Research Article

Microwave-Assisted Pyrolysis of Mixed Agricultural Wastes for Bio-Oil Production

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Abstract | The agricultural sector generates large quantities of residue each year. Recently, microwave-assisted pyrolysis (MAP) has emerged as a method for valorizing agricultural waste into bioenergy products. Product distribution in MAP, specifically gas, bio-oil, and biochar, has a significant dependence on both feedstock type and process parameters. The present study investigated the potential for producing bio-oil from a mixture of blueberry waste, corn cobs, and rice husk. The pyrolysis for the MAP runs had a target temperature of 544°C, which was reached over 36 minutes, corresponding to an average heating rate (AHR) of 15.11°C/min. The MAP process produced 18.33% bio-oil, 36.66% biochar, and 45.01% as non-condensable gases. The relatively low oil yield was a result of the slow heating rate and long pyrolysis time, which favored gas production. Interestingly, the bio-oil and gas produced from this process can be used as renewable biofuels or as sources of energy to run pyrolysis at the farm (local, small-scale) level in rural applications. The study shows a novel route for converting common agricultural residues into energetically valuable products using MAP. Both gas and bio-oil streams can be utilized as renewable feedstocks for mini-scale pyrolysis in rural areas; however, the low lipid yield is attributed to the long residence time and conservative heat transfer associated with the microwave technique. Further optimization of the heating profile could enhance the bio-oil fraction without compromising the biochar value.

Received | May 20, 2025; **Accepted** | June 23, 2025; **Published** | June 30, 2025
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Citation | Hasan, I.J., H.J. Hasan and H.J. Kadhim. 2025. Microwave-assisted pyrolysis of mixed agricultural wastes for bio-oil production. *Pakistan Journal of Agricultural Research,* 38(2): 110-118.
DOI | https://dx.doi.org/10.17582/journal.pjar/2025/38.2.110.118
Keywords | Agricultural waste, Biofuel, Bio-oil, Bio-char, Microwave pyrolysis, Valorization

Introduction

Agro-residues are generated in large quantities as a byproduct of food and fiber production. These residues are rich in organic content but are often burned openly in the field after harvest in many areas, especially in developing countries. Open-field burning significantly contributes to air pollution and the release of greenhouse gases (GHGs), thereby exacerbating climate change and posing a threat to public health (Ravindra *et al*., 2019). Given the projected 48-56% increase in global energy demand by 2040 due to population growth, urbanization, and industrial development, as well as the environmental consequences of fossil fuel dependence, sustainable energy alternatives for waste management and energy production are highly needed.

These wastes are primarily composed of lignocellulosic biomass, including cellulose, hemicellulose, and lignin, which are suitable for producing biofuels and value-added chemicals. However, their complex and recalcitrant structure, which refers to the resistance of plant cell walls to microbial enzymes, limits their suitability for biological conversion processes (Nomanbhay *et al*., 2017). In this context, valorization of agro-residues through thermochemical conversion technologies presents an opportunity for generating clean energy and developing alternative approaches to agricultural waste management. Among these technologies, pyrolysis is a thermochemical conversion method of organic matter in an oxygen-limited environment. Pyrolysis has received significant attention for its ability to convert biomass into biochar, bio-oil, and non-condensable gases with relatively low emissions rates (Zhang *et al*., 2020; Ong *et al*., 2019). However, conventional pyrolysis (CP) utilizes external electrical heating, which is energy-intensive and, in most cases, has inefficient thermal transfer.

Microwave-assisted pyrolysis (MAP) has recently been recognized as a more sustainable alternative to CP. In MAP, microwave radiation interacts directly with biomass. It also enables rapid and even heating, along with more precise control of operational variables, resulting in energy reductions and improved yield and quality (Zhang *et al*., 2017; Chen *et al*., 2016). Some operational variables that can be modified when performing MAP include microwave power, reaction temperature, feedstock particle size, purge gas type, presence of catalyst or absorber, and biomass type, and all of these variables impact product distribution (Zhang *et al*., 2020; Foong *et al*., 2020; Beneroso *et al*., 2017).

Previous studies have demonstrated the effectiveness of MAP on various single feedstocks. For example, Liu *et al*. (2021) explored blueberry crop residue (BCR) as a renewable bioenergy substrate. Zeng *et al*. (2021) investigated the microwave pyrolysis of maize cobs with Fe-modified biochar as a catalyst, resulting in increased production of phenolic compounds in the bio-oil. The implementation of microwave-assisted catalytic fast pyrolysis (MACFP) on rice husks using hierarchical mesoporous catalysts has been reported to enhance the production of aromatic hydrocarbons (Li *et al*., 2020). Furthermore, assessment of MAP performance by using torrefied tea waste combined with organic solvents to achieve optimal char and oil production was performed (Hamzah *et al*., 2022).

Despite increasing interest in using MAP, the majority of scientific investigations into MAP have concentrated on singular feedstock studies within a controlled laboratory environment. In practical agricultural operations, mixed agro-residues often emerge simultaneously, especially in areas that practice intercropping or multi-crop farming. Scientific comprehension remains limited regarding how inherent ash in mixed feedstocks exhibits synergistic effects, antagonistic interactions, or catalytic influence. Mixed biomass types exhibit highly variable microwave absorption and thermal characteristics, which can impact energy transfer processes, product distribution, and pyrolysis efficiency.

The study aims to evaluate the potential of a mixed feedstock co-composting of blueberry waste, corn cobs, and rice husk to produce bio-oil, bio-char, and gas through MAP. The study will focus on the yields of these products, analyze heating rate profiles and pyrolysis indices, and characterize the bio-oil by its chemical composition using GC-MS. The results and findings of these investigations will enhance our understanding of feedstock synergy, ash catalysis, and the improvement of bio-oil yield from mixed agricultural waste feedstocks.

Materials and Methods

Materials

A combination of blueberry waste, corn cobs, and rice husk was collected in a wet form from local farms in separate boxes for this study. The mixture was placed in a hot air oven and dried at 80 °C for 3 hours. The dried feedstock was sieved and ground to an average particle size of 150 μm, and then stored in polythene zip-closure bags to prevent moisture absorption. Graphite powder (particle size: 100 μm) was used as a susceptor to convert microwave energy into heat. The pyrolysis reactor consisted of a spherical borosilicate glass flask with a bottom containing a susceptor containing the feedstock. The flask was wrapped in a cylindrical muffle made of ceramic wool-based insulation for thermal insulation, with Teflon® tapes used to provide structural support (Hamzah *et al*., 2024a, b; Fodah *et al*., 2022).

Characteristics of feedstocks

Proximate analysis, elemental analysis, and higher heating value (HHV) determinations were conducted on the feedstocks. Moisture, volatile compounds, fixed carbon, and ash content were determined using a thermogravimetric analyzer (TGA, Perkin Elmer STA 600) using the ASTM E1131-08 standardized method. For moisture analysis, ~10 mg of the sample was heated to 110 °C under a nitrogen atmosphere (flow rate: 100 mL/min) and maintained at this temperature. The temperature was then increased to 900 °C at a rate of 80 °C/min and maintained at that temperature to assess the concentration of volatile compounds until a constant mass was achieved. Furthermore, to determine the amount of fixed carbon, the sample was maintained at a constant temperature of 900 °C for 45 minutes after the purge gas was switched to air at a rate of 100 mL/min. From this, the ash content was determined by measuring the mass of the residue. The calculations used the following equations:

$$M\,(\%) = (W0-W1)/W0\times100\% \quad \ldots.(1)$$
$$V\,(\%) = (W1-W2)/W0\times100\% \quad \ldots.(2)$$
$$A\,(\%) = W3/W0\times100\% \quad \ldots.(3)$$
$$Fixed\ carbon\,(\%) = 100-M-VM-A \quad \ldots.(4)$$

Where: M stands for moisture; VM refers to volatile matter; A represents Ash; W_0 represents the initial mass of the sample used; W_1 represents the mass of the sample at 110 °C; W2 represents the mass after heating to 900 °C; W3 represents the final residue mass after combustion.

Elemental composition (C, H, N, S) was measured using an Elementar Vario EL III elemental analyzer with a 2 mg sample combusted in an oxygen environment. The evolved gases (CO_2, NO_2, and SO_4) and water (H_2O) were analyzed via a thermal conductivity detector, with oxygen content determined by difference:

$$Oxygen\,(\%) = 100 - C - H - N - S - Ash \quad \ldots(5)$$

Experimental methodology

The MAP experiments were conducted using a customized multimode microwave oven (ProA, Toronto, Canada) with a modified top part of the unit to accommodate a gas purging pipe, temperature sensor, and a vapour collector. A total of 6g of feedstock mixture, composed in a ratio of 1:1:1, was mixed with 3g of graphite susceptor and placed in a 500 mL three-neck borosilicate flask. A Chromel-Alumel thermocouple (accuracy ±2 °C) was inserted into the flask to monitor the feedstock temperature during pyrolysis, protected from microwave interference by a stainless steel sheath. Before the start of each run, a nitrogen purge was initiated at a flow rate of 50 mL/min for 10 minutes to remove all oxygen from the chamber.

The microwave power (in watts) and treatment time (in seconds) were controlled via the microwave oven's interface. The experiments were stopped when the pyrolysis temperature reached 450 °C, with temperature being recorded every 30 seconds. After the reaction was complete, the experimental setup was allowed to cool naturally, and then biochar and bio-oil were collected. The mass of the biochar produced was estimated by weighing the flask. Bio-oil was recovered from the condensers and the connected collection apparatus. Each experimental run was performed in triplicate, and results were reported as average % values. Future studies should incorporate a complete statistical analysis to strengthen the reliability of the observed performance trends.

GC/MS analysis of bio-oil

Gas chromatography-mass spectrometry (GC/MS, Agilent 7890, 5975C) was used to analyze the chemical composition of the bio-oil. A 0.25 µL oil sample was injected at 220 °C. The GC oven was gradually increased from room temperature to 350°C at a rate of 5°C/min over 30 min. High-purity helium (2.0 mL min^{-1}) was used as the carrier gas, and separation was accomplished on an Rxi-5Sil MS column (30m, 0.25 mm I.D., 0.25 µm film thickness). The MS detector used an electron ionization source set at 70 eV and scanned the 50-500m/z range. Identification of compounds was made by matching the spectra to the NIST library, accepting only compounds that matched the spectra with a match factor of 80% or above.

Pyrolysis product and pyrolysis analysis

According to Hamzah *et al*. (2022, 2024), product yields were calculated as follows:

Oil mass (g): $D_{oil} = (D_{Cond.\ after\ exp.} - D_{Cond.\ before\ exp.}) +$

$(D_{elbow\ joint\ after\ exp.} - D_{elbow\ joint\ before\ exp.}) + (D_{adopter\ joint\ after\ exp.} - D_{adopter\ joint\ before\ exp.}) + (D_{collector\ flask\ after\ exp.} - D_{collector\ flask\ before\ exp.})$ …(6)

Char mass (g): $D_{char} = (D_{flask\ after\ exp.} - D_{flask\ before\ exp.})$ ….(7)

Gas mass (g): $D_{gas} = 100 - (D_{oil\ yield} + D_{char\ yield})$ ….(8)

Char yield (wt.%) = (D _Char Weight / Feedstock Weight × 100 …(9)

Oil yield (wt.%) = (D_Oil Weight / Feedstock Weight) × 100 ….(10)

Gas yield(wt.%) = 100 - (Char Yield + Oil Yield) …(11)

Microwave energy consumption (J/s):

Microwave energy = Microwave power W x Total pyrolysis time (min) ….(12)

Conversion (wt.%)= oil yield (wt.%) + gas yield (wt.%) ….(13)

Pyrolysis index (PI): $PI = A \times B \times C / P_{EC} \times T$ …(14)

Where A is the feedstock mass (g), B is the higher heating value of feedstock (J/g), C is conversion (wt.%), P_{EC} is energy consumption(J/s), and T is pyrolysis time (s). A higher PI indicates more favorable pyrolysis conditions and efficiency.

Results and Discussion

Characterization of feedstock

This study focused on three types of agricultural residues: blueberries, corn cobs, and rice husks. Conducted dry basis elemental and proximate analysis of the three agricultural residues, providing the results shown in Table 1. The elemental composition of blueberry pulp waste was determined to contain 49.3 % C, 6.2 % H, 1.7 % N, 0.3 % S, and 42.6 % O. Blueberry pulp has relatively low ash content and a high volatile matter content (73.2 wt% %), thus making it a highly favorable sample for heating value. The fixed carbon content was 17.70 wt%, indicating that the material has moderate potential to form char when subjected to thermal conversion. The blueberry pulp does include a small amount of ash that could serve as a catalyst and microwave susceptor. The presence of ash will likely enhance microwave energy penetration, assimilation, and efficiency during the pyrolysis reaction.

Corn cobs had similar elemental content of 44.1 wt% C, 5.3 wt% H, 1.6 wt% % N, 0.2 wt% % S, and 48.8 wt% % O. The corn cob consists of a greater amount of volatile material, 80.4 wt% %, and a smaller amount of fixed carbon (12.3 wt% %). This indicates that corn cobs are highly reactive to heat, facilitating thermal breakdown of the material. Furthermore, the ash content was low (1.3 wt%), which likely resulted in a limited inorganic interface during the pyrolysis process. This characteristic can lead to a higher production of bio-oil.

Table 1: *Proximate and elemental composition of blueberry waste, corn cobs, and rice husk waste: analysis of moisture, volatile matter, ash, fixed carbon, and major elements (C, H, O, N, S) by percentage.*

Parameter	Blueberry waste (%)	Corn cobs (%)	Rice husk waste (%)
Proximate analysis			
Moisture content	5	6	4
Volatile matter	73.2	80.4	65.5
Ash content	4.1	1.3	17.3
Fixed carbon	17.7	12.3	13.2
Elemental analysis			
Carbon (C)	49.3	44.1	46.8
Hydrogen (H)	6.2	5.3	5.1
Oxygen (O)	42.6	48.8	47.5
Nitrogen (N)	1.7	1.6	0.5
Sulfur (S)	0.2	0.2	0.1

In contrast, rice husks contained approximately 47.9 wt% carbon, 5.1 wt% hydrogen, 1.5 wt% nitrogen, 0.1 wt% sulfur, and 45.4 wt% oxygen. While rice husks had a lower volatile matter index of 65.5 wt%, compared to the other two feedstocks, they had a significantly higher ash content of 17.3 wt%, which is consistent with current literature (Hamzah *et al.*, 2022; Fodah *et al.*, 2022). The higher ash content in rice husk could affect its catalytic properties, acting as a microwave susceptor, possibly influencing the pyrolysis route and energy absorption characteristics. Additionally, the fixed carbon content of 13.2 wt% indicates a promising potential for char production (Table 1, Figure 1).

All three feed fractions had similar higher heating values (HHVs) tested using a bomb calorimeter. The HHVs calculated for blueberry waste, corn cob waste, and rice husk waste were 17.8 MJ/kg, 17.1 MJ/kg, and 15.6 MJ/kg, respectively (Table 2). These values confirmed the energy potential of each residue, and this work produced an average HHV of 16.9

MJ/kg, indicating promise for the joined process to maximize energy yields from heterogeneous feedstock inputs. All calorimetric experiments were conducted in triplicate, and the reported average for each observation is provided.

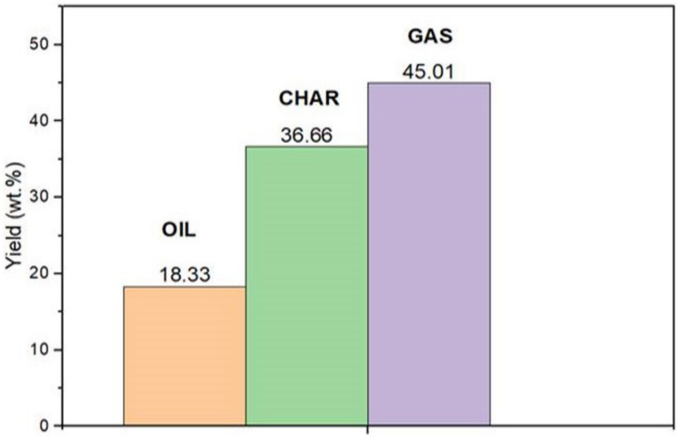

Figure 1: *Product yield from microwave-assisted pyrolysis of mixed biomass feedstock (blue berry, corncobs, and rice husk waste): distribution of oil, char, and gas yields (wt.%).*

Table 2: *Higher heating value (hhv) of individual and blended biomass feedstocks: blueberry waste, corn cobs waste, rice husk waste, and their mixture (in MJ/kg).*

Material	Higher heating value (HHV)
Blueberry waste	17.8 MJ/kg
Corn cobs waste	17.1 MJ/kg
Rice husk waste	15.6 MJ/kg
Blueberry, corn cobs, rice husk waste mixture	16.9 MJ/kg

Microwave-assisted pyrolysis (MAP) process

The MAP experiments were conducted using a laboratory-scale microwave reactor at a power of 400 W. The feedstock mixture consisted of a total of 6 grams, at a 1:1:1 ratio, comprising 2 grams of blueberries, 2 grams of corn cobs, and 2 grams of rice husks. The feedstock was mixed evenly with 3 g of graphite powder, a microwave susceptor that enhances microwave energy absorption. The utilization of graphite powder was crucial, as biomass is a poor microwave absorber, and its addition was necessary to enhance microwave energy absorption. For the pyrolysis of the feedstock mixture, the reaction was constantly maintained at a microwave power of 450 W until it reached a final reaction temperature of 544 °C after 36 minutes. The average heating rate (AHR) was 19.25 °C/min, which was sufficient for thermal breakdown but still characterized a slow heating profile (Table 3, Figure 2). The slower heating profile was attributed to the heterogeneity of the feedstock and the microwave transparency of the biomass components, which subsequently led to thermal storage in the biomass, affecting the coupling and, consequently, limiting heating, consistent with the previous studies (Liu *et al.*, 2021; Zeng *et al.*, 2021; Beneroso *et al.*, 2017). The yields of each product obtained from pyrolysis were 18.33 wt% bio-oil, 36.66 wt% bio-char, and 45.01 wt% non-condensable gases (Table 3). These findings suggest that the process favoured gas evolution over its liquid phase, most likely attributable to prolonged reactor residence time, slow heating rates, and the potential catalytic influence of the ash constituents in the feedstock. The relevant thermal profiles and product yield distribution for the product yields shown in Table 4 are shown in Figures 1-3, illustrating the overall heating rate and product development throughout the reaction time of the pyrolysis process.

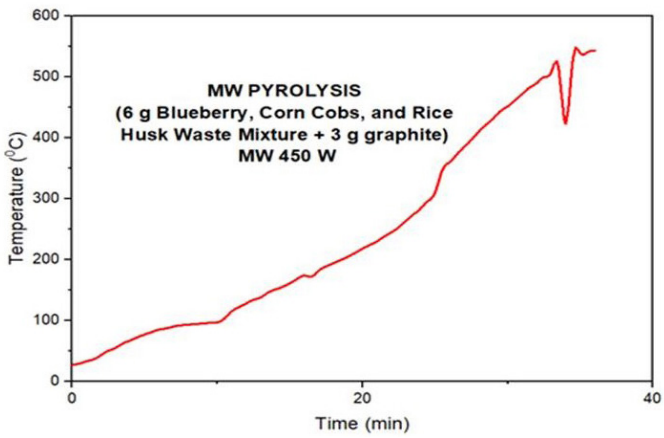

Figure 2: *Product yield distribution from microwave pyrolysis of blue berry, corn cobs, and rice husk waste mixture with graphite at 450W.*

Table 3: *Experimental conditions and product yields from co-pyrolysis of blueberry waste, corn cobs, and rice husk mixture: char, oil, gas yields, conversion efficiency, heating rate, reaction time, final temperature, HHV, and energy output.*

Feedstock	Char yield (wt%)	Oil yield (wt%)	Gas yield (wt%)	Conv. (wt.%)	AHR °C/min	Time (min)	Temp. (°C)	HHV MJ/Kg	Power KJ
Blueberry 2g, Corn Cobs 2g, and Rice Husk 2g Waste Mixture	36.66	18.33	45.01	63.34	19.25	36	544	33.3	729

Table 4: *Time-Resolved Temperature and heating rate profile during microwave-assisted pyrolysis (450 W) of biomass mixture (6 g of blueberry, corn cobs, and rice husk waste mixture + 3 g graphite): detailed thermal progression throughout the 36-minute experiment.*

MW Pyrolysis (6 g of blueberry, corn cobs, and rice husk waste mixture + 3 g graphite) microwave 450 W								
Time (min)	Temp. (˚C)	Heating rate (˚C/min)	Time (min)	Temp. (˚C)	Heating rate (˚C/min)	Time (min)	Temp. (˚C)	Heating rate (˚C/min)
0	27		12.5	134	12	25	310	28
0.5	29	4	13	138	8	25.5	347	10
1	33	8	13.5	146	16	26	360	78
1.5	36	6	14	151	10	26.5	373	26
2	43	14	14.5	155	8	27	385	24
2.5	50	14	15	161	12	27.5	397	24
3	55	10	15.5	168	14	28	410	26
3.5	62	14	16	174	12	28.5	422	24
4	67	10	16.5	172	-4	29	432	20
4.5	72	10	17	182	20	29.5	444	24
5	77	10	17.5	189	14	30	452	16
5.5	81	8	18	194	10	30.5	462	20
6	85	8	18.5	199	10	31	472	20
6.5	87	4	19	205	12	31.5	483	22
7	90	6	19.5	211	12	32	490	14
7.5	92	4	20	218	14	32.5	500	20
8	93	2	20.5	224	12	33	508	16
8.5	94	2	21	230	12	33.5	516	16
9	95	2	21.5	238	16	34	423	14
9.5	96	2	22	245	14	34.5	532	18
10	97	2	22.5	253	16	35	539	14
10.5	103	12	23	264	22	35.5	541	4
11	115	24	23.5	274	20	36	544	6
11.5	122	14	24	284	20			
12	128	12	24.5	296	24			

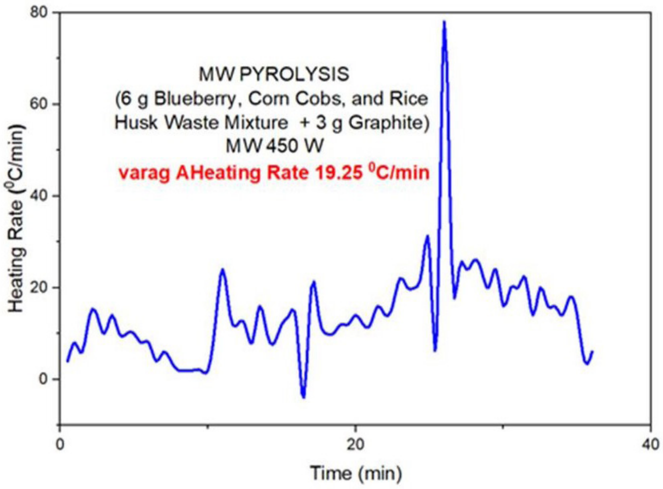

Figure 3: *Microwave pyrolysis of blue berry, corn cobs, and rice husk waste with graphite at 450W and 19.25 °C/min heating rate.*

Bio-oil composition

The bio-oil obtained was analyzed with gas chromatography-mass spectrometry (GC-MS) to determine its chemical composition (Table 5). The analysis revealed a diverse range of compounds, including hydrocarbons (alkanes and aromatics), oxygenated compounds (phenols, acids, and ketones), nitrogenous compounds, and trace amounts of sulfur compounds. This diverse collection of compounds highlights the complexity of the bio-oil matrix and supports the vision of upgrading bio-oil into higher-value fuels and chemicals. While the oxidation state of some chemicals suggests that upgrading live products through different refining steps (for instance, hydodeoxygenation) would produce a higher-quality bio-oil for use as a fuel (Hamzah *et al*., 2023, 2024a, b; Agnihotri and Mondal, 2024), Despite the detection of nitrogen and sulfur compounds, it is worth noting that these would likely not occur in sufficient quantities. It would therefore surely require some form of significant downstream processing, such as desulfurization and denitrogenation, to meet fuel standards.

Table 5: *GC-MS identified compounds in bio-oil derived from microwave-assisted pyrolysis of mixed agricultural residues.*

S.	Compounds	Composite type
1.	Cresol, Phenol, Guaiacol	Phenolics
2.	n-Octadecane, n-Hexadecane,	Alkanes
3.	2-Butanone, Cyclopentanone,	Ketones
4.	Xylene, Toluene, Naphthalene	Aromatics
5.	Propionic acid, Acetic acid,	Acids
6.	Indole, Pyridine, Quinoline	Nitrogenous compounds
7.	Benzo-thiophene, Thiophene,	Sulfur compounds

Pyrolysis index (PI) relevance

The PI of 4.07 suggests that the biochar composite has good thermal reactivity during microwave heating. A PI higher than 3.0 is the limit at which pyrolysis becomes noticeable, i.e., with effective devolatilization and decomposability, even if the heating rate is not only slow but also uniform across the sample, which is quite familiar with biomass due to its intrinsic heterogeneity. This is also assumed to be related to the short period to reach the final pyrolysis temperature (Hamzah *et al*., 2022). The PI value was on the higher end of the scale, indicating that the mixed feedstock is thermally responsive and suitable for MAP as a feedstock. Hamzah *et al*. (2022) also found that mixed biomass feedstock had higher PI values than single feedstock types, suggesting synergistic behavior during thermal decomposition, as well as interactive activities when feedstocks differ in ash content and volatile matter profiles.

Energy consumption consideration

Energy consumption is a crucial factor in assessing the scalability and economic viability of the MAP process. The application of 450 W of microwave power resulted in a relatively high specific energy input during this study, processing 6 grams of feedstock over 36 minutes, with a low bio-oil yield of 18.33 wt%. The low bio-oil yield was attributed to the biomass being microwave-transparent (Liu *et al*., 2021; Beneroso *et al*., 2017), the heterogeneity of the feedstock mixture, and the configuration of the graphite susceptor. Zeng *et al*. (2021) observed that the latter, the indomethacin-loaded, was not well distributed during microwave heating. However, while the addition of graphite enhanced microwave absorption (Mutsengerere *et al*., 2019), the average heating rate observed (19.25°C/min) suggests a limit on heat transfer efficiency. Zeng *et al*. (2021) also concluded that increasing microwave power density while improving susceptor density would be potential solutions to reduce energy use and improve conversion efficiency. Future work should focus on assessing specific energy consumption (kWh/kg of feedstock) and calculating the energy-to-product yield to evaluate the economic feasibility of the process better and inform potential energy optimizations.

Synergistic behavior analysis

By intentionally mixing blueberry pulp, corn cobs, and rice husks, this approach aimed to harness any potential synergistic properties and enhance devolatilization kinetics and product yield compared to using a single feedstock. The mixed biomass systems used in this study are likely to exhibit different thermal decomposition characteristics, as well as varying catalytic interactions (Hamzah *et al*., 2022). In this study, the relatively low ash content of blueberry pulp compared to corn cobs and rice husks likely allowed for greater volatile release than from corn cobs or rice husks. The high ash content of rice husks, specifically the silica-rich type, can lead to some catalytic cracking activity, which may contribute to secondary reactions and result in increased gas yields while suppressing bio-oil formation (Fodah *et al*., 2022). Since neither of the two tests performed had control of the other feedstocks on their own, no quantifiable evidence of the synergistic effects could be developed. As emphasized by Hamzah *et al*. (2023) and Agnihotri and Mondal (2024), comparing mixed feedstock production with individual components is a critical component and necessary for adequate characterization and potential validation of synergies.

Conclusion

This research demonstrates the technical feasibility of utilizing MAP to convert a novel source of combined biomass (i.e., blueberry pulp waste, corn cobs, and rice husks) into bio-oil, bio-char, and gaseous products. The results were promising, but supported more gas than liquid bio-oil production, which may be attributable to slow heating rates, long pyrolysis times, and the catalytic function of the ash content. This project contributes to the understanding of ash content in terms of its impact on catalysis and microwave energy absorption, enabling us to consider how heterogeneous biomass affects pyrolysis kinetics. For future optimization of MAP for bio-oil production, possible optimizations should include: microwave power and reactor time, feedstock mixing ratios, and the potential use of other catalytic additives. Downstream refining steps will be necessary to upgrade, for example, hydrodeoxygenation, to produce fuel-grade bio-oil. Future work associated with the process will also consider scale-up, including life cycle assessment (LCA) and techno-economic analysis (TEA), to support the future commercial viability of this technology in contributing to sustainable bio-oil production.

Acknowledgment

The authors would like to thank the Faculty of Veterinary Medicine and Surgery at University of Shatrah for their help and support during the experiment.

Novelty Statement

This study investigates the MAP of a mixed feedstock comprising blueberry pulp wastes, corn cobs, and rice husks, an underutilized combination of agricultural residues. It highlights the catalytic function of ash content and its potential synergistic effects in the pyrolysis of heterogeneous biomass. The findings provide new insights into improving bio-oil yield and optimizing energy absorption efficiency, which supports waste-to-energy and sustainable biomass valorization strategies.

Author's Contribution

Iman J. Hasan, Hasan J. Hasan and Hakeem J. Kadhim: Confirm the aspects of the research, including conception and design, data collection, analysis and interpretation of results, and preparation of the draft manuscript.

Hakeem J. Kadhim: Revised the manuscript and prepared it for submission.

Data availability

The data used is confidential.

Generative AI and AI-assisted technology statement

The authors declare that this manuscript was not generated using AI or AI tools.

Conflict of interest

The authors have declared no conflict of interest.

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