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REVIEW

Recent Advances in Hydrothermal Carbonization of Biomass: The Role of Process Parameters and the Applications of Hydrochar

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ABSTRACT: Biomass is a resource whose organic carbon is formed from atmospheric carbon dioxide. It has numerous characteristics such as low carbon emissions, renewability, and environmental friendliness. The efficient utilization of biomass plays a significant role in promoting the development of clean energy, alleviating environmental pressures, and achieving carbon neutrality goals. Among the numerous processing technologies of biomass, hydrothermal carbonization (HTC) is a promising thermochemical process that can decompose and convert biomass into hydrochar under relatively mild conditions of approximately 180°C–300°C, thereby enabling its efficient resource utilization. In addition, HTC can directly process feedstocks with high moisture content without the need for high-temperature drying, resulting in lower energy consumption. Based on a systematic analysis of the critical articles mainly published in 2011–2025 related to biomass, HTC, and hydrochar applications, in this review, the category of biomass was first classified and the chemical compositions were summarized. Then, the main chemical reaction pathways involved in biomass decomposition and transformation during the HTC process were introduced. Meanwhile, the roles of key process parameters, including reaction temperature, residence time, pH, feedstock type, pressure, mass ratio of biomass to water, and the use of catalysts on HTC, were carefully discussed. Finally, the applications of hydrochar in energy utilization, environmental remediation, soil improvement, adsorbent, microbial fermentation, and phosphorus recovery fields were highlighted. The future directions of the HTC process were also provided, which would respond to climate change by promoting the development of the sustainable carbon materials field.

KEYWORDS: Biomass; lignocellulose; hydrothermal carbonization; hydrochar application; fermentation

1 Introduction

Due to the rapidly growing energy demand and the severe challenges posed by global climate change, the establishment of a low-carbon, sustainable energy production system is regarded as an urgent priority. Biomass energy has been recognized as one of the major research hotspots worldwide because of its advantages of renewability, wide availability, and relatively low cost [1]. Among various resources, lignocellulosic biomass is the most abundant renewable carbon resource on Earth, primarily derived from agricultural and forestry residues. It has been estimated that approximately 200 billion tons of lignocellulosic biomass are fixed globally each year, while in China alone, the annual generation of agricultural straw biomass was estimated at around two billion tons [2]. However, in practice, a significant proportion of biomass resources is directly discarded or openly burned; the direct combustion of biomass is often accompanied by the generation of substantial smoke, leading to reduced visibility and deterioration of air quality [3], while incomplete combustion results in the release of large amounts of persistent organic pollutants [4]. Nowadays, pyrolysis and hydrothermal carbonization (HTC) are the most dominant approaches for synthesizing carbon materials derived from solid waste and lignocellulosic biomass. Compared with the conventional pyrolysis route, HTC generally offers higher energy efficiency due to the simple procedure without drying pretreatment for natural biomass. In addition, HTC is conducted under mild hydrothermal conditions, whereby high-temperature oxidative reactions are effectively avoided and emissions of smoke and persistent pollutants are markedly reduced. Meanwhile, biomass is stably converted into energy-dense hydrochar, enabling a cleaner utilization pathway and contributing to climate change mitigation. Consequently, HTC is widely regarded as an environmentally friendly biomass conversion technology with significant low-carbon potential [5]. Fig. 1 presents the distribution of publications retrieved from the Scopus database during the past 15 years (2011–2025) using "biomass" and "hydrothermal carbonization" as the search keywords. It is clearly found that the published papers related to the topics were above 100 items per year after 2020. Based on the above analysis, the development of efficient biomass conversion technologies such as HTC is essential for the realization of the "peak carbon dioxide emissions and carbon neutrality" targets proposed by the Chinese government. To provide valuable guidance for biomass conversion and HTC, in this review, the state-of-the-art advances in HTC of biomass were carefully summarized, especially focusing on the effects of key parameters on HTC and the wide applications of biomass-derived hydrochar.

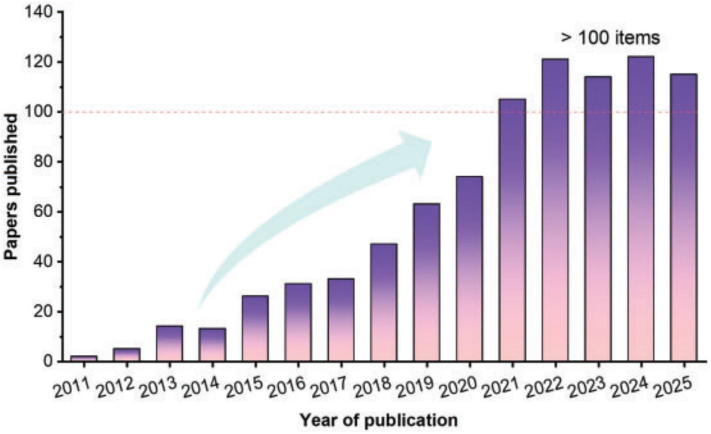

Figure 1: Annual number of publications related to biomass and hydrothermal carbonization in the past 15 years (2011–2025). The figure was based on the search results from the Scopus database

2 Overview of Biomass

2.1 Potential of Biomass

At present, over 20 billion tons of carbon dioxide have been steadily released into the atmosphere as a consequence of anthropogenic actions, and such massive and continuous emissions are being recognized as intensifying global climate change [6]. However, due to its carbon-neutral characteristics, biomass energy is considered to contribute significantly less to the accumulation of carbon dioxide compared to fossil fuels, thereby enabling effective reductions in carbon dioxide emissions. In addition, biomass utilization for energy production is a simple approach, and infertile soils unsuitable for conventional agriculture, as well as degraded or contaminated lands, have been restored through the cultivation of biomass energy crops. It is noteworthy that non-food biomass, including crop residues, biomass wastes, and various discarded materials, has also been shown to be efficiently converted and utilized, thereby allowing the tremendous potential of biomass resources within a circular economy framework to be fully demonstrated.

2.2 Classification of Biomass

Biomass is generally defined as organic matter derived from living organisms, in which the content of inorganic components, such as ash and minerals, is relatively low. Based on its origin, it is categorized into woody biomass, herbaceous biomass, aquatic biomass, and biomass derived from municipal solid waste. In China, the annual production of biomass resources was approximately 3.5 billion tons in 2020, which is equivalent to ~0.50 billion tons of standard coal. In addition, the substantial variations in the ash and carbon contents among different biomass feedstocks have been observed, and these compositional differences exert significant impacts on both the yield and physicochemical properties of hydrochar produced by HTC [7].

Woody biomass is a key global renewable resource and the most abundant organic source of energy. It has been reported that in 2010, approximately 30 EJ of energy was consumed from woody biomass, representing approximately 9% of total global primary energy use and 65% of renewable primary energy utilization [8]. Woody biomass, such as poplar, willow, pine, and eucalyptus, is characterized by a high lignin content, dense structure, and relatively high calorific value, with cellulose and lignin contents generally exceeding those of herbaceous biomass. Moreover, the elemental compositions of woody biomass exhibit lower variability with significant uniformity, and it is regarded as advantageous for large-scale processing and high-value utilization.

Herbaceous biomass is defined as organic resources that are derived from non-woody stems or seasonal herbaceous plants. According to their growth cycles, herbaceous biomass can be classified into two categories of annual and perennial plants. Annual herbaceous plants complete their life cycle within a single season, whereas perennial plants can provide biomass across multiple growing seasons. Typical herbaceous biomass examples encompass agricultural residues like wheat straw, rice straw, and corn stalks [9]. Due to their high yield and easy accessibility, they have been regarded as one of the important renewable biomass resources. It should be noted that woody and herbaceous biomass are generally named as lignocellulosic biomass.

Aquatic biomass is defined as organic matter derived from organisms that are grown in aquatic environments, including various aquatic plants, algae, and certain aquatic microorganisms. Although its carbon content is considered to be lower than that of lignocellulosic biomass, several distinctive advantages are attributed to aquatic biomass, such as its short growth cycle and relatively high nitrogen and sulfur contents. In addition, the volatile substances and fixed carbon in aquatic biomass are typically found to be of comparable levels, which is regarded as beneficial for maintaining stable reaction behavior during thermochemical conversion processes.

Urban solid waste is composed of diverse biogenic organic fractions, such as food waste, discarded paper, and natural fiber textiles. Due to the heterogeneous sources and complex composition of municipal solid waste, significant variability in its chemical constituents has been observed, which is typically characterized by relatively high carbon content and low oxygen content.

2.3 Major Components of Biomass

High-molecular-weight polysaccharides are regarded as the primary constituents of lignocellulosic biomass, among which cellulose and hemicellulose account for as comprising 60% to 80% of lignocellulosic materials and, together with lignin, are involved in forming the structural framework of plant cell walls. Cellulose is recognized as the primary constituent of green plant cell walls, with its average content in plant biomass being estimated at approximately 33% [10]. The high content of cellulose highlights its significant potential as a renewable carbon feedstock for HTC. As the most widespread organic biopolymer found in nature, cellulose is composed of β-D-glucose units linked by β-1,4-glycosidic bonds, forming a linear high-molecular-weight structure [11]. It can be extracted from a broad spectrum of biomass feedstocks and has been regarded as possessing significant renewable potential, being considered one of the most important sources for sustainable biofuel production in the future.

Hemicellulose is classified as another type of natural polysaccharide found in the cellular walls of plants and is considered the second most abundant renewable component in lignocellulosic biomass. Its structure is more complex than that of cellulose, being composed of various heteropolysaccharides, mainly including xylan, glucuronoxylan, mannan, and glucomannan. In comparison with cellulose, hemicellulose exhibits a reduced polymerization level and often presents short-chain or branched structures. As a result, its thermal and chemical stability is relatively poor, and it is typically the first component to be decomposed during thermochemical conversion processes.

Lignin is defined as an aromatic polymer with a three-dimensional network structure, which is embedded within the plant cell wall composed of cellulose and hemicellulose, collectively forming the structural framework of plant cell walls. It is primarily formed through oxidative radical coupling of three monolignol units of p-coumaryl alcohol, coniferyl alcohol, and sinapyl alcohol [12]. The lignin content typically accounts for 15%–30% of lignocellulosic biomass, with the exact proportion varying depending on plant species, growth conditions, and soil characteristics.

3 Fundamental Principles of HTC

HTC is a sustainable thermochemical process, whereby biomass is decomposed and converted into carbon-rich solid products under elevated temperatures and pressures in an aqueous environment [13]. Fig. 2A illustrates the general process flow of a typical HTC reaction. The process is generally performed at temperatures between 180°C and 300°C. Under these conditions, adequate thermal input breaks macromolecular linkages and promotes interactions between water and structural polymers such as cellulose, hemicellulose, and lignin. As a result, the macromolecular structures are decomposed into smaller units, which facilitates hydrolytic processes and subsequent chemical transformations. Concurrently, pressures ranging from 2 to 25 MPa preserve water in its subcritical form. It enhances water's dual role as a reaction medium and active reactant, improving reaction efficiency. Under these conditions, water exhibits a higher ionic product, lower viscosity, and enhanced solvating ability, which improves reactant diffusion and overall reaction efficiency. In addition to serving as a reaction medium, water participates directly in bond cleavage, molecular rearrangement, and transformation reactions, thereby influencing the decomposition of biomass and the composition and distribution of products. Under elevated temperature/pressure conditions, and in an oxygen-deficient environment, macromolecular constituents, including cellulose, hemicellulose, and lignin, are subjected to a sequence of recombination reactions, resulting in the formation of hydrochar characterized by high carbon content and enhanced structural stability [14].

The main reaction pathways taking place during HTC comprise hydrolysis, dehydration, decarboxylation, and aromatization [15]. In addition, the fundamental process of HTC is depicted in Fig. 2B [16]. Under conditions of 180°C–260°C, significant dehydration and decarboxylation reactions are induced, resulting in a pronounced reduction of oxygen-containing functional groups [17]. Concurrently, the formation of fused aromatic ring structures is promoted, thereby increasing the carbon content and markedly enhancing the calorific value of hydrochar. For example, Koprivica et al. used *Paulownia* leaves as feedstock to produce hydrochar as a potential energy source by HTC technology, and the results indicate that the hydrochars produced at higher temperatures have superior combustion properties, high energy content, stronger thermal stability, and long-time heat with higher ignition temperature [17]. Hydrolysis reaction occurred under moderate conditions of 180°C–250°C, and cellulose, hemicellulose, and lignin are broken down into sugars and other low-molecular-weight compounds [18]. Within this temperature range, the reaction rate is enhanced, thereby improving the conversion efficiency of biomass and the overall product yield [19]. As the temperature is increased to 250°C–300°C, dehydration and decarboxylation reactions are intensified, resulting in the formation of organic compounds in the liquid phase. The hydrolysis products subsequently undergo dehydration reactions, during which important intermediates such as furfural and organic acids are generated, accompanied by the shortening of molecular chain segments. This process plays a crucial role in carbon framework formation and provides radical locations for follow-up aromatization reactions [20]. Aromatization and decarboxylation are considered key secondary transformation steps during HTC. Aromatization involves the rearrangement of carbon atoms in dehydration-derived intermediates to create highly stable aromatic structures. This transformation primarily occurs among furfural, organic acids, and phenolic compounds derived from hydrolysis. Through these reactions, large aromatic macromolecular fragments, CO_2, and water are generated, thereby increasing the stability and carbon richness of the resulting carbonaceous products [21]. At elevated temperatures, organic molecules undergo condensation and polymerization reactions to form larger and more stable molecular structures. These structures constitute a significant portion of hydrochar and contribute to its high carbon content and heat resistance [22]. Through a series of physicochemical transformations, biomass is ultimately converted into hydrochar with unique structural and functional properties. Hydrochar is typically characterized by an elevated specific surface area (SSA) and a porous architecture, and robust physicochemical stability.

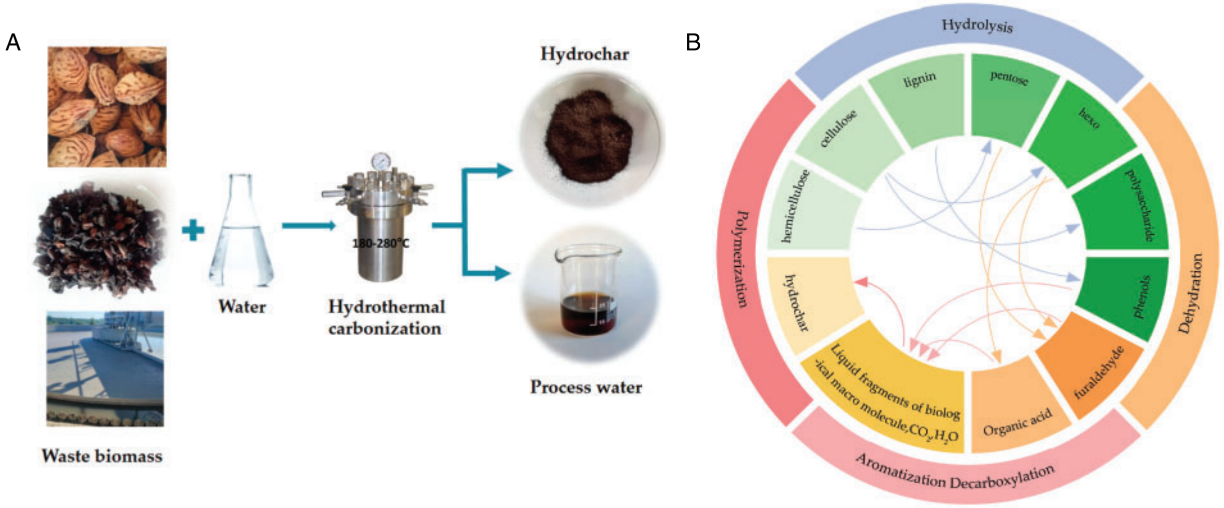

Figure 2: The schematic representation and the reaction pathways of HTC. (**A**) Process flow diagram of HTC [5]. (**B**) Proposed reaction pathways of HTC [16]

4 Characteristics of the Hydrothermal Carbonization: The Role of Process Parameters

Throughout the HTC process, the allocation and ultimate characteristics of the resulting products are governed by the combined influence of various process parameters. Among them, reaction temperature, time, pressure, pH, catalyst type, feedstock characteristics, and the biomass-to-water mass (B/W) ratio have been identified as the key factors affecting conversion efficiency and product performance. A systematic summary of the major parameters influencing the HTC process and their corresponding effects is presented in Table 1. In addition, the effects of key operation parameters on the hydrocarbon yield and its physicochemical properties are presented in Table 2. Based on the recent studies, the key roles of process parameters on HTC performance were discussed in the following sections.

4.1 Influence of Temperature

Temperature is one of the most critical parameters in the HTC process. Fig. 3 illustrates the main transformation pathways of lignocellulosic biowaste during HTC, together with the temperature-dependent variation in hydrochar yields [23]. The effect of temperature on hydrothermal reactions is essentially considered to result from the combined influence of changes in the properties of the aqueous environment and alterations within the reaction system itself (Table 1). Its primary role lies in providing sufficient thermal energy to break the chemical bonds within biomass, thereby facilitating thermolytic reactions. As the reaction temperature increases, the conversion efficiency of biomass is generally enhanced; however, it also significantly influences the composition and distribution of the resulting products [24]. The main products of the HTC process include solid, liquid, and gaseous fractions. At relatively low temperatures (180°C–200°C), solid products dominate. Under these conditions, hydrolysis and condensation reactions are favored, promoting the formation of carbon-rich hydrochar. When the temperature is increased to 250°C–300°C, dehydration and decarboxylation reactions are intensified, favoring the production of liquid-phase organics. Moderate temperature elevation has been found to enhance the carbonization and aromatization of hydrochar, thereby improving its functional properties. However, excessive temperatures may cause over-cracking or volatilization of valuable intermediates, resulting in a reduction in overall solid yield [25]. Therefore, temperature regulation in the HTC process not only directly determines the type and distribution of products but also significantly affects the quality and final application potential of the resulting hydrochar.

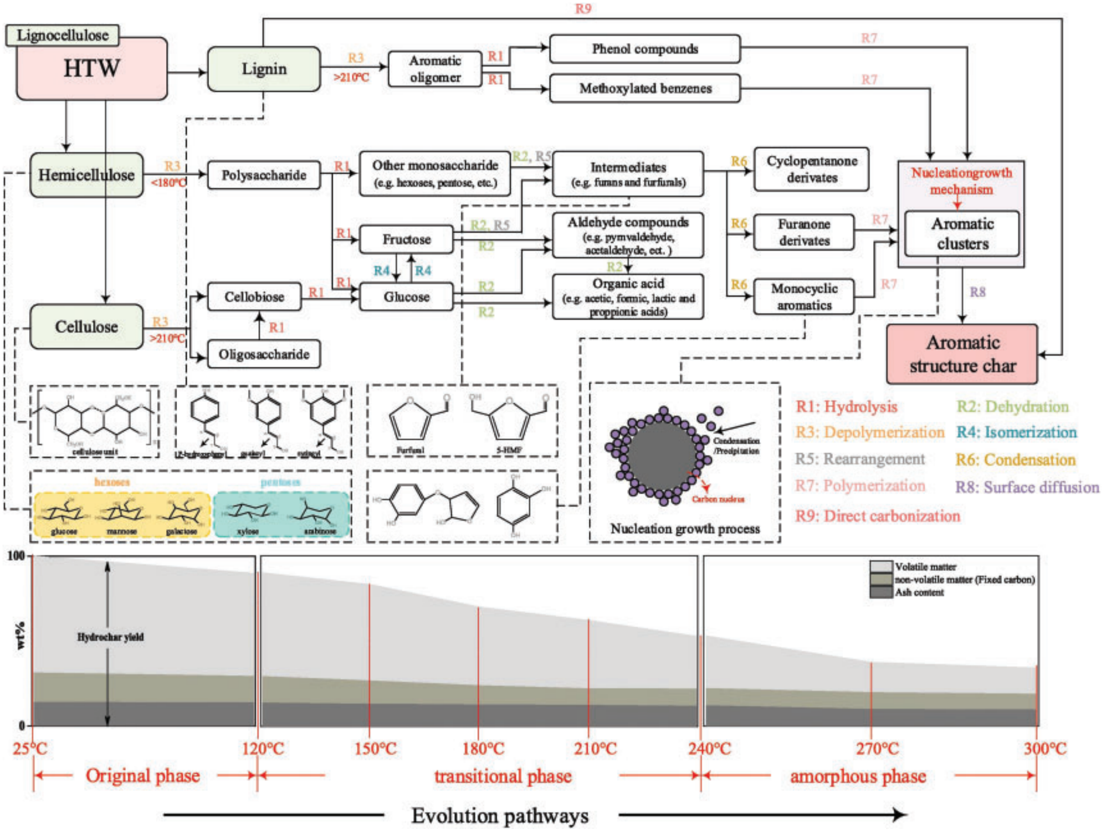

Figure 3: The evolution pathways of lignocellulosic biomass during the HTC process. Reprinted with permission from reference [23]. Copyright © 2019, Elsevier

4.2 Influence of Reaction Time

The reaction time has been found to significantly influence hydrolysis only within a certain range, beyond which its effects on reaction progression and product properties tend to plateau. Zhang et al. further observed that prolonged residence times favor the formation of solid and gaseous products, whereas the yield of liquid products exhibits an inverse trend [26]. Additionally, as reaction time increases, the porosity and SSA of the resulting hydrochar have been shown to increase. However, insufficient reaction times may lead to incomplete HTC of biomass, resulting in reduced hydrochar yield and diminished structural stability. Conversely, excessively long reaction times can cause over-carbonization, leading to structural collapse of the carbon material, decreased porosity, and reduced SSA (Table 2). These changes adversely affect the adsorption capacity of hydrochar, ultimately impacting product quality and application [27,28].

Table 1: Mechanisms influencing HTC efficiency and their key regulatory factors

Influence factors	Primary mechanism	Positive effects	Negative effects	References
Temperature	The physicochemical properties of water are changed, reaction pathway changes (such as hydrolysis, decarboxylation, and condensation) are promoted.	The dehydration of organic matter is promoted, leading to enhanced carbonization efficiency and aromatization degree, and resulting in the formation of high-quality hydrochar.	Excessively high temperatures cause the decomposition of organic intermediates, resulting in a decrease in solid yield and an increase in liquid/gaseous products.	[8,24,25]
Reaction time	The completeness of hydrolysis, polymerization, and carbonization processes is controlled, thereby influencing structural evolution and pore formation.	The extension of reaction time has been shown to increase the porosity and specific surface area (SSA) of hydrochar, thereby facilitating the formation of solid carbon.	Excessively long reaction times have been found to cause structural collapse, resulting in decreased porosity and reduced specific surface area.	[26–28]
Pressure	The reactivity of water is enhanced, and the dissolution behavior of carbon dioxide is altered, thereby influencing structural rearrangement.	The reaction rate is enhanced, functional group formation and pore development are promoted, thereby improving the functionality of product.	Excessively high pressure leads to increased energy consumption, while the marginal benefits for structural improvement are diminished.	[29,30]
pH	The acidic or basic catalytic pathways are determined, thereby regulating the formation of organic acids and reaction pathways.	Dehydration, condensation, and carbonization reactions are promoted under acidic conditions, resulting in the formation of hydrochar with a high SSA.	The decomposition of cellulose is hindered under alkaline conditions, which may result in low carbon content or surface passivation.	[31,32]
Feedstock composition	HTC pathways and the distribution of solid and liquid products are influenced.	Lignin has been shown to yield a high carbon content with a dense structure, whereas cellulose and hemicellulose predominantly produce a greater number of liquid organics.	Materials with low lignin content have been observed to produce hydrochar with low yield and loose structure, which adversely affects subsequent functional applications.	[33,34]
Biomass-to-water (B/W) ratio	The reaction environment and the concentration of soluble precursors have been altered, thereby influencing secondary carbonization.	The generation of secondary hydrochar and the overall carbon yield have been promoted by higher B/W ratios.	Although lower B/W ratios result in higher degrees of carbonization, the yields are reduced; conversely, higher B/W ratios may induce the formation of persistent pollutants.	[35,36]

(Continued)

Table 1 (continued)

Influence factors	Primary mechanism	Positive effects	Negative effects	References
Catalyst type	The reaction rate and pathways are altered, allowing for selective control over product composition.	Carbonization reactions are promoted under acid catalysis, resulting in increased carbon content and SSA.	Improve the process cost and hydrochar formation is inhibited under alkaline catalysis, with a shift toward liquid-phase products.	[37]

Table 2: Summary of key parameters in HTC and their effects on hydrochar properties

Parameter	Unit	Range	Effect on hydrochar yield	Effect on HHV	Effect on SSA	References
Temperature	°C	180–300	Yield decreases with increasing temperature.	Higher temperatures result in an increase in HHV.	Higher temperature results in reduced SSA.	[38]
Residence time	h	0.5–24	Yield decreases with increasing time.	Longer reaction time results in increased HHV.	Longer reaction time results in increased SSA.	[39,40]
Feedstock moisture	wt%	2–25	An increase in moisture content leads to higher yield.	Higher moisture content results in reduced HHV.	Higher moisture content results in reduced SSA.	[41]
pH	–	2–10	Acidic conditions (pH 2–4) lead to increased yield.	Under alkaline conditions (pH 8–10), HHV increases.	Under neutral conditions, SSA increases.	[13]
Pressure	MPa	2–5	Pressure has little effect.	Under high pressure, HHV slightly increases.	Under high pressure, SSA decreases.	[30]
Feedstock type	–	Lignocellulose, algae, sludge	Higher cellulose content leads to increased yield.	Algae result in higher HHV.	Sludge results in reduced SSA.	[42]
Catalyst dosage	mmol/g	0.01–0.1	Higher cellulose content leads to increased yield.	Use of acid catalysts results in higher HHV.	Use of acid catalysts results in higher SSA through the generation of micropores.	[13]

Note: HHV, higher heat value; SSA, specific surface area.

4.3 Influence of Pressure

Pressure is also a crucial parameter in the HTC process, significantly influencing reaction rates, product structure, and functional performance (Tables 1 and 2). In batch HTC systems, reaction pressure is inherently generated and primarily determined by the reaction temperature, water filling ratio, and feedstock composition, rather than by external gas injection [30]. As pressure increases, both the physical and chemical properties of water are altered, enhancing its reactivity and solvation capability, which in turn accelerates biomass conversion [29]. Maintaining the system pressure within appropriate ranges allows better control over biomass decomposition and hydrolysis behaviors, supporting efficient hydrothermal reactions. Furthermore, the solubility of carbon dioxide is significantly increased under high-pressure conditions, which not only facilitates the regulation of oxygen-containing functional groups on the hydrochar surface but also promotes the development of porous structures, thereby improving SSA and adsorption performance [43]. Therefore, proper regulation of reaction pressure is beneficial for enhancing the energy efficiency and conversion efficiency of the HTC process, while also providing an effective strategy for tuning the structure and optimizing the functionality of hydrochar materials.

4.4 Influence of pH

As one of the key parameters influencing the HTC process, the acid-base environment of the reaction system is not only reflected by the pH value but is also recognized to play a pivotal role in governing the reaction pathways, conversion efficiencies, and the resultant physicochemical characteristics of the hydrochar product. It has been demonstrated by previous studies that during the HTC process, a gradual decrease in system pH is typically observed as the reaction progresses. This decline is primarily attributed to the continuous generation of organic acids, including acetic acid, formic acid, lactic acid, and levulinic acid. These organic acids are not only produced as intermediate reaction products but are also regarded as essential regulators by which the reaction pathways and final product properties are influenced [44]. At reaction conditions near 180°C, the formation of organic acids is observed to be most pronounced, culminating in the system pH reaching its minimum value. However, with a further increase in temperature, these organic acids are prone to undergo condensation and repolymerization reactions, which result in a significant diminution of acidic species concentration, thereby causing the pH to elevate and gradually approach a neutral level [32]. It is noteworthy that despite the initial pH varying between 2 and 12, the pH of the reaction liquid at the end of the HTC process is consistently maintained within the range of 2.8 to 4.2, indicating that the system exhibits a certain degree of intrinsic buffering capacity [31]. The reaction is significantly catalyzed under acidic conditions—typically within the range of pH 2.5–4.0, where the hydrolysis, dehydration, and condensation of biomass macromolecules are effectively promoted, thereby accelerating the carbonization process and enhancing both the carbon content and structural density of the solid products [45,46]. For example, the carbonization degree was significantly enhanced in a baked pine system upon the addition of acetic acid [47]. Furthermore, in a study where poplar was treated with acidic process water at pH 3.5, it was demonstrated that the acidic environment effectively catalyzed the dehydration reactions [48]. However, the effects of acidic conditions on decarboxylation reactions, monomer repolymerization, and other reaction mechanisms remain insufficiently understood and warrant further investigation. Related studies have also revealed that hydrochars produced under acidic conditions typically exhibit larger SSA and pore volumes, along with smaller pore sizes, thereby demonstrating enhanced adsorption performance [49]. For instance, hydrochars produced via HCl treatment have been shown to possess significantly higher adsorption capacities compared to those obtained through deionized water or NaOH treatments [50]. Conversely, under alkaline conditions, acid-catalyzed hydrolysis reactions are suppressed, thereby hindering the depolymerization of cellulose and hemicellulose. However, the conversion efficiency of lignin is observed to increase in alkaline environments. Studies have indicated that alkaline conditions inhibit the formation of organic acids and sugars, while facilitating the production of lignin-derived monomers such as catechol and guaiacol [49]. Moreover, under high pH conditions, a reduction in both the higher heating value (HHV) and carbon content of hydrochar may be observed, accompanied by potential surface passivation phenomena, which could adversely affect its subsequent application performance. Elevated alkalinity has also been associated with an increase in the H/C ratio of the product, thereby reducing its overall energy density [51]. Overall, pH not only influences the yield and carbon content of hydrochar but also determines its pore structure and surface properties (Table 2). By optimizing the acid/base conditions of the reaction system, the reaction pathways can be more effectively directed, enabling synergistic improvements in both carbonization efficiency and the functional performance of the resulting hydrochar.

4.5 Influence of Feedstock Properties

Biomass feedstocks exhibit significant variations in their structural and chemical compositions due to differences in growth environments and growth cycles. These variations have been found to influence the reaction behavior during hydrothermal conversion and the types and distribution of HTC products. The primary components of biomass—cellulose, hemicellulose, and lignin—have been shown to possess distinct thermal reactivities and decomposition pathways under HTC conditions. Feedstocks rich in cellulose and hemicellulose tend to favor the formation of liquid products such as sugars, intermediate esters, and organic acids, whereas those with higher lignin content are more prone to producing hydrochar [34]. The influence of lignin content on bio-oil yield was investigated by Zhong and Wei using five typical lignocellulosic biomasses: Chinese fir, ash, Masson pine, poplar, and silver poplar [33]. It was observed that bio-oil yields gradually decreased with increasing lignin content, while hydrochar production significantly increased. This phenomenon was mainly attributed to the propensity of lignin-derived intermediates to undergo condensation and cyclization reactions, which reduce the stability and yield of liquid-phase products [52,53]. Furthermore, feedstock composition has been found to determine hydrochar yield, structural features, the pore size distribution, SSA, and related physicochemical properties. The regulatory effect of lignin and cellulose content on hydrochar porosity has been widely confirmed, demonstrating significant value in the development of hydrochar-based functional materials. Typical results in product yield, HHV, and SSA of cellulose-, hemicellulose-, and lignin-derived hydrochar are summarized in Table 3.

Table 3: Comparison of typical hydrochar properties derived from cellulose, hemicellulose, and lignin

Feedstock	Hydrochar yield (wt%)	HHV (MJ/kg)	SSA (m^2/g)	References
Cellulose	30–40	20–25	10–50	[54–56]
Hemicellulose	20–30	17–22	20–80	[56,57]
Lignin	50–60	24–28	5–30	[55,58]

4.6 Mass Ratio of Biomass to Water

It has been reported that lower B/W ratios typically result in reduced hydrochar yields, while a higher degree of carbonization is achieved (Tables 1 and 2). For example, during the HTC of softwood, increasing the water dosage while keeping the biomass loading constant promoted a greater extent of carbonization [36]. In contrast, higher B/W ratios have typically resulted in increased hydrochar yields, albeit with a lower degree of carbonization [35,36]. For primary hydrochar, its formation is mainly attributed to solid–solid reactions, the equilibrium of which is not significantly affected by solid concentration. As a result, the yield of primary hydrochar remains relatively constant across different biomass-to-water (B/W) ratios. In contrast, the formation of secondary hydrochar is more sensitive to the concentration of liquid-phase precursors. Under higher B/W ratios, elevated concentrations of soluble organic intermediates in the reaction medium increase the probability of polymerization, thereby promoting the formation of secondary hydrochar and contributing to an overall increase in yield [59,60]. In addition, the B/W ratio is shown to potentially influence the environmental behavior of hydrochar. Gao et al. evaluated the effect of B/W ratio on the formation of persistent free radicals (PFRs)—a class of potentially hazardous contaminants to human health—in hydrochar derived from rice straw [61]. The range of B/W ratios investigated in the experiments was from 1:2.5 to 1:20. It was found that under a higher B/W ratio of 1:2.5, the formation of PFRs was markedly increased, whereas under more diluted conditions (B/W ratio of 1:20), PFR formation was significantly decreased [61]. Consequently, a lower B/W ratio was recommended by the authors during hydrochar preparation to enhance its environmental safety. Overall, systematic studies on the impact of B/W ratio on the physicochemical properties and environmental behavior of hydrochar remain limited, highlighting the need for further in-depth investigation into its underlying mechanisms and regulatory strategies.

4.7 Influence of Catalysts

Catalysts are playing a significant regulatory role in the HTC process, where the reaction rate, pathway selection, and the composition and quality of the final products are markedly influenced, thereby fulfilling the comprehensive requirements for reaction efficiency and product selectivity [62]. Different types of catalysts exhibit distinct catalytic effects depending on the hydrolysis mechanisms involved. Typically, acidic catalysts effectively promote the hydrolysis of macromolecular polysaccharides such as cellulose and hemicellulose, accelerating the HTC process, whereas alkaline catalysts tend to inhibit char formation and favor the production of liquid-phase products (Table 1). An ideal catalyst is expected to possess high thermal stability, strong catalytic activity, economic viability, and good selectivity toward target products [37]. For instance, when dilute HCl or H_2SO_4 was introduced (pH 2–3), the SSA of hydrochar was increased from approximately 15 m^2/g to around 100 m^2/g, while the carbon yield was also improved by ~10%–15% compared to non-catalyzed conditions [63]. Conversely, alkaline catalysts such as Na_2CO_3 and KOH tend to reduce solid yields by approximately 15%–20% but promote higher production of soluble organics, shifting selectivity toward liquid products [64]. In the HTC system, catalysts could facilitate organic matter conversion by modulating reaction rates. The physical and chemical properties of catalysts also directly influence the structure and performance of hydrochar. Effective diffusion of catalytic particles into biomass enhances the decomposition of complex organic constituents such as lignin and cellulose, thereby promoting hydrochar formation. Additionally, in practical deployment, attention is required with regard to catalyst recyclability and detoxification, as residual acidic/alkaline catalysts in process water may pose environmental risks and therefore must be recovered and neutralized before disposal or reuse.

5 Applications of Hydrochar

5.1 Solid Fuel

The valorization of waste biomass for renewable energy and biofuel production has become a key development goal in many developed and developing countries, promoting the bioeconomy concept. Raw biomass is generally regarded as a low-quality fuel source due to its low energy density and relatively high ash and moisture content [53,65]. In contrast, hydrochar produced via HTC exhibits significant advantages in fuel properties, including higher carbon content, increased energy density, reduced ash and volatile matter, as well as enhanced material stability and dehydration characteristics [5]. Hydrochar has been reported to possess HHV ranging from 25.15 to 29.01 MJ/kg, and the HHV of lignite is ~25 MJ/kg [66]. Additionally, its ash content was found to be 6.7%–7.7%, which falls within the typical range for lignite ash [67]. Therefore, the overall performance of hydrochar can be comparable to that of lignite and even some commercial coals. A key advantage of the HTC process lies in its ability to transfer inorganic elements from the feedstock into the liquid phase, thereby reducing the ash content in hydrochar [68]. Low ash content is a highly desirable attribute for solid fuels, since elevated levels of specific inorganic elements in fuels and biomass can cause increased emissions, corrosion, fouling, clogging, and slagging during direct combustion [69,70].

5.2 Soil Amendment

The quality of soil has been continuously deteriorating due to the influence of multiple natural factors, particularly intensified by anthropogenic activities. This degradation is manifested through a series of adverse phenomena such as soil desertification, acidification, and alkalization, ultimately resulting in the overall decline of soil environmental conditions [71]. Such soil degradation has been recognized not only as a serious threat to agricultural productivity but also as a critical challenge to the sustainability of ecosystems and the stability of the global climate [72]. Fig. 4A shows the improvement effect exerted on degraded soil by HTC carbon materials. Degraded soils are typically characterized by low porosity and high bulk density, which may result in increased compaction, poor water retention capacity, and heightened susceptibility to erosion [73]. Owing to their porous architecture and low specific weight, adding hydrochar with the loads of 2.5–6.0 wt% has demonstrated the potential to improve soil porosity by 6.3%–11.5% and reduce bulk density by 8.2%–18.9%, thereby enhancing the structural stability of soils [73,74]. Studies have shown that hydrochar possesses the ability to adsorb and retain pesticides within agricultural systems, which helps optimize pesticide utilization and reduce the potential risk of groundwater contamination [75,76]. However, a portion of the carbon components in hydrochar can undergo rapid mineralization upon soil application, with carbon content potentially decreasing by 30%–40% within the first 12 to 19 months [77,78]. Additionally, certain organic compounds present in hydrochar may exhibit toxicity toward soil microorganisms or plants, representing a potential limitation for its application in soils. Hydrochar produced at 260°C has been reported to reduce wheat growth by 20%–30% due to its toxic effects. In contrast, hydrochar generated at lower HTC temperatures (<200°C) did not exert significant effects under nutrient-rich soil conditions [79]. However, under nutrient-deficient soils, hydrochar derived from 170°C–200°C processing was found to decrease wheat growth by up to 50%, a phenomenon described as "apparent phytotoxicity," which was attributed to nutrient scarcity exacerbated by microbial immobilization [79]. To mitigate this issue, simple washing, aerobic treatment, or low-temperature processing have been demonstrated as effective approaches to reduce toxic constituents in raw hydrochar, thereby enhancing its environmental compatibility [80,81]. The labile fraction of hydrochar can stimulate soil microbial activity, whereas the capacity of its recalcitrant fraction for long-term carbon sequestration remains a subject of debate [82]. The carbon sequestration benefits of hydrochar application in soil depend on its long-term stability over timescales ranging from decades to millennia. Its high carbon content, thermal stability, and recalcitrance are considered key attributes enabling efficient carbon sequestration in soils [83,84].

5.3 Adsorbent

Among various pollution control strategies, adsorption has been regarded as an efficient, cost-effective, and environmentally friendly approach for the removal of organic pollutants. Hydrochar is widely used as a low-cost and efficient adsorbent for aqueous pollutants due to its excellent adsorption properties [50]. Fig. 4B presents the various mechanisms that may be involved in the adsorption of aqueous pollutants by hydrochar [85]. It has been demonstrated in numerous studies that hydrochar can effectively remove typical organic pollutants such as dyes, pharmaceuticals, and pesticides. Organic pollutants are generally classified into natural and anthropogenic categories. These contaminants are widely distributed across environmental media such as water, air, and soil. Some of them can be degraded under microbial action, and even structurally stable compounds such as polychlorinated biphenyls (PCBs) are degradable by specific soil microorganisms under certain conditions [86]. However, certain organic pollutants with complex structures or high stability are poorly biodegradable in natural environments and exhibit long-term persistence, as well as teratogenic, mutagenic, and carcinogenic properties, posing serious threats to ecosystem stability and human health. The raw hydrochar typically exhibits limited adsorption capacity and generally requires physical/chemical activation to enhance its performance. Current studies have identified hydrochar as an ideal precursor for activation, with superior properties compared to untreated raw biomass [87]. In addition to alkali activation, modification with metal salts is an effective strategy for improving the adsorption performance of hydrochar. Regarding adsorption mechanisms, the interactions between organic pollutants and hydrochar primarily involve pore filling, surface complexation, ion exchange, cation bridging, π–π interactions, and electrostatic adsorption [88,89]. Under alkaline conditions, the increased negative surface charge density of HTC-derived materials strengthens electrostatic interactions with positively charged dye molecules. Moreover, the marginal effect of adsorption could decrease within a pH range of 9–11, indicating that intrinsic mechanisms such as complexation and ion exchange are also involved. Compared to heavy metal ions, organic pollutants may form more stable associations with the hydrochar surface through hydrogen bonding, thereby enhancing both adsorption efficiency and selectivity.

Unlike most organic pollutants, heavy metals cannot be naturally eliminated via biodegradation processes, and their bioaccumulation through the food chain can be progressively amplified, eventually leading to toxic concentrations in the human body and causing health issues. Stable complexes between heavy metal ions and proteins/enzymes within organisms have been formed, which interfere with normal physiological functions and result in enzyme activity inhibition, metabolic disorders, and chronic toxicity. Therefore, the efficient removal of heavy metals from environmental media by adsorption technology is a key strategy to reduce their bioavailability and curb ecological risk propagation. Hydrochar has been shown to exhibit outstanding heavy metal ion adsorption capacity owing to its tunable pore structure, high SSA, and abundant oxygen-containing functional groups on the surface [90]. For example, hydrochars derived from wheat straw, corn stalk, and sawdust activated by potassium hydroxide have been confirmed to effectively remove cadmium from water [46]. Simić et al. investigated the effectiveness of lead ion removal by corncob-derived hydro-pyrochar, which was prepared via a two-step process involving HTC followed by pyrolysis in a $MgCl_2$ medium, and the maximum Pb adsorption capacity reached up to 87.08 mg/g [91]. Additionally, alkaline-modified hydrochars have also demonstrated favorable performance in the removal of lead (Pb) and cadmium. These studies have shown that, through appropriate modification, hydrochar has been prepared as a novel, highly efficient adsorbent with tunable structure and superior performance for the removal of various pollutants. Fig. 4C illustrates the synthesis of HTC-derived carbon materials and the mechanisms by which heavy metal and organic pollutants are removed through adsorption [92]. Recently, the overall adsorption performances of lignocellulose-derived hydrochar on heavy metals, organic dyes, and hormones have been reviewed, which focused on the adsorption capacity ($q_{\max}$) and adsorption isotherm models (Langmuir, Freundlich, Redlich-Peterson model) [93]. In summary, hydrochar has demonstrated multiple adsorption mechanisms and highly tunable structures in the removal of both organic and heavy metal pollutants, indicating strong potential as an efficient and environmentally friendly adsorbent. The efforts should be directed toward further elucidating its interfacial interaction mechanisms and developing functionalization methods to enable effective removal of complex contaminants from the environment.

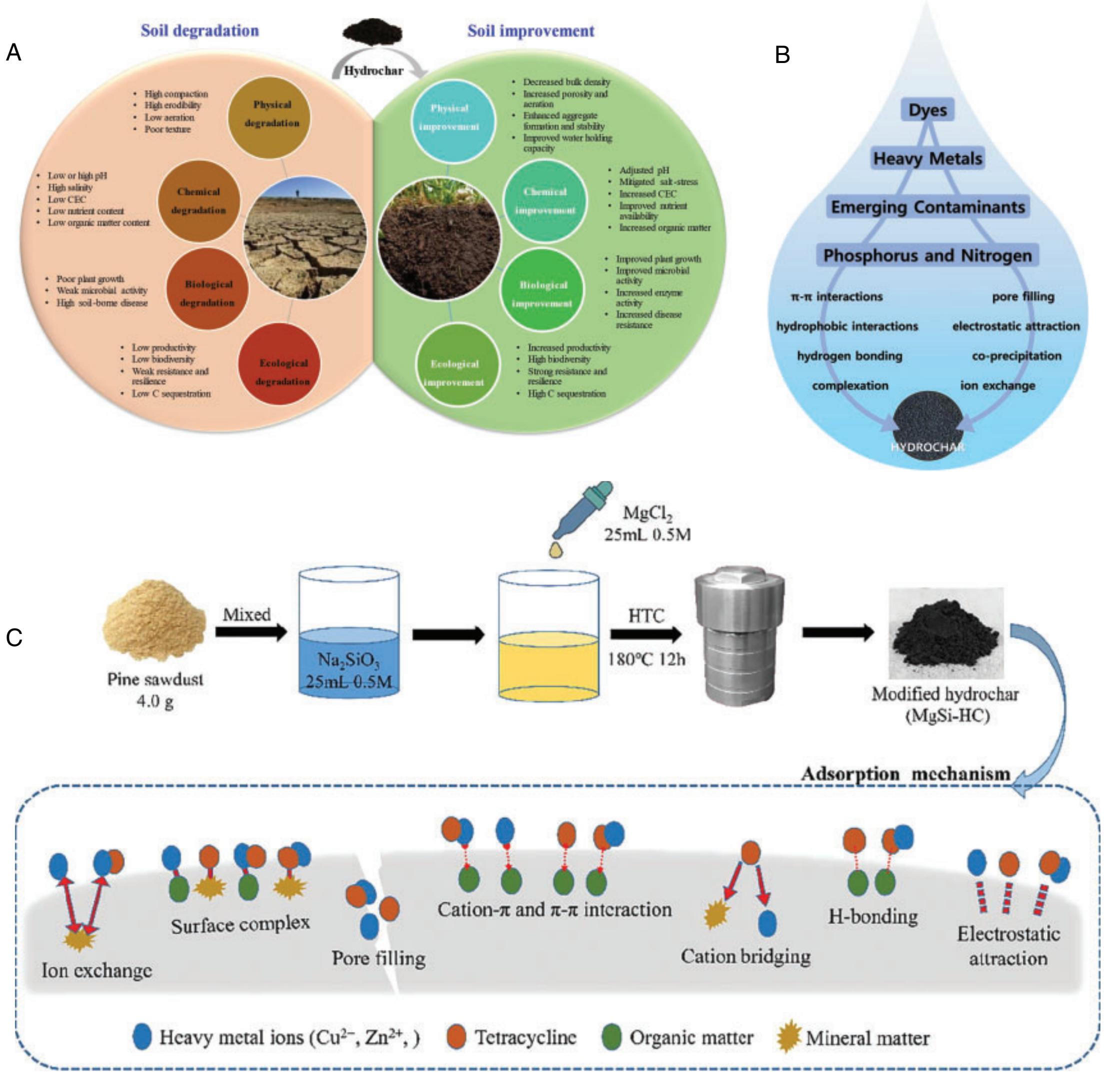

Figure 4: The application of hydrochar and its possible adsorption mechanisms. (**A**) The improvement effect exerted on degraded soil by hydrochar. Reprinted with permission from reference [94]. Copyright © 2022, Elsevier. (**B**) The possible adsorption mechanisms of water pollutants by biomass-derived hydrochar. Reprinted with permission from reference [85]. Copyright © 2023, Elsevier. (**C**) The synthesis procedure of hydrochar and the adsorption mechanisms of heavy metals and organic contaminants. Reprinted with permission from reference [92]. Copyright © 2020, Elsevier

5.4 Microbial Fermentation

Significant effects of hydrochar on the regulation of archaeal microbial community structures have been demonstrated, particularly in promoting the growth of methanogenic microorganisms. Using 10 g/L hydrochar prepared from digestate at 200°C for 6 h was reported to enhance anaerobic co-digestion of food waste and sewage sludge [95]. In this case, the cumulative methane production was improved by 27% and the microbes relevant to methane synthesis (e.g., *Methanosaeta* and *Syntrophomonas*) were largely enriched. Furthermore, it has been reported that the total methanogen abundance in the hydrochar-treated group was nearly doubled relative to the control, accompanied by a similar shift in the dominant methanogenic genus from *Methanobacterium* to *Methanosarcina* [96]. Notably, under conditions with inhibitory factors present, the enrichment of methanogens was still promoted by hydrochar addition. For example, in an

8 g/L ammonia environment, the relative abundance of *Methanosarcina* decreased to 0.6%–12.9%, whereas after hydrochar addition, its abundance was maintained at a higher level of 18.2%–22.1% [97]. At ammonia concentrations of 0.5 and 4 g/L, methane yield increased by approximately 10% with the addition of 10 g/L hydrochar, which was produced from poplar wood at 300°C for 1 h. Furthermore, under a high ammonia concentration of 8 g/L, the addition of 10 g/L hydrochar resulted in a maximum methane yield enhancement of up to 220% [98]. Given the close association between methanogens and methane production [96], the promotion of methanogen enrichment by hydrochar highlights its significant potential for application in microbial fermentation processes.

5.5 *Phosphorus Recovery*

Waste biomass contains substantial amounts of phosphorus, an element of strategic importance due to the limited natural phosphate rock reserves predominantly located in Morocco, the United States, and China. Consequently, relevant European legislation actively promotes and funds phosphorus recovery from waste streams [99]. Studies have demonstrated that up to 95% of the total phosphorus content can be recovered through the HTC of waste biomass [99–102]. During the HTC process, phosphorus is primarily partitioned into the solid phase. Subsequent acid leaching of the recovered hydrochar facilitates phosphorus removal into the aqueous phase. Finally, phosphorus can be precipitated from the alkaline-treated solution, enabling its recovery. Fig. 5 illustrates the conceptual utilization pathways of HTC-derived products by balancing phosphorus recovery, heavy metal concomitant leaching, and residual hydrochar utilization [103]. Pathway I involves the direct use of hydrochar (HC) obtained from HTC, with current applications primarily including biofuels, land applications (e.g., fertilizers and soil conditioners), and functional materials (such as adsorbents and electrode materials). Pathway II entails the recovery of phosphorus through wet chemical methods, followed by the subsequent utilization of the resulting recovered hydrochar (RHC). The results indicate that when using HCl and H_2SO_4 as extractants for a 1 h reaction, the maximum phosphorus leaching yields reached up to 79.8% (HCl) and 82.0% (H_2SO_4) [103]. Compared to the HTC process without phosphorus recovery, the integrated process could additionally yield phosphorus-containing products, which would have significant potential in the situation of the global shortage of phosphate fertilizers.

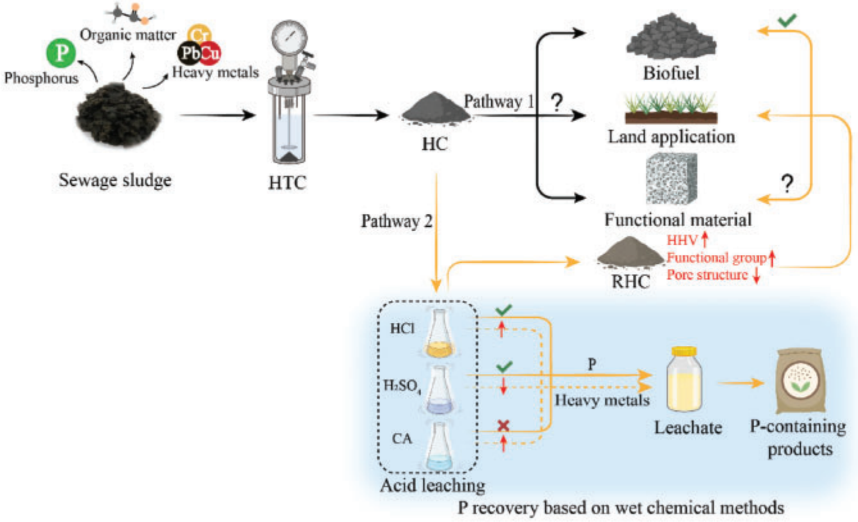

Figure 5: Comparison of the overall benefits between HTC (pathway I) and HTC combined with phosphorus recovery (pathway II). Reprinted with permission from reference [103]. Copyright © 2025, Elsevier

6 Conclusions

Biomass primarily comprises woody plants, herbaceous plants, aquatic plants, and municipal solid waste, and is recognized as a renewable resource. Its main constituents—cellulose, hemicellulose, and lignin—are high-molecular-weight organics with favorable carbon-neutral characteristics, playing a vital role in mitigating the escalating greenhouse gas emissions. HTC is an efficient and environmentally friendly thermochemical conversion technology that transforms various biomass types into hydrochar with enhanced carbon content and energy density under relatively mild reaction conditions, thereby improving its value for resource utilization. The HTC process is influenced by multiple factors, among which reaction temperature is the primary factor influencing reaction pathways. Feedstock type significantly affects reaction behavior and the final properties of hydrochar, while reaction time, pressure, and catalyst selection further regulate hydrochar yield and physicochemical characteristics. In terms of practical applications, hydrochar shows broad prospects. As a solid fuel, hydrochar exhibits high calorific value and low ash content, with combustion performance comparable to or even surpassing certain commercial coals. When applied as a soil amendment, hydrochar improves soil structure, enhances nutrient retention, and possesses potential for carbon sequestration, contributing to sustainable agriculture; however, its environmental effects require further evaluation and management. Hydrochar also demonstrates excellent adsorption capacities and, after physical or chemical modification, shows strong removal efficiencies for various organic pollutants and heavy metals, indicating its potential as a novel low-cost material for environmental remediation. In summary, HTC provides a practical pathway for the valorization and energy recovery of waste biomass. Future research should focus on in-depth elucidation of reaction mechanisms, the design of functional composite materials, and systematic evaluation of environmental behaviors and long-term benefits, aiming to facilitate the large-scale application of hydrochar in various fields.

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