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Sustainable food waste management: a critical review on biochar production and applications

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As per the FAO's estimation (Food and Agriculture Organization, USA), approximately 1.3 billion tons of food are wasted yearly, accounting for around 33% of global food production, releasing millions of tonnes of greenhouse gas (GHG) emissions on a global scale. The predominant techniques for handling food waste involve landfilling, incineration, and composting, all of which come with substantial emission-related challenges and are considered unsustainable. In contrast, advanced thermal processes such as pyrolysis and gasification have proven to be environmentally sustainable alternatives and can convert organic food waste into valuable resources such as H_2-rich gas, bio-oil, and biochar. Among these products, biochar stands out due to its numerous benefits, encompassing energy generation, carbon sequestration, climate change alleviation, soil enhancement, and wastewater treatment. This paper presents a state-of-the-art review of food waste biochar (FWBC) production and application. FWBC applications as carbon capture adsorbents, fuel, catalysts, and supercapacitors and in wastewater treatment, along with modelling and optimisation/life cycle analysis, are also reviewed. The literature review highlighted that FWBC has immense potential for carbon capture, wastewater treatment and as a catalyst. However, the research is lacking in industrial applications of biochar, and such data are scarce. Furthermore, biochar modifications improve biochar characteristics, which rely greatly on chemical processes. The paper concludes by proposing future perspectives and potential directions for the sustainable utilization of food waste through biochar production and application. The conversion of food waste into biochar holds immense potential to significantly advance the cause of sustainable food waste management.

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Sustainability spotlight

Recent literature underscores the urgency of addressing the multifaceted challenge of food waste, emphasizing its interconnectedness with broader sustainability goals. The production of biochar from food waste through thermochemical conversion not only substantially reduces the accumulation of food waste but also holds promising prospects for environmental applications such as carbon sequestration, wastewater treatment, biofuel production, energy recovery and soil enhancement. Biochar from various biomass sources has been studied in detail. However, there is no review that centres on the utilization of food waste-derived biochar (FWBC) mainly for environmental and energy applications. This is the first of its kind, and it encompasses a comprehensive exploration of practical applications of FWBC, including carbon capture, fuel, catalysts, supercapacitors and wastewater treatment. The review also highlights the modelling and optimization analysis and life cycle assessment of turning food waste into biochar. Sustainable food waste management is expected to be crucial in mitigating climate change and achieving carbon neutrality, which is in line with the Sustainable Development Goals of the United Nations. This thorough analysis seeks to provide significant advantages to researchers, especially those working on food waste management and establishment of a circular carbon economy based on food waste.

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1. Introduction

Food waste is a serious worldwide issue with significant effects on the economy, society, and environment. Approximately one-third of the food produced for human consumption worldwide is estimated to be wasted each year by the Food and Agriculture Organisation of the United Nations (FAO).[1] Food waste is a problem that affects every stage of the food supply chain, from preparation and distribution to consumption and distribution. A large amount of food is thrown away in both rich and developing nations because of factors such as spoiling, overproduction, ineffective distribution, and consumer behaviour.[2,3] In developed nations, supermarkets and households frequently dispose of large amounts of edible food at the end of the supply chain, resulting in consumer-driven waste.[4] In contrast, in developing nations, inefficiencies in transportation, insufficient infrastructure, and subpar storage facilities cause problems mostly in the early phases of the supply chain. According to published research, the amount of food lost in wealthy nations is equal to the entire amount of food produced in sub-Saharan Africa.[2] The socio-economic dimensions of food waste are accentuated by the paradox of hunger amidst abundance. Kummu *et al.* (2012)[5] conducted a comprehensive analysis, revealing that food losses and waste contribute to resource inefficiencies, placing an economic burden estimated in the trillions of dollars annually. In addition, resources such as water, energy, and land are wasted in the production, processing, and transportation of discarded food. Water resources are also impacted by food waste; an estimated 250 cubic kilometres of water, or the yearly flow of Russia's Volga River, is consumed in the production of discarded food.[5] Furthermore, the environmental consequences of food waste extend beyond the sheer volume of discarded food. Because food waste contains a lot of organic matter, inappropriate handling, such as open dumping, can cause the organic matter to decompose and emit a considerable amount of greenhouse gases, including methane, into the environment.[6–8] Therefore, the food wastage not only squanders valuable resources but also generates substantial greenhouse gas emissions, contributing to climate change. These startling figures highlight the critical need for efficient methods of managing food waste that not only lessen their negative effects on the environment but also support sustainable practices.

Governments and international organizations are increasingly recognizing the urgency of addressing food waste and implementing regulatory measures and policy initiatives. The European Union's commitment to reducing food waste by 50% by 2030 exemplifies global efforts in this direction.[9] Food recovery programs, facilitated by non-profit organizations and technological platforms, aim to redirect edible but surplus food from retailers, restaurants, and farms to food banks and charitable organizations.[4] These initiatives not only address hunger but also contribute to minimizing food waste. Changing consumer behavior is a fundamental aspect of effective food waste management. Strategies include educational programs, nudges in retail settings, and the promotion of mindful consumption practices.[10] A paradigm shift toward circular economy approaches is gaining traction in the discourse on food waste management. Circular economy models emphasize the importance of minimizing waste, promoting recycling, and creating closed-loop systems. Food waste is transformed into valuable products including methane, bioethanol, syngas, chemicals, and carbon materials, mostly from organic components such as proteins, fats, carbs, and lipids.[11,12] Recent literature explores the concept of converting food waste into valuable resources through various treatment techniques such as physical, chemical, and biological.[13–15] For example, the biological conversion process, anaerobic digestion (AD), has been the subject of extensive research for the conversion of food waste into value-added products. Its noteworthy benefits, which include affordability, comfortable operation conditions, and comparatively low energy usage, are the reasons for this attention.[16] However, it's important to remember that AD usually requires a long residence period and high-quality feedstock.[17,18] Furthermore, because post-consumer food waste is so diverse, there are now barriers to the chemical or biological conversion of food waste into valuable commodities. The economic conversion of post-consumer food waste into useful resources is hampered by this heterogeneity.[19] Thermochemical conversion, as opposed to the previously discussed biological conversion, is distinguished by its speed and ability to produce high yields of value-added products.[20,21] As a result, popular upcycling techniques include thermochemical transformations including gasification, pyrolysis, and hydrothermal carbonisation (HTC).[22,23]

In recent times, the transformation of food waste into advanced carbon materials has emerged as a paradigm shift, moving away from traditional practices such as landfilling and incineration.[24] One promising avenue in this regard is the utilization of food waste for biochar production, an innovative and environmentally friendly approach gaining traction in recent years.[25] The production of biochar from food waste not only diverts organic material from landfills but also transforms it into a valuable resource with diverse applications. Biochar is a carbon-rich material characterised by high porosity and thermal stability derived from the thermal degradation of a diverse range of biomass feedstocks.[26,27] Historically, farmers have utilised biochar, a carbonaceous substance renowned for its stability and resistance, to enhance the quality of the soil. Pyrolysis, gasification, hydrothermal carbonisation, torrefaction, and other carbonisation methods can be employed to generate biochar.[28,29] Food waste biochar can be generated using a range of techniques, including carbonisation, gasification, and pyrolysis.[30]

Fig. 1 shows that biochar has become a viable option for managing food waste and a variety of other environmental uses. The generation of biochar from food waste is now much more efficient and scalable because of advances in pyrolysis technology. The quality and properties of the resultant biochar are dependent on the optimisation of pyrolysis parameters, including temperature, residence time, and feedstock content.[31,32]

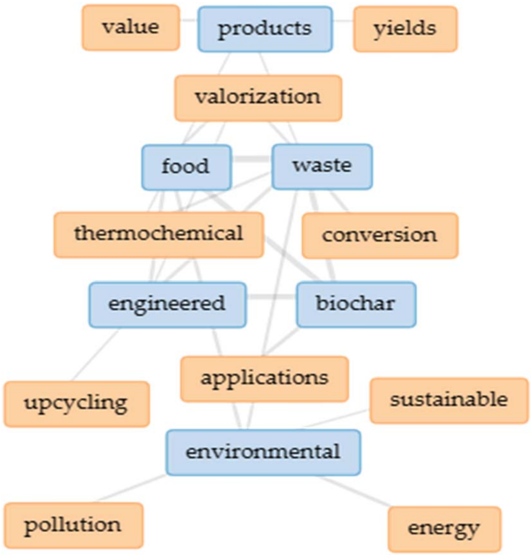

Fig. 1 Overview of the thermochemical conversion of food waste into biochar for diversified environmental applications.

The production of biochar from food waste through thermochemical conversion not only substantially reduces the accumulation of food waste but also holds promising prospects for environmental applications such as carbon sequestration, wastewater treatment, biofuel production, energy recovery and soil enhancement.[33,34] Biochar is an emerging product designed to enhance soil fertility and promote plant growth across various agricultural soil types. It holds distinct advantages over compost, offering long-term carbon sequestration and soil remediation. Additionally, biochar production does not generate odors, allows for simultaneous energy generation, and boasts ease of storage and transport.[35] Notably, carbon black and other additives sourced from petroleum can be replaced by biochar in polymers. There are benefits of adding biochar to plastics, including decreased weight, increased strength, and improved electrical conductivity. Electrical conductivities of biochar generated at 900 °C typically range from 0.03 to 4 S cm^{-1}.[36] The addition of catalysts may be able to achieve higher conductivities. The conversion of food waste into carbon filler offers a dual strategy to upcycle this significant waste stream and reduce reliance on carbon filler materials generated from fossil fuels, provided that food waste as filler can produce comparable performance benefits to other fillers.[19] While the production of biochar from food waste holds immense promise, challenges remain. These include the need for standardized quality parameters and scaling up production for broader implementation. Recent literature underscores the urgency of addressing the multifaceted challenge of food waste, emphasizing its interconnectedness with broader sustainability goals.

From socio-economic disparities to environmental consequences, technological innovations, and regulatory measures, understanding diverse facets is crucial for formulating effective strategies. Therefore, this review centers on the utilization of food waste-derived biochar for mainly environmental and energy applications. It encompasses a comprehensive exploration of major and emerging biochar production routes from food wastes and practical applications including carbon capture, fuel, catalysts, supercapacitors and wastewater treatment. The review also highlights the modelling and optimization analysis and life cycle assessment of turning food waste into biochar. Sustainable food waste management is expected to be crucial in mitigating climate change and achieving carbon neutrality, which is in line with the Sustainable Development Goals of the United Nations. This thorough analysis seeks to provide significant advantages to researchers, especially those working on the establishment of a circular carbon economy, the thermochemical conversion of food waste into biochar, and the sustainable valuation of food waste.

2. Biochar production technologies

Different feedstock varieties and production methods will undoubtedly result in biochar with distinct properties and performances. Appropriate techniques should be selected based on the optimal operating conditions, which include factors such as heating rate, temperature, operating duration, and the type of biomass. These conditions are crucial in guaranteeing the stability of biochars and ensuring that they fulfil the particular requirements of their intended application.[37,38]

2.1 Combustion

Combustion, the most fundamental and widely employed technique, is the earliest thermochemical conversion method. It consists of burning the biomass feedstock in the presence of oxygen to produce heat or electricity as the primary output. The process of combustion can be summarised as follows:[39,40]

$$C_xH_{y(s)} + O_{2(g)} \rightarrow H_2O_{(g)} + CO_{2(g)}$$

The combustion process occurs at a temperature range of 800–1000 °C, and a moisture level of less than 50% is preferred for the biomass (food waste).[41] Industrial-scale process upscaling presents significant challenges owing to operational and environmental considerations. Through this process, a considerable amount of hazardous pollutants, including nitrogen oxides (NO_x), sulphur oxides (SO_x), and heavy metals, are discharged into the environment. Moreover, corrosion and fouling are also reported in specific types of combustors.[42] Table 1 presents the benefits and limitations of incineration.

2.2 Gasification

Gasification, which occurs in the presence of gasifying agents (air, steam, oxygen, nitrogen, CO_2, or a mixture thereof), converts biomass into a fuel gas (product gas) through the partial combustion of biomass at a high temperature (800–1200 °C). CO, CO_2, H_2, CH_4, H_2O, N_2, and C_xH_y make up the majority of the produced gas, which can be utilised for heat, power, or CHP purposes.[44,45]

Table 1 Advantages and disadvantages of combustion[43]

Advantages	Disadvantages
Decrease the waste volume and weight	Production of a huge amount of flue gases with CO_2
Decrease the landfilling demand	High operating cost and investment
Recovery of the energy (heat or electricity)	High maintenance cost
Handle waste without pre-treatment	Originate hazardous waste that needs safe disposal
Reduce the waste transportation cost	Require a highly trained workforce
Require minimum site area	

Biochar is a byproduct of gasification, together with particulates, tars, ash, and oil. This process is not an efficient method for the production of biochar from food waste, mainly due to its low yield of 10 wt%, with the remainder consisting of liquid (5 wt%) and gaseous products (85 wt%).[46] Gasification chemistry is complex and involves several reaction steps:[38,47,48]

(i) Drying: in this stage, the moisture content of the feedstock is decreased and typically falls within the range of 5% to 35% at temperatures of about 100 °C.

(ii) Pyrolysis: waste undergoes thermal decomposition in the absence of oxygen during this phase. Consequently, biochar and condensable and non-condensable pyrolysis vapours are produced. The condensable portion of the vapours will form liquid tars.

(iii) Oxidation: during this stage, the organic vapours, solid carbonised material, and oxidising agent undergo a chemical reaction, resulting in the production of carbon monoxide (CO). Hydrogen is additionally oxidised to generate water. Sub-stoichiometric amounts of oxygen can induce partial carbon oxidation, which results in the formation of carbon monoxide.

(iv) Reduction: at 800–1000 °C, reduction reactions take place in the absence of oxygen. The primary reactions involved are water gas shift, bounded, and methane reactions.

2.3 Pyrolysis

Pyrolysis is an endothermic process in which the thermal decomposition of biomass occurs in the complete absence of oxygen. Elevated temperatures induce the formation of unstable radicals from chemical bonds within the feedstock (food waste). These radicals subsequently engage in reactions with each other, resulting in the formation of low molecular weight molecules that are more stable.[49,50]

A number of factors, such as the characteristics of the biomass (food waste), the intended products, and the particular pyrolysis method utilised, cause pyrolysis to occur within the temperature range of 280–850 °C. In the same way, pressures can vary from hypobaric to atmospheric to elevated levels.[51] In gasification and combustion processes, pyrolysis is the initial stage. Moreover, pyrolysis can be classified into rapid, intermediate, slow, and torrefaction based on heating rates, solid residence times, reaction temperatures, and product yields.[52] Fast pyrolysis involves heating biomass rapidly to around 500 °C with short solid/vapour residence times, followed by rapid quenching to optimise the synthesis of bio-oil. Slow pyrolysis, on the contrary, occurs at low reaction temperatures, long solid residence times, and gradual heating rates, all of which contribute to the generation of substantial quantities of solid char. Intermediate pyrolysis utilises reaction conditions that fall between those of rapid and slow pyrolysis, thereby producing solids, gases, and liquids with intermediate yields.[53] Table 2 displays the characteristics of these processes.

Table 2 Characteristics of different pyrolysis processes[51]

Process	Conditions (temperature, solid residence time)	Product profile (wt%)		
		Liquid	Solid	Gas
Fast	∼500 °C, seconds	75	12	13
Intermediate	∼400 °C, minutes	40	30	30
Slow	∼300 °C, hours/days	30	35	35

In a study by Selvarajoo *et al.* (2020),[52] banana peels were utilized for biochar production, demonstrating not only effective waste management but also the potential for enhancing soil fertility. Similarly, work by Zhang *et al.* (2023)[53] focused on the pyrolysis of kitchen waste, showcasing the production of biochar with high carbon content and its positive effects on soil nutrient retention. Tang *et al.* (2018)[54] investigated the co-pyrolysis of plastic waste made of polyvinyl chloride (PVC) and organic food waste, namely soybeans. The study's main focus was on the tar and charcoal products that were produced, and it looked at how temperature changes and the materials' makeup affected the pyrolysis process. In an effort to explore the impacts of feedstock characteristics and pyrolysis temperature, Zhang *et al.* (2017)[55] conducted a study. The three additional biomass types (sugarcane, pine, and oak) and peanut shells were used in the research to produce biochar. The potential use of biochars made from digestate from waste food (DFW) for agronomic applications was evaluated in a study conducted by Opatokun *et al.* (2016)[56] at various pyrolysis temperatures. By pyrolyzing potato peel waste (PPW) in a laboratory-scale auger pyrolyzer at 450 °C, Liang *et al.* (2015)[57] reported a biochar production of 30.5%. Animal fats were the subject of a study by Hassen-Trabelsi *et al.* (2014)[58] that looked into another form of food waste. The study revealed that biochars produced through the pyrolysis of animal fats had a high ash concentration and a low carbon content, making them an unappealing option for renewable energy production. More recently, food waste has been turned into energy by the use of microwave irradiation, which can produce bio-oil and solid residue.[59] Liu *et al.* (2014)[60] specifically looked at mixed food waste made up of white rice, vegetable leaves, and meat/bones in a catalytic microwave pyrolysis study.

Food waste primarily comprises lignocellulosic compounds such as cellulose, hemicellulose, and lignin. Each compound follows a unique thermal degradation pathway, depending on the temperature of the process. The various stages involved in the production of biochar from food waste are as follows: moisture is first removed at 100 °C, then hemicellulose begins to degrade between 200 and 260 °C, followed by cellulose decomposition between 240 and 350 °C, and finally, lignin breakdown occurs between 280 and 500 °C. Food waste biochar typically has low pore volume, surface area, and crystallinity due to the physicochemical structure of the feedstock. Thus, additional modifications may be necessary for specific applications, such as chemical, physical, or biological activation methods.[61,62]

2.3.1. Pyroformer. The Pyroformer is a patented intermediate pyrolysis system developed by Hornung and Apfelbacher. A Pyroformer is an auger screw reactor with two coaxially rotating screws enclosing a carbon steel compartment in a horizontal position. The reactor is suitable for biomass with a high ash content, and it functions at a maximum pressure of 1 MPa and employs an external heating system *via* heating bands.[63] A mixture of new feedstock and recycled char fraction is conveyed *via* the internal shaft along the reactor, which is maintained at standard pyrolysis temperatures. As the external screw returns biochar to the inlet zone, feedstock heat transfer increases. The biochar layer hinders fast pyrolysis by regulating the temperature and heating rate of the feed. The Pyroformer discharges any biochar that is not recycled in the reactor through the solid drop-out pipe.[64] A schematic of a Pyroformer is depicted in Fig. 2.

A summary of several recent research studies on food waste pyrolysis is reported in Table 3.

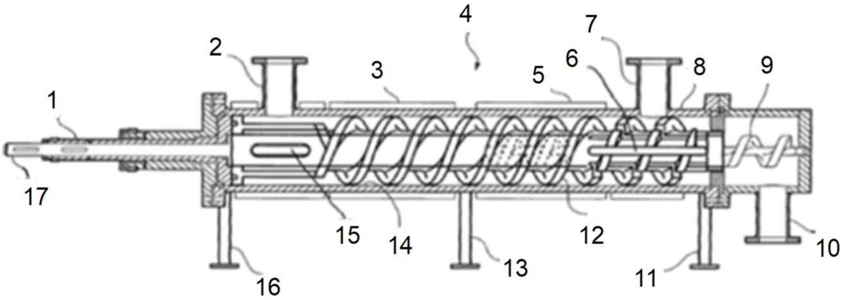

Fig. 2 Pyroformer reactor.[65]

Table 3 Recent research on food waste pyrolysis

Biomass	Operating conditions	Reactor type	Biochar yield (%)	References
Orange peel	Temperature: 400 °C Heating rate: 30 °C min^{-1} Residence time: 2 hours	Batch reactor	33.6	66
Potato peel waste	Temperature: 480 °C Heating rate: 20 °C min^{-1} Residence time: 8 s	Batch reactor	30.5	57
Ceylon tea waste	Temperature: 500 °C Heating rate: 5 °C min^{-1} Residence time: 1–2 s	Fluidised bed reactor	35.7	67
Pine nutshell	Temperature: 550 °C Residence time: 20 min	Fixed-bed reactor	34.11	68
Grape pomace	Temperature: 300 °C Heating rate: 10 °C min^{-1} Residence time: 2 h	Tubular furnace	55.1	69
Digestate food waste	Temperature: 500 °C Heating rate: 10 °C min^{-1} Residence time: 2 h	Tubular furnace	42.97	70
Raw food waste	Temperature: 600 °C Heating rate: 5 °C min^{-1} Residence time: 1 h	Fixed-bed reactor	28.4	71
Food and market waste	Temperature intermediate reactor 450 °C Temperature reformer 700 °C Residence time: 10–20 min	Pyroformer	22	72
Food waste	Temperature: 200 °C Residence time: 30 min	Mini batch reactor	57	73

2.3.2. Engineered biochar. Biochar generated through the previously mentioned methods possesses an unspecified number of functional groups and a restricted surface area and pore structure. The goal of activating biochar is to enhance its texture by forming or removing internal pores, thereby expanding its potential uses.[23,74,75]

In general, physical and chemical treatments are distinguished as activation methods. CO_2, steam, and air at high operating temperatures (up to 1000 °C) are commonly known as physical activation treatments. Increasing textural qualities such as porosity can be achieved relatively cheaply and in an environmentally friendly manner through physical activation treatment. Physical post-modification activation is generally considered more environmentally friendly and has less global warming potential than chemical activation.[76,77] CO_2 gas has emerged as the favoured activating agent owing to its low reactivity, even when subjected to operating temperatures exceeding 700 °C.[78]

Acids (*e.g.*, H_3PO_4, HNO_3, and H_2O_2), bases (*e.g.*, KOH and NaOH), or salts (*e.g.*, K_2CO_3, $ZnCl_2$, and $MgCl_2$) are utilised for chemical activation.[79] The biochar is impregnated with these before chemical activation occurs in an inert gas atmosphere.[80] One of the most effective and widely used methods for producing highly porous biochar is through activation using KOH. The volume and temperature of activation of the chemical agent have a direct impact on porosity. Chemical activation has several advantages over physical activation, such as lower energy consumption due to shorter activation time and lower activation temperature, resulting in higher porosity and yield of engineered biochar production.[80–82]

3. Biochar applications

3.1 Carbon capture

The challenge of decarbonizing industry and its systems is urgent due to limited low-carbon options available for heavy industries such as steelmaking, cement manufacturing, *etc.* Many countries heavily rely on such energy-intensive industrial processes powered by fossil fuels. Given the anticipated industrial growth and the imperative for decarbonization, carbon capture (CC) becomes essential for both economic development and sustainable decarbonization strategies. A promising avenue for carbon sequestration involves using CO_2 sorbents, potentially acting as a sink for CO_2 utilization.[83–85] Adsorption denotes the preferential attraction of substances from gas or liquid phases onto a solid surface. In the realm of carbon capture, various porous materials have undergone testing for their ability to adsorb CO_2 molecules. CO_2 binds to these surfaces through physical and chemical adsorption processes. The efficiency of adsorbents is assessed based on several parameters such as capacity, selectivity, temperature, adsorption/desorption rates, regeneration costs, and so on.[86]

Recent years have seen research into different adsorbents such as zeolites, carbon nanomaterials, mesoporous carbon, *etc.* for CO_2 capture. However, drawbacks such as high production costs and competition in adsorption have hindered their widespread use.[87,88] Lately, biochar has emerged as a potential CO_2 adsorbent owing to its high specific surface area, porous structure, and strong attraction to nonpolar compounds.[89] Since biochar can be produced through pyrolysis from abundant biomass and various wastes, it has become an important tool for carbon capture. Additionally, it's considered an environmentally friendly material for CO_2 capture.[90] Importantly, biochar is highly inexpensive compared to other CO_2 adsorbents, presenting a notable cost-effective advantage.

Igalavithana *et al.* (2020)[91] investigated the adsorption of CO_2 using a combination of FWBC wood waste. They found that biochar from 40% FW resulted in more than 99% recyclability. They also discovered that the micropore development through KOH activation substantially increased CO_2 adsorption. It was also confirmed by Yuan *et al.* (2022).[12] The authors reported that biochar using KOH activation at 600C produced the highest CO_2 uptake of 2.54 mmol g^{-1} at 25 °C. The CO_2 uptake decreased with the rise in temperature and was found to be 1.60 mmol g^{-1} at 50 °C, indicating the dominance of physisorption. The adsorption isotherms were modeled using the Langmuir equation, indicating monolayer adsorption in this CO_2 capture process. They also found that at 25 °C and 1 bar, the CO_2 uptake was around 10 times higher compared to the N_2 uptake at 1 bar. This showcases the superior CO_2 adsorption capability of food waste biochar over N_2, making it a favourable candidate for treating low-concentration CO_2 in flue gases.

The biochar also manifested consistently strong CO_2 adsorption curves, underscoring its exceptional cycle stability, a key factor for practical applications in CO_2 capture. Similar results are also reported by Liu *et al.* (2020)[70] in their studies on coffee grounds based biochar. They activated the biochar using a combined ammoxidation process and KOH activation. They observed that adsorbents treated using melamine *via* ammoxidation methods exhibited well-developed microporosity, substantial nitrogen doping, and higher pyrrolic nitrogen content—known for active adsorption sites. As a result, they demonstrated the highest CO_2 uptake of 2.67 mmol CO_2 g^{-1} of sorbent at 35 °C. Kim *et al.* (2020)[92] developed biochar using spent coffee grounds and activated it using solid-state K_2CO_3. They noted that with increasing activation temperature and duration, the specific surface area and total pore volume increased to 2337 m^2 g^{-1} and 1.15 cm^3 g^{-1}, respectively. Amongst various prepared samples, the porous carbon activated at 700 °C for 5 hours demonstrated the most significant CO_2 adsorption, measuring 4.54 mmol g^{-1} at a temperature of 25 °C and a pressure of 1 atm. Further studies on CO_2 adsorption using food waste biochar are shown in Fig. 3.

Carbon capture using food waste-based biochar is also being explored using machine learning (ML). ML is having a dominant influence across various fields of study, covering physics, chemistry, materials science, *etc.* revealing its considerable potential as a powerful emerging tool for carbon capture applications. It has significant advantages over conventional laboratory experiments as well as computational simulations with regard to the design and optimization of advanced materials. Some of the advantages are swift screening of vast datasets within short time frames, precise anticipation of material characteristics and the real understanding of the intrinsic

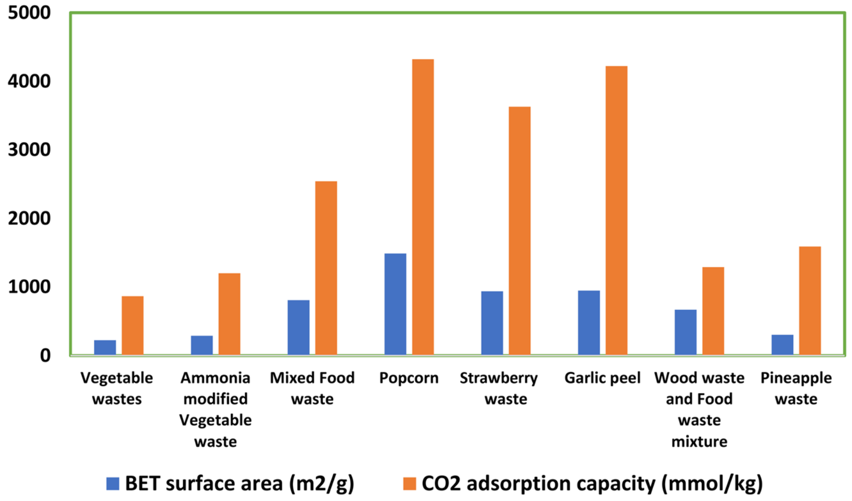

Fig. 3 CO_2 adsorption using food waste biochar.[23,91,93–97]

connection between these characteristics and particular applications.[98] Consequently, researchers are empowered to streamline the design, testing, and improvement of both experimentally and computationally intensive issues of the process.

As the adsorption process presents numerous potential designs and configurations, due to temperature and pressure swings, ML methods can offer extensive support in rapid screening and exploration of these options. Recent investigations conducted over the past few years have shown the potential.[81] The authors used ML to systematically map CO_2 adsorption as a function of its parameters and the adsorbent properties. Sun *et al.* (2019)[99] also created a sophisticated deep neural network model that underwent training using simulation data. This enabled the exact prediction of isotherm, mixture, and equilibrium properties. It resulted in effectively obtaining a continuous isotherm function, optimizing a chemical process.

The biochar use for carbon capture and utilisation has the potential to connect carbon capture objectives for agricultural, urban, and industrial domains. This method, including biochar and soil sequestration techniques, can potentially extract approximately 2.3–5.3 gigatons of CO_2 annually.[100] Furthermore, utilizing food waste to create engineered biochar for CO_2 capture contributes enormously to the attainment of multiple UN SDGs. These include SDG 11: promoting sustainable cities and communities and SDG 13: addressing climate action. It also helps in attaining SDG 12: encouraging responsible consumption and production.[23]

It can be concluded that these adsorbents have huge potential for carbon capture and offer various positives such as cost-effectiveness, renewability, and capability to eliminate various contaminants. Extensive research efforts over the last decade have focused on these materials. However, several challenges thwart the practical, large-scale implementation of biochar-based adsorbents for CO_2 removal. Mainly, existing experiments predominantly employ simulated gas mixtures comprised of pure CO_2 or simple combinations of gases (*e.g.*, CO_2, N_2, and H_2O). Few studies have examined biochar-based adsorbents in practical, large-scale applications, compelling further exploration to develop specific biochar-based adsorbents suited for particular gas compositions in flue gases.[101] In several cases, biochar has shown less carbon capture efficiency than conventional adsorbents.[102] The performance can be adjusted by incorporating modifications, demanding extra costs and increasing the carbon footprint of biochar-based adsorbents. These aspects have not been quantified yet. Furthermore, grasping the principles and mechanisms for biochar regeneration and disposal is equally critical to complete the CO_2 capture and reuse cycle. The regeneration ability remains a key feature. Varying degrees of CO_2 adsorption capacity loss after cycles are reported in the literature, indicating the need for appropriate regeneration techniques.[103–105]

3.2 Catalysts

Catalyst production can be the most expensive aspect of most processes, notably emission control. This has prompted considerable initiatives to recover and recycle discarded catalysts, especially those synthesized or classified as platinum group metals (PGMs). Recently, there has been an increase in interest in the research and development of catalytic materials derived from inexpensive and abundant components on Earth, intending to enhance the overall sustainability of catalytic processes, reduce costs, and minimise the dependence on PGM catalysts.

Biochar, synthesised from a variety of feedstocks such as food waste, exhibits several important characteristics, including surface area, pore volume, gross calorific value, surface functional groups, cation exchange capacity, and structural stability. These features enhance its applicability across multiple catalytic applications. In general, the utilisation of wastes and waste-derived materials in the context of catalytic applications can be categorised as follows:[34,106]

- Direct implementation of waste as a catalyst, pre-catalyst, or support without any pre-treatment.

- Pre-treatment, including physical and/or chemical activation, before the waste's utilisation as a catalyst, pre-catalyst, or catalyst support.
- The selective extraction of chemical components for the preparation of a catalyst, pre-catalyst, or support.

Additionally, the rich pore structure and abundance of surface functional groups, which can be altered in a number of ways, facilitate the catalytic potential of biochar in a wide range of chemical processes, such as chemical synthesis, biodiesel production from biomass, environmental pollution degradation, biomass upgrading, hydrolysis, dehydration, pyrolysis, gasification, and bio-oil upgrading.[13,107] The properties of biochar are greatly affected by the biomass feedstock, modification techniques, and preparation conditions. The catalytic qualities of biochar, which depend on its physical and chemical properties, affect the final product, potential reaction mechanisms, and rate of conversion. In general, the heterogeneous biochar-based catalysts can be categorised into two distinct types: acid and alkali catalysts.

3.2.1. **Biochar-based acid catalysts.** An acid catalyst from biochar is formed through acid treatment, notably when treated with an acid reagent containing sulphur. Sulfonation is the primary method by which biochar is converted to a heterogeneous-acid catalyst. Concentrated sulfuric acid, oleum, gaseous sulphur trioxide, chlorosulfonic acid, sulfamic acid, sulfosalicylic acid, and *p*-toluene sulfonic acid are frequently employed reagents in the sulfonation process.

Direct sulfonation may also be utilised to produce amorphous carbon-bearing SO_3H, COOH, and OH groups from partially carbonised organic substances. This carbon substance exhibited remarkable insoluble Brønsted acid activity, making it highly effective for various acid-catalysed processes, such as hydrolysis. In comparison to niobic acid, H-mordenite, and resins such as Amberlyst-15 and Nafion NR50, these acid catalysts have shown greater reactivity and selectivity for crystalline cellulose, glucose, and cellobiose hydrolyses.[93,94]

Coconut shell biochar has been used as a solid acid catalyst for the co-pyrolysis of corn stover and high-density polyethene for the production of aromatics. The coconut shell biochar was mixed with the nitric acid solution in different concentrations, temperatures, and times to synthesise a solid biochar-based catalyst. The study revealed that higher temperature, longer treatment time, and lower nitric acid concentration significantly improved the catalytic efficiency of biochar in the synthesis of aromatics. Concurrently, these factors decreased the production of aliphatics and oxygenates. The highest aromatic hydrocarbon yield of 56.1% was achieved at 90 °C, with a nitric acid concentration of 1.0 mol L^{-1} and a treatment time of 10 hours.[74]

Sulfonating walnut shell biochar with concentrated H_2SO_4 was prepared as a solid acid catalyst for the transesterification of microalgal oil (*Chlorella minutissima*). The walnut shell was initially pyrolysed at 500 °C, then sulfonated by sulfuric acid at 100 °C for 5 hours. An optimised algal biodiesel yield of 82% was achieved at 65 °C, a reaction time of 60 minutes, a methanol-to-oil ratio of 12 : 1 and a biochar-based acid catalyst concentration of 5 wt%. Moreover, the reusability and stability of the synthesised catalyst were also examined five times under equal transesterification process conditions. The biodiesel yield decreased from 82% to 71% due to the weak interaction between the poly-aromatic hydrocarbon structure and SO_3H.[63]

3.2.2. **Biochar-based alkali catalysts.** An alkali-based biochar catalyst is synthesised through the impregnation of biochar with alkali compounds at high temperatures. Moreover, impregnating biochar with alkali metals can modify its surface chemistry and porosity features. Carbon compounds such as biochar can act as a catalyst for the conversion of NO to NO_2 in the presence of oxygen.[107,108] Anthonysamy *et al.* studied the catalytic oxidation of NO to NO_2 over rubber seed shell biochar at ambient temperature. The biochar doped with Ce was impregnated with different concentrations of cerium nitrate solution and then calcined under N_2 to obtain cerium oxide-loaded biochar.[109] Similarly, Daimary *et al.* studied potato peel biochar as a green catalyst for biodiesel production from waste cooking oil. The pyrolyzed biochar, rich in alkali and alkaline earth metals, was calcined at 700 °C for 3 hours using a muffle furnace. The maximum transesterified biodiesel yield of 97.5% from waste cooking oil was obtained at 60 °C, a methanol to oil ratio of 9 : 1, a reaction time of 2 hours and a biochar catalyst concentration of 3 wt%.[110]

Additionally, biochar can function as a carrier of catalysts.[111] Bitonto *et al.* synthesised nanostructured CaO supported onto avocado seed biochar as a catalyst for the transesterification of waste cooking oil to FAME. The avocado seed was pyrolysed for two hours at 900 °C, with a heating rate of 10 °C min^{-1}. The CaO-supported biochar catalyst was developed by the precipitation process. In short, biochar was initially suspended in an aqueous solution of $Ca(NO_3)_2 \cdot 4H_2O$, and NaOH drops were added to the mixture to acquire calcium hydroxide precipitation. A FAME yield of 96% was achieved by utilising the nanostructured CaO deposited onto biochar (7.3 wt%) at 99.5 °C, with a methanol to sunflower cooking oil molar ratio of 15.6 after 5 hours.[112]

In addition to biodiesel production, bio-oil upgrading, and reforming, the application of biochar-based catalysts can be advantageous in several catalytic processes. In order to facilitate the expansion of these processes, it is imperative to establish biochar production systems at an industrial level. The logistical challenges associated with collecting and transporting raw materials to the facilities that manufacture biochar, in addition to competing end-users, are the most significant obstacles to expanding biochar production. Furthermore, it may be challenging to modify the properties of biochar with the goal of achieving the desired product. In this context, it is crucial to study high surface area, active sites, optimal pores, and activation methods while considering the impacts of important production process variables at a scale-up level.[113]

3.3 Fuels

Direct biochar combustion is frequently utilised in co-firing facilities, where biochar and coal are combined as a feedstock. The physical and chemical composition of biochar is marginally distinct from that of coal. Therefore, the implementation of biochar as a feedstock in coal-firing power plants to generate electricity holds significant promise in mitigating global carbon dioxide emissions.[114] Co-firing refers to the simultaneous combustion of two or more fuels. One notable benefit of the process is its potential for utilisation in an existing facility to sustain the combustion of a novel fuel. This eliminates the necessity to allocate additional financial resources to build a new facility.[115] The production of steel and iron is one of the biggest industries in the world, responsible for around 20% of industrial energy usage. The primary source of this energy comes from coal and coke, leading to significant carbon dioxide emissions globally.[116] Considerable attention has been dedicated to biochar as a potential substitute for thermal power generation and steel-making industries.[117] Safarian conducted a comparative analysis of five distinct biochars derived from varying feedstocks, replacing coal and coke in different energy-intensive stages of the steel manufacturing industry, including coke-making, sintering and blast furnaces.

Generally, biochar must possess specific physicochemical properties, such as a fixed carbon content above 80% and a calorific value greater than 27 MJ kg^{-1}, to be a viable substitute for coke. Biochar can be used in the coke-making process to produce bio-coke. However, the amount of biochar added should be limited to 2–10% to avoid any adverse effects on the end product. When it comes to the sintering process, the ideal range for the substitution of biochar is between 40% and 60% to ensure a high-quality sinter product and maintain a product yield of at least 80%. Biochar has the potential to completely replace pulverised coal and partially replace coke in blast furnace technology.[118] In addition to direct combustion, biochar-derived carbon molecules are used to store and generate electrochemical energy in supercapacitors and fuel cells.[119]

3.4 Fuel cells

Fuel cells are highly efficient technological devices that utilise an electrochemical oxidation reaction to convert chemical energy into electrical energy.[120] In the direct carbon fuel cell (DCFC) technology, the chemical energy contained in solid carbon is transformed directly into electrical energy through an electrochemical oxidation reaction.[121] Jafri *et al.* studied the potential of utilising oil palm kernel shell (PKS) biochar for power generation using DCFC technology. The PKS biomass was initially treated with HCl at different concentrations from 0.1 to 4.0 M for structural modification. The DCFC that utilised the PKS biochar achieved a maximum power density of 3.3 mW cm^{-2} at an operating temperature of 850 °C, resulting in the lowest total cell resistance.[121]

A Microbial Fuel Cell (MFC) is another type of fuel cell that has been increasingly recognised as an effective solution for wastewater treatment and energy recovery. Biochar has recently gained significant attention due to its exceptional conductivity and cost-effectiveness, making it very suitable for utilisation in MFCs.[122] An MFC is a device consisting of two chambers, one anodic and one cathodic, which are separated by a proton exchange membrane. Biochars are applicable to the cathode, anode, and membrane of an MFC.[123]

Despite the apparent viability of the MFC as an alternative to conventional fuel cells, its limited oxygen reduction reaction rate (ORR) of 2.58 electrons per oxygen molecule and low voltage output (0.164–0.221 V) hinder its widespread application. Biochar-based electrodes emerged as a highly viable substitute for the traditional carbon and graphite electrodes employed in MFCs. Due to their superior stability, conductivity (10–100 S m^{-1}), and specific surface area (838–949 m^2 g^{-1}), biochar-based electrodes have the potential to serve as substitute materials for traditional electrodes in MFCs.[124]

Biochar-based activated carbon was produced in a study by modifying granular corn straw with KOH solution and pyrolysing it at 900 °C for one hour. When employed as both the anode and cathode in a bioelectrochemical system, biochar demonstrated superior performance in terms of power density and dye removal from simulated wastewater compared to carbon-felt

Table 4 Biochar-based cathode, anode, and catalyst in MFC studies

Biomass feedstock	Preparation method	MFC	Remarks	Ref.
Coconut shell	Pyrolysis at 500 °C and a rate of 10 °C min^{-1} for 1 hour	Anode	Max power density 38.72 mW m^{-2} Among the biochar-derived anodes tested, copper performed the best in terms of power production, significantly outperforming the zinc anode	126
Watermelon rind	Pyrolysis at 400 °C, 500 °C, 600 °C, and 700 °C for 12 hours; biomass was pre-treated	Cathode	Max power density 0.262 W m^{-3} The biochar sample (pyrolysis at 700 °C): high porosity and irregularity of pore sizes The presence of pyridinic nitrogen and graphitic nitrogen has contributed to high performance in oxygen reduction	127
Eggplant	Pre-activated with potassium trisoxalatoferrate(III) trihydrate; pyrolysis at 800 °C and a rate of 5 °C min^{-1} for 1 hour	Cathode	Max power density 667 mW m^{-2} Pyrolysed biochar with a biomass-activating agent weight ratio of 1 : 2 and pyrolysis at 800 °C, had the biggest power density, more graphitic structure, and most effective chemical oxygen demand removal, recorded as 80.5% Stable performance to catalyse the oxygen reduction reaction for 240 hours	128

electrodes. This was ascribed to the biochar's elevated content of oxidising agents.[125] Table 4 summarises several studies that utilised biochar as a cathode, anode and catalyst in MFCs.

3.5 Supercapacitors

Supercapacitors, classified as ultracapacitors or electrochemical capacitors, have emerged as a promising technology for energy storage owing to their favourable characteristics such as high power density, quick charge–discharge capabilities, and extended cycle life. The electrode material is a crucial component in a supercapacitor and significantly impacts its performance.[119,129] Supercapacitors work by storing charge through the polarisation of ions in the electrolyte when a voltage is applied, causing the ions to be attracted to the surface of the electrode material. An essential characteristic of this material is its reasonably sized pores to accommodate the ions. The charge storage process occurs through redox reactions involving surface functionalities, such as COOH, OH, or N and P-based functional groups.[119] Biochars, distinguished by extensive porosity and substantial surface area, have been reported as an ideal electrode material for supercapacitor applications.[80] The performance of several biochar-based supercapacitors is tabulated in Table 5.

3.6 Wastewater treatment

Rapid industrialization, urban growth, and improved living standards have remarkably increased the demand for water worldwide. This intensified usage leads to the production of huge amounts of wastewater. A considerable portion of this wastewater is released into the environment untreated posing a critical environmental hazard.[135–137] The variety of pollutants found in this wastewater such as heavy metals, pesticides, emerging contaminants, and various organic substances poses significant risks to human health, nutrition, agriculture, and aquatic ecosystems.[138,139]

It has been found that the accumulation of toxic heavy metals in the human body can cause gastrointestinal and kidney dysfunction, hypertension, nervous system disorders, immune system dysfunction, and damage to red blood cells.[140–142] The industrial organic dyes discharged in wastewater have the potential to induce chromosomal abnormalities at very low concentrations. The harmful impacts of pesticides include slight skin irritation or allergic reactions to more serious symptoms such as severe dizziness, headaches, or nausea.[143] Some pesticides such as organophosphates, can potentially lead to convulsions, coma, and possibly, fatal outcomes. Furthermore, antibiotics and various other organics present in wastewater contribute to chronic and acute adverse reactions.[144] As a result, there is an earnest need to develop viable technologies to mitigate environmental pollution caused by untreated wastewater.

Numerous techniques have emerged to address wastewater cleanup efficiently, encompassing advanced oxidation processes (AOPs), adsorption, membrane treatment, *etc.* Despite their distinct mechanisms and operational procedures, all these methods rely on functional materials to attain optimal removal of pollutants.[145,146] Due to its outstanding material properties, FWBC has drawn considerable attention in the wastewater treatment for the removal of heavy metals and organic pollutants. It can be used as a potential adsorbent, for activating oxidising agents, for enzyme immobilization and a composite membrane component.

Xing *et al.* (2021) exploited an environmentally friendly approach to create biofilm-attached biochar from mixed food waste, with the aim to remove Cd and Pb from wastewater. Their findings signalled that modification of the biochar with bacterial biofilm decreased the specific surface area but improved the average pore size and the adsorption efficacy for Cd and Pb.[147] The removal process was found to be mainly driven by electrostatic attraction and complexation. Additionally, competitive adsorption between the two metal ions showed a preference for adsorbing Pb, although a large number of functional groups participated in Cd ion removal. An additional study by Liu *et al.* (2023)[106] determined that FWBC demonstrated remarkable adsorption performance for As(v) with no alterations. The adsorption process seemed to align with Langmuir adsorption, resulting in a maximum As(v) adsorption capacity of 76.764 mg As(v) per g adsorbent.

Table 5 Performance of different biochar-based supercapacitors

Biomass feedstock	Preparation method	Remarks	Ref.
Apple waste	Hydrothermal carbonization at 200 °C and KOH activation	Specific capacitances: 260–290 F g^{-1} engineered biochar with high specific surface area (2000 $m^2\ g^{-1}$)	130
Coffee grounds	One-step carbonization and activation with KOH	Specific energy of 35.4 Wh kg^{-1} at 11 250 W kg^{-1} and 23 Wh kg^{-1} for a 3 s charge and discharge current rate Specific power 30 000 W kg^{-1}	131
Fishbone	One-step carbonization at 850 °C and no chemical activation	Specific capacitance of 476 F g^{-1} Biochar with the specific surface area of 1337 $m^2\ g^{-1}$ N-Doped engineered biochar	132
Orange peel	HTC at 150 °C and KOH activation	High capacitance of 1300 F g^{-1} N-Doped engineered biochar	133
Potato peel	Carbonization with sodium hypophosphite and thioacetamide; KOH activation	S- and P-doped engineered biochar specific surface area of 1912 $m^2\ g^{-1}$ Specific capacitance of 323 F g^{-1}	134

It was also noted that pH value and adsorbent dosage significantly impacted the adsorption process. The authors used density functional theory (DFT) calculations, which highlighted the formation of ionic bonds between arsenic and biochar surfaces. FWBC also effectively removed organic pollutants from wastewater. Viet *et al.* (2023)[148] applied acid-activated food waste biochar to eliminate 4-chlorophenol in wastewater. The activation process particularly increased chlorophenol adsorption by 20%, accomplishing 97.8% adsorption and a maximum chlorophenol uptake of 108.7 mg g^{-1}.

Magnetization of biochar to create magnetic biochar (MBC) has gained increased attention in wastewater treatment owing to its similarity to biochar properties and the added advantage of magnetic separation.[149] MBC is synthesized by combining magnetic materials such as Fe, γ-Fe_2O_3, Fe_3O_4, and BC using methods such as pyrolytic activation and chemical co-precipitation (Qu *et al.*, 2021).[150] Wang *et al.* (2020)[151] produced MBC from pine nut shells for acid chrome K removal, exhibiting enhanced dye removal capacity compared to the original biochar. Moreover, MBC could be easily retrieved from water using an external magnetic field. The authors found that the adsorption process predominantly involved monolayer electric attractions between the charged MBC surface and dye molecules, alongside existing hydrophobic interactions (π–π interaction) among the dye molecules. Likewise, Dong *et al.* (2021)[152] successfully created MBC using pomelo peel to remove phenol. Their findings noticeably yielded the excellent phenol removal capacity of MBC compared to the non-magnetic biochar, with MBC achieving a maximum adsorption of 39.32 mg g^{-1} for phenol.

MBC also demonstrated simultaneous adsorption of Cr(VI) along with phenol. The characterization studies stressed the dominance of physical adsorption due to π–π interactions between the aromatic ring and MBC layers. Chu *et al.* (2020)[153] also observed that MBC from food waste exhibited high efficiency in eliminating dyes (methylene blue and methyl orange) when integrated with heterogeneous ultrasound-assisted Fenton process. The deduction rate of total organic carbon (TOC) from dye-contaminated wastewater reached 60.0% within 3 hours, indicating significant potential for practical applications.

Additionally, biochar-based activation systems have also been reported to degrade antibiotics from wastewater. Wang *et al.* (2023)[154] examined FWBC for sulfamethoxazole (SMX) decomposition. The designed biochar was piled into a fluidized bed reactor and could consistently remove SMX in a municipal wastewater plant. Their findings also implied that higher pyrolysis temperatures enhanced antibiotic elimination by increasing the exposure of more active sites. Similarly, Liang *et al.* (2022)[155] observed that higher pyrolysis temperatures increased TOC deduction. However, higher temperatures also lead to a high cost of the process, impacting the economics of antibiotic removal.

The authors reported that a remarkable 75% removal of SMX from contaminated water was completed in 75 minutes. FWBC also serves as a coagulant aid in wastewater treatment, as demonstrated by Yang *et al.* (2021).[156] Their study reported a significant increase in copper coagulation with increasing doses of FWBC alongside polyaluminum chloride (PAC). Additionally, sludge dewaterability and organic dye removal exhibited enhancements in its presence as a coagulation aid. Moreover, the consolidation of FWBC and PAC proved efficient in treating industrial plating wastewater. The plating wastewaters usually contain diverse heavy metal concentrations. This versatility highlights FWBC's potential as a greatly promising coagulant aid in wastewater treatment applications.

Currently, significant advancements have been made in utilizing food waste-derived biochar for wastewater treatment. Although biochar demonstrates exceptional pollutant removal capabilities in controlled contaminated water, the real water environment offers greater complexity, which necessitates detailed investigation. The accomplished adsorption effectiveness for pollutants with modifications such as magnetization remains limited.[120] The efficacy of adsorption is revealed by the physical and chemical characteristics of modified adsorbents, suggesting the potential for innovative modification methods to improve adsorption performance. There are also concerns around the potential toxicity of biochar by-products and the possible leaching of hazardous chemicals and heavy metals. This highlights the need for evaluating their industrial usability. A long-term monitoring system is thus necessary to prevent secondary pollution. The sustained safety and stability of food waste biochar seem to be key necessities for future applications.

4. Modeling and optimisation

4.1 Overview of modelling in biochar production

The key goal of the pyrolysis process is to obtain maximum conversion of the input material and yield of product. Modelling and optimising the process is crucial to achieving these goals, as it increases the understanding of the interrelationship among the process parameters and their effects on biochar yield and physiochemical properties, by means that are typically more efficient and economical than experimental studies. Significant research and development into models aiding in the understanding of biochar production can be observed in the literature, including kinetic, particle and reactor models (Fig. 4).

4.2 Kinetic modelling approaches

The chemical kinetics of pyrolysis are crucial in understanding the complex reaction phenomena and curating mathematical models. Since pyrolysis is a complex process that generates a wide variety of intermediate components and products, devising a model that is capable of accounting for all reaction mechanisms presents a significant challenge. Therefore, kinetic models can be categorized as lumped models and other distributed models. Lumped models simplify the pyrolysis process by generalising the reaction products as either a volatile gas, tar or biochar. Two types of lumped models exist: one-step global and two-stage semiglobal models. The former presents

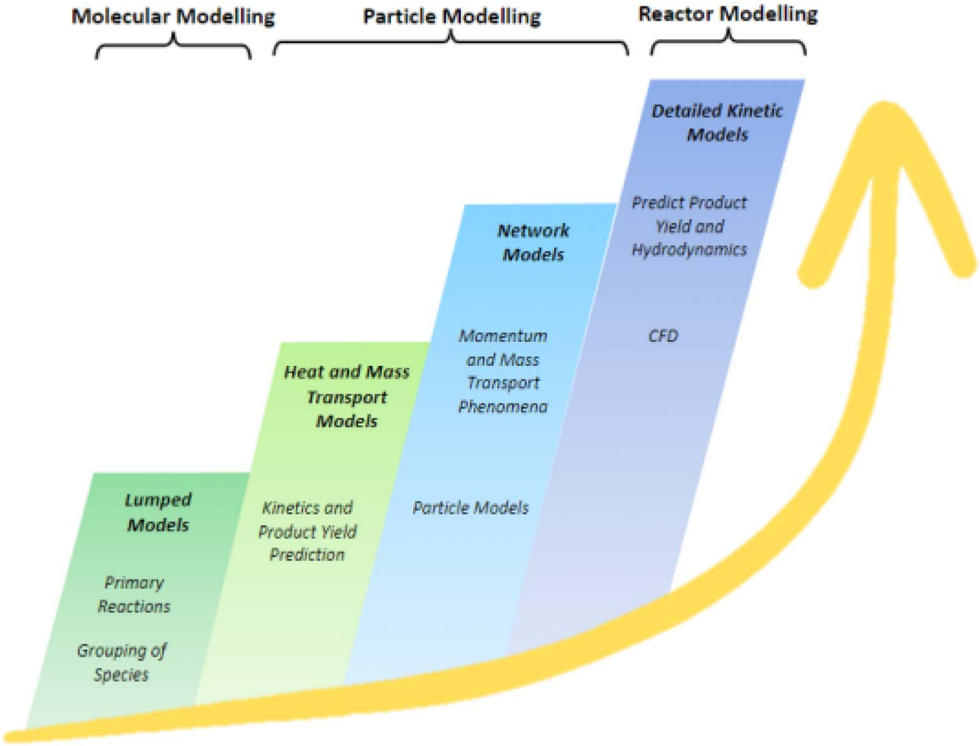

Fig. 4 Different models employed in the understanding of biochar production.

the simplest type of pyrolysis model, representing pyrolysis as a single step first-order reaction; thus, Hameed *et al.* (2019)[157] discussed how most researchers using kinetic models employ the global reaction model coupled with the relevant volume and heat transfer equations.

The kinetic parameters for these lumped models are often obtained experimentally or from iso-conversional methods such as the Kissenger–Akahira–Sunose (KAS) and Flynn–Wall–Ozawa (FWO). Lumped models depict a pyrolysis process controlled by the overall reaction rate, excluding extensive structural data and utilising kinetics obtained experimentally and validated *via* modelling. Limitation of the classical models include their consideration of only primary reactions, excluding more complex, but often key reaction mechanisms. Models that fall outside conventional reaction order models have been derived with the aim of addressing lumped model shortfalls. These distributed kinetic models include biomass deactivation models (DMs), distributed activation energy models (DAEMs) and nucleation growth models.[158] The models define pyrolysis on a molecular level and are appropriate for estimating the yield of biochar, and unlike lumped models, they consider pyrolysis aspects including cross-linking and fragmentation reactions. Nonetheless, the models are specific to each feedstock, and precise solid–gas phase mechanisms are still excluded.

4.3 Heat and mass transfer modelling

Heat and mass transport models have also been widely studied, with the parameters in these models being crucial for establishing kinetics and product yields. These can predict the impact of intraparticle heat and mass transfer on particle heating, drying and devolatization, and can help better understand the pyrolysis process at various temperature and under flux rate conditions. Nonetheless, product distribution cannot be determined with sufficient accuracy *via* the reaction kinetics, and thus, a sufficient heat and mass transfer model has yet to be derived, which Vikram, Rosha & Kumar (2021)[158] attribute to the lack of in-depth knowledge of secondary pyrolysis.

4.4 Particle-level modelling

Particle models integrate reaction models with transport equations to investigate the overall biomass thermochemical degradation. As proposed by Miller & Bellan (1997),[159] pyrolysis particle model approaches can be either macro particle models controlled by reaction kinetics or micro particle approaches limited by diffusion. The mechanisms employed within many particle models follow the assumption that the biomass undergoes pyrolysis at a low heating rate to negate the effects of spatial temperature profiles, or, in contrast, at high heating rates to avoid considering the heating duration. Several other assumptions are commonly made within particle models, including that there is a global Arrhenius pyrolysis mechanism, thermal equilibrium exists between solids and volatiles, heat transfer throughout the solid material occurs by conduction phenomena only, and that all gases exist in an ideal state. These assumptions induce inaccuracies as neither the weight loss during this period nor heat transfer limitations resulting from temperature control issues can be discounted.[158] Subsequently, pairing transport equations with reaction models is preferred within particle models to sufficiently study the thermochemical degradation of the biomass, comprising both heat and mass transfer effects.

4.5 Reactor modelling and CFD simulations

Of all models that have been integrated into various reactor configurations for the study of pyrolysis parameters, such as phenomenological models, CFD is the most dominant. CFD simulations have been employed to model the pyrolysis of biomass at various levels, with extraordinary accuracy, while being one of the youngest branches of mathematical modelling.[160] The models combine the principles of fluid mechanics with laws such as energy and momentum conservation over specific domains, solving transport phenomena problems. Nonetheless, reactor models neglect the effect that specific operating conditions, such as shrinkage or the presence of inorganic components within the biomass, have on the process. Furthermore, inaccuracies within the input parameters employed within these models have been observed to lower residence time, influencing bed hydrodynamics, subsequently generating values for volatile production that lack accuracy. As a result of lacking decomposition kinetics, to date, no reliable CFD model for pyrolysis has been developed.

4.6 Machine learning and data-driven modelling

Machine learning based models can be observed throughout the literature a useful engineering tool to predict the yield and physiochemical properties of biochar, as seen in the studies of Haq *et al.* (2022), Khan *et al.* (2022)[161,162] and many others. Examples of models and algorithms employed for yield prediction, and property modelling and optimisation include Artificial Neural Networks (ANNs), Random Forest Regression (RFR), Support Vector Regression (SVR), Adaptive Neuro-Fuzzy Interface System (ANFIS) and Gradient Boosting Regression.[163] ANNs have been found to be a useful engineering tool to model pyrolysis due to their great potential to learn complex, non-linear relationships between a number of inputs and one or more outputs, as highlighted by Ascher, Watson & You (2020). Arumugasamy & Selvarajoo (2015) and Selvarajoo, Muhammad & Arumugasmy (2019)[164–166] both employed MatLab to model biochar production using a two layer feed forward ANN model. Selvarajoo, Muhammed & Arumugasamy (2019)[166] employed a durian rind and banana peel feedstock and an ANN with a 2,1 configuration and tansig and purelin transfer functions, respectively. The model was trained based on back propagation using the popular Levenberg–Marquardt optimisation algorithm, producing an R^2 value of 0.999, illustrating high model accuracy. The authors reported that biochar with the greatest energy content in relation to char yield and heating value was obtained at 325 °C with a 47 wt% yield achieved after 30 minutes residence time and a heating value of 25.9 MJ kg^{-1}. Selvarajoo *et al.* (2019)[166] observed that heating rate had minimal impact on the char yield and heating value. Arumugasamy & Selvarajoo (2015)[165] investigated the effects of temperature and reaction time on the biochar yield, establishing that an ANN model with a 2-20-1 configuration provided the best performance, giving a correlation coefficient, *r*, of 0.999.

4.7 Process simulation with ASPEN plus

The chemical process simulation software, ASPEN Plus, has also been widely applied by researchers to study the pyrolysis process. The software contains physical and thermodynamic models and an extensive database of chemical components and their pure regressed parameters, which can be employed to execute accurate pyrolysis simulations. AlNouss *et al.* (2021)[167] conducted a study on the pyrolysis of five fruit waste types – orange peel, mango endocarp, date pits, apricot kernel shell and banana peel using the simulation software. They assumed a steady state, kinetic-free equilibrium, isobaric conditions and the absence of tar formation with an RYield reactor type for the transformation of biomass. The model found that date pits produced 50.92 wt% char yield, the highest of all tested fruit, likely due to high elemental carbon[168] and inferred that date pits were the best suited for biochar production. George Adeniyi *et al.*, (2022)[169] employed APSEN Plus to develop a steady-state model to predict product yields for different banana wastes. The simulation made assumptions including steady-state, isothermal operation that neglected the effect of particle size distribution, with the solid char component constituted of elemental carbon and SiO_2. The simulation employed an RYield reactor block to break down the non-conventional components, followed by RGIBBS to compute chemical and phase equilibrium through minimising the system's Gibbs free energy. The yield for biochar and bio-oil were 51.4–67 wt% and 26.7–35 wt%, respectively, showing that banana waste appears to be inherently more suitable for char optimised production processes.

4.8 Optimisation techniques

In the preparation of biochar, pyrolysis temperature, heating rate and residence time are the most important and influential parameters (Gupta, Das & Mitra, 2023)[163] and thus modelling and optimisation studies frequently focus on these three factors. Various optimisation methodologies can be observed in the literature, including Taguchi design, Box Behnken design (BBD) and response surface methodologies. Response Surface Methodology (RMS) is a widely applied method of optimisation within the studies of pyrolysis, noted by Campos *et al.* (2020)[170] to achieve effective results with very few experiments required. Siddiqui *et al.* (2019)[171] employed the RSM technique Central Composite Design (CCD) to model and optimise the slow pyrolysis of pomegranate peel with respect to maximising biochar characteristics and yield. The study identified optimum conditions at 300 °C, 20 minute retention time and a 3 mm particle size, producing a maximum yield of 54.9%. The study also found temperature to be an important parameter for biochar yield, while noting that time and particle size had a low impact. This is supported by the cabbage waste study by Pradhan *et al.* (2020)[172] in which temperature was observed as more influential to biochar yield compared to sample size and mass. Nonetheless, the study by Vieira *et al.* (2020)[173] on biochar yield from rice husks using Taguchi's method indicated that out of temperature, time and heating rate, no single parameter showed a significant impact on biochar yield. Yadav *et al.* (2020)[174] also used CCD to model and optimise the yield of biochar from rice husk and found the optimum conditions to be 432 °C, 4 °C min^{-1} and 40 min, respectively, producing a yield of 54.65%. Their ANOVA analysis confirmed that the quadratic model was significant, computing an R-value of 287.48 and an improved R^2 of 0.99 compared to Siddiqui *et al.* (2019).[171] Liu and Huang (2018),[175] Kumar *et al.* (2021)[176] established, using BBD, the maximum biochar yield for peanut shell, with optimum conditions identified at 400 °C and 20 °C min^{-1}, with the model showing that increasing the nitrogen flow rate and temperature acts to reduce the biochar yield.

4.9 Techno-economic analysis (TEA)

Conducting a techno-economic analysis (TEA) is a key feature in the development of pyrolysis biochar production at an industrial scale as it enables identification of process profitability and thus, feasibility. Kumar, Saini & Bhaskar (2020)[177] lists the key components comprising a TEA as process modelling, design engineering, energy balance and economic evaluation. The overall cost of a plant computed in a TEA considers many factors, including feedstock collection, equipment, transportation, and labour costs, in addition to influential factors such as plant location. Heat integration optimization techniques, such as a PINCH analysis, are also available and utilised to reduce utility costs. Kumar, Saini & Bhaskar (2020)[177] conducted a TEA that found a slow pyrolysis biochar production plant was economically feasible, costing $523.6 per year per tonne feedstock and producing a positive benefit-cost-ratio of 1.02, indicative of a 9.97-year payback period for the investment. Kumar *et al.* (2020)[176] identified areas for further plant optimisation, including efficient use of byproducts and reduced energy consumption. Liu *et al.* (2022)[178] employed a flow chart established in Aspen Plus V8.4 to simulate the pyrolysis of rice straw and sugarcane bagasse and conducted an economic assessment. It was established that the biochar obtained from rice straw has higher yield, lower energy consumption and costs associated in comparison to that of sugarcane. Sahoo *et al.* (2021)[179] conducted a TEA of three small-scale portal systems: Biochar Solutions Incorporated (BSI), Oregon Kiln (OK) and Air Curtain Burner (ACB). The TEA illustrated that the global warming impact of the three biochar production systems was 0.25–1.0, 0.55, and 0.61 t CO_2eq per t biochar for BSI, OK and ACB, respectively. Furthermore, Sahoo *et al.* (2021) demonstrated that per tonne of biochar, the MSP for OK, ACB and BSI was $1600, $580 and $3000–$5000, respectively; however, considering government subsidies and grants, this could be reduced by between 30 and 387% depending on the system.

5. Life cycle assessment (LCA)

The purpose of a Life Cycle Assessment (LCA) is to understand and assess the holistic sustainability impact of a process or system. An LCA considering all the relevant stages from collection to end-of-life treatment is known as a cradle-to-grave approach.[180] LCAs identify opportunities to promote sustainable practices, typically in the areas of resource recovery, energy generation, and environmental conservation; in doing so, LCAs provide the basis for informed decision making to better establish new or review existing technologies. When partaking in LCAs ,it is preferential to align with the relevant governing

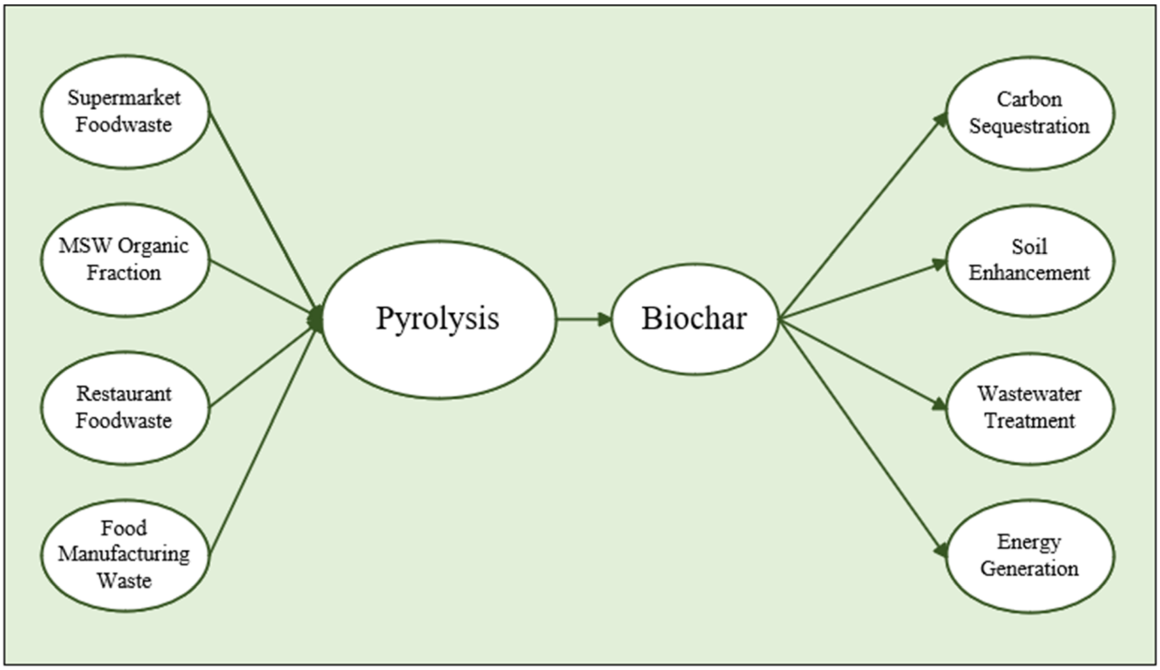

Fig. 5 Biochar life cycle.

body policies, for example in the United Kingdom it is required to follow the BSI standards 14040 (British Standards Institution, 2006)[181] and 14044 (British Standards Institution, 2018),[182] 'Chemical Engineering Design' (Sinnott & Towler, 2020)[180] is also a good frame of reference for undertaking an LCA.[183] Considering the LCA process can be time consuming due to large amounts of varying factors, many software's have been developed to aid in the LCA process, including; EcoPro 1.3, GaBi 2.0, Simapro 3.1, and KCL-ECO. Users should be aware of the effects of using different LCA software programs, as the results may vary between them.[184]

In relation to pyrolysis biochar, it is relevant to utilise LCAs to assess the overall economic, social, and environmental impacts and compare them with other established technologies such as anaerobic digestion (AD), landfilling, incineration, composting and hydrothermal decomposition.[185] Such technologies are well established in the worldwide community, and many evaluations on preferred techniques have been conducted.

It is important, whilst undertaking an LCA, to define early on the boundaries and methodologies one will review. Two approaching methods can be utilised; the attributional model focuses on the functional unit (FU) and the environmental impact of that specific amount, whilst the consequential model varies the FU and analyzes the impact of this variation.[89,186] Regarding system boundaries, it is recommended that for an LCA focussed on pyrolysis biochar, a cradle-to-grave approach be undertaken as outlined by Valero & Valero (2013).[187] This approach focusses on the entire process from sourcing of the raw material to the final usage, as outlined in Fig. 5. Currently, most food waste can be found in the organic fraction of municipal waste or from the food industry waste. The FU recommended for the LCA centring on pyrolysis biochar could be '1 tonne of food waste processed' or '1 tonne of biochar produced.' It is paramount for each approach that care be taken to evaluate each stage in the process to allow for informed decision making and minimisation of oversights and errors that could cause a large effect.

During an LCA, the impact categories being examined should be well-established and understood in relation to the FU. The most common relevant impact categories for pyrolysis biochar relate to the following; Global Warming Potential (GWP) (Keller *et al.*, 2022),[188] Acidification Potential (Sun *et al.*, 2023),[189] Eutrophication Potential (Gievers *et al.*, 2021),[190] Ozone Depletion Potential (ODP) (Gahane *et al.*, 2022),[191] Land Use Impact (Brassard *et al.*, 2021),[192] and Water Use Impact (Zhu *et al.*, 2019).[97] Table 6 outlines the impact categories with relevant testing methods and measures. These impact categories should also be checked using sensitivity analysis to provide an understanding of the effects of changing relevant parameters.

Following the LCA process, the output should be reviewed to establish and identify the key weak areas of the process or design, evaluate the consistency and reliability of the results, and from this, provide relevant and complete recommendations regarding the proposed technology. For pyrolysis, due to the usage of fossil fuels to provide the heating for thermal degradation, typically it is found that greenhouse gases (GHG) are the main source of discomfort with the use of the technology in comparison to other prevalent technologies, such as anaerobic digestion. In addition, if the content of the food waste is high in nitrogen or phosphorus and the biochar is spread to land as a soil enhancement, it can lead to high amounts of eutrophication. However, this is also prevalent in other forms of waste management strategies such as anaerobic digestion and composting.

6. Scalability and regulatory challenges of biochar applications

6.1 Scalability challenges

The FWBC scalability is one of the biggest issues due to the intrinsic heterogeneity of food waste feedstocks. Depending on the food waste sources and presence of moisture, contaminants, *etc.*, there will be variation in the physicochemical properties of the resulting biochar.[193] A large-scale consistent biochar production would thus require robust preprocessing strategies, including drying, homogenisation, and contaminant removal. This will increase operational complexity and cost. Additionally, food waste is often generated at small scales across several areas, resulting in uneconomical collection and transport. It is also environmentally challenging. Thus, establishing a stable and scalable feedstock supply chain remains a major logistical hurdle.[194] The economic viability of FWBC systems is also contingent on the development of end-use markets for the product. The economic success of FWBC systems also depends on developing markets for the end

Table 6 Summaries of the impact potentials and methodologies

Impact potential	Impact indicator	Factor	References
Global warming potential (GWP)	$CO_{2.E}$	IPCC characterisation factors for greenhouse gases	188
Acidification potential	Hydrogen ion release potential	Potential per unit substance emitted (*e.g.* $kg_{SO_2.E}$)	189
Eutrophication potential	Nitrogen and phosphorus content	Potential per unit of nutrient emitted (*e.g.* $kg_{N.E}$)	190
Ozone depletion potential (ODP)	Potential for ozone layer depletion	Identification of ozone depleting factors such as $CFC\text{-}11_E$	191
Land use impact	Changes in land cover and biodiversity	Biotic production or habitat quality factors	192
Water use impact	Freshwater consumption	Water scarcity footprint per unit of water consumed (m^3)	97

products. While there are potential uses in soil enhancement, water treatment, and construction materials, the market is currently held back by inconsistent performance, a lack of product standardization, and limited awareness among potential users.

6.2 Regulatory challenges

FWBC production and application are constrained by an underdeveloped regulatory landscape. The lack of standardisation in FWBC quality poses a significant barrier to regulatory approval and market trust. Several food wastes may contain hazardous substances such as heavy metals, PAHs and so on. The resulting biochar will thus be contaminated with these hazardous substances. There will also be inconsistent levels of pH and nutrients. Though EBC (European Biochar Certificate) certification schemes provide preliminary frameworks, they are not universally accepted or integrated into national regulatory systems (EBC, 2022).[195] The major issue is the land application of FWBC and the environmental and human health risks associated with it. Another significant barrier is that the integration of FWBC into carbon offset and emissions trading systems remains limited by the complexity of biochar carbon accounting. Although biochar is frequently promoted as a promising negative emissions technology, the verification and quantification of its carbon sequestration potential remain complex and poorly standardised. This lack of clarity particularly hinders small- and medium-sized enterprises from accessing carbon markets or securing finance through emissions trading schemes. Consequently, alongside regulatory uncertainty and potential health and environmental concerns, the challenges associated with carbon accounting present significant obstacles to the widespread adoption of the FWBC.[196]

7. Conclusions and future perspectives

Food waste is a worldwide issue that adversely impacts the economy, society, and the environment. UK food waste significantly contributes to global greenhouse gas emissions, amounting to more than 20 million tonnes. Sustainable waste management strategies have been legally mandated in developed nations, reflecting the seriousness of the issue. The food waste hierarchy in the UK has been established to mitigate and reduce its consequences effectively. In contrast to municipal waste, food waste comprises more than one-third of all urban waste generated by human activities. Consequently, it is the most substantial form of solid refuse on a global scale that necessitates appropriate treatment in order to promote environmental sustainability.

As discussed in the review, diverse methods for food waste disposal have been developed, including composting, landfilling, biological and thermochemical conversion. The most undesirable approach is landfilling, which releases large amounts of methane, odour, and leachate (liquid), adversely impacting the environment, society, and human health. Incineration, the conventional method of waste disposal, produces more carbon emissions than advanced thermal conversion methods such as gasification and pyrolysis. Anaerobic digestion is a waste management process that converts biomass into biogas and digestate. However, using food waste as feedstock poses several challenges, such as low methane production, process instability due to volatile fatty acids, digester foaming from high protein and lipid contents, and low buffer capacity due to quick digestion.

Producing value-added products such as biochar is one of the most promising ways to utilise food waste and ensure sustainability within the waste management process. This review thoroughly discussed various food waste biochar production technologies such as combustion, gasification and pyrolysis. The review delved at great length into FWBC applications and their great importance in a variety of pertinent issues such as carbon capture, fuel production, energy storage, catalyst application and wastewater treatment. It also extensively discussed various modelling and optimization techniques available in FWBC production and application. It was found that FWBC has great potential in a variety of applications, but there are several challenges to overcome.

In order to implement FWBC adsorbents for CO_2 removal, researchers must work on real-world scenarios dealing with industrial flue gases, which will give insight into the interactions between CO_2 and non-CO_2 gases and their impact on CO_2 adsorption. Unfortunately, such data are scarce. Additionally, we have limited information on the durability and resoluteness of biochar-based adsorbents. This is despite the vital necessity for high adsorption capacities and prolonged cycle performance to ensure the economic feasibility of the technology. It has been realized that the CO_2 adsorption capacity of biochars was lower than that of activated carbon. Similarly, the stability of biochar is critical for its applications in industrial/domestic wastewater treatments. As the biochar properties will be influenced by food waste compositions (which keep changing), this can potentially lead to unpredictable performance of food waste-based biochar. This poses a considerable challenge for extensive industrial use. The other challenges are biochar modifications, which rely greatly on chemical processes. This usually entails complex operational procedures, high expenses, and the prospective generation of hazardous waste. Another challenge the review found is the lack of modeling studies on biochar applications. The review notes that there are a number of modeling studies on biochar production. These studies also focus more on laboratory applications and not on industrial applications. Besides, mathematical models must analyse a variety of feedstocks and not a single feedstock, as thermochemical reactions involved in biochar production will vary depending on the feed compositions and process parameters. A dynamic model must be examined to obtain more detailed findings. A powerful ML approach has been considered a promising route for synthesizing high-performance engineered biochar. The ML methods also possess limitations due to their inability to rely on fundamental physical laws for new estimates. It is therefore essential to safeguard the model's application within its applicable domain. The ongoing research is focused on creating specific

ML methods and algorithms to perform learning tasks more efficiently. It is possible that advancements in multi-task learning and transfer learning could rationalize the learning process and improve the precision of model's predicting capacities on material properties and FWBC application. This will be especially helpful when data availability is limited.

The extent of FWBC application shows significant variation, and although this technology reveals considerable potential in producing useful products, supplementary advancements are vital before widespread industrial application can take place. The scalability, LCA assessment and regulatory challenges are also crucial for its full application. However, with increased refinement, biochar remains a promising field for ongoing development, particularly in rural areas that have access to carbon supply and agricultural land. Effective development of biochar materials derived from food waste necessitates interdisciplinary collaboration among researchers in thermochemical engineering, materials science, environmental engineering and data science.

Conflicts of interest

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

Data availability

No primary research results, software or code have been included and no new data were generated or analysed as part of this review.

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