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Energy Recovery from Pumpkin Peel Using Microwave-Assisted Pyrolysis

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Abstract: The significant quantities of food waste that require disposal have a high environmental impact, and the depletion of non-renewable fuel sources has heightened the need to investigate sustainable and efficient methods of biomass conversion into energy. This research focuses on utilising pumpkin peel as a feedstock for energy recovery through microwave pyrolysis under different operating conditions. The study demonstrated that a higher biochar yield (11 wt%) was achieved at 0.9 kW. However, results revealed that superior quality biochar was obtained at 1.2 kW, characterized by high carbon content (70.33%), low oxygen content (23%), and significant pore formation in the carbon surface area. Optimal operating conditions, such as 1.2 kW, resulted in superior quality biochar and higher bio-oil generation. The pumpkin peel demonstrated the potential for CO_2 (carbon dioxide) sequestration, with a rate of 14.29 g CO_2 eq/kg. The research findings contribute to the exploration of sustainable solutions for biomass conversion and emphasize the importance of utilizing food waste for energy production while mitigating environmental impacts.

Keywords: microwave pyrolysis; food waste; biochar; bio-oil

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1. Introduction

One third of the world's food is wasted, with Australian households generating 2.5 million tonnes of food waste annually, equivalent to around 4 kg per household per week [1]. The disposal of food waste has a significant environmental impact and economic cost, and contributes to water source depletion, with 25% of agricultural water consumption dedicated to food growth, amounting to 2600 gigalitres per year in Australia [1]. The economic loss due to food waste is substantial, estimated at AUD 36.6 billion annually [1–4]. Additionally, food waste disposal accounts for 8% of global greenhouse gas emissions, predominantly through the release of methane during decomposition in landfills [1,5]. The disposal of fruits, organic waste, and vegetables obstruct sustainable development in household, commercial, and agricultural sectors [6,7]. Vegetables and fruits constitute a significant portion of food waste, representing 23–65% [6]. In Australia, the household sector alone produces between 150,695 and 461,721 tonnes of fruit and vegetable waste per year [1]. To address these challenges, utilizing food waste as a fuel feedstock is a viable option to reduce the environmental impact and develop clean energy sources.

Common destinations for food waste include food recovery, composting, landfill, incineration, and animal feed [1,8–10]. However, these treatment methods have limitations in terms of scale, efficiency, pre-treatment requirements, management complexity, and output product selectivity [9–12]. Waste-to-energy (bioenergy) processes offer a green alternative, including biochemical methods such as anaerobic digestion and fermentation, as well as thermochemical methods like conventional and microwave pyrolysis [7,10–13]. The biochemical approach utilises organic biomass for biogas and alcohol fuel production [10,13]. Conventional and microwave pyrolysis can be applied to any biomass type to generate biochar, bio-oil, and biogas [11,14]. Microwave pyrolysis holds an advantage over conventional pyrolysis due to its rapid and efficient heating mechanism. In microwave pyrolysis, electromagnetic waves directly target the material, distinguished by volumetric heating (electromagnetic energy), hence the better heat distribution, versatility of biomass uses, and high energy conversion efficiency through rapid and controlled heating. Unlike conventional pyrolysis, microwave-assisted pyrolysis transfers the heat energy through the interaction of the molecules inside the biomass rather than by heat transfer from external sources [11,15–17]. Overall, it results in faster and more uniform heating, leading to reduced processing times and higher energy yields. This technology also allows for precise control over temperature gradients, minimizing the formation of undesirable byproducts and enhancing the overall product quality. Additionally, microwave pyrolysis reduces energy consumption and emissions, making it a greener and more sustainable option for waste treatment and resource recovery [14,18].

Not all materials are natural microwave absorbers, and hence a microwave susceptor (MS) is essential in microwave pyrolysis to initiate and enhance the heating efficiency. MS absorbs microwave energy and initiates biomass heating, promoting uniform and rapid heating of the material being processed, leading to faster reactions, improved yields, and enhanced overall efficiency [14]. The three by-products obtained from microwave pyrolysis, namely biochar, bio-oil, and biogas, have diverse applications, including power generation, heat production, chemical recovery, soil conditioning, fuel production, and electrochemical sensors [14,19]. Most of the agricultural waste is formed by lignocellulosic compounds, which have a range content of three fibres: lignin, cellulose, and hemicellulose. Biomass nature (fibre composition) is a relevant factor in terms of the yield and characterisation of the by-products; for example, biomass with a high cellulose content is favourable for bio-oil production, while biochar is derived from lignin [7,10,11,20,21].

The high energy conversion efficiency of microwave pyrolysis reduces biomass treatment procedures, lowers processing costs, mitigates GHG (greenhouse gas) emissions from food waste decomposition, and facilitates clean energy recovery from the three by-products [6,7,11]. Previous work has reported food waste processing using highly time-consuming technologies and expensive technologies, such as fermentation methods and biomass pre-treatment [8]. While several studies focus on the conversion of food waste into valuable applications or energy analysis [15,22], the evaluation of yield, quality, and energy value of the by-products is often overlooked. This research aims to study the energy recovery of by-products from the microwave pyrolysis of pumpkin peel biomass under varied operating conditions, specifically focusing on biochar and bio-oil yield and quality. The study also includes economic and environmental analyses of the custom-made microwave pyrolysis system.

2. Experiments and Methods

Microwave-Assisted Pyrolysis System and Experimental Procedure

The components of the microwave pyrolysis system are depicted in Figure 1. The pyrolysis process involves the thermochemical conversion of biomass in the absence of oxygen, achieved by purging the system with nitrogen at a flow rate of 5 L/min. The biomass is placed in a chamber operating under a vacuum environment of up to 50 kPa, and pyrolysis is conducted using a 3 kW microwave generator with an auto-tuner for impedance matching. Gaseous products are extracted from the reactor and subsequently converted into bio-oil using various condensers and an ice bath. Following biomass pyrolysis, the resulting biochar is accumulated within the chamber, while liquid and gaseous by-products are collected in separate flasks. Microwave power levels are controlled using the control panel for optimising the by-product yield. No pre-heating treatment was considered in biomass processing and by-product characterisation.

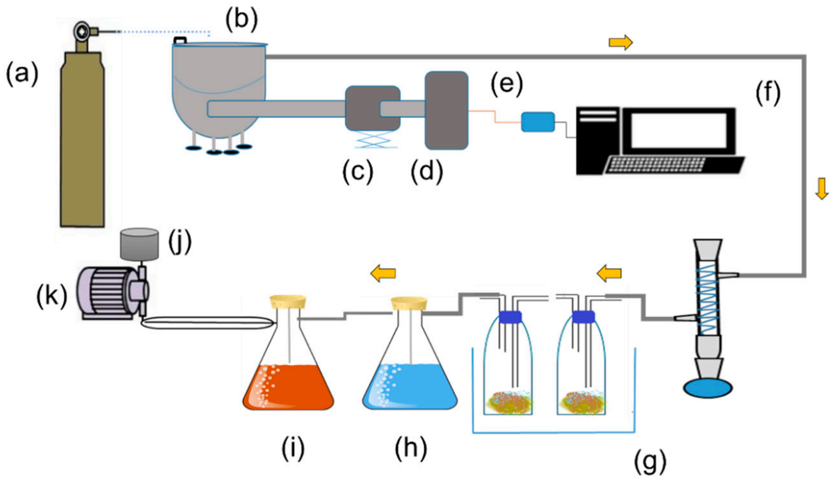

Figure 1. Schematic diagram of microwave pyrolysis system. (**a**) Nitrogen gas; (**b**) chamber; (**c**) auto tuner; (**d**) microwave generator; (**e**) data logger; (**f**) computer system; (**g**) two sets of condensers; (**h**) biogas collection; (**i**) bio-oil flask; (**j**) filter; and (**k**) vacuum pump.

- Characterisation technique and optimisation

Biochar and bio-oil by-products were characterised using CHNS FlashSMART for elemental analysis and Nicolet iS50 FT-IR Spectrometer (Australia) for Fourier Transform Infrared Spectroscopy (FTIR) data, and the thermogravimetric analysis (TGA) of food biochar was conducted with a Netzsch STA 449F3 Jupiter Simultaneous Thermal Analyser under nitrogen environment. A Zeiss Sigma VP Field Emission Scanning Electron Microscope (Germany) was used to obtain scanning electron microscopy (SEM) images and energy dispersive spectroscopy (EDS) data. LHV was obtained by the elemental analysis of biochar and bio-oil, and biogas composition, as reported in [11,14]. The variance analysis of by-product yield was performed using ANOVA Excel, version 2308.

- Synthesis of by-products

Pumpkin peel was utilized as the feedstock, with approximately 45 g of biomass subjected to pyrolysis at three microwave power levels (0.9 kW, 1.2 kW, and 1.5 kW). The treatment duration for all power ranges was 40 min. To enhance the heating process, activated carbon was employed as a microwave susceptor (M.S), added at a 10% weight ratio to the biomass. The resulting biochar, bio-oil, and biogas obtained from the microwave process were collected to assess their characteristics and calculate the yield. Each combination of experiments was repeated three times to ensure representative results.

3. Results

3.1. By-Products Yield

The microwave pyrolysis process employed raw biomass containing approximately 25 wt% moisture content from pumpkin peel. The ultimate analysis of raw feedstock provides an idea about the energy potential of the biomass, whose composition is 48.79% carbon, 7.52% hydrogen, 3.97% nitrogen, and 39.72% oxygen, estimating an HHV of 23.2 (MJ/kg), as reported in [23]. Table 1 presents the yields of by-products obtained from food waste feedstock under various operating conditions. From the experimental repetition at varied microwave power, yield variance ranges of 3.98% ± 0.11–11.14% ± 0.25; 20.32% ± 0.16–27.83% ± 0.06; and 62.21% ± 0.06–73.67% ± 0.013 were obtained for biochar, bio-oil, and biogas, respectively. Moreover, a standard deviation of between 3.34 and 4.96 was attained from the three experimental designs of by-products. Remarkable differences were observed in the performance of food waste biochar. A high microwave power of 1.5 kW resulted in a 65% decrease in biochar yield compared to 0.9 kW. Conversely, increasing the microwave power from 0.9 kW to 1.2 kW led to a 37% higher bio-oil yield.

Table 1. By-product yield of pumpkin peel feedstock.

Microwave Power (kW)	By-Product Yield (wt%)		
	Biochar	Bio-Oil	Biogas
0.9	11.14 ± 0.25	20.32 ± 0.16	68.54 ± 0.39
1.2	9.96 ± 0.01	27.83 ± 0.06	62.21 ± 0.06
1.5	3.98 ± 0.11	22.35 ± 0.05	73.67 ± 0.013

The increased bio-oil production can be attributed to the moisture content and elevated heating rates during pyrolysis, facilitating the formation of condensable gases [11,24,25]. However, excessive temperatures beyond the optimal range for bio-oil generation caused thermal breakdown, resulting in a reduced bio-oil yield [11,20]. This phenomenon was observed at 1.5 kW. Higher power levels contribute to increased heating rates during pyrolysis, favouring the thermal decomposition of heavy intermediate vapours into syngas [11,26]. As a result, a biogas yield of up to 74 wt% was achieved at 1.5 kW.

3.2. By-Products Characterisation

3.2.1. Biochar Analysis

The Fourier Transform Infrared Spectroscopy (FTIR) data of the biochar samples are presented in Figure 2. Both food biochar samples exhibited similar curves in terms of chemical composition, stretches, and peaks. This outcome was expected, as food waste is lignocellulosic biomass, generating comparable chemical bonds [27,28]. The spectra results of the biochar were influenced by the microwave power level employed during the pyrolysis process. Biochar produced at higher microwave power levels displayed a slightly greater loss of aliphatic C-H compounds. In contrast, a minor degradation of O-H (cellulose) was detected at 0.9 kW. Notably, a significant variation was observed in the range of 700 to 1800 cm^{-1} due to the dehydration of hemicellulose (C=O) and lignin groups (C-O-C), resulting in the loss of aliphatic C-H, C-O-C, and olefinic C=C compounds [24].

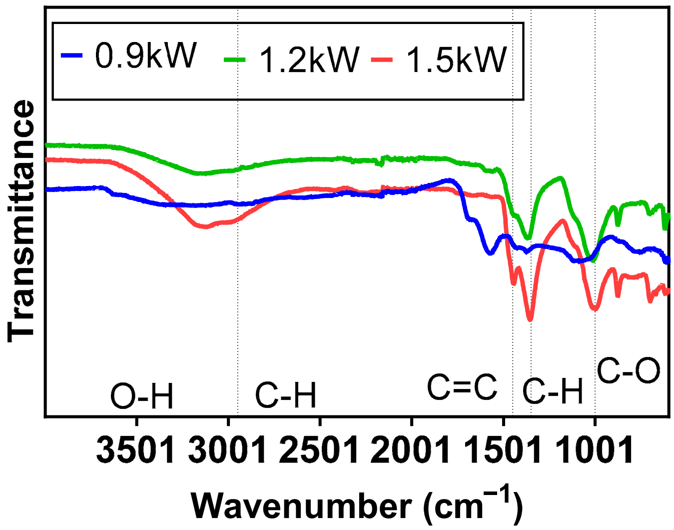

Figure 2. Biochar FTIR spectrum of pumpkin peel at various microwave pyrolysis powers.

Since the FTIR curves of the biochars exhibited similar characteristics at various power levels and considering that the highest biochar yield was achieved using low power, the remaining biochar characterization can focus on biochar produced with up to 1.2 kW. The CHNS (carbon, hydrogen, nitrogen, and sulphur) elemental analysis of the food waste biochar is presented in Table 2. High power resulted in biochar with a high carbon concentration (70 wt%) and low oxygen content (23 wt%). The increased microwave power from 0.9 kW to 1.2 kW facilitated a greater thermal decomposition of water, CO, and CO_2 in the biomass, reducing the oxygen concentration and increasing the carbon content [11,29]. Biochar generated at 1.2 kW exhibited lower H/C (0.04) and O/C (0.3) ratios compared to 0.9 kW. These values indicate the carbonization and aromatization degree of the biochar, respectively [29,30]. The low H/C ratio implied that the aromatization reaction occurs during pyrolysis, which is associated with the polymerization process of the biomass, resulting in the loss of O and H compounds [29,30]. The highest energy value of 24.6 MJ/kg was obtained when pyrolysis was conducted at 1.2 kW for a duration of 40 min.

Table 2. CHNSO ultimate analysis of biochar obtained from pumpkin peel.

Microwave Pyrolysis Conditions	C%	H%	N%	O *%	S%	H/C	O/C	LHV (MJ/kg)
0.9 kW for 40 min.	60.10	2.80	1.60	35.5	-	0.05	0.60	19.3
1.2 kW for 40 min.	70.33	2.59	4.08	23.00	-	0.04	0.30	24.6

O *, oxygen was calculated considering the difference between the total percentage and all the remaining elements.

The SEM (Scanning Electron Microscope) images of the food waste biochar are presented in Figure 3. The thermal behaviour of the lignocellulosic structure observed in each biomass was similar. Low power resulted in a gradual thermal decomposition of the biomass fibre compounds, leading to the formation of biochar with a uniform pore structure, high pore volume, and low surface area. However, a low pyrolysis temperature can obstruct the pores and hinder pore formation, since the temperature may not be sufficient for the complete devolatilization of different volatile compounds [27,31]. Tar agglomerates and hexagonal prism-shaped agglomerates are indicated by red rectangles. High microwave power generates large pores (marked with a white rectangle) and promotes microporosity development [27,30]. Clean and well-defined pores are highlighted by a green rectangle. The excessive temperature achieved with high power can cause surface irregularities and structural damage to the biochar [11,30]. Table 3 presents the EDS (Energy Dispersive Spectroscopy) data obtained from the two biochar samples, with carbon, oxygen, and potassium being the main elements with the highest concentrations—minor presences of S, Si, Ca, and Mg were detected.

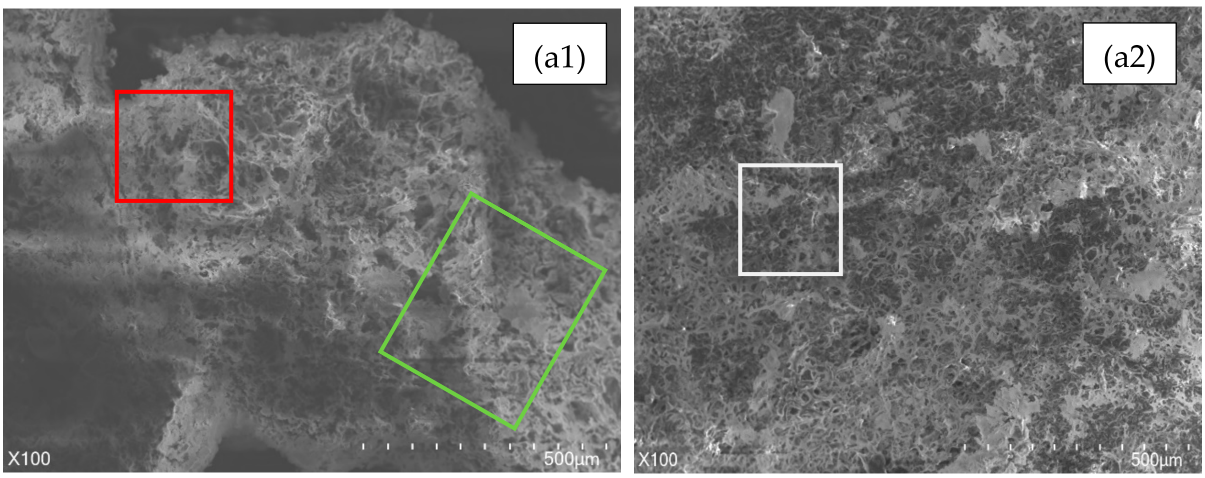

Figure 3. Scanning electron microscope (SEM) images of pumpkin peel biochar produced at (**a1**) 0.9 kW and (**a2**) 1.2 kW for 40 min and 10% microwave susceptor.

Table 3. Energy dispersive spectroscopy (EDS) data of various food waste biochars.

Element (wt%)	Pumpkin Peel	
	0.9 kW	**1.2 kW**
C	25.08	9.09
O	30.08	40.38
Mg	1.97	1.65
P	3.45	5.26
S	1.03	0.84
Cl	7.52	5.69
K	27.79	33.47
Ca	2.34	
Si	0.75	3.62

The optimal microwave power that resulted in the highest yield, energy value, and desired carbon structure of the biochar was determined to be 1.2 kW. Therefore, only the biochar generated at 1.2 kW was considered for the subsequent analyses. The thermal stability of the pumpkin peel biochar was illustrated by the TGA (thermogravimetric analysis) curves in Figure 4—overall, the biochar sample demonstrated good weight stability through the temperature changes. Weight loss was observed in the early stage of thermal decomposition (from 80 °C up to 200 °C). This thermal degradation is linked to the moisture weight loss of biochar [11]. Higher weight loss was detected between 250 °C and 750 °C. This phenomenon is attributed to the breakdown of lignin compounds occurring in the later stages of the pyrolysis reaction [11,14].

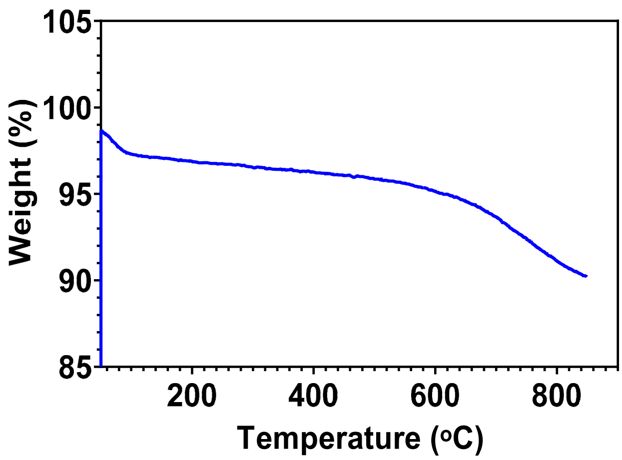

Figure 4. Thermogravimetric analysis (TGA) of pumpkin peel generated at 1.2 kW for 40 min.

3.2.2. Bio-Oil Analysis

The FTIR spectrum of food waste bio-oil obtained at various power levels is presented in Figure 5. The analysis of the pumpkin peel bio-oil revealed a notable difference in the peak intensity of OH (phenols) and ketones. A lower microwave power (0.9 kW) resulted in bio-oil with higher concentrations of phenolic functional groups. Conversely, at 1.2 kW, bio-oil with a higher content of ketones and carboxylic acids and a lower concentration of OH groups was generated. Increased power levels contributed to higher heating rates, which enhanced the quality of the bio-oil by increasing the formation of aromatic functional groups and improving the heating value. However, excessive temperatures can have an adverse effect on bio-oil quality due to the high pyrolysis temperature, leading to the breakdown of aromatic compounds and their conversion into phenolic groups [11,26,32].

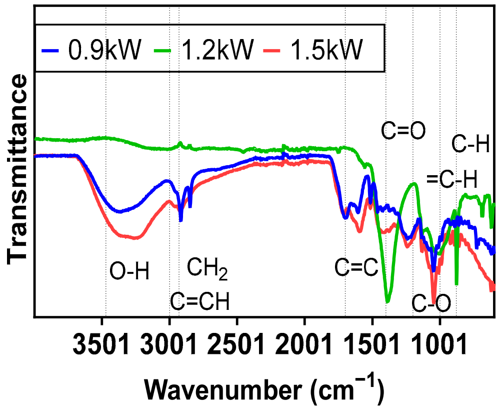

Figure 5. Bio-oil FTIR spectrum of pumpkin peel at various microwave pyrolysis powers.

Based on the functional groups present in the bio-oil of the food waste, only the sample produced at 1.2 kW was considered for further analysis. Table 4 displays the CHNS elemental analysis of the pumpkin peel bio-oil generated at 1.2 kW. The feedstock attained a heating value of 13.1 MJ/kg. An O/C ratio of 2.1 was obtained, indicating a high content of aromatic groups and a deoxygenation reaction during pyrolysis [11,33]. The carbon and oxygen content can be improved by using a different type of microwave susceptor, increasing microwave power and reducing the reaction treatment or removing the biomass moisture content.

Table 4. Ultimate analysis of bio-oil obtained from pumpkin peel.

Microwave Pyrolysis Conditions	C%	H%	N%	S%	O *%	H/C	O/C	LHV (MJ/kg)
1.2 kW/40 min	29.82	7.35	1.10	-	61.93	0.24	2.13	13.10

O *, oxygen was calculated considering the difference between the total percentage and all the remaining elements.

3.3. Energy Balance of the Microwave Pyrolysis Process

For energy balance calculations, the focus was on studying the by-products with the highest yields, heating values, and optimal characteristics, which were achieved at 1.2 kW for 40 min with the addition of a 10% microwave susceptor. Since this study only involves solid and liquid analysis, the energy from biogas was not considered. The biomass weight (45 g), yield, and heating value were considered to calculate the energy output of the by-products. The total output kWh, including the energy generated from the biochar and bio-oil by-products, is presented in Table 5. The total output energy amounted to 0.07 kWh. This performance was primarily achieved due to the yield and energy value of the bio-oil.

Table 5. Energy balance of pumpkin peel by-products using microwave pyrolysis.

Microwave Pyrolysis Conditions	By-Product Energy (kWh)		Total Output Energy (kWh)
	Char	Oil	
1.2 kW/40 min	0.02	0.05	0.07

The energy consumed during the microwave pyrolysis of food waste was calculated based on a microwave power of 1.2 kW and a treatment time of 40 min. To estimate the electrical consumption, the energy consumption, and an electrical efficiency conversion rate of 80% were considered. The operating conditions of the microwave system were the same for both biomasses, resulting in a consumption of 1 kWh during pyrolysis. The efficiency of the energy conversion process was determined by comparing the total output energy to the electrical consumption. The energy operating conditions of the microwave pyrolysis system and the energy balance are presented in Table 6. The energy recovery for pumpkin peel biomass was determined to be 6.9%. It is worth noting that this value could be improved by including biogas energy data through the generation of methane and hydrogen, as reported in [11,34].

Table 6. Energy recovery efficiency of the microwave pyrolysis process for 45 gr biomass.

Microwave Power (kW)	Time (min)	Energy Consumption (kWh)	Electrical Consumption (kWh)	Energy Conversion Effic. (%)
1.2	40	0.8	1.00	6.99

3.4. Economic Analysis

The economic analysis of the microwave pyrolysis system was conducted based on the study outlined in [11]. This analysis focuses on one scenario: the production of pumpkin peel biochar at 1.2 kW (with an electrical consumption of 1 kWh), as shown in Table 7. The analysis excludes the cost of biomass and microwave susceptor since the feedstock is derived from food waste, and the biochar produced during the pyrolysis process can be used as a microwave susceptor. The cost was estimated based on 650 g of biomass and the yield of by-products obtained at 1.2 kW. The electricity cost and maintenance cost were calculated using price factors of 20.19 c/kWh [11] and 33 USD/year [35], respectively. The value of biochar as a sellable product was estimated to be approximately AUD 0.55/kg [36], while the bio-oil was valued at AUD 1.45/L [11]. The total by-product value was calculated considering the yield and the total quantity of biomass used. The economic balance of the microwave pyrolysis process for pumpkin peel was determined to be AUD 0.01.

Table 7. Techno-economic analysis of food waste biomass using the microwave pyrolysis system.

Item	Pumpkin Peel		
	Energy (kWh)	**Value (c/kWh)**	**Amount (AUD)**
Electricity consumed	1	20.19	0.20
Maintenance			0.09
Total operating cost			0.29
Item	**B.G * (kg, L)**	**Value (unit)**	**Amount (AUD)**
Biochar (AUD/kg)	0.06	0.55	0.04
Bio-oil (AUD/L)	0.18	1.45	0.26
Total income			**0.30**
Total gained			**0.01**

* B. G: By-product generated in kg (unit) obtained from the total biomass and yield.

3.5. Carbon Footprint Analysis

Bio-oil and biogas can be used for power generation, which is beneficial for reducing GHG emissions, e.g., by using biofuel and generators, respectively. However, biochar shows an extra value associated with carbon storage (carbon dioxide sequestration). Figure 6 illustrates the carbon dioxide (CO_2) impact of various biomass management scenarios and energy generation methods. The microwave pyrolysis treatment of 45 g of food biomass produces 0.07 kWh of energy. In comparison, a power plant generates 0.115 kg of CO_2 to produce the same amount of energy. This calculation takes into account the energy produced (0.07 kWh) and an impact factor of 1.57 kg CO_2/kWh for traditional energy sources [11]. Alternatively, the incineration of the waste biomass can result in 0.0675 kg CO_2 emissions. The disposal of waste leads to emissions of 57 kg CO_2 per tonne [11], resulting in a total of 0.0026 kg CO_2 emissions.

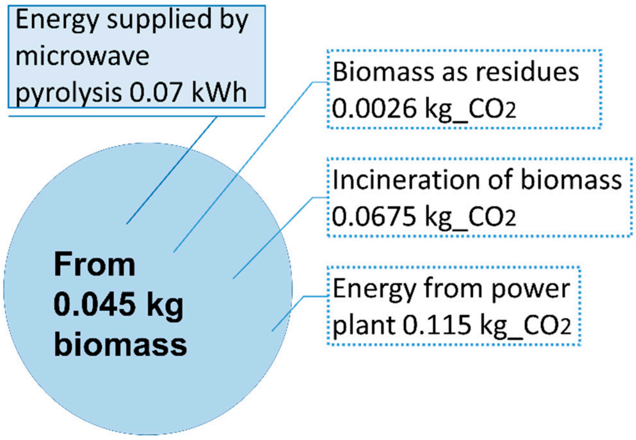

Figure 6. Scheme of CO_2 emission for different energy sources and its impact on waste management.

The primary advantage of employing microwave pyrolysis as a biomass conversion method is the production of biochar, which possesses a notable affinity for CO_2 and exhibits a significant carbon dioxide adsorption capacity [37]. The potential for CO_2 reduction through the utilization of biochar was determined based on studies cited in [38]. This calculation took into account the yield and fixed carbon content of each biochar. Table 8 presents the carbon dioxide sequestration capacity of pumpkin peel biochar generated using a microwave power of 1.2 kW for 40 min. Pumpkin peel biochar demonstrated a CO_2 reduction potential of 14.29 g CO_2 eq/kg.

Table 8. CO_2 sequestration potential of food waste biochar.

	Pumpkin Peel
Biochar yield, %	10
Fixed carbon, %	48.71
CO_2 reduction potential, g CO_2 eq/kg	14.29

4. Discussion

This study assessed the conversion of food waste biomass into energy using microwave-assisted pyrolysis under different operating conditions. The analysis focused on the yield, CHN (carbon, hydrogen, nitrogen) elemental properties, functional group quality, and energy output of biochar and bio-oil. Pumpkin peel was utilized as the feedstock, and three operating conditions were employed (0.9 kW, 1.2 kW, and 1.5 kW). The biomass exhibited varying behaviours at different microwave power levels. Lower power (0.9 kW) resulted in a higher biochar yield (11 wt%), while the same power level led to the lowest bio-oil generation (20.3 wt%) due to intrinsic biomass characteristics. Biochar and bio-oil characterization revealed that 1.2 kW produced by-products with a high carbon content and low oxygen concentration, yielding high-energy heating value. At 1.2 kW for 40 min, the biochar exhibited well-defined pores, while bio-oil exhibited high aromatic functional groups and low oxygen content, indicating superior quality.

The energy balance analysis demonstrated that the food waste feedstock generated an output energy of 0.07 kWh, primarily attributed to the high energy generation from bio-oil. The energy conversion efficiency of the microwave pyrolysis system using food waste reached 6.9%. An economic feasibility analysis using the same scenario yielded a cost balance of AUD 0.01. The potential for the carbon dioxide sequestration of pumpkin biochar was found to be 14.29 g CO_2 eq/kg.

This work also provides relevant findings related to the future application of biochar in advanced carbon nanomaterials due to its notable characteristics and quality generated from microwave pyrolysis—with promising uses in the electrochemistry sector and supercapacitor fabrication. It is recommended for future research to study the biogas composition from pumpkin peel and evaluate its energy potential in global energy recovery using microwave-assisted pyrolysis. Moreover, the optimisation of bio-oil quality is suggested, through esterification techniques (post-treatment) or by changing the microwave operating conditions (input power, microwave susceptor, reaction time). At the same time, this work provides the initial point to explore the processing of different types of agricultural wastes.

Author Contributions: S.A. Methodology, Formal analysis, Writing—original draft, Visualization, Data curation. M.V.J. and G.B.: Conceptualization, Writing—review and editing, Supervision, Project administration. All authors have read and agreed to the published version of the manuscript.

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Conflicts of Interest: The authors declare no conflict of interest.

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