocks

Feedstock	HHV (MJ/Kg)
Tea waste (TW)	13.4
Polypropylene (PP)	44.7

RESULTS AND DISCUSSION

MW-Assisted Pyrolysis and Co-Pyrolysis of Polypropylene and Tea Waste

Here is the conventional method of testing using a bomb calorimeter to determine the heating value. Biomass (TW), heavy hydrocarbon polymers (PP), and oil yield were tested, and HHVs were identified using this method [6,14]. The feedstock utilized in our studies has a high heating value, as shown in Table 2, and HHVs of product oil yield in Table 3.

Table 3 indicates the experimental result of MW-assisted pyrolysis and co-pyrolysis of TW and PP at MW power, which was preferred at 450 W. The studied oil, gas, and char yields were reported. Benzene derivatives, like carboxylic acids linked to the benzene ring, are produced in MACP by combining the lignin and polyphenol structure of tea waste powder with polypropylene's hydrogen and carbonate content. The GCMS analysis of co-pyrolysis Oil of (PP:TW) reported the Benzene, toluene, phenol, furfural, furan, naphthalene, indene, and xylene are aromatic hydrocarbons that can be synthesized by manipulating biomass and polypropylene species with MACP. The recovered oil contained various aromatic compounds, including oxygenated molecules and mono-aromatics [4,14].

By co-pyrolyzing (PP: TW) with a KOH catalyst, the gaseous product yield dropped to 33.6%, but the oil and char yields rose to 34.8% and 31.6%, respectively. Using microwave co-pyrolysis without a catalyst resulted in a maximum gas yield of 41.67% by weight, see Figure 1. This matches with the study by (Hamzah et al., 2024a) where oil yield was increased using the KOH catalyst, when they are co-pyrolyzed rice straw and paraffin wax (plastic-like) [6].

Temperature and Heating Rate Profiles of MW-Assisted Co-Pyrolysis of (TW: PP)

The temperature profiles shown in Figure 2 correspond to the co-pyrolysis of (biomass: heavy hydrocarbons), tea waste, and polypropylene, as shown in Table 3. The temperature profiles were obtained by co-pyrolyzing the feedstock at a microwave power of 450 W. After 17 minutes of operation using graphite as the susceptor; the reactant temperature reached 701-718 C°. Experiment C4 (TW: PP) with a KOH catalyst had the highest oil yield (34.8 wt%)

Table 3. Experimental result of MW-assisted pyrolysis and co-pyrolysis of TW and PP

Exp. NO.	Plastic PP (g)	Tea Waste (g)	KOH catalyst (g)	AHR (°C/min)	Oil yield (wt.%)	Gas yield (wt.%)	Char yield (wt.%)	Conv. (wt.%)	Heating value (MJ/kg)	Pyrolysis time (min)	Pyrolysis Temp. (°C)	MW Energy (kJ)
C1	10	10	-	4.8	35	14.6	50.4	49.6	13.7	86.5	450	3114
C2	10	10	-	48.6	55.3	37.7	7	93	45.7	20	550	540
C3	10	10	-	40.4	27.95	41.67	30.38	69.62	36.7	17	718	459
C4	10	10	2	39.4	34.8	33.6	31.6	68.4	37.2	17	701	459

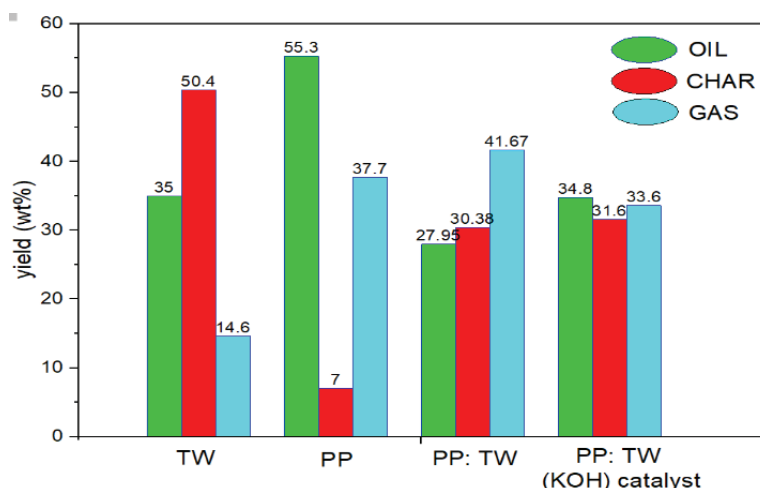


Figure 1. Oil, char, and gases yields of MW-assisted pyrolysis and co-pyrolysis of PP and TW.

and heating value (37.2 MJ/Kg), even though the average heating rates ranged from 39.4 to 40.4 °C min⁻¹. In contrast, the gas yield is at its highest (41.67 wt%), and char yield is at its lowest (31.6 wt%) during co-pyrolysis with no catalyst, these results are matches with the study by (Neha & Remya, 2022) [16]. Experiments involving microwave co-pyrolysis and their respective heating rate profiles are detailed in Table 3. The graphite susceptor shows great promise in Figure 2's heating rate profiles because of its excellent thermal stability, high average heating rate, and high heating rates (40.4 °C/min) attained in the first co-pyrolysis phase. The fact that non-condensable gases can be produced in large quantities by rapidly heating samples is well-known [17,18].

Microwave Energy Consumed and Higher Heating Values of Co-Pyrolyzed Biomass and Heavy Hydrocarbons

We used a bomb calorimeter to measure the higher heating values of MW Co-pyrolysis (tea waste and

polypropylene) oil, as shown in Table 3. All of the combustion tests were carried out within a specific minute range. All samples' HHVs are provided in Table 3. Biomass, heavy hydrocarbons, other feedstocks, and the KOH catalyst impacted the HHV of MW-pyrolysis oil [4]. Compared to separate pyrolysis, which requires a lot of energy and time, microwave energy consumption is the best (459 KJ) when used to co-pyrolyze tea waste and polypropylene. Additionally, the reaction time is lowered.

Synergy Effect on Product Yields of MW Co-Pyrolysis

A synergistic effect occurs when the effects of two or more substances are amplified when brought together. Results are more impressive when accumulated than when considered separately. Potentially, this is the end product of chemical processes involving carbon and hydrogen-containing compounds [6]. The term "synergistic effect" describes the positive or negative impact of an interaction between particles of different materials. Select the suitable

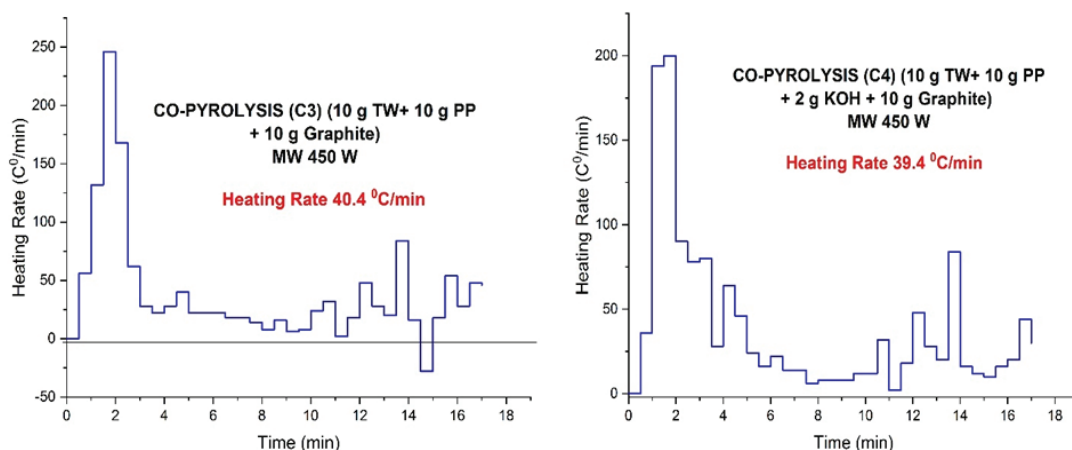


Figure 2. Temperature and Heating Rate Profiles of MW co-pyrolysis of PP: TW.

feedstock and optimize the process to get the most out of your pyrolytic products. Finding out how two materials synergize when pyrolyzed together is essential. Experimental values were derived using microwave-assisted co-pyrolysis of biomass and heavy hydrocarbons. One may obtain theoretical values for biomass (TW) and heavy hydrocarbons (PP) using separate pyrolysis procedures. To find out if the co-pyrolysis of biomass mixtures has a synergistic impact, one can compare the experimental and theoretical values of the parameters. By combining the effects of biomass and heavy hydrocarbons on the two feedstocks, their combined influence on pyrolysis was determined. Yields from pyrolysis, average heating rate, and conversion are defined below. The expected and measured product yields are displayed in Figure 3. Results for TW and PP from microwave

co-pyrolysis, as a result of synergy, are shown in Table 4. When compared to co-pyrolysis without a catalyst, which had a synergistic effect on oil yield (-17.2) and char yield (-5.02), co-pyrolysis with a KOH catalyst had a synergistic impact that improved oil yield (-17.0). Because the KOH catalyst improves the oil yield, and reduce the char (1.3); These results are matches with the study by [19].

Pyrolysis Index

Many variables affect the outcome of PI, including conversion, feedstock mass, outstanding heating value, pyrolysis time, and pyrolysis energy consumption. The value can be between zero and infinity, with more significant numbers indicating a higher pyrolysis efficiency. Table 5 displays the effect of MW-assisted pyrolysis individually and

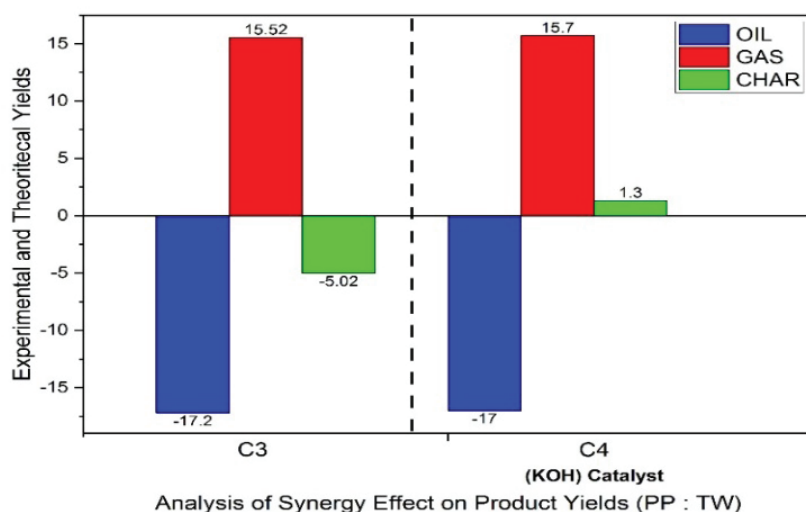


Figure 3. Effect of synergy on product yields of polypropylene and tea waste.

Table 4. Effect of synergy on product yields of microwave co-pyrolysis of (PP: TW)

Exp. NO.	Polypropylene PP (g)	Tea waste TW (g)	(KOH) catalyst (g)	Synergy effect on oil yield	Synergy effect on gas yield	Synergy effect on char yield
C4	10	10	2	-17.0	15.7	1.3
C3	10	10	-	-17.2	15.52	-5.02

Table 5. Pyrolysis index of MW-assisted pyrolysis and co-pyrolysis of TW and PP

Exp. NO.	Polypropylene (g)	Tea Waste (g)	KOH catalyst (g)	Pyrolysis Time (min)	Pyrolysis index
C1	-	10	-	86.5	4.4
C2	10	-	-	20	76.98
C3	10	10	-	17	88.12
C4	10	10	2	17	86.58

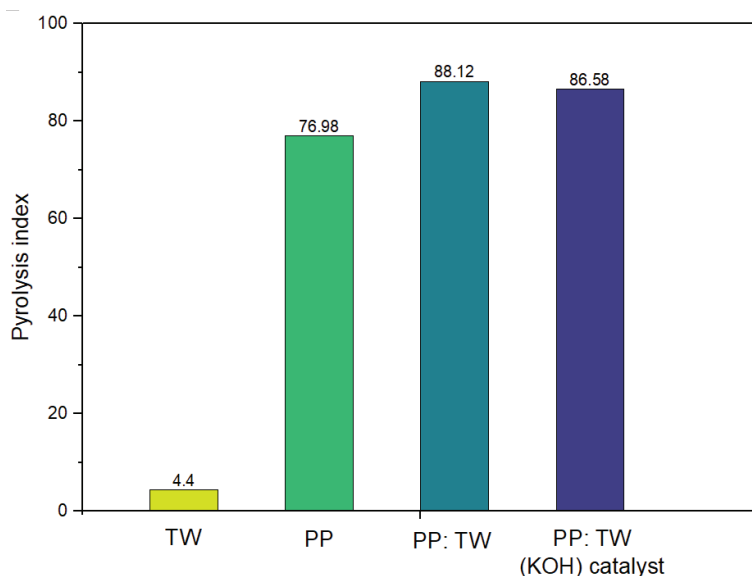


Figure 4. Pyrolysis index of MW-assisted pyrolysis and co-pyrolysis of TW and PP.

co-pyrolysis of (PP, TW) with and without KOH catalyst on the pyrolysis index (PI).

Figure 4 shows the maximum pyrolysis index of co-pyrolysis of TW: PP without using a catalyst was (88.12); it indicates that There is an inverse relationship with the reaction time, as the higher the PI, the lower reaction time, compared to if the pyrolysis was individual. The effect of the KOH catalyst was to reduce gas production, which contributed to reducing the conversion rate, and this affected the reduction of PI by a small percentage. A high PI of co-pyrolysis of (PP: TW) represents the efficiency of the process in terms of calorific value, reaction time, conversion rate, and energy consumed [20,21].

Analysis of Products

The blends of fifty-weight percent polypropylene and fifty-weight percent tea waste were pyrolyzed by microwave to explore the synergism that occurs during the co-pyrolysis process and its impact on the composition of the result. Ten grams of polypropylene and ten grams of tea waste powder were thoroughly combined in this particular instance. Consequently, a MW susceptor of 10 grams of graphite powder was added. After collecting the obtained liquid products, they were dissolved and then diluted with dichloromethane. GC–MS was used to analyze the phase of the fluid sample that had been extracted with dichloromethane. In microwave-assisted pyrolysis of polypropylene added to tea waste in a mass ratio of 10:10 grams, the surface area of the char produced after co-pyrolysis varied depending on whether or not a KOH catalyst was used. Compared to MW pyrolysis, which uses a KOH catalyst, the co-pyrolysis that does not involve the catalyst has a higher internal pore area. The char from PP: TW (123-196 m² /g) results from this. The char pore area

would have been dramatically affected by the developed gases during the co-pyrolysis process. Following the completion of the GCMS analysis for the oil that was produced by microwave co-pyrolysis of (PP: TW), it was discovered that aromatic hydrocarbons were the most prevalent group in both of the oils that were created by co-pyrolysis. (93.6 %) was the selectivity of aromatic hydrocarbons [22,23]. Cycloalkanes and alkenes were found in the oil produced through co-pyrolysis (27%). The synergy that resulted from the co-pyrolysis process led to the synthesis of cyclic aliphatic compounds and benzene derivatives. Co-pyrolysis exhibits a high selectivity for the following compounds: 1,2,3-trimethyl benzene (17.7%), O-xylene (7.5%), ethylene benzene (6.2%), ethylbenzene (5.8%), and naphthalene (4.7%). A comprehensive examination of the compounds discovered this. Co-pyrolysis resulted in the production of carbon numbers that fell between C6 and C24, according to the examination of the distribution of carbon numbers. Compounds of the chemical formula C8 (31.5%), C15-C24 (22.4%), and C9 (14.4%) were discovered to be the most prevalent in this range, these results are matches with the study by (Neha & Remya, 2022) [16]. Approximately 88% of the 20 carbon elements were found in the oil produced through co-pyrolysis. The elemental hydrogen level is estimated to be somewhere between 8.5 and 10.5%. Because of the significant amount of oxygen transferred from the waste tea into a gaseous fraction, the elemental oxygen content was low, ranging from 0.9% to 2.9%. As a result, the high carbon and hydrogen content of the oil produced by co-pyrolysis increased its energy density. The result matches with the study by [23,24] when they co-pyrolyzed rice straw and paraffin wax (plastic-like) [6].

CONCLUSION

Polypropylene and waste tea have emerged as potentially valuable feedstocks for producing oil, gasses, and char. The reaction had a temperature range of 700 to 718 °C. Approximately 17 minutes was the reaction time. In terms of oil production, it was discovered that the most effective method was the co-pyrolysis of TW: PP with a KOH catalyst. Using a KOH catalyst, the oil and char yield increased to 34.8 wt% and 31.6 wt%, respectively. It was discovered that the maximum pyrolysis index of co-pyrolysis of TW: PP without using a catalyst was 88.12 after 17 minutes of reaction time, and the maximum gas output was 41.68 wt%. The synergy of co-pyrolysis TW: PP improved the oil yield (-17.0) with the KOH catalyst and (-17.2) without the catalyst. Also, the synergy effect improved char yield (-5.02) without a catalyst. More of the internal pore area is present in the co-pyrolysis process that does not involve the catalyst. Consequently, the char from PP: TW (123-196 m² /g) is produced. During the co-pyrolysis process, the gases produced would have had a significant impact on the pore area of the char. Aromatic hydrocarbon selectivity was 93.6%. Cycloalkanes and alkenes made about 27% of co-pyrolysis oil. The synergy of co-pyrolysis produced cyclic aliphatic molecules and benzene derivatives. carbon number dispersion. In this range, C8 (31.5%), C15-C24 (22.4%), and C9 (14.4%) compounds were most common. This work needs further future study to fill in the gaps, for example the economic value of converting tea waste and polypropylene into a source of fuel or useful chemicals on a large scale.

DECLARATION OF COMPETING INTEREST

The authors declare that they have no known competing financial interests.

DATA AVAILABILITY

The data that has been used is confidential.

AUTHOR CONTRIBUTIONS

All authors contributed to the study conception and design. Material preparation, data collection and analysis were performed by [Husam Talib Hamzah], [Sridevi Veluru], [Suhair Abdulhadi Mahdi], [M. Tukarambai] and [Venkata Rao]. The first draft of the manuscript was written by [Husam Talib Hamzah] and [Thamer Adnan Abdullah] and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

CONFLICT OF INTEREST

The author declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

ETHICS

There are no ethical issues with the publication of this manuscript.

STATEMENT ON THE USE OF ARTIFICIAL INTELLIGENCE

Artificial intelligence was not used in the preparation of the article.

REFERENCES

- [1] Hassan MA, Salem H, Bailek N, Kisi O. Random forest ensemble-based predictions of on-road vehicular emissions and fuel consumption in developing urban areas. *Sustainability* 2023;15:1503. [\[CrossRef\]](#)
- [2] Menzel CM. Effect of global warming on the yields of strawberry in Queensland: a mini-review. *Horticulturae* 2023;9:142. [\[CrossRef\]](#)
- [3] Lee J, Kim S, You S, Park YK. Bioenergy generation from thermochemical conversion of lignocellulosic biomass-based integrated renewable energy systems. *Renew Sustain Energy Rev* 2023;178:113240. [\[CrossRef\]](#)
- [4] Talib Hamzah H, Sridevi V, Seereddi M, Suriapparao DV, Ramesh P, Sankar Rao C, et al. The role of solvent soaking and pretreatment temperature in microwave-assisted pyrolysis of waste tea powder. *Bioresour Technol* 2022;363:127913. [\[CrossRef\]](#)
- [5] Hamzah HT, Sridevi V, Surya DV, Palla S, Yadav A, Rao PV. Conventional and microwave-assisted acid pretreatment of tea waste powder: analysis of functional groups using FTIR. *Environ Sci Pollut Res* 2023;30:1–12. [\[CrossRef\]](#)
- [6] Hamzah HT, Sridevi V, Surya DV, Ramesh P, Rao CS, Palla S, et al. Synergistic effects and product yields in microwave-assisted in-situ co-pyrolysis of rice straw and paraffin wax. *Process Saf Environ Prot* 2024;182:45–55. [\[CrossRef\]](#)
- [7] Osman AI, Qasim U, Jamil F, Al-Muhtaseb AH, Jrai AA, Al-Riyami M, et al. Bioethanol and biodiesel: bibliometric mapping, policies and future needs. *Renew Sustain Energy Rev* 2021;152:111677. [\[CrossRef\]](#)
- [8] Kan T, Strezov V, Evans TJ. Lignocellulosic biomass pyrolysis: a review of product properties and effects of pyrolysis parameters. *Renew Sustain Energy Rev* 2016;57:1126–1140. [\[CrossRef\]](#)
- [9] Erkus H, Calhan R. Co-pyrolysis of spent tea waste and tangerine peels with different catalysts by microwave-assisted pyrolysis. *Bioenergy Res* 2022;16:1099–1107. [\[CrossRef\]](#)
- [10] Fu J, Lin S, Cai B, Liang J, Chen Z, Evrendilek F, et al. Catalytic co-pyrolysis of coffee grounds and polyethylene: a comparison of HZSM-5 and HY. *Fuel* 2024;362:130815. [\[CrossRef\]](#)

- [11] Ben Abdallah A, Ben Hassen Trabelsi A, Veses A, García T, López JM, Navarro MV, et al. Enhancing the production of syngas from spent green tea waste through dual-stage pyrolysis and catalytic cracking. *Catalysts* 2023;13:1334. [\[CrossRef\]](#)
- [12] Potnuri R, Rao CS, Surya DV, Kumar A, Basak T. Utilizing support vector regression modeling to predict pyro product yields from microwave-assisted catalytic co-pyrolysis of biomass and waste plastics. *Energy Convers Manag* 2023;292:117387. [\[CrossRef\]](#)
- [13] Hilal L, Žabčić M, Rocha-Meneses L, Ghenai C, Inayat A. Production of bio-oil by co-pyrolysis of the coffee and tire wastes. *Proc World Congr New Technol* 2023;9:1–6. [\[CrossRef\]](#)
- [14] Talib Hamzah H, Suhair Abdulhadi M, Sridevi V, Thamer Adnan A. Microwave-assisted pyrolysis and co-pyrolysis: oil, char, and gases – a technological review. *El-Cezeri J Sci Eng* 2024;11:186–198. [\[CrossRef\]](#)
- [15] Liu Y, Liu Y, Chen R, Wang H, Gao H, Wang Y, et al. Microwave pyrolysis of sewage sludge for bio-oil production: effects of organic components and mechanisms. *Fuel Process Technol* 2024;253:108023. [\[CrossRef\]](#)
- [16] Neha S, Remya N. Co-production of biooil and biochar from microwave co-pyrolysis of food-waste and plastic using recycled biochar as microwave susceptor. *Sustain Energy Technol Assess* 2022;54:102892. [\[CrossRef\]](#)
- [17] Terapalli A, Kamireddi D, Sridevi V, Tukarambai M, Suriapparao DV, Rao CS, et al. Microwave-assisted in-situ catalytic pyrolysis of polystyrene: analysis of product formation and energy consumption using machine learning approach. *Process Saf Environ Prot* 2022;166:57–67. [\[CrossRef\]](#)
- [18] Hamzah HT, Veluru S, Hasan HM, Abed HY, Mahdi HS, Hamdullah NA, et al. Microwave assisted pyrolysis of biomass feedstock fundamentals and the effect of process parameters – a review. *J Phys Conf Ser* 2023;2550:012003. [\[CrossRef\]](#)
- [19] Burra K, Gupta A. Kinetics of synergistic effects in co-pyrolysis of biomass with plastic wastes. *Appl Energy* 2018;220:408–418. [\[CrossRef\]](#)
- [20] Suriapparao DV, Sridevi V, Ramesh P, Sankar Rao C, Tukarambai M, Kamireddi D, et al. Synthesis of sustainable chemicals from waste tea powder and polystyrene via microwave-assisted in-situ catalytic co-pyrolysis. *Bioresour Technol* 2022;362:127813. [\[CrossRef\]](#)
- [21] Raza M, Abu-Jdayil B, Al-Marzouqi AH, Inayat A. Kinetic and thermodynamic analyses of date palm surface fibers pyrolysis using Coats-Redfern method. *Renew Energy* 2022;183:67–77. [\[CrossRef\]](#)
- [22] Hamzah HT, Veluru S, Hasan HJ, Abdullah TA, Gudapati G. Innovative biosensors from agro-waste: laser and microwave approaches for current and future applications in environmental health. In: Neelancherry R, Gao B, Wisniewski A, editors. *Agricultural waste to value-added products*. Singapore: Springer; 2024. p. 1–12. [\[CrossRef\]](#)
- [23] Hamzah HT, Alawi NM, Hasan HM, Abed HY, Veluru S, Hamdullah NA, et al. Effect of acids and alkaline pretreatment of used tea waste powder under microwave-assisted pretreatment. *Key Eng Mater* 2023;960:149–160. [\[CrossRef\]](#)
- [24] Chen Z, Zhao M, Liu Y, Lv Y, Khan SN, Tariq G, et al. Comprehensive pyrolysis characteristic and kinetic analysis of industrial-sludge and rice straw: blending and pellet. *J Clean Prod* 2024;440:140887. [\[CrossRef\]](#)

Graphical abstract

