



Microwave pyrolysis of various wastes and analysis of energy recovery

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ABSTRACT

The abundance of waste resources can be utilized to generate sustainable and clean energy. Microwave-assisted pyrolysis is an effective technique for converting various materials, including wood chips, plastic, food, and general hospital waste, into by-products with significant energy recovery potential. The yield and quality of these by-products were studied under optimized microwave pyrolysis conditions. Polyethylene plastic and general hospital waste produced high biochar heating values (31.6–37.9 MJ/kg), exhibiting high carbon content, low oxygen concentration, high aromatic compounds, and lower extractive content. The pyrolysis of food waste, based on the operating conditions and feedstock properties, resulted in high bio-oil (35 %) and biogas (57 %) generation. Energy balance analysis indicated that wood chips biomass (16.7 %) and hospital waste (14.8 %) achieved the highest energy efficiency.

1. Introduction

The disposal of different types of solid waste has become a significant environmental issue due to environmental hazards and greenhouse emissions. Considerable interest exists in finding innovative applications for solid residues, given the potential to generate income through resource and energy recovery and avoid environmental hazards, such as pyrolyze plastic waste can reduce water and soil contamination and generates clean oil (Akram and Butt, 2022; Ali et al., 2020). Food waste, textiles, wood waste, animal, and clinical waste are part of the municipal solid waste (MSW) classification (Ali et al., 2020; Kabir and Khalekuzzaman, 2022). Waste generation is associated with the high level of resources consumed by the industrial, construction or municipal solid waste sectors (Chen and Liu, 2021; Gutierrez-Gomez et al., 2021). During 2018–19 Australia generated 12.6 million tonnes (Mt) of municipal solid waste, 21.9 Mt. in the commercial sector, and 27 Mt. from the construction and demolition segment (Joe Pickin et al., 2020).

Some sub-classifications of MSW sectors are food, general hospital, plastic, and agricultural waste (Ilyas et al., 2020; Joe Pickin et al., 2020; Zawawi et al., 2015). The treatment or disposal of hospital waste consists of incineration, chemical disinfection, autoclaving, and disposal to landfill (Bamakan et al., 2022; Health, 2021; Ilyas et al., 2020). In terms of waste, Australia generated 5.09 Mt. waste during the 2018–19 period, of which 85 % of non-hazardous waste was disposed to landfill, 14 % was used as compost, and 2 % was processed using anaerobic digestion treatment (Joe Pickin et al., 2020). Also, approximately 2.54 Mt. of

plastic residues is produced annually in Australia. Only 13 % was recycled, whereas 15 % was used for energy conversion (Joe Pickin et al., 2020). Though waste is an environmental issue, feedstock is an energy source and is an excellent alternative to developing sustainable energy and reducing environmental harm (Ferrari et al., 2022; Liu et al., 2022).

Microwave-assisted pyrolysis has gained interest due to its versatility in application in diverse types of waste materials without the need for a pre-treatment (Fang et al., 2021; Zhang et al., 2022). Microwave pyrolysis is an efficient method to convert waste into valuable by-products, such as biochar, bio-oil, and biogas (Fang et al., 2021; Wallace et al., 2019). The benefits of microwave pyrolysis heating comprise high thermal efficiency, uniform distribution of internal heating, low thermal inertia, and rapid response— whose properties differ from conventional pyrolysis (Fang et al., 2021; Zhang et al., 2022). However, the energy recovery and quality of the by-products are variable and depend on the waste classification (feedstock nature) and the operating pyrolysis conditions, e.g., nitrogen flow, vacuum range, microwave susceptor, input power and reaction time (Allende et al., 2022; Ilyas et al., 2020; Mutsengerere et al., 2019).

The fibre composition and the proximate analysis of the waste material are relevant aspects that determine the behaviour of a particular feedstock under the microwave pyrolysis process, e.g., by-product yield and heating value (Amalina et al., 2022; Mukherjee et al., 2022). Lignocellulosic is composed of cellulose, hemicellulose, and lignin compounds. Waste with high lignin content contributes to producing a

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high biochar yield with a high energy value. Cellulose content is related to the biochar surface area (Amalina et al., 2022; Cheng and Wang, 2018). The fibre composition of wood biomass involves 40–55 % cellulose, 20–40 % hemicellulose, and 18–25 % lignin compound. In contrast, the lignocellulosic composition of food waste is 60–65 % cellulose, 6–8 % hemicellulose, and 5–10 % lignin (Adewuyi, 2022; Bruna Steil et al., 2016). The physicochemical characteristics of feedstock, such as moisture content, fixed carbon, volatile matter, and ash content, significantly impact the by-product properties. Waste with high fixed carbon content is favourable to increased biochar yield, and high volatile matter concentration promotes liquid and gaseous formation (Chowdhury Zaira et al., 2017; Wantaneeyakul et al., 2021). The proximate analysis varies based on the material nature, e.g., properties of plastic waste comprise 94.77 wt% volatile matter and 4.98 wt% ash content (Yao et al., 2018). In wood waste, the ash content, volatile matter, and fixed carbon percentage are 0.4–1 wt%, 82 wt%, and 17 wt %, respectively (Chowdhury Zaira et al., 2017). The systematic analysis of energy recovery and by-product quality of diverse feedstocks, based on optimal microwave processing, has not been studied.

This work investigates the yield and quality of the by-products generated from various feedstock under optimized microwave pyrolysis conditions (1–1.5 kW microwave power and 60–120 min reaction time), using a static custom-made system of 3 kW. The thermochemical conversion of PET plastic, wood chips, hospital and food waste were studied to evaluate their energy efficiency and identify the optimal feedstock to generate higher by-product yield during the microwave pyrolysis process.

2. Material and methods

2.1. By-product synthesis

Fig. 1 shows the custom-made microwave pyrolysis system used in this work. The chamber containing the feedstock is kept under vacuum and nitrogen (flow rate of 4 m/L) atmosphere using a vacuum pump (g) and N₂ cylinder (a), respectively. The variable microwave power is applied to the system and the reflected power is controlled using a manual tuner. The solid by-product is collected in chamber (b). Various flasks are used to condense gaseous compounds into bio-oil products, which are collected in the final flask (e). The biogas is collected between sections (b) and (e) and the bio-oil is collected in condensers (e) and (f), which consist of flasks inverted into an ice bath. The experimental conditions involve a microwave power range of 1–1.5 kW and a reaction

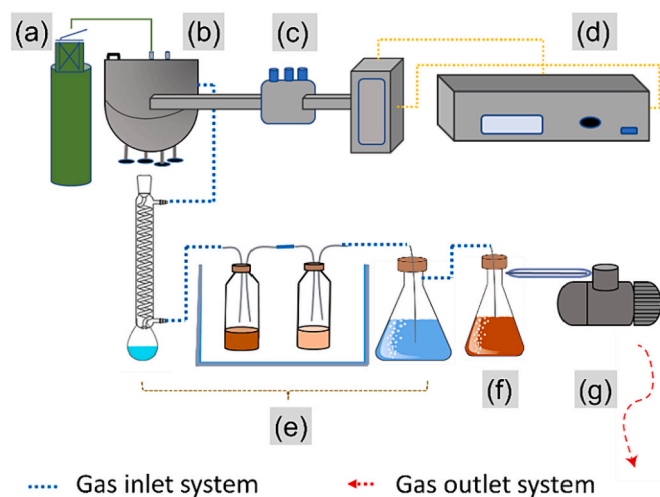


Fig. 1. Configuration of microwave pyrolysis system (a) nitrogen gas; (b) chamber; (c) tuner; (d) microwave generator; (e) condensers; (f) flask of bio-oil collection; (g) vacuum pump.

Table 1

Experimental microwave-assisted pyrolysis setup and by-product yield.

Feedstock	By-product yield (%)			Experimental ranges	
	Biochar	Bio-oil	Biogas	Microwave Power (kW)	Time (min)
Wood chips	16 ± 0.4	28 ± 0.9	56 ± 1.2	1	60
General hospital waste	11 ± 0.8	32 ± 1.77	57 ± 0.6	1	90
Plastic waste	13 ± 1.1	33 ± 2.0	54 ± 0.7	1.5	90
Food waste	8 ± 0.63	35 ± 3.7	57 ± 0.8	1.5	120

time of 60–120 min.

In each experiment, 60 g of feedstock (4 types of waste materials) was used in conjunction with 10 % activated carbon, which was the microwave susceptor to initiate the thermochemical conversion process. The first group involved wood chips, whose dimensions were approximately 30 mm. The general hospital waste comprised face masks, nitrile gloves, syringes, and vials. The plastic feedstock contained a mixture of polyethylene terephthalate (PET, from water bottles) and high-density polyethylene (HDPE, milk bottles). The food waste composition was 20 % chicken bones, 40 % rice and 40 % vegetable peels (carrots, broccoli, and potatoes). The raw material was not thermally treated before the pyrolysis process, maintaining the constant moisture content between 10 wt% and 20 wt%. The experimental design and energy balance calculation are based on the previous experimental work developed by (Allende et al., 2022). The statistical analysis of by-product yield and energy balance data was achieved using ANOVA in Excel.

2.2. Characterisation

Bio-oil was studied using GS-MS under concentration as Toluene D8, 30 to 400 amu (NIST/EPA/NIH Mass Spectral Library 2014). Thermogravimetric analysis (TGA) of bio-oil and biogas was performed using a Netzsch STA 449F3 Jupiter Simultaneous Thermal Analyzer. Biogas composition carried out by Shimadzu Triple Quadrupole 8040 GC-MS/MS. Biochar properties were assessed using a micromeritics 3-flex surface analyzer for BET surface area and pore volume. JEOL 7001F SEM also was considered for the Scanning electron microscopy (SEM) images.

3. Result and discussion

The operational conditions of microwave pyrolysis are shown in

Table 2

CHNSO elemental analysis and BET surface area of various biochar samples.

Analysis	W. C	G. H. W	P. W	F. W
Surface area (m ² /g)				
BET Surface Area	23.51	3.0578	0.6304	27.65
t-Plot external surface area	34.908	4.6942	1.2781	40.83
Pore volume (cm ³ /g)				
Single point desorption total pore volume calculated <19.9898 nm	0.0081	0.003946	0.001352	0.0285
CHNSO elemental analysis				
N%	0.16	5.46	0.31	4.2
C%	78.06	74	86.94	63.18
H%	2.43	7.57	1.36	3.13
S%	0	0.16	0	0
O%	14.15	4.1	2.22	11.55
H/C	0.03	0.1	0.02	0.05
O/C	0.181	0.06	0.03	0.19
LHV (MJ/kg)	28.4	37.9	31.6	25.2

W.C: wood chips, G.H.W: general hospital waste, P.W: plastic waste and F.W: food waste.

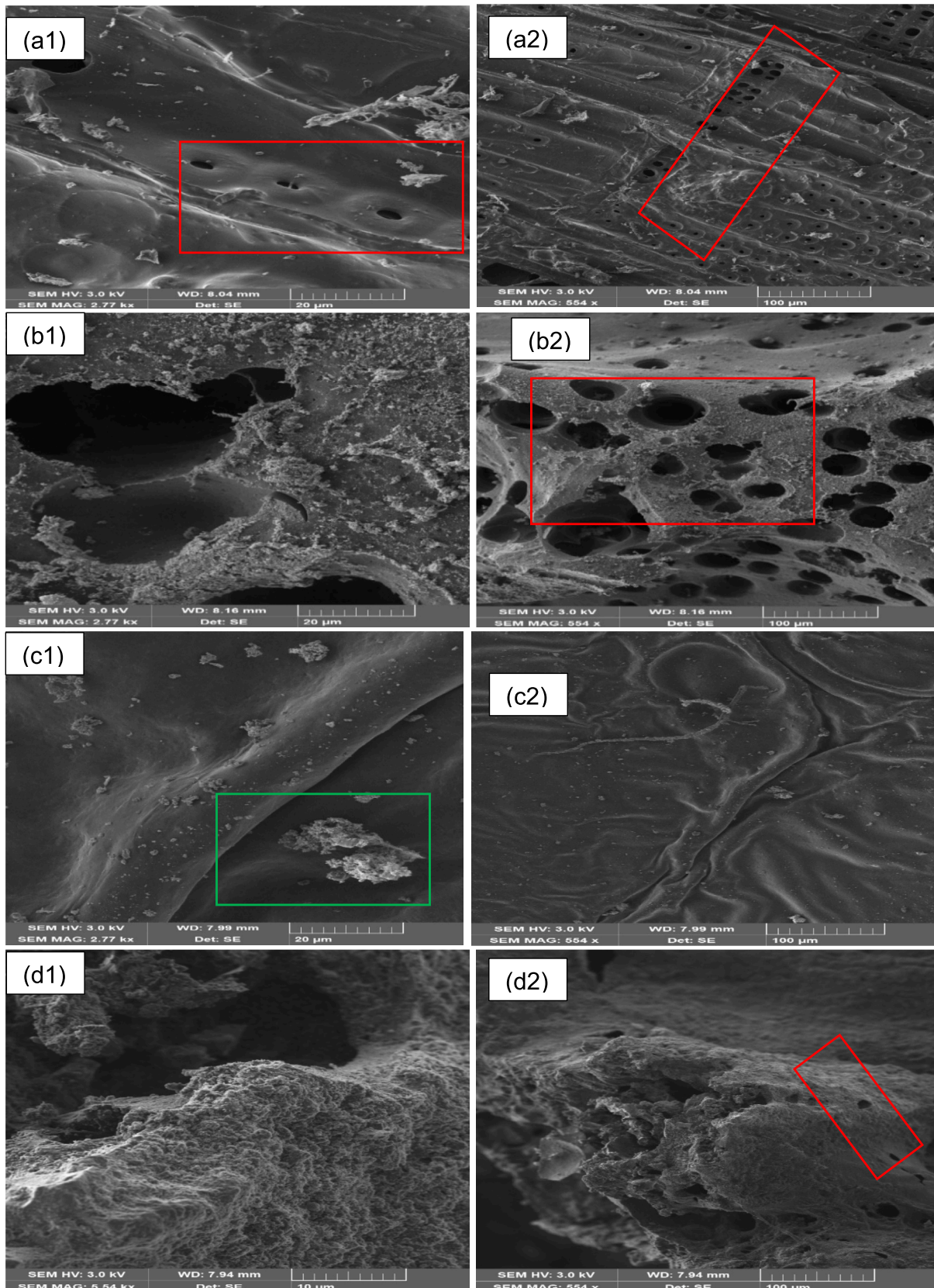


Fig. 2. Scanning Electron Microscope (SEM) images of biochar produced from (a1, a2) wood chips at 1 kW for 60 min; (b1, b2) plastic at 1.5 kW for 90 min; (c1, c2) general hospital waste at 1 kW for 90 min; and (d1, d2) food waste at 1.5 kW for 120.

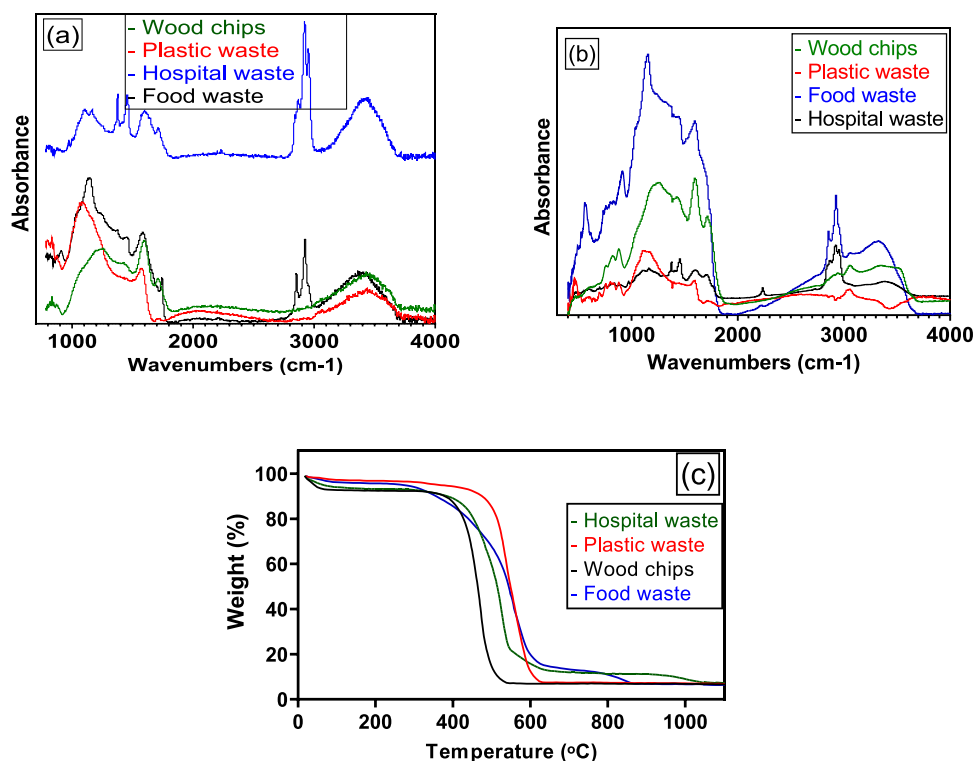


Fig. 3. (a) Fourier-transform infrared (FTIR), (b) Diffuse Reflectance Infrared Fourier Transform (DRIFT) spectroscopy, and (c) TGA curves of various biochar.

Table 1. The criteria of parameter selection were based on the processing of each feedstock, several operating combinations were experimented with until finding the appropriate microwave power and treatment time to fully process the waste material. To establish the initial standard conditions of waste processing previous work reported by (Allende et al., 2022) was considered.

The results of the by-product optimization of four feedstock are shown in Table 1. Wood chip biomass obtained the highest biochar yield (16 %). High solid production is associated with the nature of the wood feedstock. Materials with a high fibre of lignin compound (18–25 % in wood) are favourable to increasing the biochar yield (Adewuyi, 2022; Bruna Steil et al., 2016; Mukherjee et al., 2022). Food waste, hospital and plastic waste achieved high bio-oil and biogas yields. Studies of proximate analysis of plastic waste report 94.77 wt% volatile matter and 4.98 wt% ash content (Yao et al., 2018). Under the pyrolysis reaction, biomass with high volatile matter content is beneficial for bio-oil generation and syngas (Chowdhury Zaira et al., 2017). The moisture content in feedstock is another relevant factor in bio-oil production. Free water existing in feedstock produces higher exhaust gas volume, which improves the liquid formation (Mierzwa-Hersztek et al., 2019; Yaning et al., 2017). For instance, the bio-oil performance increased by 3 % when the feedstock was switched from hospital waste to food waste.

3.1. Biochar characterisation

Table 2 shows the ultimate analysis of various biochars obtained in the microwave pyrolysis process. The variation of four biochar elemental analyses was 27 % carbon, 82 % hydrogen and 84 % oxygen. For example, due to its hydrocarbon composition, the solid product from plastic feedstock had high carbon content (87 %) and low oxygen content (2.22 %). Wood biochar also obtained a heating value of 28.4 MJ/kg. This result is related to the fibre composition of wood biomass with a high presence of lignin. The lignin compound has a higher carbon concentration and lower oxygen content than cellulose (Cheng and Wang, 2018). Therefore, biomass with high lignin content is preferable

for generating biochar with a higher energy value (Cheng and Wang, 2018; Chowdhury Zaira et al., 2017).

The carbon concentration was similar in wood chips and general hospital waste, around 78 %. Plastic biochar showed a lower oxygen presence than wood chips (84 %) and lower hydrogen than hospital waste (68 %). High carbon and hydrogen concentrations are favourable for increasing the heating value of hospital waste (39.2 MJ/kg). Established pyrolysis time and microwave power are crucial to achieving the optimal temperature for wood biochar production, and some work reported temperatures between 600 °C to 700 °C (Chatterjee et al., 2020; Tomczyk et al., 2020). The pyrolysis condition is enough to reduce the volatile matter and promote the breakdown of the C—O bond, releasing oxygenated compounds (14.28 % oxygen in wood chip biochar) (Shin Ying Foong et al., 2020; Solar et al., 2016). Hydrogen reduction of biochar is relative to polymerisation reactions (Halim and Swithenbank, 2016; Shin Ying Foong et al., 2020). On the other hand, high hydrogen concentration is due to the decomposition of light organic compounds (Mierzwa-Hersztek et al., 2019; Shin Ying Foong et al., 2020).

Plastic biochar had the lowest ratio of graphitization ($H/C = 0.02$) and aromatization ($O/C = 0.03$). Hospital residues and food wastes attained the highest values of H/C (0.1) and O/C (0.19), respectively. An inferior H/C value involves increased aromatic functional groups, generating higher structural stability. Moreover, low O/C produced from plastic is related to reduced hydrophilicity and polarity properties. The high molar ratios indicate that high pyrolysis temperature reached by microwave power and heating rates can lead to surface polar functional groups and aromatization (Elnour et al., 2019; Mierzwa-Hersztek et al., 2019; Wantaneeyakul et al., 2021).

The BET surface area and pore volume of biochar obtained from various waste samples are shown in Table 2. Biochar obtained from food waste showed the highest surface area of 27.65 m²/g. A prolonged reaction time, high organic material content and higher microwave power contributed to the decomposition of organic biomass structure, generating a higher release of volatile matter and surface area formation (Allende et al., 2022; Tomczyk et al., 2020). This biochar quality can be

Table 3
Ultimate analysis and Identification of bio-oil functional groups generated from different feedstocks.

		W.C	G.H. W	P. W	F. W
CHNS elemental analysis					
N%		0.52	1.2	0.26	4.59
C%		62.39	76.55	75.46	61.38
H%		7.29	10.65	10.4	8.6
O%		25.68	7.28	12.05	14.98
H/C		0.12	0.14	0.14	0.14
O/C		0.41	0.1	0.16	0.24
LHV (MJ/kg)		27.8	38.6	37.4	30.4
Functional groups					
Classification	Compounds	Concentration (%)			
	Benzene	0.88	0.9	2.2	0.66
	Bicyclo[4.4.1]undeca-1,3,5,7,9-pentaene	–	1.97	–	–
Aromatic		0.88	2.85	2.19	0.66
	Acetic acid, methyl ester	–	–	4.96	–
	2H-Pyran-2-one, tetrahydro-	–	–	3.14	–
	Nonanoic acid	3.33	3.36	3.87	–
	Carbonic acid, eicosyl vinyl ester	2.18	7.63	5.15	–
	Benzoic acid, methyl ester	–	1.65	–	–
Carboxylic acid	Oxalic acid, hexadecyl propyl ester	–	6.69	–	–
	n-Decanoic acid	–	3.11	–	–
	Acetic acid	–	–	–	4.1
	Benzoic acid	–	–	–	9.3
	Dodecanoic acid	–	–	–	4
	2(3H)-Furanone, 5-heptyldihydro-	–	–	–	3.9
		5.5	22.4	17.1	21.2
	Hexanal	–	1.7	2.94	9.4
	Heptanal	3.3	–	3.42	5.06
	Pentadecanal-	0.17	–	–	–
Aldehydes	Furfural	–	–	–	4.37
	Decanal	–	–	–	1.45
		3.48	1.7	6.36	20.27
	Tridecane	13.5	–	19.08	–
Alkanes	Nonadecane	–	8.03	14.42	–
	Cyclohexadecane	–	1.63	–	–
		13.5	9.66	33.5	0
	Formononetin	7.73	–	5.2	4.43
	2-Thiophenecarboxylic acid, 5-nonyl-	–	–	2.86	–
	Phenol	6.23	–	–	9.77
	Creosol	16.35	–	–	–
	Phenol, 2-methoxy-	5.32	–	–	–
	Phenol, 3-methyl-	6.5	–	–	–
Phenols	Phenol, 4-ethyl-2-methoxy-	5.78	–	–	–
	trans-Isoeugenol	4.63	–	–	–
	2,4-Di-tert-butylphenol	4.93	–	–	–
	Phenol, 4-ethyl-	–	–	–	16.69
		57.47	0	8.06	30.89
	1-Octanol, 2-butyl-	2.89	–	5.62	–
	1-Decanol, 2-hexyl-	3.21	10.28	13.68	–
	2-Hexyl-1-octanol	5.47	7.22	–	7.23
	Hexadecanol, 2-Methyl	3.94	–	–	0.28
Alcohols	1-Dodecanol, 3,7,11-trimethyl-	–	3.36	–	–
	2-Isopropyl-5-methyl-1-heptanol	–	3.36	–	–
	Dodecanoic acid	–	5.35	–	–
	1-Decanol, 2-octyl-	–	8.82	–	–
		15.51	38.39	19.31	7.51
	2-Heptadecanone	–	3.66	8.71	–
	2-Dodecanone	–	1.64	–	–
Ketones	4-Methyl-2-oxopentanenitrile	–	–	–	6
	2-Undecanone	–	–	–	3.61
		0	5.3	8.7	9.6
Phosphine	Triphenylphosphine oxide	–	–	3.85	–
		0	0	3.85	0
	Bicuculline	–	–	0.89	–
Alkaloid	Heptanediamide, N,N'-di-benzoyloxy-	–	19.65	–	–
		0	19.7	0.9	0
	Phenol, 2-methoxy-4-(1-propenyl)-	3.65	–	–	3.83
Guaiacol		3.65	0	0	3.83
	1,3-Di-O-acetyl- α -d-ribofuranose	–	–	–	5.97
Sugars		0	0	0	5.97

W.C: wood chips, G.H.W: general hospital waste, P.W: plastic waste and F.W: food waste.

Table 4
Composition and heating value of the gaseous fraction.

Sample	CO ₂ (%)	CH ₄ (%)	H ₂ S (%)	O ₂ (%)	N ₂ (%)	LHV (MJ/kg)
Wood chips	1.265	0.795	0.507	19.73	77.30	0.28
Hospital general waste	0.655	0.342	0.027	21.04	77.85	0.12
Plastic waste	0.726	0.382	0.028	19.91	78.47	0.14
Food waste	0.626	0.339	–	21.34	77.99	0.12

reached if the input power does not exceed the optimal biochar temperature. Otherwise, the volatiles will release quickly, inducing higher devolatilization of lignin compound and small pore size formation (Leng et al., 2021; Tomczyk et al., 2020; Zhang et al., 2017). Plastic and hospital waste biochar produced the lowest surface area of 0.6304 m²/g and 3.0578 m²/g. A t-plot micropore area was not observed in any of the biochar samples.

The characteristics and structure of biochar generated from different feedstock and microwave pyrolysis conditions are shown in Fig. 2. The red rectangle indicates deep, uniform, and significant structure decomposition observed on the surface of the plastic biochar. The development of surface area irregularities and pore volume is due to the volatilization of organic materials (Elnour et al., 2019; Halim and Swithenbank, 2016; M. Waqasa et al., 2018). The SEM image of hospital waste biochar showed a solid surface with some agglomerates, as indicated by the green rectangle. A low reaction temperature produced agglomerates and blockage of pores. Low microwave heating is not enough to complete the volatilization of compounds, preventing the development of pores on the biochar surface (Halim and Swithenbank, 2016; Leng et al., 2021). At the same time, food waste biochar produced at a longer pyrolysis time (120 min) led to higher temperatures and gradual thermal breakdown of the fibre compounds (cellulose and lignin), generating clean pores and higher surface area (Leng et al., 2021; Waqasa et al., 2018; Shin Ying Foong et al., 2020; Wallace et al., 2019).

FTIR and DRIFT results of different biochars are illustrated in Fig. 3 (a) and (b). Biochar generated from wood chips was like GO spectra (oxidised carbon), having no C—H or Ar—H presence (Wu et al., 2015). No organic compounds were observed in biochar produced from plastic waste. However, the Si—O stretch was observed at 1000 cm⁻¹, representing an amorphous structure due to the lack of crystallinity bands at 800 cm⁻¹. Moreover, 3050 cm⁻¹ shows a small Ar—H band (Hoslett et al., 2019). Biochar produced from hospital waste showed a C—H stretching region (between 3000 and 2800 cm⁻¹), comparable to polypropylene spectra. Low nitrile groups (C≡N) appear at approximately 2235 cm⁻¹, which is relative to nitrile content on the surface of the biochar (Chen et al., 2015; Hoslett et al., 2019). Food waste biochar shows a broad O—H stretching region and is less oily than the bulk from Ge (Alghashm et al., 2018).

Table 5
By-product energy and energy recovery efficiency of various waste feedstocks.

Feedstock	By-product energy (kWh)		Total output energy (kWh)	
	Char	Oil	Gas	–
Wood chips	0.076	0.13	0.003	0.208
General hospital waste	0.07	0.206	0.001	0.277
Plastic waste	0.068	0.206	0.001	0.276
Food waste	0.034	0.177	0.001	0.212

Feedstock	Microwave power (kW)	Time (min)	Energy consumption (kWh)	The electrical consumption (kWh)	Energy conversion efficiency (%)
Wood chips	1	60	1	1.3	16.7
General hospital waste	1	90	1.5	1.9	14.8
Plastic waste	1.5	90	2.25	2.8	9.8
Food waste	1.5	120	3	3.8	5.7

The thermogravimetric analysis (TGA) was essential to study the stability of char products. Fig. 3 (c) shows the thermal decomposition behaviour of diverse biochars. All the biochar types showed similar decomposition between 40 °C to 100 °C, which is associated with the evaporation of residual moisture and light compounds volatilization of the feedstock (He et al., 2019; Shin Ying Foong et al., 2020). The breakdown of hemicellulose and cellulose happens in the 150 °C - 350 °C range (Brickler et al., 2021; Shin Ying Foong et al., 2020). Food waste had the highest loss mass, of 5 %, in this temperature range. The weight difference can be relative to the lignocellulosic composition of the biomass. Between the temperatures range 350 °C - 600 °C a considerable weight reduction was observed. This mass loss was around 80 %, 79 %, 69 % and 90 % for food, hospital, plastic, and wood chips biomass, respectively. The variation in weight was due to the volatilization of organic and inorganic materials and the decomposition of ligneous compounds (Brickler et al., 2021; He et al., 2019). At the last stage of microwave pyrolysis (after 650 °C) a gradual thermal weight loss was observed, which was linked to the biochar stability and the release of low molecular weight compounds (Brickler et al., 2021; Waqasa et al., 2018; Shin Ying Foong et al., 2020).

3.2. Bio-oil characterisation

Table 3 shows the elemental composition and energy value of different bio-oil samples. The wood chips bio-oil exhibits the lowest hydrogen content (7.29 %) and H/C factor (0.12). A low H/C ratio involves a higher aromatic compound, which is associated with low pyrolysis temperature and the formation of C—O bonds (AlDayyat et al., 2021; Halim and Swithenbank, 2016). In contrast, high microwave power and treatment time lead to high heating temperatures, generating the thermal decomposition of aromatic groups and causing more phenol compound formation (Yaning et al., 2017). The bio-oil produced from hospital waste and plastic materials had the lowest oxygen presence (7.28 % to 12.05 %) and O/C ratio (0.1 to 0.16). Low oxygen content implies higher stability, higher heating value, lower viscosity, and lower acidity (Iáñez-Rodríguez et al., 2021; Negahdar et al., 2016). Oxygen reduction is associated with a deoxygenation reaction that consists of the subtraction of oxygen atoms from the feedstock (AlDayyat et al., 2021; Yaning et al., 2017). On the other hand, the hydrolysis reaction produced from water vapours (volatiles) promotes increased oxygen content in the bio-oil composition (Supramono et al., 2015; Zhang et al., 2017).

The classification of bio-oil functional groups comprises ketones, aldehydes, alcohols, phenols, aromatics, and carboxylic acid (Czajczyńska et al., 2017; Nhuchhen et al., 2018; Yaning et al., 2017). Table 3 shows the bio-oil GC—MS analysis of the four feedstocks. Results indicate that the wood chips and food waste bio-oil had the highest phenol content of 57 % and 30 %, respectively. Phenolic compounds are associated with the feedstock nature and the thermal decomposition of lignin

compounds (Nhuchhen et al., 2018; Zhao et al., 2021). Nevertheless, the concentration of aromatic groups in food waste bio-oil was 77 % lower than in hospital waste. Higher pyrolysis power can lead to higher pyrolysis temperatures, causing more breakdown of phenol groups and aromatic compound formation (Liu et al., 2021; Zhao et al., 2021). Moreover, a high heating value is related to a high aromatic presence due to the oxygen reduction (deoxygenation reaction) and the increased H/O ratio (Qu et al., 2021; Wang et al., 2021; Wang et al., 2022). Food waste obtained the highest ketones concentration (9.6 %), and food waste generated 80 % fewer alcohol groups than hospital waste.

3.3. Biogas characterisation

Secondary reactions of condensable gases and the volatiles breakdown generate permanent gas products, forming H₂, CO₂, CO, and CH₄ (Jing et al., 2021; Zhang et al., 2022). Table 4 shows the comparison of the biogas composition of four different feedstock. Biogas from wood chips resulted in the highest heating value, obtaining 113 % higher than hospital and food waste. The high biogas heating value is related to increasing syngas production (Halim and Swithenbank, 2016; Xiqiang Zhao et al., 2011). Thus, the CH₄ fraction generated from wood chips was higher than hospital and food feedstock. This result is expected due to the thermal decomposition of a lignocellulosic compound of wood biomass, particularly, the breakdown of cellulose and hemicellulose that promotes the syngas formation (Mukherjee et al., 2022). The H₂S presence in biogas acts as a contamination compound and hence is undesirable (Yentekakis and Goula, 2017). Food and hospital wastes had the lowest H₂S fraction (0 to 0.027 Vol%). The formation of CO₂ and CH₄ decreased with increasing microwave power (Halim and Swithenbank, 2016; Shi et al., 2020). For instance, increasing power from 1 kW to 1.5 kW resulted in a 50 % decrease in CO₂ formation for wood chips and food waste biomass feedstock.

3.4. Energy balance of different feedstocks

The total energy production of various feedstock generated at different operating pyrolysis conditions is shown in Table 5. The energy value of the by-products includes the calorific value, the weight of the feedstock (60 g) and the yield of by-products obtained from the microwave pyrolysis. The highest output energy is obtained from general hospital wastes (0.277 kWh) and plastic feedstock (0.276 kWh). Wood chips reached the highest biogas energy (0.003 kWh) but the lowest bio-oil production (0.130 kWh), resulting in lower total output energy (0.208 kWh). Then, general hospital waste attained 33 % higher total energy output than wood chips.

Table 5 shows the energy balance obtained from the by-products generated in the microwave pyrolysis process using the four feedstock types. The energy consumed during the pyrolysis process was calculated considering microwave power, treatment time and electrical efficiency conversion (80 %). The energy balance calculation involved the relationship between the energy content of the by-products and the electrical energy consumed by the pyrolysis system. Wood chip biomass had the highest energy efficiency, 70 % higher than plastic waste. The calculation of energy efficiency involves the ratio of the total output energy and the energy consumed. The high energy efficiency was reached using low microwave power, short pyrolysis time, and high biochar energy. Despite this, hospital waste obtained the highest total output energy (0.277 kWh), and its energy efficiency was 13 % lower than wood chips. The low energy balance of food waste was relative to high microwave power consumption (1.5 kW), longer treatment time (120 min) and inferior by-product energy.

4. Conclusions

This study revealed that depending on the type of waste feedstock and its physicochemical properties, the behaviour of the by-products is

significantly different under varied microwave pyrolysis conditions. It is noticed that the nature of the feedstock was a relevant factor in the composition of the biogas fraction. Methane generation was 57 % lower in food waste biomass than wood chips. The H₂ production is associated with the breakdown of aromatics groups (C=C and C—H), while CH₄ involves higher decomposition of methoxyl compounds, which contributes to increased gas heating value. The biogas composition of the food waste and wood chips showed a 50 % decrease in CO₂ formation for a 0.5 kW microwave power reduction.

General hospital waste achieved a high biochar heating value (37.9 MJ/kg) due to its great elemental composition (high concentration of carbon and hydrogen and low oxygen content). In contrast, the energy value of food waste biochar was 34 % lower than hospital waste biochar because of its high O/C ratio. The heating value of bio-oil generated from wood chips was around 28 % lower than plastic and hospital waste. This disparity is attributed to the high carbon concentration of plastic bio-oil (75.46 %). Both plastic and hospital waste feedstocks also produced bio-oil with a high H/C ratio, low oxygen content, and the presence of aromatic compounds. While hospital and plastic wastes achieved the highest output energy, wood chips exhibited the highest conversion efficiency (16.7 %) due to its high biochar yield and low energy consumption during pyrolysis (1 kW for 60 min). This research highlighted the utilisation of various waste feedstock capable of obtaining higher energy valorisation and better by-product quality.

CRedit authorship contribution statement

Scarlett Allende: Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Graham Brodie:** Writing – review & editing, Validation, Supervision. **Mohan V. Jacob:** Writing – review & editing, Visualization, Validation, Supervision, Resources, Project administration.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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