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Hydrothermal carbonization for organic solid waste treatment: A comprehensive review

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ABSTRACT

Hydrothermal carbonization (HTC) has emerged as a promising thermochemical technology for sustainable management of organic solid waste. Unlike conventional thermal processes, HTC operates at moderate temperatures (180–250 °C) and enables the direct conversion of high-moisture feedstocks without energy-intensive drying. This review critically summarizes recent advances in HTC of diverse organic wastes, including food waste, sewage sludge, agricultural residues, and municipal solid waste. The outstanding advantages of HTC, such as high carbon recovery, improved hydrochar fuel properties, reduced greenhouse gas emissions, and effective nutrient retention, are highlighted. The effects of key operating parameters on hydrochar yield and quality are systematically evaluated. Reaction pathways governing the formation of solid, liquid, and gaseous products are also discussed. Potential applications of hydrochar in energy production, environmental remediation, and soil improvement are presented. Despite these benefits, challenges related to scale-up and process optimization remain. Overall, HTC offers a versatile and sustainable platform for converting organic waste into valuable resources, supporting circular economy strategies.

Keywords: hydrothermal carbonization, organic solid waste, hydrochar, energy recovery, sustainable waste treatment.

INTRODUCTION

The rapid growth of global population, urbanization, and changes in consumption patterns have led to a continuous increase in the generation of organic solid wastes (Libra et al., 2011; Pauline and Joseph, 2020; Shen, 2020). Major waste streams include food waste, the organic fraction of municipal solid waste (OFMSW), sewage sludge from wastewater treatment plants, agricultural residues, livestock manure, and anaerobic digestion digestate (Al Ramahi et al., 2021; Azaare et al., 2021; Nakano et al., 2025; Wang et al., 2022a). These materials are typically characterized by high moisture content, heterogeneous composition, and rapid biological degradability, which pose significant technical and environmental challenges for conventional waste management strategies (Libra et al., 2011; Nakano et al., 2025).

Traditional treatment routes for organic solid waste, such as landfilling, composting, incineration, and dry thermochemical conversion, suffer from inherent limitations (Pham et al., 2025a; Pham et al., 2025b; Pham et al., 2021). Landfilling is associated with long-term environmental risks, including greenhouse gas emissions, leachate generation, and land use constraints (Corvalán et al., 2021). Composting and biological stabilization, while environmentally benign, often result in limited energy recovery and may face issues related to odor emissions and product quality (Moscoviz and Jimenez, 2021; Nguyen et al., 2014). Incineration and pyrolysis require extensive pre-drying of feedstocks, making them energetically and economically unattractive for wet organic wastes such as food waste and sewage sludge (Pauline and Joseph, 2020; Singh et al., 2024; Wang et al., 2019). Consequently, alternative technologies capable of efficiently processing wet waste streams while enabling energy and material recovery are urgently required. Among the emerging waste-to-energy technologies, hydrothermal carbonization (HTC) has attracted considerable attention over the past two decades as a promising solution for the treatment and valorization of wet organic solid wastes (Libra et al., 2011; Nakano et al., 2025; Pauline and Joseph, 2020; Singh et al., 2024).

HTC is a thermochemical conversion process conducted in liquid water under subcritical conditions, typically at temperatures between 180 and 250 °C and autogenous pressures of 2–6 MPa (Libra et al., 2011; Nakano et al., 2025; Singh et al., 2024). Under these conditions, complex organic matter is transformed into a carbon-rich solid product, known as hydrochar, along with an aqueous phase containing dissolved organics and nutrients and a minor gaseous phase dominated by carbon dioxide (Durak et al., 2026; Sangaré et al., 2024). Hydrothermal carbonization generally exhibits moderate to relatively high operating costs compared with other biomass conversion technologies, primarily due to its requirements for elevated temperatures, high-pressure reactors, and subsequent treatment of process water (Lucian and Fiori, 2017). Energy consumption represents a major cost component, including both thermal energy for maintaining reaction conditions and electricity for system operation, with reported demands of approximately 1170 kWh of heat and 160 kWh of electricity per ton of hydrochar (Lucian and Fiori, 2017). The production cost of hydrochar is typically in the range of 150–200 € t^{-1}, depending on process scale and feedstock characteristics (Lucian and Fiori, 2017). Despite these relatively high operational demands, HTC can be economically competitive with thermochemical processes such as pyrolysis and gasification, particularly because it avoids the energy-intensive drying step required for these technologies (Pauline and Joseph, 2020; Wang et al., 2019). In comparison, biological processes such as anaerobic digestion generally exhibit lower operating costs due to milder operating conditions, although they require longer retention times and produce lower-value products. Therefore, although HTC is not the least expensive option in terms of operating cost, it remains a cost-competitive and technically advantageous technology for the treatment and valorization of wet biomass streams.

From a technological perspective, HTC offers several advantages over conventional waste treatment methods. The process improves the dewaterability and handling properties of solid residues, achieves effective pathogen reduction, and enhances the energy density and stability of the resulting hydrochar (Roslan et al., 2023; Wang et al., 2019; Zhao et al., 2014b). Furthermore, HTC exhibits a high degree of feedstock flexibility and can accommodate heterogeneous and contaminated waste streams that are challenging for biological processes (Berge et al., 2011; Petrović et al., 2024; Reza et al., 2016). These features make HTC especially attractive for municipal and industrial waste management systems. Furthermore, although the effects of key process parameters—such as temperature, residence time, and solid-to-liquid ratio—have been widely investigated for individual biomass feedstocks, far fewer studies systematically examine reaction mechanisms and their influence on the qualitative properties of HTC products derived from complex or mixed wastes. This gap remains significant. While recent reviews have reported progress in elucidating HTC mechanisms, the relationships between operating conditions and the qualitative characteristics of hydrochar are still insufficiently addressed, particularly for heterogeneous waste streams (Wu et al., 2023). Despite these advances, a critical evaluation of HTC performance across different organic waste streams remains limited. Most existing studies focus on single feedstocks, and systematic comparisons under comparable operating conditions are rarely conducted. This lack of comparative analysis makes it difficult to distinguish the influence of intrinsic feedstock composition from that of process parameters, thereby hindering the development of generalized optimization strategies (Libra et al., 2011; Lucian and Fiori, 2017; Reza et al., 2014). For example, food waste typically produces hydrochar with higher energy density, whereas sewage sludge often yields hydrochar characterized by higher ash content and lower calorific value; however, these differences are frequently reported under varying experimental conditions, which limits direct comparison and obscures mechanistic interpretation (He et al., 2013; Sevilla and Fuertes, 2009).

In addition to hydrochar production, increasing attention has been paid to the valorization of the HTC aqueous phase and the integration of HTC with complementary technologies. Numerous studies have investigated the coupling of HTC with anaerobic digestion, where process water is converted to biogas and solid residues are stabilized and upgraded (Al Ramahi et al., 2021; Aragon-Briceño et al., 2022; Satari et al., 2025). Other integration pathways include the use of hydrochar as a solid biofuel, soil amendment, carbon sequestration agent, or precursor for advanced carbon materials (Petrović et al., 2024; Semaan et al., 2022). System-level assessments have demonstrated that such integrated configurations can significantly enhance overall energy recovery and environmental performance (Corvalán et al., 2021; Usack et al., 2019). Existing reviews typically address specific aspects of HTC process, such as co-HTC processes or the fuel properties of hydrochar, while a comprehensive critical assessment that integrates fundamental mechanisms, process optimization, operational constraints, and practical technological barriers across diverse organic waste streams remains limited. Consequently, a holistic synthesis of this knowledge is still scarce, as also highlighted in recent publications (Wang et al., 2022b).

Despite the growing interest in HTC, systematic comparisons regarding the influence of different organic waste types—such as food waste, agricultural residues, and sewage sludge—on hydrochar yield and properties under similar operating conditions remain scarce. This lack of systematic evaluation complicates the development of unified optimization strategies. Recent studies indicate that the physicochemical characteristics and energy-related parameters of hydrochar are strongly governed by both feedstock type and processing conditions; however, the reported findings are often presented individually, without consistent comparisons across different waste categories (Reza, 2022). Moreover, limited attention has been given to complex or mixed industrial organic wastes containing high levels of inhibitors, heavy metals, salts, or recalcitrant organic compounds. These components can significantly influence hydrolysis, polymerization, and aromatization reactions during HTC, thereby affecting both hydrochar quality and process water composition. Nevertheless, such heterogeneous waste streams remain underrepresented in current literature, despite their increasing relevance in real-world waste management systems (Berge et al., 2011; Funke and Ziegler, 2010; Reza et al., 2016).

Another important limitation concerns the insufficient understanding of the relationship between macromolecular composition and HTC product distribution. The relative proportions of cellulose, hemicellulose, lignin, proteins, and lipids strongly influence reaction pathways and determine the formation of hydrochar, aqueous-phase organics, and gaseous products (Funke and Ziegler, 2010; Libra et al., 2011; Sevilla and Fuertes, 2009). However, the impact of these macromolecular components on the qualitative composition of the liquid phase, including organic acids, phenolic compounds, and nitrogen-containing species, remains poorly understood. This knowledge gap is particularly important for evaluating downstream valorization and integration opportunities (Reza et al., 2014).

Against this background, the objective of this review is to provide a comprehensive and critical overview of hydrothermal carbonization as a technology for the treatment of organic solid wastes. The review systematically discusses the fundamental principles and reaction mechanisms of HTC, the influence of feedstock characteristics and operating conditions, the properties and potential applications of HTC products. This work aims to clarify the current state of knowledge, identify key research gaps, and outline future perspectives for the sustainable implementation of HTC within modern waste management and circular economy frameworks.

FUNDAMENTALS OF HYDROTHERMAL CARBONIZATION

Hydrothermal carbonization is performed in a sealed reactor, where organic waste is treated in the presence of liquid water under subcritical conditions. The process typically operates at temperatures between 180 and 250 °C, generating autogenous pressures of approximately 2–6 MPa. Depending on the characteristics of the feedstock and the targeted product properties, residence times may range from several minutes to a few hours. Table 1 shows an overview of the benefits and drawbacks associated with hydrothermal carbonization.

Under these operating conditions, water plays a crucial multifunctional role as a solvent, reactant, and catalyst. At elevated temperatures, its increased ionic product enhances acid–base-catalyzed reactions, thereby promoting the depolymerization and transformation of complex organic

Table 1. Overview of the benefits and drawbacks associated with hydrothermal carbonization (Czerwińska et al., 2022; Singh et al., 2024)

Benefits	Drawbacks
- The process operates under comparatively mild temperature conditions. - It requires a relatively short residence time, enhancing process efficiency. - Wet biomass can be directly utilized as feedstock without prior drying. - Energy-intensive drying steps are avoided, thereby reducing overall energy consumption. - The process contributes to a significant reduction in waste volume. - Energy densification of the feedstock is achieved, improving its fuel properties. - The resulting solid product exhibits hydrophobic behavior and enhanced grindability. - Pretreated feedstock demonstrates improved dewatering characteristics. - Operating parameters can be readily monitored and controlled.	- The liquid phase generated contains a complex mixture of organic and inorganic compounds that requires further treatment. - Additional separation of solid and liquid fractions is necessary, along with drying of the solid product prior to downstream applications. - An appropriate filtration strategy must be carefully selected according to the physicochemical characteristics of the final product.

structures. As a result, HTC produces three main product phases: (i) hydrochar, a carbon-rich solid material; (ii) process water, which contains dissolved organic compounds and nutrients; and (iii) a gaseous phase composed predominantly of CO_2, along with minor amounts of CO, H_2, and light hydrocarbons. Figure 1 illustrates the process flow diagram of HTC.

One of the principal advantages of HTC is its broad feedstock flexibility. The technology has been successfully applied to a wide range of organic solid wastes, including food waste and the organic fraction of municipal solid waste, which are characterized by high moisture content and biodegradability; sewage sludge and anaerobic digestate, for which HTC enhances dewaterability, pathogen reduction, and energy density; agricultural and agro-industrial residues such as straw, manure, and fruit or vegetable processing wastes; and mixed or contaminated waste streams, where HTC can function as both a stabilization and pretreatment method. Nevertheless, feedstock composition plays a decisive role in determining process performance and product characteristics. It significantly influences hydrochar yield, elemental composition, ash content, and higher heating value (HHV), as well as the quantity and chemical profile of the process water.

The HTC process involves a complex network of simultaneous and sequential reactions, as schematically illustrated in Figure 2. Hydrochar formation during hydrothermal carbonization of organic solid waste at 180–250 °C occurs via multiple concurrent pathways, including solid–solid conversion, liquid-phase reactions, and secondary carbonization (Pauline and Joseph, 2020; Zhao et al., 2014a). Firstly, the solid–solid conversion pathway involves the direct transformation of

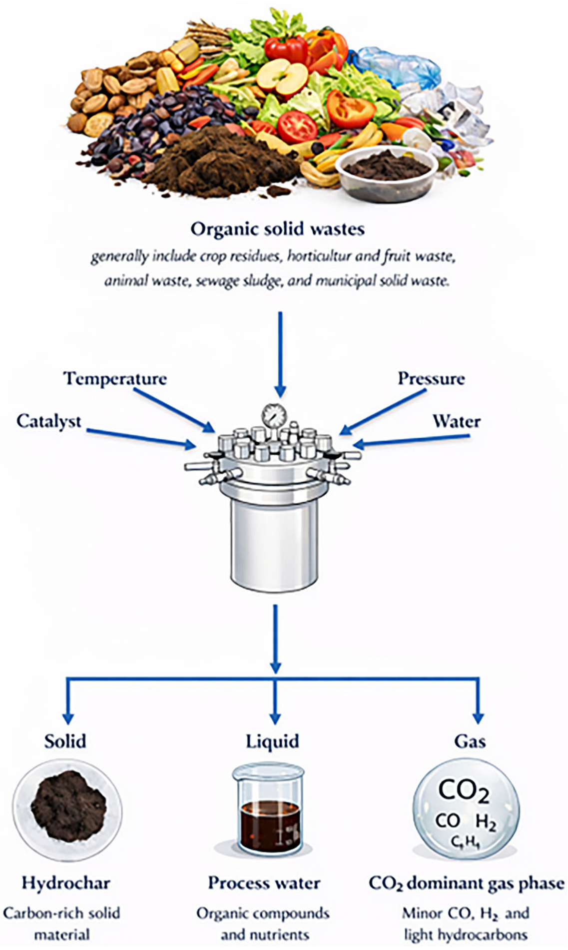

Figure 1. Process flow diagram of hydrothermal carbonization

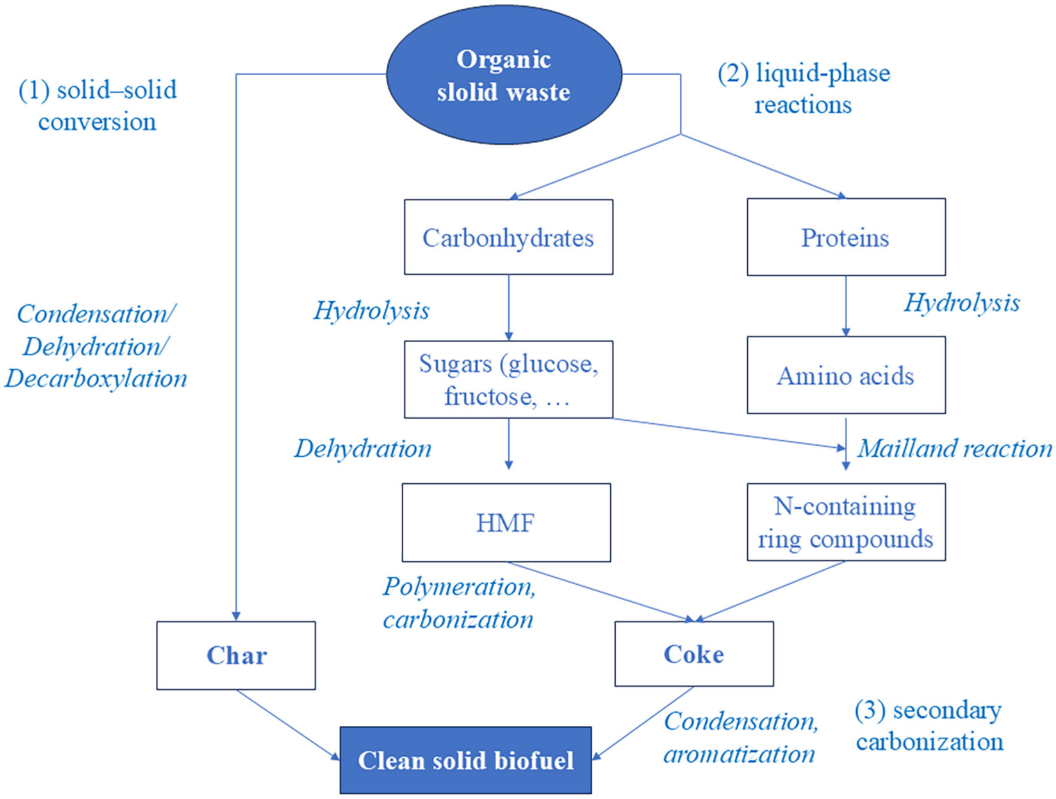

Figure 2. Schematic clean solid biofuel formation in HTC of organic solid waste (Pauline and Joseph, 2020; Sevilla and Fuertes, 2009; Zhao et al., 2014a)

biomass components, especially lignin-rich fractions, through dehydration, decarboxylation, and condensation reactions. This pathway results in the formation of a carbon-rich solid (char) that partially preserves the original structural features of the biomass (Zhao et al., 2014a). Secondly, the liquid-phase pathway is initiated by the hydrolysis of cellulose and hemicellulose into soluble monomers such as glucose and xylose. These intermediates are subsequently dehydrated into furan derivatives (e.g., 5-hydroxymethylfurfural and furfural), which undergo polymerization and condensation to form spherical carbonaceous particles (hydrochar microspheres). Moreover, amino acids released from protein hydrolysis in biowaste can further react with sugars to form nitrogen-containing heterocyclic compounds via the Maillard reaction (Kruse et al., 2007). The brown coloration and characteristic odor of hydrochar provide clear evidence of the occurrence of Maillard reactions (He et al., 2013). This pathway plays a key role in controlling the morphology and surface properties of hydrochar (Zhao et al., 2014a). Finally, the secondary carbonization pathway involves the further transformation of soluble intermediates and oligomers via intermolecular condensation and aromatization reactions, leading to the formation of highly condensed coke-like carbon structures with higher carbon content and lower oxygen functionality (Zhao et al., 2014a). Overall, hydrochar formation in HTC is governed by the interplay of these pathways, with their relative contributions depending on process conditions such as temperature, residence time, and feedstock composition. At higher temperatures (approaching 250 °C), secondary carbonization and aromatization reactions become more pronounced, resulting in hydrochar with enhanced structural stability and a higher degree of carbonization. In the HTC process, the reaction mechanism mainly involves hydrolysis, dehydration, decarboxylation, condensation, polymerization, and aromatization.

Hydrolysis

In the HTC process, elevated temperatures and pressures allow water to exist in a subcritical state. Under these conditions, water, enriched with hydronium ions, exhibits an increased ionic product of H^+ and OH^-, thereby promoting hydrolysis reactions (Pauline and Joseph, 2020). Hemicellulose begins to hydrolyze at approximately 180

°C, whereas cellulose decomposes at around 230 °C, and lignin at temperatures above 260 °C (Reza et al., 2014). The higher hydrolysis temperature of lignin is attributed to its greater abundance of stable ether bonds. Hemicellulose is primarily degraded into xylose, while cellulose is converted into various oligomers (e.g., cellobiose, cellohexaose, cellopentaose, cellotetraose, and cellotriose), as well as glucose and fructose (Pham et al., 2023). In contrast, lignin decomposes into phenol and other phenolic derivatives. Additionally, starch and sucrose are hydrolyzed to yield glucose and fructose (Pauline and Joseph, 2020).

Proteins undergo hydrolysis to form polypeptides, which are further broken down into smaller oligomers such as tetramers, trimers, and dimers. These dimers may exist as either linear or cyclic dipeptides (Zhuang et al., 2019). Due to the relatively higher stability of peptide bonds, protein hydrolysis occurs more slowly than that of carbohydrates (Wang et al., 2018). Ultimately, the complete hydrolysis of these oligomers results in the formation of amino acids.

Dehydration and decarboxylation

Dehydration is commonly associated with the removal of hydroxyl groups, whereas decarboxylation involves the thermal cleavage of long-chain carboxylic acids. Decarboxylation generally occurs only after substantial dehydration has taken place, while dehydration can proceed with minimal or no decarboxylation (Titirici et al., 2007). Although both reactions may occur simultaneously, dehydration typically proceeds at a faster rate than decarboxylation (Funke and Ziegler, 2010).

Dehydration mainly proceeds through the elimination of hydroxyl groups, during which glucose first fragments into intermediates such as dihydroxyacetone, glyceraldehyde, and erythrose, followed by further dehydration to form 5-hydroxymethylfurfural (HMF) or 1,6-anhydroglucose; continued dehydration of these intermediates leads to water formation (Kabyemela et al., 1999). In addition, various soluble compounds are generated, including erythrose, furfural derivatives (HMF, furfural, and 5-methylfurfural), and acids and aldehydes such as acetaldehyde, acetylacetone, glyceraldehyde, glycolaldehyde, and pyruvaldehyde, which may also arise from furfural decomposition (Aida et al., 2007; Kabyemela et al., 1999). Water is further produced during condensation reactions among soluble fragments in the liquid phase (Funke and Ziegler, 2010).

Decarboxylation occurs via the partial removal of carboxyl groups, where degradation of carboxyl and carbonyl functionalities produces CO_2 and CO, respectively (Pauline and Joseph, 2020). Carbon dioxide may additionally originate from formic acid generated during cellulose degradation, cleavage of intramolecular bonds, and other condensation reactions (Pauline and Joseph, 2020). In contrast, lignin is less affected by hydrothermal carbonization due to its higher structural stability associated with phenolic structures (Lu et al., 2014). The relatively high heating value of HMF (22.06 MJ/kg) may also contribute to the increased higher heating value (HHV) of the resulting solid char.

Condensation and polymerization

Polymerization reactions driven by intermolecular dehydration or aldol condensation are considered the predominant pathways (Kabyemela et al., 1999). When monomers such as glucose and fructose undergo these reactions, soluble polymers are formed, accompanied by the generation of C=O and C=C functional groups (Sevilla and Fuertes, 2009). The C=O groups arise from dehydration of hydroxyl groups in the monomers, whereas the C=C linkages originate from keto–enol tautomerism (Pauline and Joseph, 2020).

Amines react with sugars containing carbonyl groups to produce nitrogen-containing heterocyclic compounds, including pyrrole (N-5), pyridine (N-6), as well as pyrazine and indole derivatives. Maillard reactions occur, leading to the formation of polymeric compounds known as melanoidins. These reactions yield a variety of intermediates and products, such as aldehydes, furans, pyrroles, pyrazines, and pyridines (Wang et al., 2018).

Aromatization

Aromatic molecules are generated through the decomposition of oligo- and monosaccharides. Subsequent condensation of these aromatized species leads to the formation of aromatic clusters (Sevilla and Fuertes, 2009). Alkaline conditions further promote the development of aromatic structures (Nelson et al., 1984). The polymerized compounds then undergo rearrangement, forming nitrogen-incorporated monocyclic and dicyclic aromatics such as pyrazine, indole derivatives, pyrrole (N-5), pyridine (N-6), and quaternary-N structures (Wang et al., 2018). These aromatic domains are regarded as the fundamental building blocks of HTC coal because of their high stability under HTC conditions.

The concentration of aromatic clusters in the liquid phase gradually increases until a critical supersaturation level is reached, triggering a nucleation burst. The nuclei formed subsequently grow outward through diffusion processes (Sevilla and Fuertes, 2009). Consequently, hydrochar microspheres develop via a nucleation–growth mechanism consistent with the LaMer model (Mer, 1952). As reaction time and temperature increase, the diameter of the resulting microspheres also becomes larger (Sevilla and Fuertes, 2009). Elevated temperatures enhance fragmentation of unreacted feedstock and promote aromatization and repolymerization, leading to the formation of solid char particles (Lin et al., 2016). The pores observed on the hydrochar surface are likely associated with gas release from volatile components during the process.

FEEDSTOCKS FOR HYDROTHERMAL CARBONIZATION

One of the most significant advantages of HTC is its exceptional flexibility with respect to feedstock selection. Unlike conventional thermochemical conversion technologies such as pyrolysis or gasification, which typically require dry biomass, HTC can efficiently process wet organic materials without the need for energy-intensive drying. This characteristic makes HTC particularly suitable for the treatment of a wide variety of organic solid wastes with high moisture content, including municipal, agricultural, and industrial residues (Berge et al., 2011; Libra et al., 2011; Wang et al., 2022a). As global waste generation continues to increase, the ability of HTC to convert diverse organic waste streams into valuable carbonaceous products has attracted growing attention in both waste management and renewable energy sectors. Table 2 summarizes the main types of feedstocks used in the HTC process, along with typical examples, advantages, and limitations.

Among the most widely investigated feedstocks for HTC are food waste and the OFMSW. These materials are characterized by high moisture content, high biodegradability, and significant fractions of carbohydrates, proteins, and lipids. Studies have shown that HTC can effectively stabilize these substrates while simultaneously producing hydrochar with enhanced energy density and improved fuel properties (Aragón-Briceño et al., 2021). During HTC, easily hydrolysable components such as sugars and starch are rapidly decomposed and transformed into intermediate compounds including furfurals and organic acids, which subsequently undergo polymerization and aromatization reactions to form hydrochar (Titirici et al., 2012). As a result, hydrochars derived from food waste typically exhibit higher carbon content and reduced oxygen-to-carbon (O/C) ratios compared with the original feedstock, leading to higher heating values (HHV) that can reach 20–26 MJ kg^{-1} depending on process conditions (Lucian et al., 2018; Wang et al., 2022a). In addition to energy recovery, HTC treatment can significantly reduce odor, improve waste stability, and decrease the volume of municipal organic waste requiring disposal.

Another important category of HTC feedstocks is sewage sludge and anaerobic digestate, which are generated in large quantities from wastewater treatment plants and biogas facilities. These materials typically contain high moisture levels (often exceeding 80%), substantial ash content, and complex organic structures that limit their direct utilization as fuels. Hydrothermal carbonization has proven to be an effective approach for upgrading these residues into more energy-dense hydrochar while simultaneously improving sludge dewaterability and hygienization (Danso-Boateng et al., 2015). Under hydrothermal conditions, the breakdown of extracellular polymeric substances and cellular structures facilitates the release of bound water, leading to improved solid–liquid separation after treatment. In addition, HTC can reduce pathogenic microorganisms and partially immobilize certain contaminants, making the resulting hydrochar more suitable for subsequent energy recovery or material applications (Heilmann et al., 2010; Zhai et al., 2016). For digestate streams derived from anaerobic digestion processes, HTC can also act as a post-treatment step that enhances carbon recovery while generating process water rich in soluble organics that may be recycled or further treated for energy production (Ipiales et al., 2021).

HTC has also been extensively applied to agricultural and agro-industrial residues, such as crop straw, animal manure, fruit and vegetable

Table 2. Main types of feedstocks used in the HTC process

Feedstock type	Typical examples	Advantages	Limitations	Key references
Food waste & OFMSW	Household food waste, kitchen waste, organic fraction of municipal solid waste	High moisture content (no drying required); high biodegradability; good hydrochar yield; suitable for energy recovery and AD integration	Heterogeneous composition; high ash and salt content; potential formation of inhibitory compounds in process water	(Aragon-Briceño et al., 2022; Dhull et al., 2024; Singh et al., 2024; Śliz et al., 2022b; Wang et al., 2022a; Wang et al., 2018)
Sewage sludge	Wastewater treatment sludge	Abundant and continuously available; pathogen reduction; improved dewaterability; nutrient-rich hydrochar	High ash content lowers HHV; presence of heavy metals; disposal regulations for hydrochar reuse	(Merzari et al., 2020; Singh et al., 2024; Wilk et al., 2023a)
Anaerobic digestate	Solid/liquid residues from biogas plants	Enhances carbon recovery; improves solid fuel properties; enables circular integration with AD; reduces waste volume	Low carbon content compared to raw biomass; high mineral content; variable composition	(Belete et al., 2021; Ipiales et al., 2021)
Agricultural residues	Straw, husk, corn stover, manure	Abundant lignocellulosic resource; higher carbon content; produces hydrochar with improved HHV; relatively low contamination	Requires size reduction; seasonal availability; lower reactivity compared to wet wastes	(Minaret and Dutta, 2016; Singh et al., 2024; Zhang et al., 2018)
Agro-industrial waste	Fruit peels, vegetable waste, olive pomace, winery waste	High organic content; good conversion efficiency; valorization of industrial by-products; potential for high energy yield	Variable composition; may contain oils or inhibitors affecting reaction pathways	(Wang et al., 2018; Zhang et al., 2018)
Algal biomass	Microalgae, macroalgae	High lipid/protein content; rapid conversion; suitable for wet processing; potential for high-value products	High nitrogen content → N-rich hydrochar; energy-intensive cultivation; limited large-scale availability	(Heilmann et al., 2010; Nakano et al., 2025; Singh et al., 2024)
Mixed municipal waste	Contaminated or mixed organic waste streams	Handles heterogeneous waste; reduces landfill burden; stabilizes contaminants; flexible feedstock acceptance	Requires pre-sorting; inconsistent product quality; potential presence of plastics/inorganics	(Berge et al., 2011; Śliz et al., 2022a; Śliz et al., 2022b)
Industrial organic residues	Pulp sludge, food processing waste	Consistent supply; scalable; often pre-treated; good integration with industrial systems	May contain chemicals or additives; regulatory constraints; variable ash content	(Hämäläinen et al., 2022; Mihajlović et al., 2018; Reza et al., 2016; Wang et al., 2018)

processing waste, winery residues, and other biomass by-products. These feedstocks are generally rich in lignocellulosic components, including cellulose, hemicellulose, and lignin, which strongly influence the carbonization pathways during HTC (Sevilla and Fuertes, 2009; Wang et al., 2022a). Carbohydrate-rich materials typically undergo rapid hydrolysis and dehydration reactions, producing intermediate compounds that contribute to the formation of spherical carbon structures in hydrochar. In contrast, lignin-rich biomass tends to produce hydrochar with higher aromaticity and structural stability due to its more recalcitrant molecular structure. Hydrochars derived from agricultural residues often exhibit relatively low ash content and favorable fuel properties, making them attractive candidates for solid biofuel production, soil amendment, or carbon-based material applications (Funke and Ziegler, 2010; Titirici and Antonietti, 2010; Wang et al., 2022a).

In addition to these relatively homogeneous biomass resources, HTC has demonstrated considerable potential for treating mixed or contaminated organic waste streams. Examples include autoclaved municipal solid waste, off-specification compost, and organic residues from mechanical–biological treatment (MBT) facilities. These waste streams are typically heterogeneous and difficult to process using conventional thermal technologies. However, the hydrothermal environment enables effective hydrolysis and carbonization even in the presence of mixed organic components and impurities (Babinszki et al., 2020; Berge et al., 2011). In such cases, HTC can serve not only as a conversion technology but also as a stabilization and pre-treatment process that reduces environmental risks while facilitating downstream resource recovery. For instance, HTC treatment can decrease the biological activity and odor potential of organic wastes while concentrating carbon in the hydrochar fraction.

Despite the broad applicability of HTC to different feedstocks, the chemical composition of the input material strongly influences process performance and product characteristics. Key parameters include the relative proportions of carbohydrates, lipids, proteins, lignin, and inorganic matter. Feedstocks rich in carbohydrates and lipids generally produce hydrochars with higher carbon content and improved heating values due to enhanced dehydration and polymerization reactions during HTC. In contrast, high ash or mineral content can dilute the energy density of the resulting hydrochar but may contribute to nutrient recovery potential in agricultural applications (Heilmann et al., 2010; Michel et al., 2025). Similarly, the presence of proteins and nitrogen-containing compounds may influence the nitrogen content of hydrochar and the composition of the process water generated during the reaction.

Furthermore, the choice of feedstock affects not only the characteristics of the solid hydrochar but also the composition of the liquid and gaseous phases produced during HTC. The process water typically contains a variety of soluble organic compounds, including organic acids, phenolic derivatives, and sugars, which originate from the decomposition of biomass polymers (Wang et al., 2022a). These compounds may represent both a challenge and an opportunity: while they can increase the chemical oxygen demand (COD) of the aqueous phase, they may also serve as substrates for downstream anaerobic digestion or other biological conversion processes. Consequently, understanding the interactions between feedstock composition and HTC reaction pathways is essential for optimizing process conditions and designing integrated waste-to-energy systems.

Overall, the wide range of feedstocks suitable for hydrothermal carbonization highlights the versatility of this technology for sustainable waste management and biomass valorization. By enabling the conversion of diverse organic residues into energy-rich hydrochar and potentially valuable by-products, HTC represents a promising pathway for improving resource recovery and reducing the environmental impacts associated with organic waste disposal.

INFLUENCE OF OPERATING PARAMETERS

The performance of hydrothermal carbonization and the physicochemical properties of the resulting products are strongly governed by operating parameters. Among these, reaction temperature, residence time, solid-to-liquid ratio, heating rate, and the use of additives or process water recirculation have been identified as the most influential factors. Understanding the individual and combined effects of these parameters is essential for process optimization, energy efficiency, and scale-up of HTC systems. Table 3 presents the relationship between HTC processing conditions and key hydrochar properties for different precursor materials.

Reaction temperature

Reaction temperature is the most critical operating parameter in the hydrothermal carbonization process. It determines the amount of thermal energy supplied to the system, directly influencing the breakdown of feedstock components. An increase in temperature significantly accelerates the degradation of organic matter as well as subsequent polymerization reactions (Wang et al., 2019). At relatively low temperatures, depolymerization reactions dominate, resulting in the fragmentation of intermediate compounds. In contrast, higher temperatures favor polymerization and condensation pathways, promoting the formation of more aromatic and condensed carbon structures that ultimately lead to hydrochar production (Akhtar and Amin, 2011).

Decomposition of lignocellulosic biomass becomes particularly pronounced at temperatures around 180 °C. Under these conditions, hemicellulose – due to its lower thermal stability – is preferentially hydrolyzed, whereas cellulose and lignin require more severe conditions

Table 3. Relationship between processing parameters and selected hydrochar properties for diverse precursor materials

Biomass	T (°C)	Residence time (min)	Catalyst	Hydrochar yield (%)	HHV (MJ/kg)	Fixed carbon (%)	Reference
Dewatered sewage sludge	260	30–480	–	53–66.19	10.8–12.06	6.14–9.15	(Peng et al., 2016)
Wood chip	240	60	2% $Fe(NO_3)_3{\cdot}9H_2O$ 4%$Fe(NO_3)_3{\cdot}9H_2O$	56.08 55.32	26.80 30.05	42.95 44.31	(Wang et al., 2023)
Sewage sludge	200	120	Sulfuric acid	6.20	18.96	10.04	(Wilk et al., 2023b)
Municipal solid waste	260	300	Acetic acid	45	32.56	38.81	(Fallah et al., 2023)
Sewage sludge / wheat straw	300	90	–	35.27	36.96	ND	(Zhang et al., 2023)
Spent mushroom substrate	180–260	60	–	57.2–38.32	14.9–17.06	11.6–13.5	(Kojić et al., 2021)
Soybean residue	200–300	120	–	42.9–32.3	19.1–22.0	42.3–19.2	(Ahmad et al., 2021)
Swine manure	200–280	0–60	–	58.7–50.2	12.4–16.0	9.2–15.7	(Xiong et al., 2019)
Banana stalk	160–200	60–180	–	75.3–57.8	18.1–18.9	16.9–44.3	(Islam et al., 2019)
Miscanthus	180–220	60	–	73–51	19.66–21.18	10.83–22.9	(Mihajlović et al., 2018)
Tobacco stalk	180–260	120	–	80–59	18.72–21.42	15.6–26.77	(Cai et al., 2016)
Grape pomace	180–220	60	–	86–66	24.49–26.13	25.84–26.64	(PetroviĿ et al., 2016)
Thickened Sludge	190–250	30 and 60	–	49.4–77.2	18.66–20.71	4.25–6.12	(Merzari et al., 2020)
Digested Sludge	190–250	30 and 60	–	64.6–82.8	7.97–9.37	0.13–2.06	(Merzari et al., 2020)
Dewatered Sludge	190–250	30 and 60	–	67.6–88.2	15.33–16.30	4.04–9.94	(Merzari et al., 2020)
Spent coffee grounds	180–220	60–300	–	79.17–87.6	23–33	22.84–34.78	(Afolabi et al., 2020)

for effective degradation (Kambo and Dutta, 2015; Petrović et al., 2024). During hydrolysis, complex biopolymers are converted into smaller molecules such as oligosaccharides and amino acids. These intermediates subsequently undergo dehydration, condensation, and polymerization reactions, forming the carbon-rich solid product (Funke and Ziegler, 2010). The progression of these pathways intensifies with increasing temperature and longer residence time.

Carbonization reactions are generally favored at temperatures up to approximately 250 °C. When temperatures approach 375 °C, liquid oil fractions begin to form, while temperatures beyond this threshold predominantly promote gas production (Zhai et al., 2016). Furthermore, Liu et al., (2012) and Sun et al., (2010) reported that maximum solid yields were achieved at temperatures below 200 °C. Although higher carbonization temperatures increase the carbon content and aromaticity of hydrochar, they simultaneously reduce solid yield due to intensified thermal degradation and solubilization of organic matter into the liquid and gaseous phases. Elevated temperatures also enhance dehydration and decarboxylation reactions, lowering oxygen content and decreasing O/C and H/C atomic ratios. Consequently, the resulting hydrochar exhibits improved fuel characteristics, as summarized in Table 3.

Elemental analyses reported in the literature consistently demonstrate a decline in H/C and O/C ratios with increasing temperature, reflecting progressive coalification and the development of more condensed carbon structures (Nakano et al., 2025; Petrović et al., 2024). However, excessively high temperatures may diminish overall energy recovery and carbon retention, as a greater fraction of carbon is transferred to non-solid phases (Śliz et al., 2022b; Zhao et al., 2014b). Therefore, an optimal temperature range—commonly between 200 and 230 °C—is often identified to balance hydrochar quality and yield, particularly for wet organic feedstocks such as sewage sludge, food waste, and digestate (Demol et al., 2025; Wang et al., 2019).

Residence time

Residence time determines how closely HTC reactions approach thermodynamic equilibrium at a given temperature. In general, extending the reaction time enhances hydrolysis and subsequent secondary reactions, slightly increasing carbonization severity and the HHV of hydrochar (Libra et al., 2011; Nakano et al., 2025). However, once a minimum duration – typically 0.5–1 h – is reached, its influence becomes less pronounced compared to that of temperature (Durak et al., 2026; Singh et al., 2024).

Prolonged treatment can promote secondary char formation from dissolved intermediates in the process water, particularly at elevated temperatures (Lucian et al., 2018; Picone et al., 2024). Although this phenomenon may increase the apparent solid yield, it can reduce process controllability and overall energy efficiency. From an industrial standpoint, shorter residence times are often preferable because they improve reactor productivity and reduce capital and operational costs without significantly compromising hydrochar quality (Ghavami et al., 2022; Sangaré et al., 2024).

Increasing residence time also intensifies overall reaction severity, facilitating the development of more stable and polyaromatic carbon structures. For lignocellulosic biomass, secondary hydrochar formation is strongly influenced by residence time, whereas the conversion of non-dissolved monomers depends more heavily on temperature (Petrović et al., 2024). Longer durations allow greater release and subsequent transformation of intermediate compounds, thereby affecting the structural evolution of the solid product.

Experimental findings support these observations. Gao et al., (2013) showed that the physicochemical properties of hydrochar derived from water hyacinth varied with reaction time. Similarly, Zhang et al., (2015) reported that short residence times produced hydrochar surfaces with visible fissures, while longer treatments (up to 6 h) led to the formation of microspherical particles. With extended reaction times, these microspheres tended to aggregate, resulting in distinct surface textures, and their diameter increased progressively (Khan et al., 2021).

Despite these structural modifications, the overall effect of residence time on hydrochar properties remains less significant than that of temperature (Table 2). Islam et al., (2019) found that during the carbonization of banana stalks at 200 °C, extending the reaction time from 60 to 180 min decreased hydrochar yield from 61.8% to 57.8%, while only slightly increasing HHV (from 18.7 to 18.9 MJ/kg) and more noticeably raising fixed carbon content (from 35.0% to 44.3%). In comparison, increasing the temperature from 160 to 200 °C at a constant residence time of 180 min resulted in more substantial changes: yield decreased from 72.8% to 57.8%, whereas HHV and fixed carbon content increased significantly.

Overall, while residence time contributes to structural development and secondary reactions, temperature remains the dominant factor governing hydrochar yield and fuel quality. Therefore, careful optimization of residence time at a selected temperature is necessary to achieve hydrochar with targeted characteristics.

Pressure

Pressure plays a critical, albeit largely indirect, role in the HTC process by maintaining water in the liquid or subcritical state and thereby controlling its physicochemical properties. In typical HTC systems, pressure is autogenously generated and generally ranges from 2 to 6 MPa, depending on the reaction temperature and solvent characteristics (González-Arias et al., 2022). Within this range, the physicochemical characteristics of the resulting hydrochar tend to remain largely unchanged (Czerwińska et al., 2022).

The frequently observed positive impact of higher temperatures on HTC performance cannot be attributed solely to thermal effects. As temperature increases, the internal pressure of the reactor also rises. Consequently, part of the improvement associated with elevated temperatures may actually be linked to the accompanying pressure increase. Nevertheless, most HTC studies operate under autogenous pressure, and relatively few investigations have specifically isolated the effect of pressure as an independent variable.

Yan et al. (2018) examined the direct influence of reaction pressure by injecting N_2 to raise the internal pressure while keeping temperature and residence time constant. Their results showed that higher initial pressure enhanced dewaterability, yielding filter cakes with lower moisture content compared to those produced at lower pressures. However, increasing pressure adversely affected the calorific value of the hydrochar, as higher pressures led to a reduction in energy content.

Conversely, Minaret and Dutta (2016) found that pressure changes had no significant impact on the overall HTC process. Under elevated pressures, Brunauer–Emmett–Teller (BET) surface area measurements and scanning electron microscope (SEM) analyses revealed no notable structural differences. Only slight increases in HHV and hydrogen content, along with a small decrease in oxygen content, were observed. In a similar study on lignocellulosic biomass, Gülec et al. (2021) concluded that pressure did not substantially modify hydrochar composition, although ash content increased as pressure rose.

Catalyst

The addition of acids, bases, or inorganic salts can significantly modify reaction pathways during HTC by altering pH and catalytic activity. Acidic conditions generally enhance hydrolysis and dehydration reactions, resulting in higher carbonization degrees and lower O/C ratios in hydrochar (Libra et al., 2011; Singh et al., 2024). Alkaline additives, on the other hand, may promote solubilization of organic matter and suppress char formation, which can be beneficial when HTC is used as a pre-treatment for anaerobic digestion (Al Ramahi et al., 2021).

HTC is a promising thermochemical route for converting wet biomass and organic wastes into value-added carbon materials under mild conditions. However, the interplay of hydrolysis, dehydration, decarboxylation, condensation, and polymerization reactions complicates process control. Catalyst addition has therefore emerged as an effective strategy to direct reaction pathways, enhance carbon retention, improve surface functionality, and tailor hydrochar properties. Organic and inorganic catalysts significantly affect HTC kinetics and product quality. They can reduce operating temperature, promote hydrolysis, facilitate denitrogenation and deoxygenation, increase solid yield, and enrich surface functional groups. Organic acids and alcohols create acidic environments that accelerate reactions (He et al., 2022).

Citric acid is widely recognized as a cost-effective and environmentally benign additive that enhances biomass conversion. It promotes biopolymer hydrolysis followed by dehydration and carbonization, increasing carbon enrichment and hydrochar yield (Sarrion et al., 2022). Higher citric acid concentrations (0.1–0.5 M) significantly improved carbon content and mass yield in sludge-derived hydrochar (Sarrion et al., 2022). It also induces in situ formation of secondary acids (e.g., formic and acetic acids), intensifying hydrolysis and polymerization through autocatalytic effects. Additionally, it enhances dissolution of inorganic fractions and introduces functional groups, resulting in rougher and more porous structures (Ma et al., 2021). Enhanced cellulose depolymerization has also been linked to the formation of larger carbon spheres in lignocellulosic systems (Faradilla et al., 2020). Acetic acid improves carbon concentration and thermal stability but often lowers hydrochar yield, indicating greater fragmentation relative to polymerization. Its weaker carbon-enrichment capacity compared to citric acid relates to its single carboxyl group. Protic solvents such as methanol and ethanol donate hydrogen and facilitate dehydration, improving hydrochar production in protein- and carbohydrate-rich feedstocks (Djandja et al., 2023).

Inorganic additives further regulate HTC by dissolving minerals, lowering ash content, and intensifying hydrolysis and dehydration. Strong acids improve fuel properties, nutrient solubilization, porosity, and stability. Sulfuric acid-assisted carbonization of sewage sludge markedly increased specific surface area due to enhanced structural degradation and metal redistribution (Wilk et al., 2023b). Alkaline additives show contrasting effects: CaO can increase hydrochar yield and ash content while reducing organic matter and polycyclic aromatic hydrocarbons, whereas NaOH mitigates SO_2 and NO_x emissions during combustion and lowers moisture diffusivity (Zhang et al., 2020). Metal chlorides modify morphology and surface chemistry, reduce reaction temperature, catalyze dehydration and decarboxylation, and enhance thermal performance via furfural derivatives and pseudo-lignin formation (Qi et al., 2021; Zhang et al., 2020).

In summary, although all operating parameters influence the HTC process, their roles differ significantly in both mechanism and extent of impact. Reaction temperature is the primary controlling factor, as it directly governs reaction pathways, carbonization severity, and the physicochemical properties of hydrochar. In contrast, residence time plays a secondary role by controlling the extent and completion of these temperature-driven reactions; its influence becomes less pronounced once sufficient reaction time is achieved. Pressure, under typical autogenous HTC conditions, has a limited and mostly indirect effect, primarily maintaining the reaction medium rather than significantly altering hydrochar characteristics. Similarly, solid loading affects mass transfer and process efficiency but does not fundamentally control product formation. Catalyst addition can modify reaction pathways and enhance specific properties; however, its effectiveness strongly depends on temperature and feedstock composition. Therefore, temperature remains the dominant parameter, while residence time, catalyst, pressure, solid loading,... act as secondary factors that refine and optimize the overall process.

HYDROTHERMAL CARBONIZATION PRODUCTS

Hydrothermal carbonization generates three main product streams: hydrochar, process water, and a minor gaseous phase. The properties and potential applications of these products depend strongly on feedstock characteristics and operating conditions, and their effective utilization is critical for achieving favorable energy and environmental performance of HTC-based systems (Libra et al., 2011; Nakano et al., 2025; Pauline and Joseph, 2020).

Hydrochar

Hydrochar is the primary solid product of HTC and has been extensively studied as a solid biofuel and carbonaceous material. Compared to raw organic waste, hydrochar typically exhibits higher carbon content, lower oxygen content, improved grindability, and significantly enhanced dewaterability (Durak et al., 2026; Singh et al., 2024; Wang et al., 2019). These properties result in higher HHV values, often comparable to low-rank coals, particularly for lignocellulosic wastes and digestate-derived feedstocks (Demol et al., 2025; Nakano et al., 2025).

From an energy perspective, hydrochar can be utilized directly as a solid fuel for combustion or co-firing, or as an intermediate for further thermochemical conversion such as gasification or activation (Petrović et al., 2024; Semaan et al., 2022). Beyond energy applications, hydrochar has attracted increasing interest as a soil amendment, carbon sequestration agent, and precursor for functional carbon materials, including adsorbents and catalyst supports (Petrović et al., 2024). However, the suitability of hydrochar for soil or environmental applications depends on its ash content, nutrient composition, and potential contamination with heavy metals, particularly when derived from sewage sludge or municipal waste streams (Roslan et al., 2023; Wang et al., 2019).

Fossil coal includes anthracite, bituminous coal, subbituminous coal, and lignite. Anthracite, also known as hard coal, is considered the highest grade due to its low volatile matter (VM) content, very high fixed carbon content (92–98 wt%), and elevated HHV of 35–40 MJ/kg (Singh et al., 2024). Bituminous coal, an intermediate-rank coal, contains approximately 60–80 wt% fixed carbon and is the most widely used coal for electricity generation, with a typical heating value of 24–35 MJ/kg (Singh et al., 2024). Subbituminous coal has a fixed carbon content of 60–70 wt% and an HHV ranging from 19 to 26.7 MJ/kg, which is higher than that of lignite (10–20 MJ/kg) (Singh et al., 2024). Lignite, or brown coal, represents the lowest rank and is characterized by the smallest proportion of fixed carbon (35–45 wt%) (Singh et al., 2024).

HTC-derived biocoal is a solid, stable, hydrophobic, and clean-burning material with a fuel value comparable to that of lignite (Funke and Ziegler, 2010). Table 4 presents the physicochemical characteristics of hydrochar produced from agricultural waste. The primary solid product of the HTC process, in terms of mass yield, is the carbon-rich char formed during carbonization. A notable feature of this material is its relatively high fixed carbon content (Lynam et al., 2011). As a result, biocoal has been explored for numerous applications, including use as a renewable energy source; hydrogen storage (Berge et al., 2011; Libra et al., 2011); removal of antibiotic resistance genes and pathogens from livestock mortalities; treatment of plant residues (Ducey et al., 2017); and adsorption-based removal of heavy metals such as antimony, arsenic, copper, cadmium, and lead from aqueous solutions (Han et al., 2017). Furthermore, biocoals can adsorb pesticides, thereby reducing contamination of water resources (Singh et al., 2024).

Table 4 highlights the significant influence of feedstock type on the physicochemical properties of hydrochar produced via HTC. Despite being processed under comparable temperature ranges (150–300 °C), distinct variations in carbon content, surface characteristics, and yield are observed among different agricultural wastes. In general, lignocellulosic residues such as orange peels, grape seeds, and walnut shells tend to produce hydrochar with higher carbon content (typically >70 wt%) and more stable structures, which can be attributed to their inherent lignin-rich composition and greater resistance to hydrothermal degradation. This observation is consistent with previous studies indicating that lignin-rich biomass yields more carbon-dense hydrochar with enhanced fuel properties.

In contrast, food-related wastes (e.g., kitchen waste and food waste) generally exhibit lower carbon content (approximately 47–52 wt%) and higher oxygen content, reflecting their higher fraction of easily degradable components such as carbohydrates and proteins. These materials undergo extensive hydrolysis and solubilization during HTC, resulting in lower structural stability and relatively moderate surface areas. Similarly, biomass with higher ash or protein content tends to produce hydrochar with lower energy density but enhanced nutrient content, making it more suitable for soil amendment rather than fuel applications.

Regarding textural properties, a wide variation in surface area (3.29–94 m^2/g) and pore structure is observed across feedstocks. Woody and seed-based materials (e.g., walnut shell and grape seeds) exhibit relatively higher surface areas and more developed pore structures, likely due to their rigid lignocellulosic frameworks. Conversely, soft biomass such as watermelon peel and lettuce produces hydrochar with limited porosity, which may result from the collapse of cellular structures during hydrothermal treatment. These findings indicate that feedstock composition plays a critical role in determining the adsorption potential and surface functionality of hydrochar.

Furthermore, while reaction time and solid-to-water ratio vary across studies, their influence appears secondary compared to feedstock composition and reaction temperature. Increasing temperature generally promotes dehydration and decarboxylation reactions, leading to carbon enrichment and reduced O/C ratios across all feedstocks, regardless of origin. However, the magnitude of these changes remains strongly dependent on the intrinsic properties of the precursor material.

Overall, feedstock is one of the key factors governing the properties of hydrochar. Lignocellulosic biomass generally promotes the formation of carbon-rich, energy-dense hydrochar, whereas food waste and protein-rich materials tend to produce more functionalized products that are better suited for environmental and agricultural applications.

Process water

The aqueous phase produced during HTC contains a wide range of dissolved organic

Table 4. The physicochemical properties of hydrochar obtained from agricultural waste

Feed stock	Reaction temperature (°C)	Reaction time (h)	Solid: water ratio	Solid yield (wt%)	Surface area (m^2/g)	Pore volume (cm^3/g)	Pore size (nm)	C (wt%)	H (wt%)	O (wt%)	N (wt%)	Ref.
Kitchen waste	150	12	-	37.13	13	0.027	8.008	47.86	5.737	37.09	2.71	[57]
Food waste	250	0.33	-	51	6.07	0.064	6.29	52	5.07	38.1	3.38	[58]
Orange peels	190	24	-	51.58	34.06	0.04	5.57	78.85	-	19.12	1.23	[59]
Apple chip pomace	190	0.25	1.12	27	5.89	-	4.29	72.99	7.13	14.09	3.81	[60]
Taro	180	2	1.25	-	9.23	0.05	18.8	64.9	5.79	26.9	0.97	[61]
Lettuce	180	2	1.25	-	6.28	0.05	32.7	59.2	6.72	30.2	3.92	[62]
Watermelon peel	180	2	1.25	-	3.29	0.02	27.6	55.7	6.5	2.77	35.1	[63]
Soyabean residue	180	2	1.25	-	5.99	0.04	21.2	68.6	6.08	3.93	21.4	[60]
Grape seeds	300	24	1.1	33.32	18.32	0.068	8.98	70.88	3.65	26.45	1.01	[64]
Walnut sheell	240	4	1.1	-	94	0.033	0.86	71.33	5.09	23.21	0.07	[65]
Apple waste	230	4	1.4	53	61	2.41	-	73.7	5.7	18.5	2	[66]

compounds, including organic acids, sugars, phenolics, and nitrogen-containing species (Al Ramahi et al., 2021; Piccinno et al., 2016). Although often considered a wastewater stream, process water represents a significant fraction of the chemical energy originally contained in the feedstock. Numerous studies have demonstrated that HTC process water can be effectively treated and valorized via anaerobic digestion, leading to enhanced overall biogas production and system energy recovery (Al Ramahi et al., 2021; Ipiales et al., 2021; Satari et al., 2025).

After the filtration step, the remaining liquid fraction – commonly referred to as process water – still contains suspended biocoal particles. This aqueous phase consists of a range of organic compounds, notably organic acids, furfurals, phenolic substances, and their derivatives, which are formed through the hydrolysis of simple sugars during the HTC process (Berge et al., 2011; Funke and Ziegler, 2010). When short residence times are applied, the characteristics of HTC process water are particularly suitable for anaerobic digestion (AD), enabling subsequent biogas production. In addition, this liquid stream contains inorganic nutrients such as potassium and phosphate, along with short-chain carboxylic acids that contribute positively to plant growth (Bevan et al., 2021).

However, the liquid fraction may also present operational and environmental challenges, both within the HTC system and upon discharge into the environment. Among 680 investigated organic compounds, thirteen were identified at trace concentrations in the process water (Bevan et al., 2021). To lower total organic carbon (TOC) levels and remove excess nutrients, biological treatment—either anaerobic or aerobic—is typically required (Funke and Ziegler, 2010). Following appropriate treatment, the effluent can be repurposed as a liquid fertilizer to enhance plant development (Berge et al., 2013).

Integrating complementary technologies, such as combining AD and HTC into hybrid systems, offers a practical solution by allowing one process to utilize the by-product of the other. Research by Reza et al., (2014) demonstrated that subjecting AD digestate to HTC can yield approximately 20% and 60% higher energy recovery per kilogram of raw biomass compared to standalone HTC and AD processes, respectively. Consequently, facilities that have already invested in AD may increasingly adopt HTC integration in the coming years to maximize overall energy output.

The composition and biodegradability of process water are strongly influenced by HTC temperature and residence time. Mild HTC conditions generally produce more readily biodegradable compounds, whereas severe conditions promote the formation of refractory and potentially inhibitory substances (Picone et al., 2024). Therefore, optimal HTC conditions are required to improve biochar quality and yield, thereby ensuring energy security, reducing waste, and protecting the environment.

Gaseous products

The gaseous fraction formed during HTC process consists predominantly of carbon dioxide, accompanied by trace levels of carbon monoxide, hydrogen, and light hydrocarbons (Danso-Boateng et al., 2015; Durak et al., 2026). Owing to its relatively low heating value and limited yield, this stream is not regarded as a major energy carrier. Nevertheless, its composition offers important information regarding the underlying reaction mechanisms, particularly the progression of decarboxylation pathways throughout the HTC process (Nakano et al., 2025; Singh et al., 2024).

Among the carbonization products, the gaseous fraction represents the smallest mass proportion and possesses comparatively low economic value. The dominance of carbon dioxide in this stream is primarily attributed to extensive decarboxylation reactions. Depending on feedstock characteristics and reaction severity, carbon dioxide has been reported to account for approximately 90% of total gaseous emissions (Ramke et al., 2010). The remaining components typically include minor quantities of methane and hydrogen (Sharma et al., 2020).

Despite its formation during HTC, limited attention has been directed toward the recovery, separation, or valorization of this gaseous effluent. However, the tendency of HTC to generate mainly carbon dioxide while restricting the release of hydrocarbons such as methane and hydrogen has been recognized as an environmental advantage (Singh et al., 2024). Consequently, the implementation of HTC technology may contribute to reducing the generation and emission of harmful greenhouse gases that would otherwise arise from conventional biomass disposal practices, including landfilling or direct combustion (Bevan et al., 2021).

CONCLUSIONS

Hydrothermal carbonization has emerged as an effective thermochemical technology for the conversion of wet biomass and organic solid waste into value-added carbonaceous materials. Operating under relatively mild conditions (180–250 °C and 2–6 MPa), HTC is particularly suitable for feedstocks with high moisture content such as sewage sludge, food waste, and agricultural residues. This process not only significantly enhances the carbon content and energy properties of the resulting hydrochar, but also reduces the volume and environmental impacts of organic waste compared with conventional treatment technologies, including anaerobic digestion, composting, incineration, and pyrolysis. Feedstock composition plays a crucial role in determining product quality, with carbohydrate- and lipid-rich materials typically yielding hydrochar with higher carbon content and improved calorific value, owing to enhanced dehydration and polymerization reactions during the HTC process. In addition, key operating parameters such as temperature, residence time, pressure, solid loading, and the presence of catalysts strongly influence both the yield and properties of the hydrochar. Among these factors, temperature is considered the most dominant parameter, followed by residence time and solid loading. Increasing temperature and residence time generally leads to a decrease in hydrochar yield due to intensified decomposition reactions, resulting in greater gas formation and consequently higher system pressure. Beyond the solid product, the liquid and gaseous by-products generated during HTC also contain valuable compounds, offering additional opportunities for resource recovery and utilization. Therefore, HTC is regarded as a highly promising and sustainable technology for advancing waste-to-resource strategies, particularly in the valorization of wet biomass and organic solid waste in the future.

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