Thermochemical upcycling of food waste into engineered biochar for energy and environmental applications: A critical review

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Abstract

Environmental issues caused by food waste are important concerns for human well-being and ecosystem health. Valorization of food waste into energy and carbon materials has been extensively investigated. Here, we reviewed the most recent advancements in the thermochemical conversion of food waste into engineered biochar. Synthesis routes and practical applications of the food waste-derived biochar was succinctly reviewed. Engineered biochar is a promising alternative for mitigating environmental pollution and alleviating energy crisis. The underlying relationships between engineered biochar properties and specific applications are still unclear, therefore, machine learning-aided engineered biochar design and process optimization was proposed. Moreover, before any industrial scale implementation, detailed assessments of the environmental benefits and economic feasibility must be conducted. In the context of carbon neutrality, thermochemical upcycling of food waste into engineered biochar for energy and environmental applications can significantly contribute to attaining sustainable food waste management, mitigating environmental pollution, and addressing the energy shortage crisis and thus will eventually facilitate the fulfillment of United Nations Sustainable Development Goals (SDGs). Furthermore, the existing challenges in the practical valorization of food waste into engineered biochar are comprehensively discussed, and outlooks are proposed.

Keywords: Biochar catalyst; Pyrolysis; Carbon capture and storage; Machine learning; Sustainable Development Goals

1. Introduction

Food waste is a global issue that brings serious environmental, economic and social challenges [1-3]. Many countries have taken measures for reduction of food waste generation and sustainable management of unavoidable waste via controlling the sources and collecting the food waste separately from other wastes. The collected food waste could be further processed using various technical approaches to minimize its environmental impact and to maximize its benefits within a circular economy. Food waste, which is mainly composed of organics (i.e., carbohydrates, proteins, fats, and lipids), is hereby converted into high value-added products (e.g., methane, bioethanol, syngas, chemicals, and carbon materials) [4]. Recently, the upcycling of food waste into advanced carbon materials has been considered as an emerging paradigm shift from landfilling and incineration. The major upcycling approaches include thermochemical conversions (e.g., hydrothermal carbonization (HTC), pyrolysis, and gasification) and biological conversions (e.g., anaerobic digestion (AD)) [4, 5]. AD is extensively investigated for transforming food waste into value-added products, owing to its considerable advantages of cost-effectiveness, mild operating conditions, and relatively low energy consumption [6-9]. However, AD generally requires a long residence time and a high-quality feedstock [10].

Compared with the biological conversions discussed above, thermochemical conversion is fast and achieves high yields of value-added products [11]. Pyrolysis, a conventional thermochemical conversion, requires large amount of energy to recover

value-added products and thermal energy from food waste directly, owing to the food waste's actual characteristic of high moisture content. To effectively upcycle food waste with high moisture content, dewatering (or pre-drying) is an essential pre-treatment followed by pyrolysis. However, without pre-drying treatment, HTC is considered one promising alternative for food waste valorization, reducing extra water requirement in hydrothermal reactors and increasing conversion efficiency [11, 12]. The main products from slow pyrolysis and HTC are carbon-rich materials termed as biochar and hydrochar, respectively, which can be further activated and/or modified into advanced engineered biochar for various applications. Researchers are currently focusing on developing green, sustainable, and cost-effective thermochemical processes or integrated biological and thermochemical processes to achieve sustainable management of food waste towards a circular economy (as given in **Figure 1**). Due to the diversity and complexity of food waste, more feedstock-specific process technologies are required for food waste treatment in biorefineries and environmental protections from perspectives of environmental impact and economic feasibility [13, 14]. Solid carbon residue that cannot be further biologically decomposed or chemically extracted normally accounts for a large proportion of processed food waste. These residues can be converted into solid biochar, liquid bio-oil, and gaseous products via hydrothermal conversion or pyrolysis. So far, only a few papers have reviewed the thermochemical conversion of food waste, focusing on the operating conditions, reaction mechanisms, product distributions, and evolution pathways. In particular, the gaseous and liquid products derived from various food

wastes have been extensively investigated [15-18] in comparison to the solid biochar products. For example, Pham et al. [15] reviewed food waste-to-energy technologies involving biological conversion using AD or fermentation, and thermochemical processes including pyrolysis, incineration, hydrothermal oxidation, and gasification. Current state-of-the-art in the pyrolysis and gasification of food waste was reviewed by Su et al. [17], Murugesan et al. [18], and Makkawi et al. [19].

Therefore, it is necessary to provide a timely and comprehensive review of food waste-derived engineered biochar for environmental and energy applications, including major and emerging production routes of engineered biochar, machine learning (ML)-aided guidelines for application-targeted engineered biochar, practical applications in environmental and energy fields, and conclusions and outlook. Physical, chemical, and integrated methods are used to activate (i.e., developing new pores and controlling pore size distributions) and/or modify (i.e., doping surface functional groups) biochar into engineered biochar with wide applications, such as solid fuels, adsorbents (e.g., for CO_2 capture), and advanced catalysts (e.g., for electrochemical energy storage and conversion). The review sheds light on the sustainable upcycling of food waste into engineered biochar with high-performance applications and ultimately promotes their large-scale deployment, significantly providing benefits and guidelines to researchers from both academies and industries working in the areas of sustainable valorization of solid waste, climate change mitigation, renewable fuels, energy conversion and storage, and circular carbon economy. In the context of carbon neutrality, sustainable management of food waste,

climate change mitigation, and renewable alternative fuels need to be performed in a sustainable route to achieve United Nations Sustainable Development Goals, based on the takeaways from this comprehensive review.

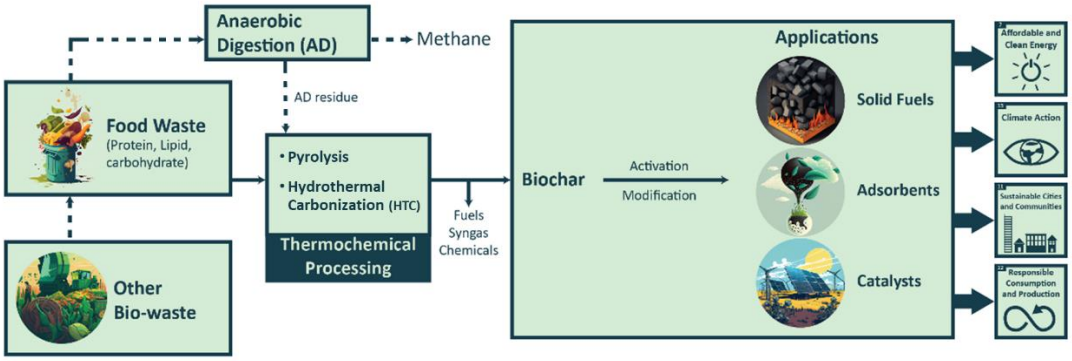


Figure 1. Schematic diagram of thermochemical processing of food waste to produce biochar and engineered biochar materials for various applications.

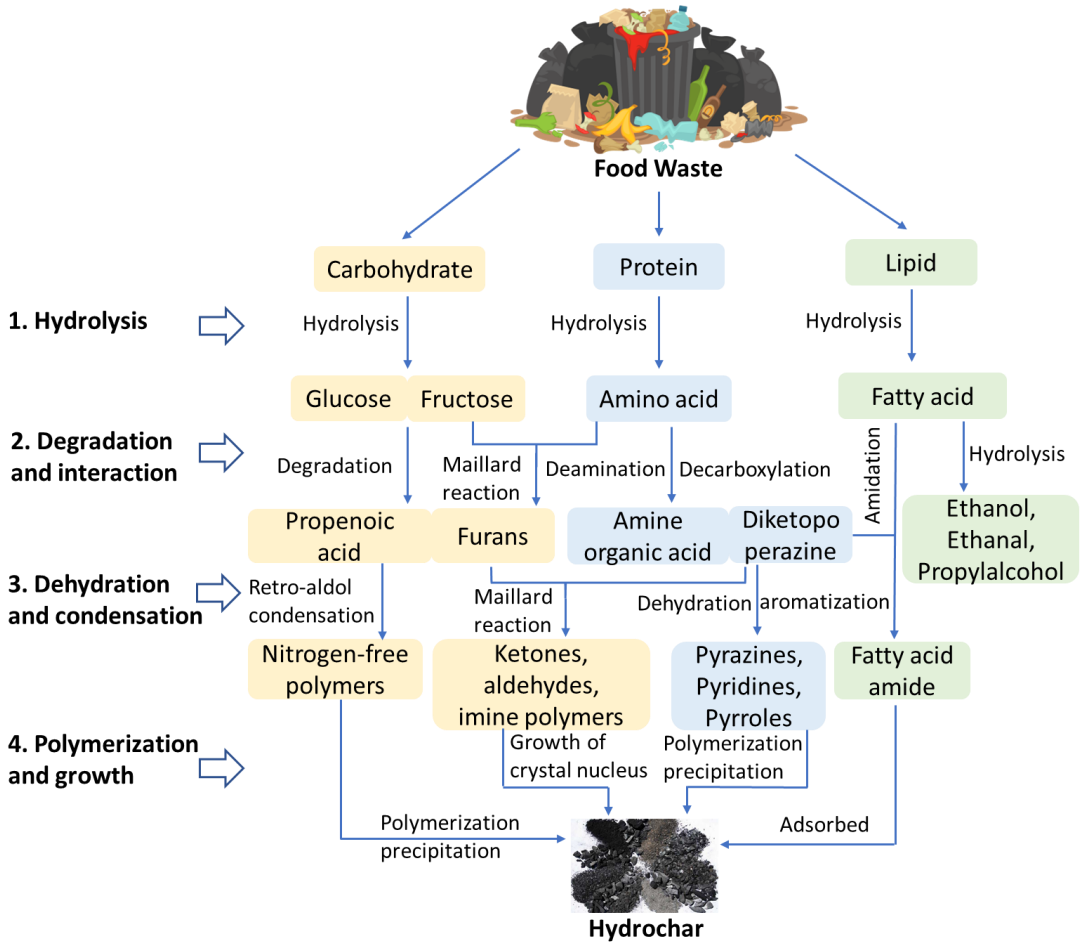
2. Thermochemical upcycling of food waste

2.1. Hydrothermal conversion

Hydrothermal conversion (HTC) allows for the synthesis of value-added carbon materials and the recovery of energy from food waste with high moisture content [20, 21]. HTC at relatively low temperature (180-265 °C) and low pressure (subcritical conditions, up to 6.0 MPa) is favorable for hydrochar production [12, 22]. Compared with other thermochemical conversion techniques, HTC for converting food waste into hydrochar as the primary product avoids the requirement for a pre-drying treatment, involves rather mild operating conditions, and features high operational

feasibility and relatively low energy consumption [4, 11, 23, 24]. HTC can recover nutrients and fatty acids in liquid food waste, which can be intensively recirculated during processing [25-27]. The range of processes and mechanisms involved in hydrochar formation from food waste via HTC are schematized in **Figure 2**. The chemical composition of food waste is complex. Lipids, proteins, and carbohydrates are main component groups. During HTC, subcritical water promotes the hydrolysis of lipids, polysaccharides, and proteins into oligomer and monomer units [28, 29]. The decomposition of proteins usually requires a minimum operating temperature of 150 °C but needs to be at least 220 °C if the protein content is high, above 30 wt.% [28]. Protein hydrolysis is typically slower than carbohydrate hydrolysis due to the higher stability of peptide bonds than glycosidic bonds.

Researchers widely investigated specific mechanisms involved in the HTC of food waste [29, 30]. Yang et al. [29] suggested that the HTC of complex food waste involved three key reactions: carbohydrates carbonization, Maillard reaction, and amidation reaction. The components of food waste play different roles in hydrochar formation. Lipids play a crucial role in hydrochar formation by inhibiting interactions between carbohydrates and proteins, and carbohydrates play a key role when proteins boost their *N*-heterocyclic functional groups. As hydrochar surface can adsorb the lipid hydrolysate, the lipids present in the food-waste do not affect the carbonization process [31].



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150 **Figure 2.** Major reactions involved in hydrochar formation via the hydrothermal
151 conversion of food waste [30]. Reproduced with the permission from Elsevier
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153 2.2. Pyrolysis

154 Compared with HTL, pyrolysis is the thermal degradation of organic materials into
155 carbon-rich by products at a moderate temperature (300-800 °C) and low pressure
156 with little or no available air. A range of atmospheres can be used to ensure anaerobic
157 conditions, including inert gases such as nitrogen, argon, or helium; reactive gases
158 such as carbon dioxide or steam; or vacuum. The properties of the products based on
159 pyrolysis are mainly influenced by the operating conditions, such as the type of inert

gas, flow rate of carrier gas, temperature, heating rate and residence time [32-35].

In general, pyrolysis has several advantages due to diverse output products (as liquid, solid, and gas), environmental friendliness and the maturity of the technology. The yields and properties of the target products can be optimized by adjusting the operating conditions of pyrolysis [36]. The valorization of food waste into biochar and bio-oil like products is a highly viable choice in accordance with circular economy principles [37]. State-of-the-art biofuel production from conventional and advanced pyrolysis and the co-pyrolysis of food waste were reviewed recently [38].

Various mechanisms are involved in the pyrolysis of food waste [39]. Glucose is one of the most abundant monosaccharides in food waste. During pyrolysis, a dehydration reaction converts glucose into anhydrosugars, which are converted to sorbitol and 1,4-sorbitan through a reduction reaction and a dehydration reaction, respectively, subsequently converted into isosorbide [40]. During the pyrolysis of triglycerides, the major component is lipids. Via decarbonylation, decarboxylation, and fragmentation reactions, glycerol can be converted into acids, esters, alcohols, hydrocarbons, and alicyclic compounds. The decomposition of steroids could generate hydrocarbons [41]. Amine and diketopiperazine species are produced during the pyrolysis of proteins. In the process, amino acids are connected by peptide bonds. Amine species are produced via the breakage of peptide bonds, while diketopiperazine species are generated because of the cyclization of amino acids [42]. To date, investigations of the food waste pyrolysis mechanisms have focused on the individual components.

However, the complex interactions between the different components in food waste during pyrolysis remain unclear and should be investigated further.

Direct pyrolysis of food waste with high water content would, while technically feasible, require considerable energy input for the drying pretreatment, and evaporation of remaining water. Therefore, integrated conversion systems, e.g., AD + pyrolysis; HTC + pyrolysis, have been developed to efficiently achieve the circular economy of food waste [43-45]. Both AD and HTC readily reduce the water content (especially bound water) from food waste by destroying the cell walls [46]. More importantly, AD recovers valuable biogas and nutrients (digestate) from food waste with high water content. The solid AD residue can then be pyrolyzed for the co-production of biochar and biofuels (e.g., syngas), as illustrated in **Figure 3.** The pyrolysis of solid AD residue from food waste has increasingly attracted the interest of researchers [47-49]. Zhao et al. [47] comparatively studied the pyrolysis of food waste and its solid digestate. Organic matter of food waste was partially consumed during AD, influencing the pyrolysis performance of the resulting solid digestate. The pyrolytic gas from food waste was of better quality because its lower heating value was high. In contrast, the bio-oil and biochar derived from the solid digestate showed better qualities as liquid fuel and carbon sorbents. Pyrolysis of the solid digestate generated fewer N-containing pollutants, indicating that AD coupled with pyrolysis is a more environmentally friendly approach for treating food waste [50].

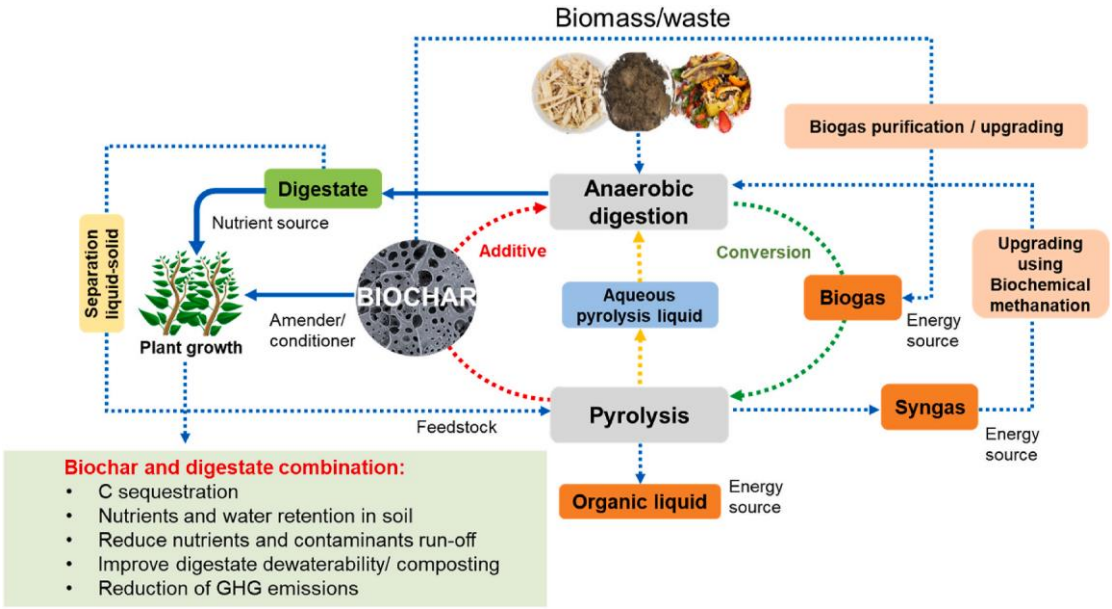

Figure 3. Integrated anaerobic digestion and pyrolysis process for efficiently converting food waste into value-added products toward sustainable food waste management [43]. Copyright permission from Elsevier (License Number: 5437490493245).

3. Development of engineered biochar derived from food waste

3.1. Activation to engineered biochar

Biochar and hydrochar have a limited surface area and pore structure, and unspecified functional groups [34, 51]. Activation treatment aims to improve the textural properties of biochar and hydrochar by creating and/or digging out the internal porous structure in order to broaden the practical applications in environmental protection and energy storage/conversion [51-53].

Generally, activation treatments are categorized as physical and chemical. In physical activation, CO_2, steam, and air at high operating temperatures (even up to 1,000 °C)

are widely used [11, 54]. Physical activation is a relatively eco-friendly and cost-effective approach for increasing textural properties (i.e., porosity). Among these post-modification treatments, physical activation exhibits lower global warming potential than chemical activation [55]. Steam and CO_2, both endothermically react with carbon via two major reactions: $C + CO_2 \rightarrow 2CO, \Delta H = 159 kJmol^{-1}$; $C + H_2O \rightarrow CO + H_2, \Delta H = 119 kJmol^{-1}$ [54]. Steam activation effectively improves the porosity and increases the number of O-functional groups on the surface of engineered biochar [56]. Due to its easy handling and low reactivity even at operating temperatures higher than 700 °C, CO_2 gas has become the preferred activating agent, making activation easier to control [57, 58]. However, in the context of carbon neutrality, CO_2 emissions from CO_2 activation are an issue. Although the surface area, total pore volume, and yield of engineered biochar are generally less than 1,000 m^2/g, 0.7 cm^3/g, and 30%, respectively, after physical activation [51, 59], the approach has several key advantages, including minimal corrosion to the activating reactor, high deployment feasibility and low production and operating costs, showing a broad commercial potential of engineered biochar-based practical applications.

For chemical activation, acidic (e.g., H_3PO_4, HNO_3, and H_2O_2), alkaline (e.g., KOH and NaOH) and salt (e.g., K_2CO_3, $ZnCl_2$, and $MgCl_2$) media are commonly used as chemical agents. These are impregnated with biochar or hydrochar before chemical activation is performed under an inert gas atmosphere [11, 60]. Porosity is directly influenced by the volume of the chemical agent used and the activation temperature. Compared with physical activation, chemical activation has the advantages of low

energy consumption due to the low activation temperature and short activation time, and high porosity and yield of the produced engineered biochar. However, issues include intensive chemical corrosion of the reactor during activation, the need for wastewater treatment due to the production of chemically contaminated wastewater, and the extra energy required for subsequent drying of the produced carbon materials. KOH activation is one of the most common and promising routes to produce well-developed porous engineered biochar. In a study engineered biochar was synthesized using KOH activation from water chestnut shells [61], achieving a surface area of 3,401 m^3/g and a total pore volume of 2.50 cm^3/g. It indicates upcycling food waste into engineered biochar has significant potential for practical applications such as gas adsorption and energy storage. However, KOH activation has considerable environmental impacts, including greenhouse gas emissions from activation and high-water consumption for the impregnation before activation and the washing after activation. The environmental impacts need to be fully assessed from a life-cycle perspective when designing a sustainable and feasible activation technique [62].

3.2. Modification of surface functional group

In addition to good textural properties, the presence of surface functional groups, such as O-, N-, and S-rich groups, critically determines the potential application performance of engineered biochar [63]. For example, typical surface O-functional groups (e.g. -OH and -COOH) dramatically improve the adsorption capacity for capturing CO_2 and removal of metal contaminants from wastewater [64-65].

Functional groups can be doped on the surface of engineered biochar through various modifications [51, 66]. To increase the oxygenated functional groups (e.g., carboxyl and phenolic hydroxyl), surface oxidation, most commonly with H_2O_2 and HNO_3, is the most commonly used method [66, 67]; surface amination, such as high-temperature ammonia (NH_3) treatment, can be used to increase amino groups [68]; surface sulfonation using concentrated sulfuric acid can be used to enrich sulfonic groups on the surface of engineered biochar. In addition to these single-heteroatom doping treatments, dual- or tri-doping treatments are used to enrich surface active sites, enhancing application performance via synergistic effects. For example, N and S dual-doping is suited for producing engineered biochar for oxygen reduction reactions (ORRs), rechargeable lithium-oxygen batteries, and supercapacitors [69-72].In addition, as shown in **Table 1**, the main advantage of food waste-derived engineered biochar materials is the production of heteroatom (e.g., O, N, S) self-doped porous carbons owing to the presence of protein.

Table 1 Comparison of food waste and lignocellulosic biomass-derived engineered biochar materials

Biomass source	Advantages	Disadvantages
Food waste	1) Relatively low ash content; 2) Relatively low temperature for carbonization and activation process; 3) Suitable for HTC to produce hydrochar; 4) Production of heteroatom (e.g., N, S) self-doped porous carbons if protein used; 5) Uniform structures	1) Pretreatment such as dewatering is required due to high water content; 2) The composition is complex, normally including starch, sugars, protein, lipids, which are difficult to regulate the pore structure.

	compared with lignocellulosic biomass-derived biochar.	
Lignocellulosic biomass	1) Less energy consumption in dewatering 2) Larger specific surface area compared with food waste-derived biochar 3) Hierarchical pore structure	1) High ash content 2) High energy consumption in the grinding process 3) Non-uniform pore structures

275

276 3.3. Machine learning-aided guidelines

277 Machine learning (ML), an artificial intelligence approach, is a promising and
278 practical alternative to laboratory experiments and computational simulations (e.g.,
279 density functional theory and Grand canonical Monte Carlo) for designing and
280 optimizing advanced materials [73]. Several major advantages of ML include
281 efficiently screening large amounts of data within a short time (at the 10^{-2} s level),
282 accurately predicting material properties, and effectively identifying the inherent
283 relationship between material properties and specific applications [74]. Recently, ML
284 has been extensively used to accelerate carbon material discovery and elucidate the
285 inherent relationships with their properties and specific applications. As of December
286 2022, *Web of Science Core Database* search using the search terms 'carbon materials'
287 and 'machine learning' retrieved 98 peer-reviewed publications; specifically, five
288 publications in 2019, 20 publications in 2020, 29 publications in 2021 and 38
289 publications in 2022, implying that the discovery and application of carbon materials
290 using ML models is an emerging research trend.

To the best of our knowledge, most of these publications focused on the forward prediction of target features based on collected datasets of input features by established models within acceptable or reasonable accuracy levels ($R^2 > 0.8$) [74-77]. For example, Yuan et al. [77] applied ML to predict CO_2 adsorption performance using biomass waste-derived carbon materials, and Li et al. [76] applied ML to predict and optimize the properties of hydrochar derived from high-moisture municipal solid waste. ML algorithms can improve solid waste-to-resource strategies and help to achieve several United Nations (UN) Sustainable Development Goals (SDGs). Typical forward prediction models are deduced from Pearson's correlation matrix, Shapley values, and others, highlighting the importance of input features for predicting target features [74, 77]. Moreover, the data generated from these models must be interpreted with expert knowledge and experience to draw new conclusions.

In addition to forward prediction, ML algorithms are powerful for supporting inverse design, greatly facilitating a paradigm shift towards a closed-loop guideline [51, 80]. Through synthesis and validation, ML algorithms enable guided experiments to discover food waste-derived biochar functional materials with bespoke properties. When integrating computational simulations with experimental validation, ML algorithms can accelerate the synthesis of biochar functional materials derived from food waste targeted toward a specific application.

Since ML is a data-driven approach, consistent data formatting (i.e., unit consistency) is an essential step in the process. Missing data is a critical issue when performing

312 ML-aided investigations. Generally, each piece of data consists of valid values for all
313 input variables, and those with unsolved missing data are discarded. Sometimes, the
314 missing data issue can be solved by data imputation. Most data are manually extracted
315 from recent publications, which are both time- and labor-consuming. Therefore, it is
316 desirable to create open databases with standard formats to accelerate the ML-based
317 discovery of food waste-derived advanced materials and their potential applications.

318

319 **4. Practical applications of food waste-derived engineered biochar**

320 Engineered biochar produced from food waste has broad applications, including solid
321 fuels, adsorbents for environmental remediation (e.g., CO_2 capture), and
322 electrochemical applications (e.g., energy storage and conversion) [11, 50, 65, 81].
323 Food waste-derived hydrochar produced via HTC has been widely developed for
324 direct use as solid fuels. Moreover, hydrochar produced from the HTC and pyrolysis
325 of food waste can be activated and/or modified to obtain high-performance
326 engineered biochar for energy and environmental applications.

327 4.1. Solid fuels

328 Because food waste is mainly composed of organic components (i.e., carbohydrates,
329 protein, and lipids), it has good potential for producing solid fuel with a relatively
330 high heating value. Currently, significant efforts have been taken to produce solid
331 fuels from food waste via HTC [82, 83]. Theppitak et al. [83] compared the pyrolysis

and HTC of food waste for solid fuel production. Compared with the biochar produced via HTC, that produced via pyrolysis at temperatures higher than 300 °C showed superior fuel properties, with a high heating value and high fixed carbon content. When the moisture content of the food waste is high (i.e., >75%), the HTC process is more suitable and economically efficient. Moreover, the HTC process removes protein from food waste and simultaneously increases the yield of biochar with a higher heating value due to the carbohydrate-rich fraction. The HTC process also resolves issues related to the heterogeneity of mixed food waste [84]. However, the impacts of factors such as biochar palletization, gas composition, NO_x emission and by-product utilization in the following thermochemical process (i.e., combustion) should be considered [85, 86]. Su et al. [24] recently studied the conversion of food waste (after extracting oil) into solid fuel by the HTC process in a large-scale plant (200 t/d). HTC conditions like residence time, temperature, can significantly influence the physicochemical characteristics, combustion behavior, and alkali metal removal capacity of the produced hydrochar. Most food wastes are composed of carbohydrates, protein, and lipids, making them suitable for the production of solid fuels with a high heating value. Compared with other biomass wastes such as agroforestry residues, food waste also has a lower ash content, especially of alkali and alkaline earth minerals, which may reduce sintering and corrosivity. However, food waste has a high moisture content, so developing a cost-effective dewatering pre-treatment remains a key challenge for advancing practical applications. Moreover, the co-production of oil fuels and biogas can greatly improve the technical- and economic

feasibility of converting food waste into energy products.

4.2. CO_2 adsorption

In the context of carbon neutrality, carbon capture is essential to mitigate climate change [87] owing to the current high atmospheric CO_2 concentration (up to 420 ppm) and the increasing annual growth rate of CO_2 (up to 2.4 ppm per year) [88]. Carbon capture, alternatively known as greenhouse gas removal or CO_2 removal mainly addresses CO_2 removal from large point-emission sources (e.g., power plants and cement industries) and even from the atmosphere (i.e., direct air capture) [89]. Among the available technical approaches, CO_2 adsorption is widely considered a promising and feasible route owing to its mild operating conditions, cost-effectiveness (especially when using solid waste as a precursor for adsorbent synthesis), high feasibility for commercial-scale application, and low energy consumption [11, 51].

The circular economy-inspired upcycling of food waste into novel carbon materials for CO_2 adsorption followed by soil remediation has been proposed with the potential of achieving negative carbon emissions [62], representing a sustainable waste-to-resource strategy that simultaneously mitigates climate change. Moreover, surplus electricity, engineered biochar material and captured CO_2 gas can be generated in a sustainable and multifunctional food waste-based system that integrates temperature swing CO_2 adsorption to reach zero carbon emissions. No waste is generated in this circular life-cycle system, which is beneficial for achieving UN Sustainable Development Goals 11 (sustainable cities and communities), 12 (responsible

consumption and production), and 13 (climate action). Engineered biochar for CO_2 adsorption is expected to have a high CO_2 adsorption capacity, low energy requirement for regeneration, excellent cyclic stability, high selectivity for CO_2 over other gases, and fast kinetic characteristics for adsorption-desorption cycles [51, 90]. The CO_2 uptake versus the surface area of food waste (e.g., fruit waste, vegetable waste, shrimp shells, coconut shells, and spent coffee grounds)-derived engineered biochar for CO_2 adsorption is investigated [62, 91, 92], illustrating two major findings. First, through effective synthesis routes, most food waste-derived engineered biochar materials have a viable CO_2 capture performance of more than 3 mol/kg at 25 °C (1 bar), in accordance with the US National Energy Technology Laboratory criterion for applicable and practical CO_2 capture. Second, the relationship between CO_2 uptake and Brunauer-Emmett-Teller surface area (S_{BET}) is not linear, suggesting that CO_2 uptake does not exhibit a directly proportional relationship with S_{BET}. However, when plotting CO_2 uptake versus S_{BET} for materials with pores smaller than β nm (S_β), an excellent linear relationship was observed between CO_2 uptake and $S_{0.8}$, implying that the performance of food waste-derived engineered biochar materials for CO_2 adsorption is significantly mediated by the surface area, limited by narrow pores smaller than 0.8 nm at 25 °C (1 bar) [62, 93]. As shown in a typical case study presented, the spent coffee grounds generated from Starbucks® is upcycled into engineered biochar with a high-performance CO_2 adsorption capacity of 4.54 mol/kg at 25 °C (1 bar) via simple and sustainable synthesis routes [92], demonstrating the great potential for commercial-scale food waste conversion for CO_2 capture

applications.

Before globally deploying CO_2 adsorption techniques using food waste-derived engineer biochar materials as adsorbents, several existing challenges or barriers must be addressed. First, CO_2 selectivity over other gases (e.g., N_2) is a critical factor in the potential performance of commercial-scale CO_2 adsorption [94, 95]. To the best of our knowledge, food waste-derived engineered biochar materials have relatively low CO_2 selectivity, which could result in low CO_2 purity when evaluating cyclic performance using pressure temperature swing or temperature vacuum swing CO_2 adsorption [94]. Moreover, low CO_2 purity products would require further gas sorption and separation treatments to obtain high-purity CO_2 gas for sustainable and practical CO_2 utilization, dramatically increasing the investment for CO_2 capture. Therefore, how to efficiently design engineered biochar materials derived from food waste with high CO_2 selectivity remains a significant challenge to be investigated.

Second, integrating ML to guide high-performance CO_2 adsorbent preparation is considered a promising route to accelerate the deployment of practical CO_2 adsorption applications [96]. However, thus far, only CO_2 adsorption capacity has been predicted by applying ML to synthesize and optimize engineered biochar materials [74, 97]. Other critical indicators, especially CO_2 selectivity, also need to be incorporated into ML models. In addition, following the inverse design perspective, the low CO_2 selectivity issue might be solved via several iterations of ML model development and experimental validation [98].

Third, environmental impact and economic feasibility are the key factors to assess the emerging CO_2 adsorption technologies from both life cycle and techno-economic perspectives, verifying if environmental benefits and economic feasibility could be achieved [56, 62]. A paradigm shift to interdisciplinary collaboration in CO_2 adsorption research is urgently required to achieve the global adoption of CO_2 adsorption technologies that can be deployed globally. Collaboration between material science, data science, thermochemical engineering, and environmental engineering researchers is required for developing adequate advanced CO_2 adsorption systems using food waste-derived engineered biochar materials.

4.3. Energy storage and conversion

Biochar derived from food waste can be activated or modified as engineered biochar materials; N-doped engineered biochar materials show particularly high potential for electrochemical applications [81, 99]. To ensure stable performance, many work have focused on the synthesis of engineered biochar materials with stable properties using specific food waste instead of mixed waste. **Table 2** summarizes the preparation, properties, and performance of engineered biochar materials derived from various food wastes, including carbohydrates (e.g., fruit and starch), protein (e.g., fish), and chitin-enriched waste (e.g., shrimp shell), for advanced electrochemical applications, such as supercapacitors, batteries, ORRs, and hydrogen evolution reactions (HERs). In general, the electrochemical performance of these engineered biochar materials is influenced by the textural structure (e.g., hierarchical porous structure), specific

surface area, heteroatom (e.g., N, S, P, and O) doping, and active metal (e.g., transition metal) loading. Accordingly, these parameters depend on the feedstock type and activation/modification methods used. Carbon materials possessing high specific surface areas, hierarchical porous structure, multiple heteroatom-doping, and metal catalyst loading have been shown to exhibit high electrochemical performance. In particular, hierarchical engineered biochar materials synthesized from food waste have been developed for supercapacitor applications (**Table 2**). Even in the absence of metal catalysts, the maximum capacitance can reach 476,000 F/kg, with high cycling stability (90.9% of the original capacitance retained after 10,000 cycles at 1,000 A/kg current density) [100]. This high performance is attributed to the properties of fishbone, which is mainly composed of protein (N, S, and C source) and $CaCO_3$ (self-template), thereby producing N- and S-doped engineered biochar. The selection of a suitable type of food waste is important for the synthesis of functional carbon materials. For example, shrimp shell composed of chitin (N and C source) and inorganic $CaCO_3$ (self-template) is considered a promising candidate for producing N-doped engineered biochar [101-103]. Gao et al. [101] prepared N-doped hierarchical engineered biochar from shrimp shells containing abundant mineral scaffold ($CaCO_3$) as a self-template combined with KOH activation. Shrimp shells were first activated by KOH in an Ar atmosphere to produce micropores at 700 °C, and then the $CaCO_3$ was removed using acetic acid to form hierarchical engineered biochar, which exhibited a high specific capacitance of 348,000 F/kg in a 6 *M* KOH electrolyte. Wang et al. [103] synthesized a N and P co-doped engineered biochar material

461 embedded with bimetallic phosphide ($FeCoP_2$@NPPC), via a sol-gel and
462 carbonization (N_2, 900 °C) process using sustainable N- and P-enriched chitosan and
463 transition metal salts as precursors. $FeCoP_2$@NPPC had good catalytic activities in
464 HERs, oxygen evolution reactions and overall water splitting. It requires low
465 overpotential between 114 to 150 mV at a current density of 10 mA/cm^2 for HERs in
466 0.5 *M* H_2SO_4 and 1.0 *M* KOH, while the overpotential of 236 mV for OER in 1.0 *M*
467 KOH solution. The $FeCoP_2$@NPPC material was capable of transferring electrons and
468 electrolytes and increasing the contact area of the active sites and electrolytes. More
469 importantly, the wettability and conductivity of engineered biochar can be improved
470 by doping N- and P-containing functionalities.

471 Currently, viable methods in developing carbon materials from food waste for
472 electrochemical applications are still in an early phase of development. The diversity
473 of food waste and the high cost of synthesis processes significantly limit the large-
474 scale application of waste conversion technologies. Therefore, achieving full
475 valorization of food waste into biofuels, chemicals, and high value-added carbon
476 materials remains an important challenge requiring further investigation. In addition,
477 techno-economic and life-cycle assessments of the integrated processes based on the
478 characteristics of various food wastes are necessary to meet the industrial
479 requirements for large-scale processing.

480

481 **Table 2. Examples of food waste-derived engineered biochar materials for electrochemical applications**

Feedstock	Preparation method	Engineered biochar properties	Electrochemical application	Electrochemical performance	Ref.
Rice	KOH activation with *Bacillus cereus* (N precursor)	N-doped micro- and meso-porous structure with high specific surface area (1,899 m^2/g)	Li-ion batteries (LIBs), Na-ion batteries (SIBs)	Capacity: 1,006 mA h/g in LIBs at 100 mA/g (100 cycles) and 169 mA h/g in SIBs at 100 mA/g (1,000 cycles).	[104]
Starch	Pyrolysis (Ar, 500 °C) combined with calcination (Ar, 800-1,000 °C)	Hierarchical engineered biochar with high specific surface area (2,200 m^2/g) and controlled porosity	Supercapacitor	Specific capacitance (229 F/g at 1 A/g in a 6 *M* KOH electrolyte), rate capability (211 F/g at even 10 A/g) and cycling stability (94% capacitance retention after 10,000 cycles at 2 A/g).	[105]
Potato peel	Carbonization with sodium hypophosphite and thioacetamide combined with KOH activation (N_2, 750 °C)	S- and P-doped hierarchical engineered biochar with high specific surface area (1,911.5 m^2/g) and controlled porosity	Supercapacitor	Specific capacitance of 323 F/g at 1 A/g, acceptable rate capability and cycling stability after 5,000 cycles	[106]
Apple waste	Hydrothermal carbonization (HTC) (200 °C) combined with KOH activation (CO_2, 800 °C)	Hierarchical engineered biochar with high specific surface area (2,000 m^2/g)	Supercapacitor	Specific capacitances: 260-290 F/g	[107]
Orange peel	HTC (150 °C) combined with KOH activation (800 °C)	N-doped engineered biochar and intercrossed, interlinked urchin-like $NiCo_2O_4$@3DNF framework	Supercapacitor	High capacitance of 1,300 F/g at a current density of 1 A/g, excellent rate and cyclic performance of 3,500 cycles.	[108]
Banana peel	One-step carbonization (Ar, 800 °C) and subsequent mixing with MoS_2	MoS_2 decorated engineered biochar composite with specific surface area of 269 m^2/g and suitable micropores and mesopores.	Hydrogen evolution reaction (HER)	High HER activity and excellent stability in the acid solution, including an overpotential of 150 mV at a current density of -10 mA/cm^2 and a Tafel slope of 51 mV/dec.	[109]

Sugarcane bagasse	HTC (240 °C) combined with KOH activation (800 °C)	Oxygen-rich hierarchical engineered biochar with the specific surface area of 1,436.7 $m^{2/}g$ and highly microporous.	Supercapacitor	The specific capacitance of 185.5 F/g and 150.7 F/g at a current density of 0.5and 20 A/g, respectively, and superior cycling performance with 96% capacitance retention after 10,000 cycles at a current density of 10 A/g	[110]
Watermelon peel	Carbonization combined with KOH activation	N-doped hierarchical engineered biochar with the specific surface area of 782.69 m^2/g and pore volume of 0.44 cm^3/g	Oxygen reduction reaction (ORR) for Zn-air battery (ZAB)	High specific capacity of 748.9 mA/h g and energy density of 891.2 W/h kg, close to those of the ZAB based on Pt/C	[111]
Coffee grounds	One-step carbonization/ activation with $ZnCl_2$ (600-900 °C)	N-doped hierarchical engineered biochar with the specific surface area of 1,200 m^2/g	ORR for ZAB	The half-wave potential was ~870 mV versus Reversible Hydrogen Electrode comparable to the best results reported for metal-free carbon-based materials in alkaline media	[112]
Coffee grounds	One-step carbonization/ activation with KOH (1,200 °C)	Hierarchical engineered biochar nanosheet with the specific surface area of 1,945.7 m^2/g	Supercapacitor	Specific energy of 35.4 Wh/kg at 11250 W/kg and 23 Wh/kg for a 3 s charge-discharge current rate, corresponding to a specific power of 30,000 W/kg and good cyclic performance over 5,000 cycles	[113]
Coffee grounds	$FeCl_3$ catalytic carbonization combined with KOH activation	Hierarchical engineered biochar with high specific surface area (3,549 $m^2/$ g) and large meso-/macropore volume (1.64 cm^3/g)	Supercapacitor	The high capacitance of 440 F/g at 0.5 A/g	[114]
Shrimp shell	One-step pyrolysis (Ar, 700 °C) with KOH	N-doped hierarchical engineered biochar with the specific surface area of 2,032 m^2/g	Supercapacitor	The specific capacitance of 348 F/g in a 6 *M* KOH electrolyte	[101]
Shrimp shell	One-step pyrolysis (Ar, 800 ^oC) with KOH	Hierarchical engineered biochar with a high specific surface area (1,271 m^2/g), O-doping (9.08%) and N-	LIBs, supercapacitor	As LIB anode material: specific capacity as high as 1,507 mA h/g and 1,014 mA h/g at current densities of 0.1 A/g and 0.5 A/g, respectively, good rate performance and superior cycling	[102]

		doping (2.86%)		stability; as engineered biochar-based supercapacitor: specific capacitance of 239 F/g at a current density of 0.5 A/g in 6 *M* KOH electrolyte.	
Shrimp shell	A sol-gel and carbonization (N_2, 900 °C) process	$FeCoP_2$ nanoparticles embedded in N- and P-doped hierarchical engineered biochar	ORR, HER for water splitting	A low voltage of 1.60 V to deliver a current density of 10 mA /cm^2	[103]
Crab shell	One-step pyrolysis (900 °C)	N- and S-doped hierarchical engineered biochar with the specific surface area of 827.5 m^2/g	ORR	ORR activity with an onset potential of 0.072 V and a half-potential of 0.110 V (vs. Ag/AgCl) in alkaline electrolytes	[115]
Fish	Pyrolysis with $ZnCl_2$ (900 °C)	N-coated hierarchical engineered biochar with the specific surface area of 850 m^2/g	ORR	Half-potential of 0.060 V lower than that on 20 wt.% Pt/C catalyst	[116]
Fishbone	One-step carbonization (850 °C) without chemical activator	N- and S-doped hierarchical engineered biochar with the specific surface area of 1,337 m^2/g	Supercapacitor	Specific capacitance of 476 F/g and high cycling stability with 90.9% of the original capacitance retained after 10,000 cycles at a 1 A/g current density	[100]

482

5. Conclusions and outlook

Thermochemical conversions are a promising route for upcycling food waste into high value-added fuels and advanced carbon materials due to the short residence times required, high yields of a wide range of products, high conversion efficiencies and feasible deployment for practical applications. Numerous research focused on optimizing thermochemical reaction conditions with controllable product distributions and elucidation of the reaction mechanisms and evolution pathways. The production of food waste-derived gaseous and liquid products via thermochemical conversions has been widely explored elsewhere. This review summarizes the processes of producing biochar and hydrochar via the slow pyrolysis and HTC of food waste and their by-products. Engineered biochar synthesis through activation (i.e., physical and chemical) and surface modifications (i.e., O-, N-, and S-doping) can be further optimized using ML approaches. Moreover, engineered biochar-based practical applications, such as solid fuels, adsorbents (i.e., CO_2 adsorption), and advanced catalytic conversions (i.e., electrochemical catalysis), were thoroughly reviewed.

Food waste is a promising and sustainable alternative to solid fuels. It is often characterized by high-water content. HTC enables the direct conversion of food waste into hydrochar for solid fuel applications. HTC operating conditions (i.e., temperature, pressure, and residence time) significantly affect the physicochemical properties, combustion behavior, and alkali metals contents of the resulting hydrochar. Compared with other biomass waste, such as agroforestry residues, food waste has a lower ash

content, especially of alkali and alkaline earth minerals, which is beneficial for reducing both sintering and corrosive risks during thermochemical conversions. However, because of the high moisture content, developing a low-cost and efficient dewatering pre-treatment remains a key challenge. The co-production of bio-oil fuels (from waste cooking oil) and biogas (from AD pre-treatment) dramatically increases both the technical and economic feasibility of thermochemical upcycling.

Biochar and hydrochar can be activated and/or modified into advanced engineered biochar materials for energy and environmental applications. Owing to its stable physicochemical properties, tunable pore structures, effective surface functional groups and cost-effectiveness, engineered biochar has been widely synthesized into advanced carbon materials for adsorption and electrochemical applications. In the context of carbon neutrality, paradigm shifts to interdisciplinary collaboration are urgently needed to achieve the circular economy of food waste. For example, material science, data science, thermochemical engineering, and environmental engineering are the basic requirements for developing an advanced CO_2 adsorption system using food waste-derived engineered biochar. Moreover, the wide range of feedstocks and lack of synthesis guidelines for engineered biochar greatly limit its commercial applications. A powerful ML approach has been considered a promising route for synthesizing high-performance engineered biochar. ML can be used not only to accurately predict practical performance using engineered biochar but also to efficiently provide inverse design guidelines to synthesis engineered biochar for a specific application. In addition, both environmental benefits and economic feasibility need to be verified

using techno-economic and life-cycle assessments before food waste-derived engineered biochar can be synthesized and applied on an industrial scale.

To accelerate the practical applications of food waste-derived engineered biochar materials, several efforts need to be made in the future as follows:

(1) AD is still the dominant pre-treatment for sustainable food waste management into methane and solid residue, owing to that it has a better techno-economic feasibility compared with the direct thermochemical processes (e.g., pyrolysis, gasification). However, it is still necessary to perform thermochemical routes for further upcycling solid residue into high value-added engineered biochar materials. In the future, more efforts should be made in the integrated AD and follow-up thermochemical routes for full valorization of food wastes.

(2) For the application of food waste-derived engineered biochar as an adsorbent, most of the current research has focused on the conventional pollutants removal (e.g., VOCs adsorption, CO2 capture). More efforts need to be made in the development of food waste-derived engineered biochar with functionalized properties, in order to adsorb and convert emerging contaminants into value-added products, simultaneously.

(3) Many investigations have been performed in the conversion of diverse food waste to biochar materials for solid biofuel productions or carbon material applications, but these studies mainly focused on the optimization of processing and utilizing conditions. To date, less work has been done in the techno-economic and life-cycle assessment of the whole process including biofuels and carbon materials production and applications, which is beneficial to promoting the industrial applications of food

548 waste-derived value-added products.

549

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