Food waste to biochar; a potential sustainable solution for Australia: a comprehensive review

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Hemal Chowdhury
UNSW Sydney
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REVIEW

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Food waste to biochar; a potential sustainable solution for Australia: a comprehensive review

Piyal Chowdhury[1], Tamal Chowdhury[2], Hemal Chowdhury[3*] and Elza Bontempi[4]

Abstract

Australia generates a significant amount of food waste (FW) every year, creating a substantial burden on its economy, environment, and resources. Several waste management practices, such as landfilling, composting, and anaerobic digestion, are available in Australia. However, landfilling of FW is not environmentally viable, composting requires substantial space, and anaerobic digestion is expensive. The conversion of FW into biochar offers a sustainable solution to this problem, and pyrolysis is an effective technology for this transformation. The conversion of FW into biochar offers Australia significant benefits, particularly considering the country's unique soil properties. Therefore, this review explores the potential FW streams for biochar conversion. We identify and review potential pyrolysis technologies, as well as discuss FW-based biochar's unique properties and activation methods. The effects of process parameters, such as temperature and pressure, on biochar properties have also been considered. Additionally, we discuss biochar's potential applications for climate change mitigation. Finally, we address the current challenges related to FW-based biochar and propose potential solutions.

Highlights

- Australia generates around 31.2 Mt of food waste annually, mostly from food and beverage processing industries.
- Current waste management practices have many limitations, but pyrolysis offers an effective solution to this problem.
- Converting food waste to biochar helps tackle the waste problem and fight climate change.
- Process parameters, such as temperature and residence time, significantly impact biochar yield and properties.

Keywords Biochar, Food waste, Pyrolysis, Climate change, Circular economy, Recycle

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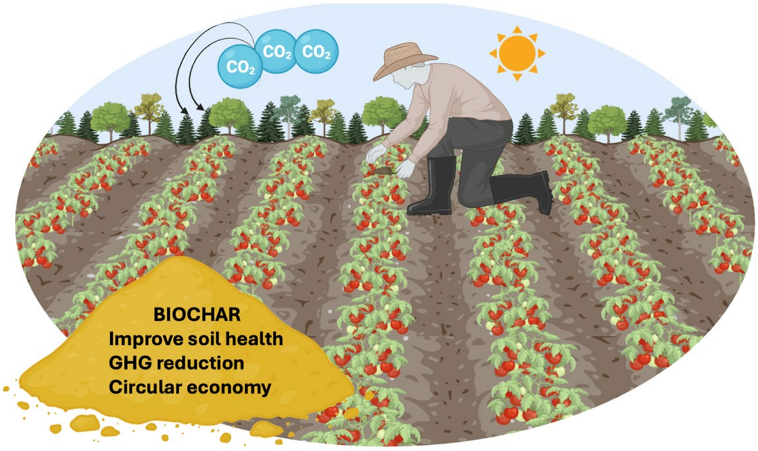
*Correspondence:
Hemal Chowdhury
h.chowdhury@unsw.edu.au
Full list of author information is available at the end of the article

Graphical Abstract



1 Introduction

Food waste (FW) is becoming an increasingly significant global issue, driven by modernization, rapid population growth, and urbanization. According to one study, approximately 1 billion tonnes of food are wasted worldwide each year (Palansooriya et al. 2024). This amount is expected to rise in the future, with projections suggesting that by 2030, global FW could reach 2.1 billion tonnes (Hegnsholt et al. 2018). FW is a highly complex and heterogeneous material consisting of various organic components compositions and properties. It contains a substantial proportion of biopolymers, such as proteins (7%–27.8%), lipids (10%–35%), and carbohydrates (35.1%–67%) (Su et al. 2022). The chemical and physical characteristics of FW vary from country to country and, at times, even within the same country. To determine the composition of organic matter, analyses such as proximate and ultimate analysis are conducted, assessing parameters such as moisture, fixed carbon, volatile content, ash, hydrogen, nitrogen, oxygen, and sulfur (Pour and Makkawi 2021). Tables 1 and 2 present the proximate and ultimate analysis of FW from various countries.

Table 1 High heating value and proximate analysis of FW from different countries

FW source	Proximate analysis (mass%)				High heating value (HHV, MJ kg^{-1})	Reference
	Moisture	Volatile	Ash	Fixed carbon		
Australia	Dry basis	73.4	5.5	21.1	15.7	(Opatokun et al. 2015, 2016; Pour and Makkawi 2021)
China[a]	Dry basis	79.7	10.0	10.3	-	(Pour and Makkawi 2021; Zhang et al. 2015)
Japan	8.0	61.5	7.7	22.8	19.1	(Pour and Makkawi 2021; Tanaka et al. 2008)
India	7.60	70.1	7.4	14.9	22.9	(Kadlimatti et al. 2019; Pour and Makkawi 2021)
South Korea[b]	Dry basis	79.0	3.8	17.3	19.5	(Jo et al. 2017; Pour and Makkawi 2021)
USA	Dry basis	84.9	3.3	12.9	21.9	(Caton et al. 2010; Pour and Makkawi 2021)
China[c]	Dry basis	81.6	12.6	5.7	-	(Liu et al. 2014; Pour and Makkawi 2021)
Singapore[d]	7.8	75.2	2.5	14.5	20.8	(Pour and Makkawi 2021; Yang et al. 2016)
China[e]	Dry basis	84.9	10.5	4.6	-	(Lin et al. 2020; Pour and Makkawi 2021)
Germany	13.1	77.2	4.6	5.1	23.3	(Ouadi et al. 2019; Pour and Makkawi 2021)
Coefficient of variation (%)	29.1	9.3	50.3	50.3	12.9	

[a] Comprises of bones/meat/waste oil (38.7%), vegetables/fruits (36.2%), and brown/white rice (25.1%).

[b] Comprises of apple (7%), daikon (2%), egg (3%), fish (12%), meat (4%), napa cabbage (9%), onion (20%), orange/mandarin (7%), potato (20%), ramen/rice (16%).

[c] Includes bones/meat (23.1%), vegetable leaves (44.2%), and white rice (32.7%).

[d] Includes eggs/meat (21.4%), noodle/pasta/ rice (68.2%), and vegetable matter (10.4%).

[e] Includes meat (20 mass%), vegetable leaves (45 mass%), white rice (35 mass%).

Table 2 Ultimate analysis (mass%) of food samples collected from various countries

FW source	Oxygen	Carbon	Sulfur	Hydrogen	Nitrogen	Reference
Australia	40.8	46.1	0.2	5.7	1.7	(Opatokun et al. 2015; Pour and Makkawi 2021)
China[a]	30.3	43.3	-	8.6	5.1	(Pour and Makkawi 2021; Zhang et al. 2015)
Japan	39.7	47.7	0.1	7.6	3.9	(Pour and Makkawi 2021; Tanaka et al. 2008)
India	35.6	46.7	-	7.3	3.0	(Kadlimatti et al. 2019; Pour and Makkawi 2021)
South Korea[b]	29.7	47.5	-	12.2	2.9	(Jo et al. 2017; Pour and Makkawi 2021)
UK	23.5	56.7	0.2	8.8	4.0	(Naveed et al. 2009; Pour and Makkawi 2021)
China [c]	33.5	42.3	0.3	7.5	3.7	(Liu et al. 2014; Pour and Makkawi 2021)
Singapore[d]	40.0	47.7	0.6	7.1	2.3	(Pour and Makkawi 2021; Yang et al. 2016)
China[e]	17.6	54.3	0.3	8.1	4.7	(Lin et al. 2020; Pour and Makkawi 2021)
Germany	34.3	50.2	<0.1	8.0	2.9	(Ouadi et al. 2019; Pour and Makkawi 2021)
Coefficient variation (CoV%)	23.1	9.3	66.8	20.8	30.9	

[a] Comprises bones/meat/waste oil (38.7%), fruits/vegetables (36.2%), and brown/white rice (25.1%).

[b] Comprises of apple (7%), daikon (2%), egg (3%), fish (12%), meat (4%), napa cabbage (9%), onion (20%), orange/mandarin (7%), potato (20%), and ramen/rice (16%).

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Food is wasted for many reasons. In developed countries, food is primarily wasted at the consumer or retail level, while in developing countries, food is lost due to inadequate infrastructure and poor storage (Kim 2014). FW from primary sources typically arises from several factors, including damage during harvesting and handling, failure to meet retail standards, the decision to halt harvesting when market prices are low, inadequate or poor storage leading to spoilage at the production site, and losses caused by adverse weather conditions or diseases.

Like many developed nations, FW is Australia's significant and growing issue. According to a study, from 2020 to 2021, Australia generated around 31.2 million tonnes (Mt) of FW across the whole food supply chain (production, supply, and consumption) (Talekar et al. 2023). Over 90% of Australia's FW originated from primary production sources, households, food processing facilities, and businesses (Talekar et al. 2023). Broadacre crops, fruits and vegetables in primary production sectors produced the most FW in Australia, generating about 2.5 Mt in 2020–21 (Pickin et al. 2022). However, the largest FW came from the food and beverage processing industry, generating about 23.4 Mt in the 2020-21 financial year. The main share of waste came from fruits, nuts, vegetables, seafood, and broadacre crops (Table 3). Approximately 55% of FW of food processing facilities came from sugarcane bagasse and molasses. Households and businesses in Australia produce around 4.6 Mt of FW annually, which constitutes inedible food scrap, unsold, unconsumed, and damaged food (Pickin et al. 2022). A survey (consisting of 5272 samples) conducted in Australian households found that most Australians (47%) throw away vegetables, followed by bread and bakery items (46%), meat, and seafood (26%). Only 33% of Australians reported to dispose of fresh fruit (Fight Food Waste CRC 2020).

This waste (31.2 Mt) significantly impacted Australia's resources, environment, and economy. For example, Australia used 2600 gigalitres (GL) of water to produce this food (Talekar et al. 2023). Moreover, this amount of waste was responsible for 3% of Australia's annual GHG emissions, costing Australia $36.6 billion (AUD) annually (FIAL 2021).

During 2021-2022, Australia generated 48 Mt of organic waste (Pickin et al. 2022). Around 14.4 Mt of this 48 Mt waste is composed of garden organics, FW, biosolids, and timber waste. Approximately 58% of this 14.4 Mt waste was recycled through anaerobic digestion, composting, direct application to land, or landfill gas capture. The remaining 33.3 Mt of 48 Mt waste came from aquaculture, agriculture and forestry (Pickin et al. 2022).

1.1 Current FW management practice in Australia

Various waste management techniques (WtE) such as anaerobic Digestion (AD), composting, and landfilling are available and applied to tackle this FW issue in Australia. Fig. 1 shows the destination of FW generated in Australia in 2021 (FIAL 2021). Different sectors, such as households and processing facilities, use different WtE methods to treat FW. Landfilling is Australia's most common waste management method, with around 1172 landfills in operation (Talekar et al. 2023). Composting of FW (both commercial and on-site) is also prevalent, with

Table 3 FW production in Australia (Talekar et al. 2023)

Food commodity	Production (Kt year^{-1})	Processing (Kt year^{-1})	Production loss (Kt year^{-1})^{f}	Processing waste (Kt year^{-1})^{g}	Total waste (Kt year^{-1})
Fruits and vegetables					
Apple	307.6	89.5	32	26.8 (Pomace)	58.8
Potato	1462.0	979.5	110.0	365.5 (Peels)	475.5
Citrus	760.1	222	48	133.2 (Peels)	181.2
Tomato	436.9	222.8	127.0	15.6 (Pomace)	225.6
Wine grapes	1750	1750	14	437.5 (Grape marc)	451.2
Nuts Almonds	177.7	177.7	-	151 (Hull and Shell)	151
Dairy					
Milk	8,554,000	5,303,000	-	1600 (Whey)	1600
Seafood					
Fish	164.2	106.6	-	58 (Bones heads viscera scales muscles skins fins)	58
Broadacre crops					
Sugarcane	31,500	31,500	475	12,900 (Molasses and bagasse)	13,375
Household and business					
Mixed food	4600	-	-	-	4600

[a] Loss at the production site was not taken into consideration.

[b] Measured by applying the percentage or proportion of waste produced during the processing of each food commodity.

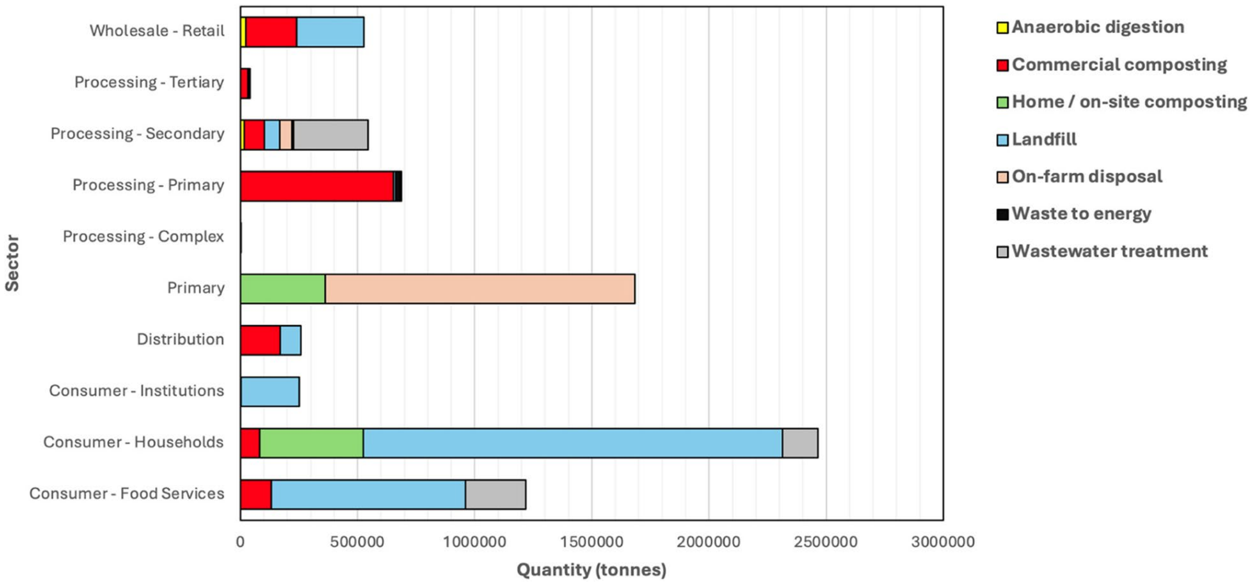

Fig. 1 Volume of FW generated in Australia in 2021, by destination (FIAL 2021)

around 150 facilities nationwide converting waste into products like fertilizers (Australasian Bioplastics Association 2024). Another popular WtE option is AD, with over 200 facilities treating waste (Tait et al. 2021), but also direct disposal on the farm where it originates is a common practice.

While various FW management techniques are employed in Australia, waste distribution and treatment methods vary considerably across different sectors. A previous study found that approximately 85% of FW generated at the production stage is left uncollected and is instead utilized to enrich the soil. Around 11% is repurposed for animal feed, and 4% is directed towards composting (Talekar et al. 2023). Food processing facilities incinerate sugar bagasse for energy and use half of the molasses for domestic ethanol production, with the rest exported. These facilities use the rest of FW in anaerobic digestion (2%), composting (16%), and animal feed (27%) (Talekar et al. 2023). Businesses and households dispose of 83% of their waste in landfills, with the remainder recycled through AD and composting (Talekar et al. 2023). (Please note that these numbers could vary. We could not find the updated numbers).

While these waste management strategies have their advantages, they are not without drawbacks. Landfilling of FW is not sustainable as it has a considerable impact on the environment (although it is the most straightforward management technology). Landfill disposal of FW can lead to methane emission, generating a potent greenhouse gas (GHG), which exacerbates climate change (Krause et al. 2023). Additionally, the landfilling of FW is also responsible for significant public health concerns. The elements present in decomposed FW have been linked to carcinogenicity and may also have harmful effects on the kidneys, liver, and nervous system (Nandomah and Tetteh 2023). It is also very expensive to collect and transport FW(Pradhan et al. 2024). For example, landfill charges range from \$50 to \$200 per tonne of waste based on the waste type and landfill site location (Pickin et al. 2018). Composting requires a large area and a long time to decompose (Jouhara et al. 2017). The main disadvantage of AD is that it is costly to set up (De Baere 2006), and the process needs to be monitored and maintained (due to the generation of toxic sulphur compounds during the fermentation process), which is time-consuming (Chen et al. 2008).

1.2 Alternative approach

Considering the limitations of traditional approaches, thermochemical approaches such as gasification, pyrolysis, incineration, hydrothermal carbonization (HTC), and liquefication have been adopted to treat FW. Pyrolysis has several advantages over other thermochemical processes. For example, gasification requires high energy (Singh et al. 2022, Sajid et al. 2022, 2023), incineration produces a significant amount of NO_x emission and fly ash (Jacob et al. 2021), and liquefaction faces some safety-related challenges (Istrate et al. 2020; Singh et al. 2022). The main challenge of pyrolysis is that an extra step is needed to dry FW, as it contains moisture. HTC is useful as it does not require this step. However, the main problem with HTC is that the control is less flexible than that of pyrolysis, as it occurs under high pressure in a closed system (Yang et al. 2023). Moreover, HTC also faces problems in solid-phase and water-phase product separation (Yang et al. 2023). For these reasons, converting FW through pyrolysis presents a promising solution.

However, strong policy support, infrastructure development, and market integration are needed for the successful implementation of such thermochemical technologies. The Australian government has recognized this and incorporated sustainable FW management into its National FW Strategy, which emphasizes facilitating business improvements, fostering innovation, and creating markets for repurposed FW. As part of this strategy, Australia aims to reduce FW by 50% by 2030 through a coordinated framework involving government, industry, businesses, and the community (FIAL 2021). The strategy identifies several action areas to achieve its goal. Policy support is a critical aspect, with the establishment of a National FW Baseline to monitor progress, as well as directing investment towards FW reduction activities. There is also a significant emphasis on business improvements, particularly encouraging businesses to adopt practices and technologies that reduce FW. These improvements include optimizing inventory management, finding innovative ways to repurpose FW, and increasing awareness of FW reduction. In addition, the strategy promotes market development, particularly the creation of markets for repurposed FW.

In this context, research plays an essential role in the strategy's success, particularly in identifying effective technologies and solutions to reduce FW. One of the key approaches for addressing FW in Australia is through the promotion of sustainable alternatives such as the conversion of FW into biochar.

Biochar is a stable, carbon-rich material that can significantly improve soil health (Száková et al. 2024). This is especially significant in Australia, where soil has low fertility (Eldridge et al. 2018). Biochar enhances soil health by increasing organic and total carbon, which improves soil texture, nutrient availability, and microbial activity. Through adsorption and ligand exchange processes, biochar strengthens organo-mineral interactions, contributing to soil stability and the buildup of soil organic carbon (SOC) (Pandian et al. 2024). Additionally, biochar mediates interactions between rhizobium bacteria, soil microbiota, and nutrient cycles, promoting efficient nutrient dynamics and microbial cooperation (Shikha et al. 2023). Biochar could also efficiently reduce GHG emissions from crop fields, grasslands, and forest land (Pradhan et al. 2024). Research suggests that agriculture in Australia is responsible for more than half of the methane emissions in 2022-23 (Climate Council 2024). So, biochar can be an effective solution to this problem.

A recent literature review revealed that there are no comprehensive reviews on FW-to-biochar technologies, particularly in the context of Australia. As a result, this study aims to identify the major FW streams and their associated conversion technologies to biochar in Australia. Additionally, it will explore how biochar can contribute to addressing climate change in the country. Conducting this review will provide valuable insights into the current state of adopted technologies within the Australian context. Moreover, the study may help identify key obstacles and enablers, guide policymakers in developing new policies, and encourage the adoption of sustainable waste management practices.

2 Pyrolysis

Biochar, a carbon-rich material, is produced from the partial combustion of organic waste or biomass in an oxygen-limited environment. Pyrolysis is a thermochemical process where organic materials, such as FW, are heated to temperatures between 300–800 °C in a controlled setting with limited or no oxygen. This process causes the materials to decompose into biochar, gases, and fuels (Fig. 2; Tan et al. 2023; Wan Mahari et al. 2022a, b). When feedstocks are burned in a limited oxygen environment, most of the nitrogen, oxygen, and hydrogen are released as gases, leaving behind a small amount of nitrogen, oxygen, and hydrogen along with a significant portion of carbon (Yadav et al. 2023). Inert gases like argon, CO_2, and vacuum pump are used to attain anaerobic conditions.

2.1 Classification of pyrolysis

2.1.1 Conventional pyrolysis

Several types of pyrolysis processes are available, including fast, intermediate, slow, flash and vacuum pyrolysis (Table 4). The main differences between these processes lie in their operating conditions, such as temperature, residence time, heating rate, and particle size of feedstocks. For example, fast pyrolysis typically operates at around 500 °C (Kim et al. 2020), while slow pyrolysis needs lower temperatures. High temperatures are optimal for bio-oil production, whereas lower temperatures favour the production of biochar (Chatterjee et al. 2020; Razzak 2024). Biochar produced through fast pyrolysis has a robust structure and high carbon content, as elevated temperatures promote greater carbonization. This makes it highly suitable as an environmental adsorbent (Nawaz et al. 2024; Razzak 2024). Moreover, biochar yielded after slow temperature pyrolysis has high volatile matter, making it suitable for soil amendment (Razzak 2024; Tomczyk et al. 2020).

Pyrolysis can also be classified into traditional heating (conventional pyrolysis follows this heating) and microwave heating based on the heating mechanism (Fig. 3; Li et al. 2022). The traditional heating mechanism in pyrolysis involves the transfer of heat from the medium or reactor to the feedstock's surface. Several traditional heating mechanisms, such as fixed bed, fluidized bed, and electric furnaces are possible. For example, pyrolysis in a fixed-bed reactor involves pyrolyzing the feedstock by contacting the bed, which acts as the heat source and provides a platform for catalysts. As the feedstocks pass through the fixed bed, they break down and decompose into bio-oil, biogas, and biochar. The main benefit of a fixed-bed reactor is that these reactors are easy to design and there is no back-mixing of feedstocks. Fluidized bed reactors, on the other hand, do not have a fixed bed and offer better heat transfer and efficiency compared to fixed-bed reactors An electric furnace employs resistive heating wire for heating purposes. Overall, traditional heating mechanisms transfer heat from the source to the surface of the feedstocks, with the surface temperature being higher than the centre of the feedstocks (Li et al. 2022).

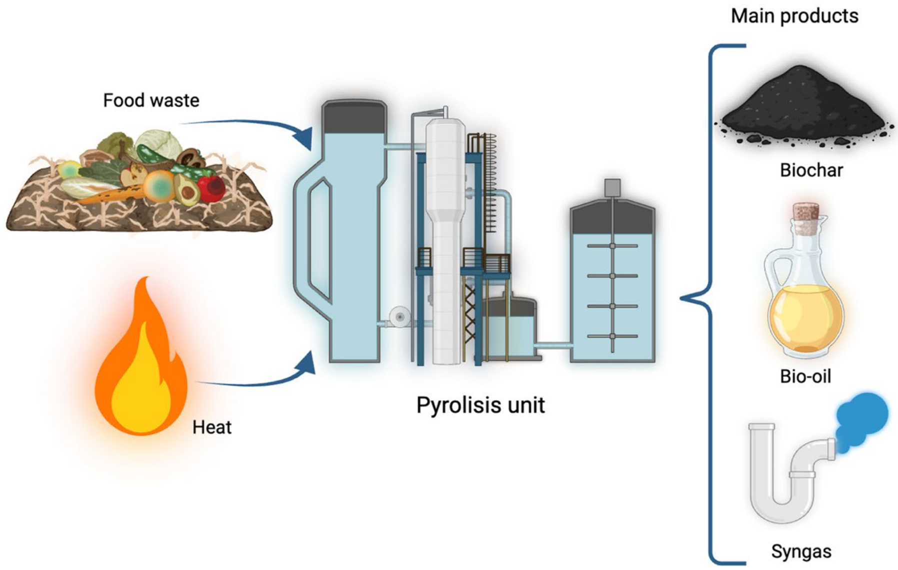

Fig. 2 Main products of a pyrolysis process. The figure was realised with Biorender.com

Table 4 Different types of pyrolysis (Mishra and Mohanty 2023)

Type of pyrolysis	Temperature (° C)	Heating rate (° C s^{-1})	Residence time (s)	Pressure (MPa)	Particle size (mm)
Slow pyrolysis	550–950	0.1–1.0	300–550	0.1	5–50
Flash pyrolysis	900–1200	>1000	<1	0.1	<0.5
Fast pyrolysis	400–1250[a]	10–200	0.5–10	0.1	<1
Vacuum pyrolysis	300–600	0.1–1.0	0.001–1.0	0.01–0.02	-
Intermediate pyrolysis	500–650	1.0–10	0.5–20	0.1	1–5

[a] Kumar Mishra et al. (2023) mentioned fast pyrolysis temperature is between 850–1250 °C. Pahnila et al. (2023) mentioned that depending on feedstock, fast pyrolysis temperature ranges from 400–800 °C to 850 to 1250 °C. Therefore, we provided this range (400–1250 ° C).

2.1.2 Microwave pyrolysis

Microwave pyrolysis (MP) is used to address the issue of uneven heat distribution, as the energy conversion takes place directly within the feedstocks. This technology converts electromagnetic radiation with a frequency range from 300 MHz to 30 GHz (but commercial microwaves operate at frequencies 915 MHz and 2.45 GHz to avoid interference between scientific, industrial, medical and communication applications) to kinetic energy (Ethaib et al. 2020). The radiation penetrates sample particles, interacting at the molecular level and ensuring uniform heat distribution.

Based on the movement of molecules, microwaves heat feedstocks through three mechanisms: conduction mechanism, dipolar polarization, and space charge polarization. When exposed to microwave radiation, polar molecules undergo dipolar polarization, which generates heat through rapid rotation and collisions (Fahimi et al. 2023). The accumulation and random distribution of free charges in a material with irregular conductivity or dielectric characteristics lead to space charge polarization. Heat is produced during this process because of field distortions and dielectric loss. A hydrogen-bonded cluster of ions travelling through a solution causes the conduction mechanism. This movement not only creates ion collisions but also produces thermal energy (Liu et al. 2024). In microwave heating, when solid-state materials can be excited by microwave radiation, it is possible to reach highly efficient heating because the target material directly absorbs the energy (Cornelio et al. 2024), and the heating starts from the core of the material, as shown in Fig. 3.

Several studies have used MP to yield biochar from FW. For example, Fan et al. (2023) subjected peanut shells to MP and found that low temperature favours the biochar yield. The same outcome was also observed by Qiu et al. (2023), and Bu et al. (2022). MP was also used on other FW, such as coffee grounds (Ma et al. 2023), FW (Allende et al. 2024, Kadlimatti et al. 2021), waste bones (Hart et al. 2022), and fruit waste (Md Said et al. 2022) to obtain biochar (Table 5). These studies reported that process parameters, such as temperature and residence time, have a significant impact on biochar yield.

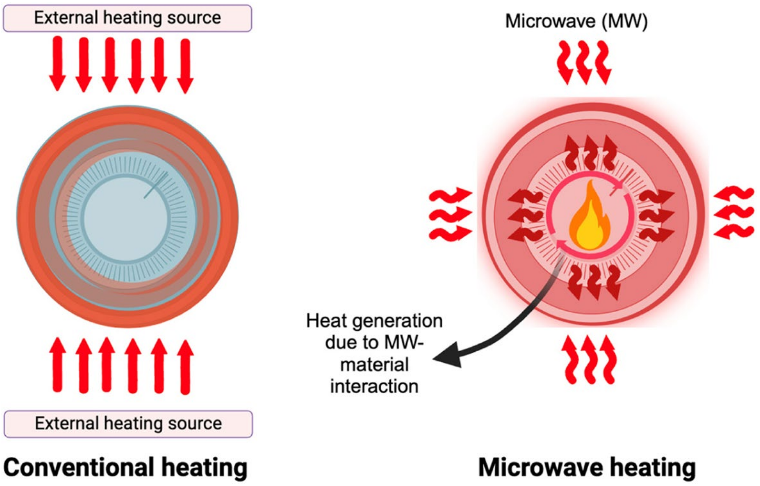

Fig. 3 Conventional heating and microwave heating difference. The figure was realised with Biorender.com

Table 5 FW conversion to biochar through microwave pyrolysis

Feedstock	**Pyrolysis conditions**	**Results**	**Reference**
Peanut shell	Temperature range: 400–600 °C, Residence time range: 10–50 minute (min), Microwave power range: 350–750 W	Biochar Yield-86 wt% and the optimum condition: Temperature: 400 °C, Residence time: 10 min, Microwave power: 350W	(Fan et al. 2023)
FW (40% vegetable peels, 40% rice, and 20% chicken bones)	Microwave power range: 1–1.5 kW, Residence time range: 60–120 min	Biochar Yield-8 ± 0.63 wt% and the optimum condition: Residence time: 120 min, Microwave power: 1.5 kW	(Allende et al. 2024)
FW	Temperature range: 300–500 °C, Residence time range: 20–40 min, Microwave power range: 150–450 W	Biochar Yield-60.03 wt% and the optimum condition: Temperature: 400 °C Residence time: 30 min, Microwave power: 450 W	(Kadlimatti et al. 2021)
Pumpkin peel	Temperature range: 200–800 °C, Residence time range: 40 min, Microwave power range: 0.9 kW–1.5 kW	Biochar yield: 11 wt% and the optimum condition: Temperature: Not available (NA), Residence time: 40min, Microwave power: 0.9 kW	(Allende et al. 2023)
Crab waste	Temperature range: 150–900 °C, Residence time range:15–20 min, Microwave power range: 1 kW	Biochar yield: 51–61 wt% and the optimum condition: Temperature: 800 °C, Microwave power: 1 kW	(Yang et al. 2024a, b)

2.2 Effects of process parameters on char yield

The type of feedstock used in pyrolysis has a significant influence on the biochar yield. Additionally, several process parameters, such as temperature, particle size, pressure, heating rate, and residence time, play a crucial role in determining the char yield (Fig. 4).

2.2.1 Residence time

Residence time refers to the duration for which the feedstock remains in the reaction chamber while undergoing thermochemical changes. The longer the residence time, the more complete the breakdown process. Fast pyrolysis typically involves a short residence time, whereas slow pyrolysis is associated with a longer residence time (Singh et al. 2022). Residence time significantly impacts biochar yield. Longer residence times result in biochar with greater pore volume and larger surface areas due to a more thorough carbonization and volatilization process. While this increases the carbon content of the biochar, it also leads to a higher ash content (Ulusal et al. 2021). Longer residence times lead to a reduction in biochar yield, as a larger portion of the material is converted into volatiles and gaseous compounds. This observation is supported by Ahn et al. (2023), who found that increasing the residence time from 10 to 30 minutes at a temperature of 300 °C resulted in a 4% decrease in biochar yield derived from FW.

2.2.2 Heating rate

The heating rate, or the rate at which temperature increases during conversion, plays a crucial role in determining the production speed. A rapid heating rate leads to quick devolatilization, promoting the development of surface area and pore structures in the biochar. In contrast, a slower heating rate increases biochar yield but results in higher volatile matter content and reduced surface area (Razzak 2024; Rohman et al. 2024, Elkhalifa et al. 2022).

2.2.3 Size of feedstock

The size of feedstock particles is a key parameter that affects char yield during pyrolysis. Larger particles require more heat to reach the core from the surface, creating a temperature gradient that favours higher char yield. During the thermal breakdown of feedstocks, when particle size is larger, the generated vapor must travel a greater distance through the char layer. This leads to the formation of more char due to secondary reactions between the vapor and the char material (Tripathi et al. 2016).

2.2.4 Pressure

Similar to particle size, the pressure inside the reactor affects the char yield. The biochar yield increases when pyrolysis is carried out at a pressure higher than ambient

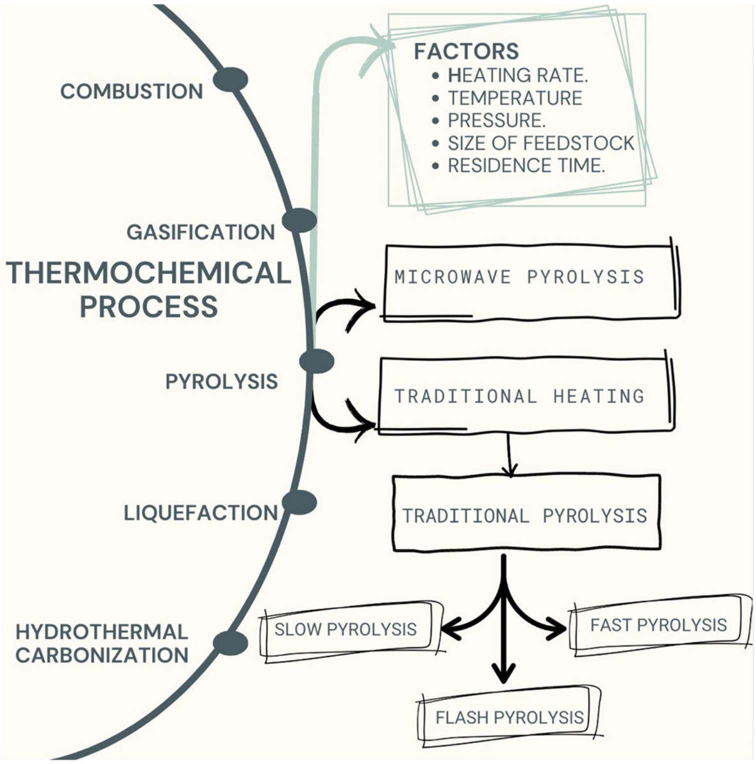

Fig. 4 Different types of pyrolysis and process parameters (Li et al. 2022)

pressure. An increase in pressure extends the residence time, allowing the vapours generated during the thermal breakdown of feedstocks to interact more with the char material. This interaction promotes the formation of additional carbon and leads to a higher char yield (Tripathi et al. 2016).

2.2.5 Temperature

Increasing the temperature during pyrolysis negatively impacts the char yield (Tripathi et al. 2016). As the temperature rises, heavy hydrocarbon materials break down more extensively. This results in the production of more gaseous and liquid fuels. As more feedstock is converted into these fuels, less material is available to form char (Tripathi et al. 2016). For example, increasing the pyrolysis temperature from 400 °C to 800 °C resulted in a 72% reduction in biochar yield from sugarcane waste (Khater et al. 2024). As the temperature increases, feedstocks begin losing hydroxyl groups due to dehydration reactions. This occurs alongside the thermal breakdown of cellulose and hemicellulose into smaller organic molecules and gases, leading to a decrease in biochar production (Moureen et al. 2024).

3 Biochar properties

Biochar possesses both physical and chemical interesting properties (Fig. 5). The physical characteristics of biochar include density, hydrophilicity or hydrophobicity, surface area, and porosity. The chemical properties of biochar include pH, functional groups, and cation exchange capacity. The type of feedstock has a significant impact on these properties. For instance, the high moisture content of FW notably influences the physicochemical properties of the resulting biochar. One study found that biochar derived from high-moisture-content digestate FW exhibits a higher surface area and greater pore volume (Wang et al. 2022). The following section discusses the properties of biochar derived from FW.

3.1 Physical properties

3.1.1 Pore volume

The texture of biochar is characterized by high ash content and porosity (Ahmed et al. 2024). Biochar surface pores are formed during pyrolysis as moisture and volatile organic compounds are released the feedstocks (Ravindiran et al. 2024). An increase in residence time during pyrolysis results in the release of more volatile organic compounds and the development of larger pore volumes. For example, Xue et al. (2019) reported that an increase in residence time from 2 hours to 4 hours leads to 1.6 times increase in total pore volume in biochar obtained from meat and bone waste.

3.1.2 Surface area and porosity

The surface area and porosity of biochar are critical factors in determining its ability to adsorb substances. These properties influence biochar's capacity to retain

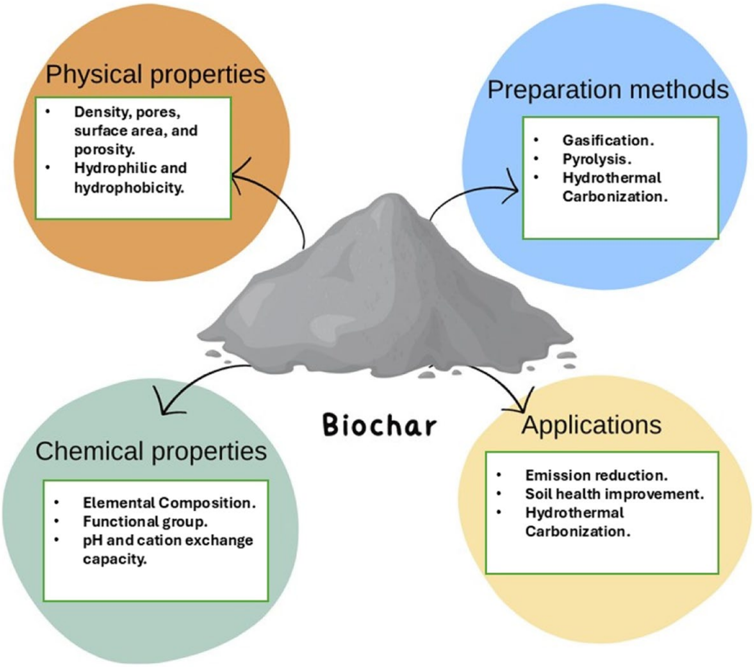

Fig. 5 Physical and chemical properties of biochar. Applications and preparation methods are also reported

water, nutrients, and pollutants. Smaller biochar particles improve soil texture, enabling it to retain water more effectively compared to larger biochar particles (Alghamdi et al. 2020). A high surface area of biochar means it can adsorb pollutants such as lead, zinc, and copper (Celignis Analytical 2024). The high porosity of biochar allows it to retain water and nutrients in the soil (Muzyka et al. 2023).

Temperature has a significant effect on the specific surface area of biochar. This is because a temperature rise promotes the formation of more pores, which, in turn, increases the specific surface area. Zhao et al. (2022) reported that increasing the temperature from 500 °C to 800 °C resulted in an increase in the surface area of biochar (obtained from FW) from 3.47 $m^2 g^{-1}$ to 11.36 $m^2 g^{-1}$.

3.1.3 Density

The biochar's density is also a key physical parameter which has a high influence on its performance. It regulates the space between biochar particles, impacting their porosity and surface area (Ahmed et al. 2024). Low-density biochar has larger pores, which enhances its ability to retain nutrients and water more effectively (Ahmed et al. 2024).

3.1.4 Bulk density

Bulk density can be defined as the ratio of the mass of biochar to its total volume (Khater et al. 2024). This parameter is critical for understanding the transport and application of biochar in agricultural applications. If the soil has a high bulk density, it will have a poor potential to absorb water (Boakye et al. 2023). Since biochar seems to possess high porosity (Muzyka et al. 2023), applying it results in a reduction of soil bulk density (Boakye et al. 2023). Process parameters, such as temperature, significantly influence the bulk density of biochar. For instance, Boakye et al. (2023) observed that increasing the pyrolysis temperature led to a reduction in the bulk density of FW-based biochar, resulting in a more porous structure.

3.1.5 Hydrophilic or hydrophobicity

The ability of biochar to absorb nutrients and regulate water content is linked to its hydrophobic or hydrophilic properties (Gray et al. 2014). The hydrophobic properties of biochar are due to the presence of alkyl functional groups on its surface (Mao et al. 2019). Biochar produced from low-temperature pyrolysis retains more aliphatic compounds in its pores than biochar from high-temperature pyrolysis. One study by Alghamdi et al. (2024) showed that biochar derived from coffee waste resulted in a 101%-130% increase in water retention (hydrophilicity) in loamy sand soil. Huang et al. (2021) reported that kitchen waste-based biochar reduces water flow over the soil surface by 17.7%, indicating a potential hydrophilic property.

3.2 Chemical properties

3.2.1 Elemental composition

Biochar primarily consists of carbon (C), hydrogen (H), oxygen (O), and nitrogen (N). Additionally, it contains other elements such as phosphorus (P), magnesium (Mg), potassium (K), calcium (Ca), iron (Fe), sodium (Na), sulfur (S), and silicon (Si) (Abukari et al. 2022). Carbon in biochar exists in both inorganic forms (bicarbonates, carbonates) and organic forms (functional groups, fatty carbon, aromatic carbon). Hydrogen (H) in biochar is present as functional hydrogen, aromatic hydrogen, and fatty hydrogen. Oxygen in biochar is largely found in functional groups (such as esters, carboxyls, and hydroxyls), as well as in metal hydroxides, oxides, sulfates, and carbonates (Abukari et al. 2022). Temperature plays a significant role in the elemental composition of biochar. For example, Xue et al. (2019) derived biochar from FW and observed that increasing the pyrolysis temperature from 300 °C to 700 °C led to an increase in C content from 55% to 89%. Additionally, H content decreased from 6% to 1%, while O content declined from 27% to 3% (Xue et al. 2019). However, an opposite trend was observed for sheep and cow bone-based biochar (Azeem et al. 2021a, 2021b). Azeem et al. (2021a) found that at a higher temperature (800 °C), biochar obtained from sheep bone waste resulted in a decrease in carbon content (from 11% to 9.4%) and nitrogen content (from 2% to 1.8%), but with an increase in oxygen (from 29.2% to 34.6%).

3.2.2 Functional group

During the pyrolysis process, cellulose in FW is transformed into aromatic carbon and fatty carbon in biochar, which helps to form the structure of the biochar (Zhang et al. 2021). Functional groups on the surface of biochar, such as carbonyl groups ($-C=O$), ester groups ($-COOR$), carboxyl groups ($-COOH$), phenolic hydroxyl groups ($-OH$), are responsible for various chemical and physical characteristics, including hydrophilicity, hydrophobicity, and cation exchange capacity (Zhang et al. 2021). Temperature has a significant effect on functional groups. At lower temperatures (≤150 °C), the impact of the dehydration process on biochar's surface functional groups is minimal. However, at temperatures between 250 °C and 350 °C, decarboxylation and esterification reduce carboxyl content, leading to a decrease in surface functional groups. At higher temperatures (500–700 °C), the total content of surface functional groups increases due to the enhancement of the aromatic structure and the transformation of alcohol groups into phenolic hydroxyl groups (Zhang et al. 2021).

3.2.3 pH

Biochar obtained from different FW exhibits different pH values (Yu et al. 2022). Biochar produced from the pyrolysis of FW is typically alkaline. It has been observed that increasing the pyrolysis temperature leads to higher pH values (Table 6; Abukari et al. 2022). This is because a rise in pyrolysis temperature causes alkali salts to separate from the organic compounds, which results in a decrease in acidic functional groups and an increase in basic functional groups (Moureen et al. 2024). Increasing the pyrolysis temperature from 350 °C to 550 °C for FW feedstocks resulted in an increase in pH values from 9.82 to 10.17 (Moureen et al. 2024). Similarly, Azeem et al. (2021a) observed that raising the pyrolysis temperature from 500 °C to 800 °C led to an increase in the pH of biochar derived from sheep bone, from 8.82 to 10.55.

3.2.4 Cation Exchange Capacity (CEC)

CEC refers to the ability of soil to adsorb or hold exchangeable cations (Kumar Mishra et al. 2023). Due to its negative surface charge, biochar is well-suited for cation exchange. Various minerals present in biochar, such as Mg, K, Ca, and Na, accelerate the formation of surface functional groups, leading to a high CEC value for biochar (Kumar Mishra et al. 2023). Increasing temperature can result in high CEC values for biochar. Pyrolysis temperature can substantially impact the CEC values of the resulting biochar. For instance, raising the temperature from 500 °C to 800 °C for sheep leg bones resulted in biochar with higher CEC values due to changes in biochar surface chemistry and porosity (Alkurdi et al. 2020). On the other hand, the mixed vegetable waste pyrolyzed at 400 °C had high CEC and its application resulted in improved CEC values for soil. Improved CEC values indicate reduced nutrient loss and improved water retention capability, which are essential for plant growth (Pradhan et al. 2022).

3.3 Activation of biochar

Biochar, known for its high surface area and well-structured pores, presents a promising low-cost substitute for activated carbon. However, biochar produced via conventional pyrolysis often lacks the pore characteristics of commercially available activated carbon (Venkatachalam et al. 2023; Hu et al. 2021). To improve its properties, physical and chemical treatments can be employed to upgrade low-quality biochar into activated carbon. Physical activation typically requires high temperatures in the presence of inert gases, while chemical activation often uses acids to enhance the biochar's surface area.

3.3.1 Physical activation

The physical activation process involves heating biochar to temperatures between 700 °C and 900 °C in the presence of CO_2, air, or steam (Venkatachalam et al. 2023). Activated carbon (AC) produced by physical activation is

Table 6 Physio-chemical properties of FW derived biochar

Feedstock	Temperature (°C)	C (%)	H (%)	O (%)	pH	Pore volume (cm^3 g^{-1})	Surface area (m^2 g^{-1})
Sheep bone (Azeem et al. 2021a)	500	11	-	29.2	8.82	11.50	90.8
Cow bone (Azeem et al. 2021b)	500	10.8	3.69	15.6	8.2	0.235	190
Cauliflower leaves (Ge et al. 2020)	120	59.71	7.02	23.57	6.47	-	<5
Kitchen waste (Xu et al. 2021)	300–600	56.88–60.46	5.89–1.67	27.99–17.79	7.25 ± 0.08 - 9.76 ± 0.02	-	1.19–10.27
Crab shell (Dai et al. 2017)	300–900	25.21–9.08	2.21–0.89	-	11.5-13.9	0.012–0.048	3.52–48.44
Sugarcane Bagasse (Haghighatjou and Shirvani 2020)	600	46.90	0.58	4.45	11.8	3.97	6.93
Pineapple peel (Otieno et al. 2021)	400	87.6	-	8.3	-	0.082	140
Spent mushroom (Zhang et al. 2020)	350–750	17.53–12.17	1.32–0.26	13.49–4.65	8.83–11.82	0.045–0.091	36.20–37.08
Spend coffee grounds (Andrade et al. 2020)	850	75.29	-	14.11	-	0.238	492
Tea leaves (Altaf et al. 2021)	500	63.70	4.69	33.26	-	0.093	81.78

clean and can be directly used. Hence, it does not require cleaning and avoids equipment corrosion and environmental pollution (Zhang et al. 2024). There are two types of physical activations, and both discussed below.

Steam activation Steam is commonly used for biochar activation (Table 7). Initial porosity is induced in the biochar through pyrolysis, while steam activation increases porosity further (Zhang et al. 2024). During the activation process, three effects occur when H_2O reacts with carbon: the removal of volatile materials, the creation of new micropores, and the additional expansion of the existing pores (Tan et al. 2017). As a result of steam activation, a significant increase in the volume and surface area of micropores in the biochar has been observed. Steam activation also increases the specific surface area of biochar and improves its structure (Tan et al. 2017). For example, Barszcz et al. (2024) derived biochar from apple waste using pyrolysis. They also employed steam activation to produce biochar with an increased number of micropores. Bélanger et al. (2024) derived biochar from corn starch waste using pyrolysis and then activated the biochar with steam. The study observed that the steam-activated biochar had a larger mean pore size.

Gas activation During this process, the gas interacts with the surface of the biochar, creating more mesoporous and microporous structures. As a result, biochar's pore volume and surface area increase (Tan et al. 2017). Various gases, such as air, NH_3, CO_2, O_2, N_2, or their combinations, can be used to activate the biochar. Among these, CO_2 is commonly employed. Following the Boudouard reaction, CO_2 reacts directly with the char (Tan et al. 2017). Wang et al. (2021) used CO_2 to activate food-derived biochar and found that CO_2 activation enhanced the lead adsorption capacity of the biochar. Yek et al. (2020) used microwave pyrolysis of orange peel waste to prepare biochar. In this study, they used both steam and CO_2 for activation purposes and found that CO_2 helped to produce more micropores in biochar. Plaza-Recobert et al. (2017) performed CO_2-based activation on loquat stones derived from biochar and obtained a significant number of micropores. Similar results were obtained by Ahmad et al. (2021) for dragon fruit waste.

3.3.2 *Chemical activation*

Compared to physical activation, chemical activation yields more AC, resulting in a better-developed microporous structure in the biochar and requiring a lower pyrolysis temperature (Sivaranjanee et al. 2024). Chemical activation is a one-step process in which oxidizing chemicals are combined with biochar and then subjected to pyrolysis. To ensure that the functionalized chemical groups are available for sorption and to remove any excess or residual chemicals, the resulting activated biochar is rinsed (Sivaranjanee et al. 2024). Various techniques, including impregnation with nanoparticles, oxidation, sulfonation, and amination, have been employed for chemical activation. Acids, oxidants, and bases, such as H_3PO_4, HNO_3, H_2O_2, NaOH, and KOH, are commonly employed as modifying agents in this process (Table 8). Along with these, SO_3H and $ZnCl_2$ are also used as modifying agents (Sivaranjanee et al. 2024).

The selection of these agents depends on the specific application of the biochar. For example, bases are used to introduce a positive charge to the biochar's surface when it is intended to adsorb negatively charged substances. This creates a significant affinity between the sorbent and the sorbate. Conversely, acids are used to introduce a negative charge to the biochar's surface, enhancing its ability to adsorb positively charged substances (Sivaranjanee et al. 2024). Several studies have reported on the chemical activation of FW. For example, some studies used $ZnCl_2$ to activate biochar derived from fruit waste and found that the derived activated carbon (AC) exhibited an excellent surface area (Feitoza et al. 2022; Georgin

Table 7 Physical activation of FW derived biochar

Feedstock	Activation temperature (°C)	Reaction time (min)	Physical agent	Pore volume ($cm^3\ g^{-1}$)	Surface area ($m^2\ g^{-1}$)	Reference
Coconut shell	850	60	CO_2	0.72	1152	(Patra, et al. 2021a; Tsai and Jiang 2018)
Almond shell	950	60	Steam	-	1261	(Nazem et al. 2020; Patra et al. 2021a)
Pistachio shell	950	30	Steam	-	1196	(Nazem et al. 2020; Patra et al. 2021a)
Coffee residue	700	120	Steam	0.33	641	(Patra et al. 2021a; Tehrani et al. 2015)
Pine nutshell	850	80	Steam	-	1058	(Chen et al. 2016; Patra et al. 2021a)
Walnut shell	950	60	Steam	-	1248	(Nazem et al. 2020; Patra et al. 2021a)
Tea waste	800	30	Steam	0.68	995	(Patra et al. 2021a; Zhou et al. 2018)
FW	700	60	Steam	0.06	101	(Patra et al. 2021b)

Table 8 Chemical activation of FW derived biochar

Feedstock	Activation method	Activation agent	Pore volume (cm^3 g^{-1})	Specific surface area (m^2 g^{-1})
Plum (Pap et al. 2017)	Chemical	H_3PO_4	0.48	829
Pineapple (Zhu et al. 2019)	Chemical and HTC	$K_2C_2O_4$	0.92	1076.3
Dragon peel (Jawad et al. 2021)	Chemical	KOH	-	756.3
Banana peel (Zhang et al. 2023)	Chemical	$MnCl_2$/KOH	0.706	1276.63
Banana peel (Sreńscek-Nazzal et al. 2024)	Chemical	KOH and Urea	0.718–1.487	1653–2718
Amazonian fruit (Serafin et al. 2021)	Chemical	KOH	0.68–0.79	1824–2004
Wine stone (Arslanoğlu 2019)	Pyrolysis	HCl	0.7767	1814.6
Food waste (Viet et al. 2023)	Chemical	HCl	0.375	336.4
Fish bone (Rashed et al. 2023)	Chemical	HNO_3, NaOH, H_2O_2, and ethanol.	0.25	99.8
Food waste (mixed) (Jia et al. 2024; Yuan et al. 2022)	Chemical	KOH	0.41	807

et al. 2021). Similarly, KOH has been used as activation agents by these studies and reported the same findings (excellent surface area of AC) (Jawad et al. 2021; Serafin et al. 2021).

Despite significant benefits of these methods, challenges remain, particularly the high energy consumption associated with physical activation (Sajjadi et al. 2019) and the use of hazardous chemicals in the chemical activation process (Sajjadi et al. 2018). Since biochar activation has these challenges, an alternative approach is to explore its direct use in various fields.

4 Biochar potential applications

Australia faces significant challenges related to FW, as described in section 1. This has profound environmental and economic implications, including the consumption of valuable resources like water and energy, as well as GHG emissions from landfilling. The Australian government has set an ambitious goal to halve the nation's FW by 2030, recognizing the need for sustainable and efficient waste management systems (FIAL 2021). Biochar production from FW, particularly through pyrolysis, presents a promising solution.

The climate change impacts of FW are particularly relevant in Australia, where agricultural practices contribute significantly to GHG emissions, with agriculture accounting for more than half of Australia's methane emissions (Climate Council 2024). Biochar, a stable, carbon-rich material produced from FW via pyrolysis, could mitigate some of these emissions. Its ability to sequester carbon for long periods, combined with its beneficial effects on soil fertility, makes it an attractive option for both waste management and climate change adaptation. Biochar's role in addressing climate change extends beyond its carbon sequestration potential. By improving soil health, biochar can increase agricultural productivity, which is vital given the challenges posed by droughts and low soil fertility in many regions. The adoption of biochar can help reduce the environmental footprint of Australian agriculture by improving soil structure, enhancing nutrient cycling, and reducing the need for chemical fertilizers, which are significant sources of GHG emissions. Biochar produced from FW could also be integrated into the circular economy model, where waste is repurposed into a valuable resource that benefits both the environment and the economy.

Biochar can offer a multifaceted solution to Australia's FW problem while also helping the country address the broader challenges posed by climate change. Its ability to improve soil quality, reduce GHG emissions, and provide a sustainable way to manage FW aligns well with national and global sustainability goals. Numerous studies have explored various uses for biochar. Biochar has been reportedly used as adsorbent (Pradhan et al. 2024). Beyond its application as an adsorbent, biochar-derived activated carbon can also be utilized as a component in electrodes for energy storage devices, such as lithium-ion batteries (Yang et al. 2024a, b). In this study, we propose its potential applications in Australia, particularly in the context of climate change impacts.

4.1 Improving soil health

Due to climate change, Australia will face significant consequences. For example, one online source mentions that by 2050, average rainfall will decrease by 20%–30%, and droughts will become more severe due to climate change. The same source reported that 99% of New South Wales

(NSW) will be affected by drought (NSW Government 2024a). Another work mentioned that Australia will encounter more multi-day fire events due to climate change (Peace and Mccaw 2024). These events will have a significant impact on soil organic carbon (SOC).

SOC is widely used to assess soil health and plays a key role in mitigating climate change. SOC increases with an increase in rainfall and decreases with an increase in temperature depending on the vegetation type, microbial activity, soil texture and land management practices. Lower SOC levels indicate poor soil health and can hamper agricultural productivity in that region. With climate change intensifying temperature rise and altering rainfall patterns, SOC loss is expected to accelerate, contributing to increased CO_2 emissions. A recent study indicates that Australian soil will emit a significant amount of CO_2 due to climate change, resulting from the loss of soil organic carbon (SOC) (Viscarra Rossel et al. 2024). In another work published by the New South Wales (NSW) government, SOC stocks in the upper interval (0–30 cm depth) across NSW and the Australian Capital Territory (ACT) are currently distributed as follows: less than 20 tonnes per hectare (t ha^{-1}) in the far western part and over 100 t/ha in the eastern highlands (NSW Government 2024a, b). However, due to climate change, NSW is projected to see an average decline of 2.5–5.1 t ha^{-1} in SOC stocks over the upper interval in the near (2030) and far future (2070) (Fig. 6; NSW Government 2024b). This will lead to a reduction in agricultural productivity until appropriate measures are implemented.

Many studies reported that FW-based biochar can increase SOC. For example, a study indicates that using vegetable and fruit waste biochar could result in an increase in SOC by 90.10% and 88.61%, respectively (Liu et al. 2023). Losacco et al. (2024) also observed an increase in SOC using biochar derived from mixed vegetable wast. The same result was observed for biochar derived from peanut shells (Xia et al. 2024), banana peel waste (Sial et al. 2019a), walnut shells (Sial et al. 2022), cow bone (Azeem et al. 2021b), waste bones (Um-E-laila et al. 2021), sheep bones (Azeem et al. 2021a), and corn residue (Yang et al. 2020).

However, biochar derived from FW can negatively affect soil biota. Due to high concentrations of soluble ammonium (NH_4) and sodium (Na), biochar from FW exhibited strong inhibition effects on soil organisms (Raček et al. 2024; Domene et al. 2015). These impacts were evident in both uncharred FW and its corresponding biochar, with the inhibition becoming more pronounced at higher application rates. Even if this application shows great potential, more detailed research is needed to understand the long-term impacts of FW-based biochar and to develop strategies to address this issue effectively.

4.2 Greenhouse gas (GHG) reduction

Agriculture in Australia is responsible for significant GHG emissions. According to an older report, emissions from the agricultural sector are projected to reach 132.51 million tonnes (Mt) CO_2 -eq by 2050 (The CIE 2013). Most of this emission will come from enteric fermentation (primarily responsible for methane, CH_4), followed by agricultural soils (nitrous oxide, N_2O), manure management (which emits both CH_4 and N_2O), agriculture residue burning (emission of various GHG gas) and rice cultivation (also a source of CH_4).

FW-derived biochar can be used to reduce these GHG emissions. For example, the amendment of corn residue derived biochar was found to reduce cumulative CO_2, CH_4, and N_2O emissions from the corn field (Yang et al. 2020). The same result was also obtained for banana peel waste derived biochar (Sial et al. 2019a). The study compared the effects of banana peel waste amendment with biochar derived from banana peel waste and found that applying the biochar to winter wheat-maize rotation cropland effectively reduced greenhouse gas emissions. Specifically, it decreased CO_2 emissions by 20.2%–42.2%, N_2O emissions by 35.48%–54.54%, and CH_4 emissions by 16%–43% compared to the peel waste amendment.

However, an opposite trend is also observed. The implementation of biochar may increase emissions. For example, compared to orange peel waste amendments, orange peel waste-derived biochar reduced CO_2 emissions by approximately 71%–88%, CH_4 emissions by 28%–39%, and N_2O emissions by 36%–50% in the wheat-maize rotation cropland. However, it increased total CH_4 emissions by 300% compared to the control (no treatment done on soil) (Sial et al. 2019b). Biochar produced from walnut shells increased CO_2 emissions by approximately 50%–73%, but decreased N_2O emissions by 36%–65% on the wheat-maize cropland compared to the control (Sial et al. 2022). These studies indicate that process parameters, such as temperature and the source of FW need to be carefully chosen to produce biochar suitable for reducing greenhouse gas (GHG) emissions.

4.3 Circular economy application: alternative use of biochar

Construction requires significant resources and generates substantial emissions. It is predicted that Australia will need around 7.5 billion tonnes of materials for construction purposes by 2060, which will result in approximately 2.6 billion tonnes of CO_2-eq emissions by the same year (Soonsawad et al. 2022). This will put significant stress on virgin materials and the environment.

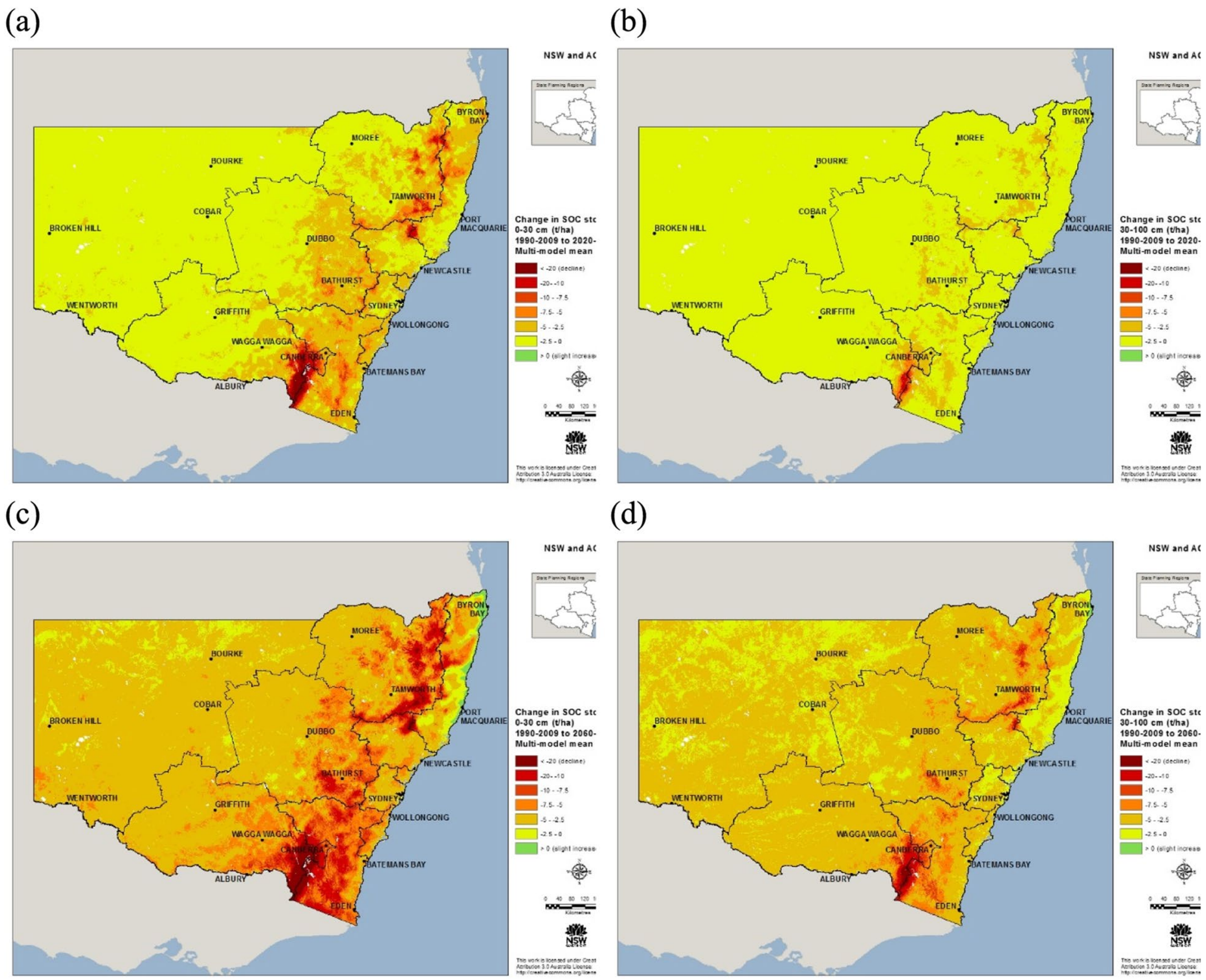

Fig. 6 Climate change impact on SOC across NSW and ACT. **a** change in SOC at 0–30 cm (t ha^{-1}) in the near future (**b**) change in SOC at 30–100 cm (t ha^{-1}) in the near future (**c**) change in SOC at 0–30 cm (t ha^{-1}) in the far future (**d**) change in SOC at 30–100 cm (t ha^{-1}) in the far future (NSW Government 2024b). Please check the supplementary file for an improved version of the figure

FW derived biochar may be used as an alternative construction material for climate change mitigation and to reduce the pressure on virgin resources. Researchers have explored FW derived biochar's performance in construction applications. For example, Chen et al. (2024) used FW digested-based biochar as an aggregate in cement composites and found that it meets all the conditions for high-strength, lightweight concrete. Gupta et al. (2018) studied the potential of FW (meat, bones, pasta, noodles, vegetable matters, and rice) and mixed wood sawdust-based biochar as an additive in cement mortar and found that it can be successfully used for this purpose. Peanut shell-based biochar was also used in cement mortar, and it was found that adding 3 wt% of biochar can increase compressive strength by 18%–20% at 7 days (Gupta and Kashani 2021). However, some challenges have also been reported. For instance, one study found that adding biochar to cement mortar and replacing sand in concrete can lead to a decrease in flexural and compressive strength (unsuitable for load bearing structures like buildings), respectively (Legan et al. 2022), then the mechanical properties of the obtained composites must be investigated in detail.

5 Sustainability

Biochar derived from FW pyrolysis offers a promising solution for addressing various environmental challenges, including waste management, soil health, and climate change mitigation. However, for biochar production to be considered a truly sustainable technology, several key factors must be considered, including feedstock selection, production methods, technological advancements, and market development. Sustainable biochar production involves several key criteria to ensure minimal environmental impact while maximising the benefits of this carbon-rich material. The heat required for pyrolysis, the thermochemical process used to produce biochar, is typically supplied by the combustion of fuel. For biochar production to be sustainable, the fuel used must come from renewable biomass sources, ensuring that the process does not contribute to the depletion of non-renewable resources. Among the various pyrolysis technologies, slow pyrolysis using biomass fuel is considered the most suitable for producing biochar with high yields, aligning with sustainability goals.

Sustainability in biochar production also relies on efficient energy use. The process should be designed to optimize energy consumption, with efforts made to recover waste heat and minimize energy losses. This helps reduce the overall carbon footprint of biochar production, making it a more environmentally friendly option compared to other waste management methods (Ducoli et al. 2023). In addition, it is essential to manage the pyrolysis exhaust gases effectively. These gases should be treated to meet environmental standards, preventing harmful emissions that could contribute to air pollution or climate change. Moreover, sustainable biochar production ensures that there is no direct contact between water and the pyrolysis products, avoiding any potential negative impacts on water resources (Afshar and Mofatteh 2024). Another important criterion for sustainable biochar production is the reburning of volatile gases produced during the pyrolysis process. By utilizing these gases, biochar production can become more energy-efficient and self-sustaining. These sustainability criteria, including the use of renewable fuels, efficient energy management, proper exhaust gas treatment, and the recycling of volatile gases, are essential to ensuring that biochar production can contribute to long-term environmental and economic sustainability (Zhu et al. 2022).

6 Challenges and future research of FW biochar in Australia

We have shown that FW conversion to biochar shows many potentials. However, this also faces several challenges in Australia. Through its national FW baseline, the country has begun identifying the major FW streams and their quantities. Nonetheless, variations in the physical and chemical properties of FW over time and across locations complicate the assessment of its biochar potential (Talekar et al. 2023). Access to this information is essential for investment purposes, and this can be achieved in collaboration with academic institutions. Additionally, FW has a high-water content, making it difficult to store and handle. There is also a lack of techno-economic analyses regarding large-scale FW drying technologies (Talekar et al. 2023). Solar-powered pyrolysis is an effective solution for Australia considering Australia's enormous solar resource potential (Hamilton et al. 2020). Furthermore, the production and utilization of biochar encounter obstacles such as limited investment, high production costs at a small scale, and the absence of large-scale production facilities (ANZ Biochar Industry Group 2022). Subsidies can be provided to reduce high production costs and encourage investment in biochar production.

Future research should focus on addressing these challenges while exploring new applications and scalability. One key area would be optimizing the biochar content in cementitious materials to minimize the reduction in compressive and flexural strength. Research should also explore how biochar can be mixed with other materials to improve its bonding with cement. Another potential focus would be studying the long-term effects of FW-based biochar, particularly the impact of high concentrations of soluble ammonium and sodium on soil biota. Efforts should be directed toward developing pre-treatment or treatment methods to mitigate these adverse effects while retaining the benefits of biochar.

7 Conclusion

This study highlights the potential of converting FW in Australia into biochar as a sustainable solution for managing Australia's substantial FW problem, which amounts to approximately 31.2 million tonnes annually. This waste represents a significant environmental and economic burden, particularly in terms of water use and greenhouse gas emissions. By leveraging pyrolysis technologies to convert FW into biochar, this process not only reduces waste but also contributes to climate change mitigation and improves soil health, particularly in Australia, where soil fertility is often low. The use of biochar derived from FW aligns with Australia's ambitious goal of halving FW by 2030, as outlined in the National FW Strategy

Despite the promising benefits, the production of biochar from FW is not without challenges. Variations in feedstock composition and the need for careful control of process parameters, such as temperature, pressure, and residence time, can affect the quality and yield of biochar. Additionally, while biochar can offer significant benefits for soil improvement and greenhouse gas reduction, further research is needed to optimize production methods and address potential environmental concerns, such as the impact of biochar on soil biota. The adoption of sustainable biochar production methods, coupled with government support and technological innovation, could provide Australia with a powerful tool to reduce FW, mitigate climate change, and promote circular economy practices.

Future research should focus on refining biochar production processes, understanding the long-term environmental impacts, and exploring the broader applications of biochar, particularly in agriculture, construction, and energy storage. By overcoming existing challenges and scaling up production, biochar could become a key element in Australia's strategy to address both FW and climate change.

Abbreviations

AD	Anaerobic Digestion
FW	Food Waste
HTC	Hydrothermal Carbonization
MP	Microwave Pyrolysis
WtE	Waste Management techniques

Supplementary Information

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Supplementary Material 1.

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Declarations

Competing interests
Authors declare no competing interest.

Author details
[1]Department of Computer Science and Engineering, University of Science & Technology Chattogram (USTC), Chattogram 4202, Bangladesh. [2]School of Photovoltaic and Renewable Energy Engineering, University of New South Wales, Sydney, New South Wales 2052, Australia. [3]School of Chemical Engineering, University of New South Wales, Sydney, New South Wales 2052, Australia. [4]INSTM and Chemistry for Technologies Laboratory, Department of Mechanical and Industrial Engineering, University of Brescia, Via Branze 38, Brescia 25123, Italy.

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