

Review

# Biowaste Valorization to Produce Advance Carbon Material-Hydrochar for Potential Application of Cr (VI) and Cd (II) Adsorption in Wastewater: A Review

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**Abstract:** The dramatic increase in the use of biomass waste has caused a serious environmental pollution phenomenon. Biowaste valorization to produce advanced material-hydrochar is regarded as a promising carbon neutrality technology for biomass waste recycling and utilization. Hydrochar obtained by hydrothermal carbonization has attracted much attention due to its regular morphology, good physical and chemical stability, and abundant oxygen-containing functional groups on the surface. This reviews the preparation of hydrochar and the basic methods of modified hydrochar and expounds on the related reaction mechanism of adsorption. The adsorption and recovery of heavy metals, Cr (VI) and Cd (II), in wastewater by hydrochar were focused on. The experimental conditions of hydrochar, such as synthesis temperature, synthesis time, modified condition, adsorption capacity, adsorption isotherm, and adsorption kinetics, were compared. The adsorption conditions of hydrochar for Cr (VI) and Cd (II) in wastewater, including the adsorption pH value, the adsorption time, the adsorption temperature, and so on, have been summarized. The review develops a better understanding of Cr (VI) and Cd (II) adsorption by hydrochar in wastewater, making an innovative perspective for the improvement and large-scale application of hydrochar as an advanced carbon material as well as biowaste utilization.

**Keywords:** hydrochar; biowaste valorization; Cr (VI); Cd (II); adsorption; wastewater



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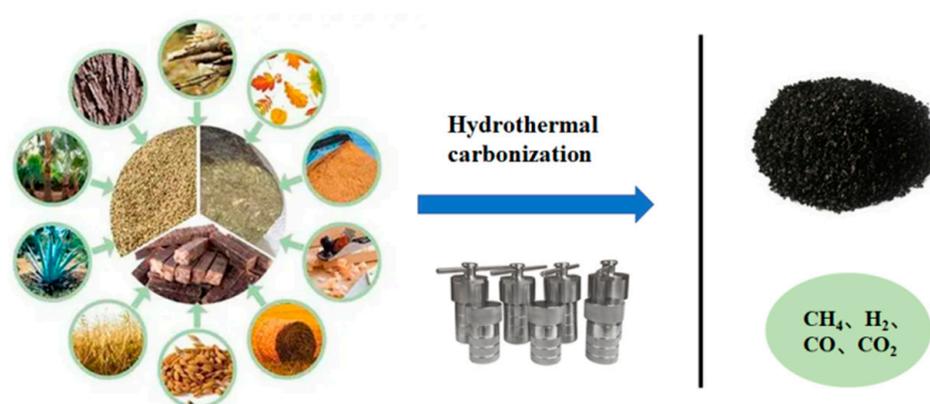
## 1. Introduction

Globally, human activities produce massive quantities of biomass waste, and because these wastes are not well managed, they cause environmental pollution, economic losses, and human health problems that seriously affect us. [1]. The use of biomass resources has an impact on climate change as well [2]. The activity around biomass in the past is a sign of the importance that mankind places on environmental protection and the use of biomass resources [3]. While biomass waste is a source of pollution, it is also a valuable renewable resource and energy source [4–6]. The logical and effective use of biomass waste not only allows for the full utilization of biomass as a renewable and clean energy source but also contributes to CO<sub>2</sub> reduction [7]. Countries throughout the world are organizing targets to reduce carbon emissions and greenhouse gas emissions by 2050 under the Paris Agreement. China has dedicated itself to peaking its emissions around 2030 and being “carbon neutral” by using 2060, which means that net carbon emissions will be nil via then [8–10]. This has supplied a significant incentive for biochar research. There is additionally a substantial amount of learning about biomass conversion technologies, primarily thermochemical, biochemical, chemical, and physicochemical processes (Table 1). The successful conversion of biomass waste has been demonstrated to be a contemporary research hotspot by lowering pollutants by pyrolytic conversion, with the resultant carbon compounds, such as biochar and hydrochar, being recyclable [11].

**Table 1.** Biomass waste resource utilization methods and products.

Resource Utilization Methods	Specific Techniques	Final Products	References
Thermochemical method	Gasification	Biomass gas	[12]
	Pyrolysis	Charcoal/Biocrude	[13]
	Direct liquefying	Liquefied oils	[14]
Biochemical methods	Compost	Organic fertilizer	[15–18]
	Hydrolysis; fermentation	Ethyl alcohol	[19]
	Biogas technology	Biogas	[20,21]
Chemical method	Indirect liquefaction	Methanol and ethers	[22]
	Esterification	Biodiesel	[23]
Physical and chemical methods	Compression moulding	Fuel	[24]

Biochar has gotten a lot of interest because of its lower cost, wide variety of raw materials, simplicity preparation techniques, and absence of pollution, and its prospective uses are being increased [25–29]. Due to their prosperous and various architectures, advanced carbon materials have evolved several functional carbons, such as carbon fibers, carbon microspheres, carbon nanotubes, mesoporous carbon, graphene, and so on [30]. Carbonaceous materials have been successfully ranked among the hot issues in inorganic materials research in the last 20 years due to their adjustable pore size, large specific surface area, great hydrothermal stability, and variable pore structure [31,32]. Biochar materials are typically generated by high-temperature thermal cracking, dry roasting, gasification, flash carbonization, and hydrothermal carbonization [33–35]. Hydrochar is the biochar created by hydrothermal carbonization [36,37]. Figure 1 depicts the improvement of hydrochar and associated products following hydrothermal carbonization treatment utilizing various source materials.

**Figure 1.** Hydrothermal carbonization of biomass [38].

In comparison to traditional methods of preparing activated carbon (physical activation, chemical activation), hydrothermal carbonization is a more advanced carbon neutrality technology with milder reaction conditions, no drying of the biomass, and the surface of the hydrochar is rich in oxygen-containing functional groups [39–42]. Hydrochar is a black solid product with carbon as the predominant skeleton and a high concentration of oxygen functional groups produced by a hydrothermal reaction at 150–375 °C and autogenous pressure with biomass or its components as the raw material, water as the solvent, and oxygen as the reaction medium [43–45].

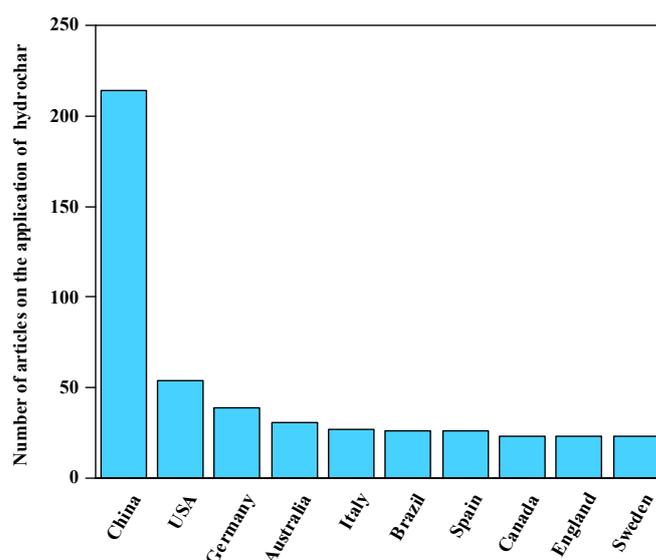
According to the study, the term “hydrothermal carbonization” is the most relevant to the subject term, followed by “adsorption”. This might demonstrate that the most recent use of biomass waste is connected to the adsorption function in water, such as heavy metal pollution, phosphorus pollution, and so on. Following that are “biomass waste”, “sewage sludge”, and “activated carbon”. These are the raw materials that are

used more frequently, while the products of hydrothermal carbonization have many benefits, including homogenous size, regular shape, strong physicochemical stability, and a surface rich in oxygen-containing functional groups. As a result, hydrochar materials have a wide range of applications, including environmental cleanup, catalyst carriers, and supercapacitors [46,47].

Therefore, the aims of the present paper were as follows: (1) investigating the adsorption of Cd and Cr on different hydrochars after different modifications or related reactions. (2) Investigate the optimum adsorption conditions for metal ions on hydrochar under different reaction conditions. (3) Investigate the characteristics of the adsorption mechanisms of different hydrochar materials under optimal adsorption conditions.

## 2. Data Sources and Methodology

The literature were collected from the Web of science related to the use of waste biomass as raw materials and the use of hydrochar to synthesize hydrochar products in recent years. The main reference literature is the newly published frontier literature and data in recent years, as well as some classical forms of literature to support the credibility of the article. In Figure 2, it can be seen that China has the highest number of publications worldwide, accounting for approximately 44.8%. Surprisingly, 76% of the total number of papers on hydrochar in English are published in only the following five countries: China, USA, Germany, Australia, and Italy. This indicates that there is more research on hydrochar in China and that there is a relatively high concentration of countries researching this topic.



**Figure 2.** The number of articles on the application of hydrochar area over the past five years.

In Figure 3, it can see the main keywords used in the articles on the application of hydrochar, and the search term “application of hydrochar” was used on the web of science. The term “hydrothermal carbonization” was the most controlled term, followed by “adsorption”. This may confirm that the most current application of biomass waste is in the adsorption function in water, including adsorption of heavy metal pollutants, phosphorus pollution, etc.; followed by “biomass waste”, “sewage sludge” and “This probably explains why biomass waste and sewage sludge are by far the most researched and useful activated biocarbon materials.

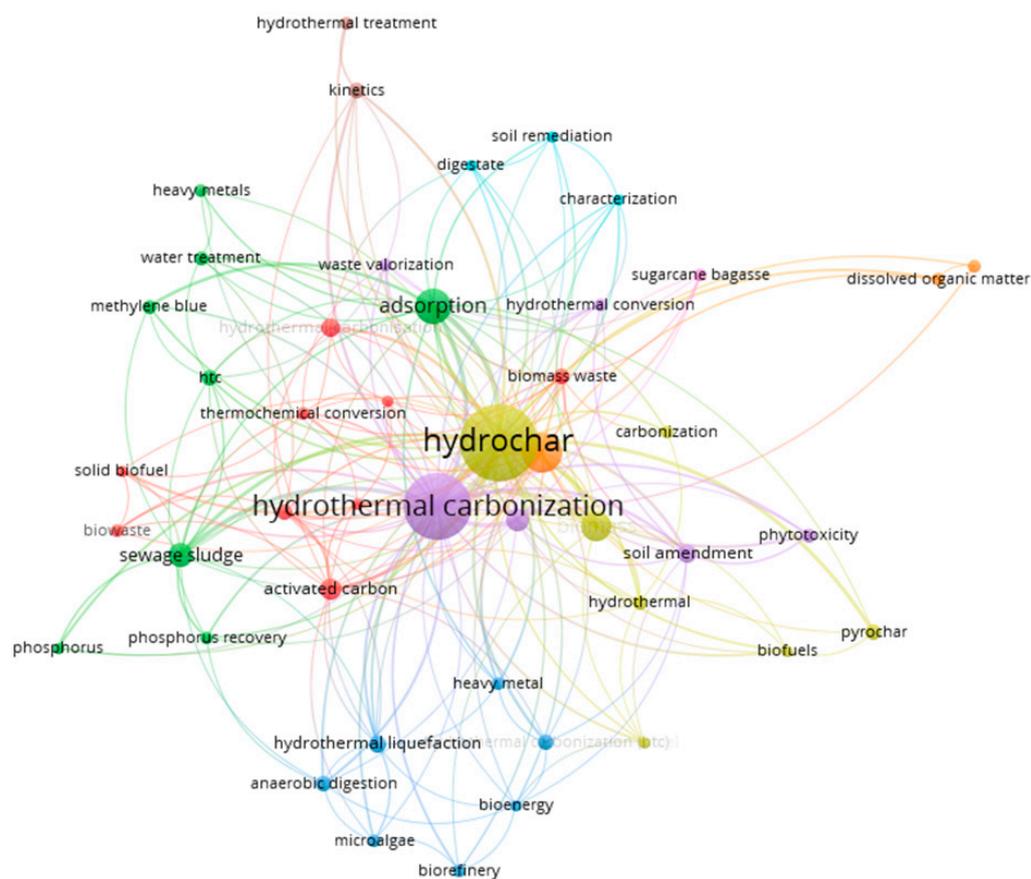


Figure 3. Heat map of keywords for articles about the use of hydrochar.

### 3. Modification of Hydrochar

The adsorption function of the hydrochar is determined by the form of the biomass feedstock, the hydrothermal carbonization reaction conditions, and the pH value of the solution. As research into hydrochar materials has improved, traditional ways of preparing hydrochar have failed to suit people’s requirements; hence, researchers have attempted to synthesize modified hydrochar for new uses. Modification refers to the application of chemical modifiers to the surface of the hydrochar in order to change the structure of the functional groups or to activate the carbon in order to enhance its quality (Table 2). The modification techniques are subdivided into physical and chemical modifications [48].

Table 2. Physical and chemical modification methods and application examples of hydrochar.

Modification Methods	Specific Methods	Application Cases	References
Physical modification	Gas activation Treatment of hydrochar at temperatures exceeding 700 °C with a variety of gases such as steam, CO <sub>2</sub> , ozone, and so on.	When activated using CO <sub>2</sub> and O <sub>2</sub> , the CO <sub>2</sub> increases the specific surface area of the hydrochar, while the pore volume of the hydrochar is also increased.	[49]
	Steam activation Following the hydrothermal treatment, the pyrolysis steam activation was performed again.	A greater post-treatment temperature would raise the carbonaceous materials’ graphitization degree.	[50]

Table 2. Cont.

Modification Methods	Specific Methods	Application Cases	References
Chemical modification	Add oxidant	Adding oxidants can enhance in the synthesis of oxygen functional groups on the surface of hydrochar, increasing its oxygen level.	[51]
	Add alkaline substances	The groups in the base contribute to chelate the reaction with the metal ions.	[52]
	Add dilute acid	Increases the quantity of carboxylate and phosphate on the surface of hydrochar, resulting in increased adsorption capability.	[53]
	Load metal salts or transition metal nanoparticles	Modification of hydrochar by immersion in a metal salt solution or by surface loading with a metal substance.	[54]

### 3.1. Physical Modification

The two main types of physical modification are gas activation and steam activation. The usual activation at temperatures above 700 °C using gases such as steam, carbon dioxide, and O<sub>3</sub> is called gas activation [55]. Roman et al. [49], for example, investigated two common oxidizing gases, oxygen and carbon dioxide, and their effects on the structural characteristics of different raw materials. They discovered that CO<sub>2</sub> increased the specific surface area of all hydrothermal coals and significantly increased the micropore volume but decreased the meso- and macropore volumes. Steam activation is the use of pyrolytic steam again for modification after hydrothermal treatment. Saeed et al. [56] prepared activated biochar using a physicochemical activation method, including pre-impregnation with NaOH and N<sub>2</sub> pyrolysis, which were used to remove Cd (II) from the water. The authors used rice husk, an agricultural waste, to obtain a modified adsorbent by modifying it to obtain a larger surface area and a more effective adsorption [57]. The specific surface area of sludge hydrochar rose from less than 10 m<sup>2</sup>/g of raw material to 600 m<sup>2</sup>/g following steam activation [50]. At the same temperature, more time allows the original structure to degrade to a higher degree of spherical. The hydrothermal carbonization process results in an increase in nitrogen content in the hydrochar structure, and the oxygen content decreases with time [58].

### 3.2. Chemical Modification

Chemical modification is the process of combining hydrochar with some chemical reagents to generate a microporous structure on the surface of hydrochar by a series of dehydration and oxidation reactions and other complicated processes. Chemical modification is far more efficient than physical modification. The main ways of chemical modification are as follows: First, add an oxidant. The oxidant oxidizes. Including an oxidant in the process of hydrothermal carbonization of biomass, or directly adding an oxidant to activate the hydrochar, will help to create oxygenated functional groups on the surface of the hydrochar and increase its oxygen content. Second, include alkaline substances. The adsorption

capacity of hydrochar was enhanced after adding alkaline chemicals, and the surface area and total pore volume were increased compared to before, making it more favorable for the chelating reaction with metal ions. Third, add diluted acid. Increasing the number of carboxylic acids and phosphoric acid on the surface of hydrochar by adding organic acids or inorganic acids such as phosphoric acid during the hydrothermal carbonization process might improve the activity of the hydrochar surface. Fourth, transition metal nanoparticles or metal salts are loaded.

There are various ways to reduce the level of heavy metal ions in wastewater. Natural sedimentation, chemical precipitation, biological techniques, ion exchange methods, and adsorption methods are the most readily realized approaches in terms of cost and feasibility. Among them, the adsorption technique has many benefits, including wide adaptability, easy operation, quick processing speed, good effect, cheap cost, recyclable usable materials, reusability of the adsorbent, and so on. Hydrochar has a multi-level pore structure, a large specific surface area, a high degree of aromatization, high stability, and a surface rich in functional groups. We will combine the advantages of hydrochar and adsorption methods to investigate the adsorption status of the products after hydrothermal heating. Hydrothermal carbonization began with pure carbohydrates such as glucose as raw materials and eventually expanded to more complex biomass as source materials.

#### 4. Potentials Application of Hydrochar for Heavy Metal Adsorption

Hydrochar is currently used in a wide range of applications. The first is as an adsorbent, as Jiang et al. [59] described, high-pressure CO<sub>2</sub> hydrothermal treatment was created to make hydrochar from banana pseudostems to adsorb methylene blue in water, which can be utilized for wastewater treatment, in order to minimize the environmental risk of banana waste and the development of fungal infections. In the presence of ammonium persulfate, bamboo and acrylic acid were used as raw materials for hydrothermal carbonization to create carboxylic acid-rich hydrochar, followed by activation with sodium hydroxide solution for the final assessment of its adsorption capacity for methylene blue [60]. Second, hydrochar may be utilized as a catalyst or as catalyst raw materials; for example, Pan et al. [61] artificially boost single dehydration efficiency by creating a series of metal hydrochar materials as catalysts. The consequences of the analysis demonstrate that the content of the preparation solution has an impact on the morphology of hydrochar. Wen et al. [62] examined microcrystalline cellulose catalytic ethanolysis in supercritical ethanol using a sulfonated hydrochar catalyst. The results indicated that a shorter reaction time and a lower catalyst dose favored the production of ethyl glucoside, while a longer reaction time and a higher catalyst dosage favored the formation of ethyl levulinate. Meanwhile, it can also be used as a soil conditioner. Hou et al. [63] used short-term hydrothermal fermentation to create a soil conditioner containing a specified amount of unstable organic carbon. The impacts of hydrothermal fermentation, classic aerobic fermentation, and heterogeneous nutrients on soil texture, dissolved organic matter development, humic acid structure, and dominating microbial taxonomic succession were studied. Scheifele et al. [64] found that adding hydrochar to the soil might increase the growth of rhizobia and boost the ability of soybeans to biologically fix nitrogen, consequently improving soybean plant growth. Fourth, it may be utilized as fuel. Jagaba et al. used raw materials such as chitosan, FeCl<sub>3</sub>, alum, zeolite, and mulberry for the removal of heavy metals from water [65]. Al-mahbashi et al. used sludge-based activated carbon to remove the heavy metal Cd (II), which is less costly to remove using sludge-based activated carbon [66]. Poomsawat et al. [67] investigated the combustion behavior of aquatic biomass and its produced char in the medium temperature range combustion process by hydrothermal carbonization. According to the findings of Parshetti et al. [68], hydrochar can be utilized as a high-calorie fuel. As can be seen from the above examples, the application of hydrochar is very promising.

The use of hydrochar for heavy metal adsorption is a popular area of research due to its abundant raw materials, low cost, and simple manufacturing techniques. As a result, it has a high prospective application value in the fields of heavy metal removal from

wastewater and environmental pollution remediation [69]. For example, Wei et al. [70] prepared hydrochar using lotus stems, and the produced material was employed for the adsorption of the heavy metal Cr (VI) in water. Li et al. [71] prepared hydrochar from maize straw to evaluate metal Pb adsorption in water. Huang et al. [72] adsorb Cu (II) in water using KOH chemically activated hydrothermally produced activated carbon spheres and discovered that the maximum adsorption of Cu (II) by the modified hydrochar was 42 mg/g and the adsorption isotherm was under the Langmuir model. Zhang et al. [73] synthesized the initial material using a hydrothermal method and then coupled it with lignin sulfonate to make a lignin sulfonate carbon adsorbent. The heavy metal Pb<sup>2+</sup> in water was adsorbed by the adsorbent. Model construction of the experimental data revealed that the second-order kinetics and Langmuir isotherms were suitable for the adsorption, which indicated that the adsorption of Pb<sup>2+</sup> by lignin sulfonate was spontaneous thermochemical adsorption. Lu et al. [74] found that the adsorption process of Pb (II) is endothermic, including both physical and chemical adsorption.

There are many factors that affect the adsorption capacity. One important factor is the surface area. Xie et al. [75] found that there may be complexation, precipitation, isostructural substitution, and physical adsorption on the surface of Cu (II). Wang et al. [76] designed a two-step hydrothermal method to modify flower-like molybdenum disulfide with iron oxide nanoparticles, mainly used to remove Hg (II) and Pb (II) in an aqueous environment. The results revealed that the whole adsorption process went through the following three stages: instantaneous diffusion, inner surface diffusion, and equilibrium. Song et al. [77] created carbon nanospheres for Ag (I) adsorption using a simple hydrothermal treatment of glucose solution. According to the results, all Ag (I) ions were reduced and deposited on the outer surface. To adsorb As (V) in water, Xue et al. [78] synthesized hydrochar from glucose. The highest adsorption capacity was 41.91 mg/g [79]. Zhang et al. [80] prepared carboxyl-rich hydrochar microspheres, characterized them, and investigated the effects of different test conditions on the sorption performance of U (VI). At the same time, we focus on the kinetic and isothermal changes in the adsorption process. Feng et al. [81] used hydrochar to adsorb Ni (II), and the results show that the second-order kinetics and the Langmuir isotherm are similar to the process and that the maximum adsorption capacity can reach 2217 mg/g. Zhou et al. [82] contributed to the purification of water resources by using glucose to make hydrochar to adsorb Th (IV) from water. He et al. [83] used maize straw, a biomass waste, to make hydrochar for the adsorption of the Zn (II) in water. The adsorption process of Zn (II) on hydrochar is consistent with pseudo-second-order kinetics and the Freundlich model and is dominated by chemisorption. This study provides a new use for hydrochar from agricultural sources.

In summary, the use of hydrochar covers a wide range (Table 3), but the more efficient application of hydrochar is still worth studying.

**Table 3.** Adsorption of heavy metals in water by hydrochar.

Heavy Metal	Source of Hydrochar	Adsorption Capacity	Adsorption Kinetic	Adsorption Isotherm	References
Cr (VI)	Lotus stems	232.56 mg/g	Pseudo-second-order	Langmuir	[70]
Pb (II)	Corn stalk	480.9 mg/g	Pseudo-second-order	Langmuir	[71]
Cu (II)	Xylose	42 mg/g		Langmuir	[72]
Cu (II)		338.976 mg/g	Pseudo-second-order	Langmuir	[75]
Pb (II)	Lignin		Pseudo-second-order	Langmuir	[73]
Hg (II)	Polrvidone	428.9 mg/g	Pseudo-second-order	Langmuir	[74]
Ag (I)		152 mg/g	Pseudo-second-order	Langmuir	[77]
As (V)		41.91 mg/g	Pseudo-second-order	Langmuir	[78]
U (VI)		285.70 mg/g	Pseudo-second-order	Langmuir	[80]
Ni (II)	Mg(OH) <sub>2</sub>	2217 mg/g	Pseudo-second-order	Langmuir	[81]
Th (IV)		69.93 mg/g	Pseudo-second-order	Langmuir	[82]
Zn (II)	Corn stalk	207.6 mg/g	Pseudo-second-order	Freundlich	[83]

#### 4.1. Application of Hydrochar in the Adsorption of Cr (VI)

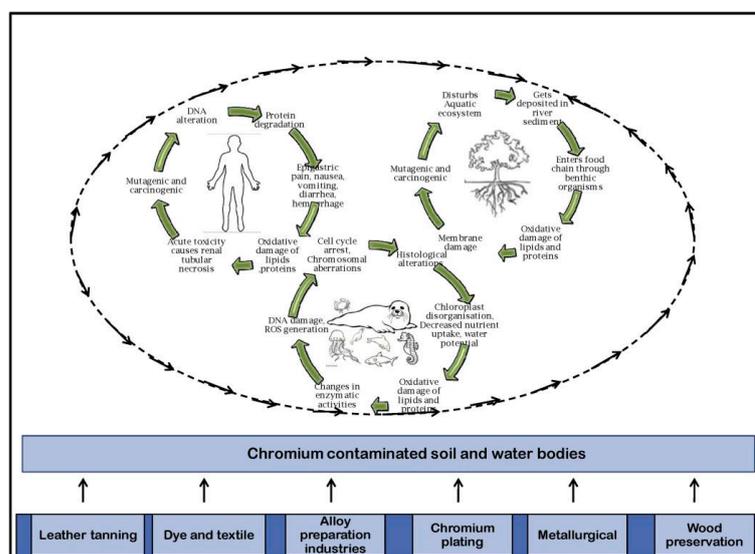
Chromium pollution is an important aspect of water environment pollution, mainly from mineral smelting, the production and use of metals and their products, and the combustion of mineral fuels [84,85]. There are the following two oxidation states of chromium: Cr (III) and Cr (VI). Among them, Cr (VI) is 100 times more toxic than Cr (III) because of its high solubility and mobility in water, which easily penetrates the cell membrane and leads to potential health risks. For human health, chromium crosses cell membranes and damages cell cells and molecular components. This leads to membrane damage, protein degradation, and denaturation of the genetic material DNA in animals, plants, and humans. Moreover, chromium (VI) induces mutations by affecting DNA-protein crosslinks, leading to strand breaks. Cr (VI) induces mutations by interfering with DNA-protein cross-linking and leading to single-strand breaks.

Cr (VI) exposure beyond the allowable limit is regarded as leading to lung cancer, which damages kidney and liver functions and can also lead to upper abdominal pain, nausea, vomiting, allergic reactions, gastric ulcers, and bleeding (Figure 4). Because it can cause great harm to people, countries are strictly controlling human intake. Table 4 summarizes the concentration standards of some regions and countries for Cr (VI) in quoted water. We can see that, among them, China, Canada, the WHO, Australia, and other places require chromium concentrations in water to be less than 50 µg/L, and the United States requires chromium concentrations in water to be less than 100 µg/L (Table 4). Currently, although there are many studies on the use of biomass as an adsorbent for the removal of hexavalent chromium, there are fewer studies on the use of hydrochar as an adsorbent. In this paragraph, a summary of the practical application of hydrochar will be presented to provide some reference for the reader (Table 5).

**Table 4.** Control Standard of Cr in Different Areas and Harm of Cr.

Metal	Region	Standard	Harm	References
Cr	China	50 ug/L		GB 5749-2022
	Canada	50 ug/L	Disruption of cell membrane;	[86]
	WHO	50 ug/L	Protein degradation;	[87]
	NZ	50 ug/L	Lung cancer;	[88]
	AUS	50 ug/L	Liver cancer; nausea;	[89]
	USEPA	100 ug/L	Gastric bleeding; gastric ulcer.	[90]
	UK	50 ug/L		[91]

Note: WHO, World Health Organization; NZ, New Zealand; AUS, Australia; USEPA, US Environmental Protection Agency; UK, United Kingdom.



**Figure 4.** Chromium toxic effects on the ecosystem [92].

We separated the materials into two groups to explore the link between sorption capacities. The first group exhibited significant sorption capacities ( $>100$  mg/g), whereas the second had sorption capacities less than 100 mg/g. We hope that this literature review helps the reader understand what causes the differences in adsorption capacities between different materials.

#### 4.1.1. Application of Hydrochar with Low Adsorption Capacity of Cr (VI)

The hydrochar produced from biomass waste and hydrothermal methods has excellent properties. In terms of the size of the material produced, it can reach the micron level. By hydrothermal treatment of chitosan microspheres, Yi et al. [93] obtained millimeter-scale hydrochar microspheres. It was shown by static adsorption that hydrochar microspheres-180 obtained at  $180$  °C could reduce the Cr (VI) concentration from 20 mg/L to 0.3 mg/L, while chitosan microspheres could only reduce it to 4.7 mg/L. In addition, the removal efficiency of hydrochar microspheres-180 was almost independent of the coexisting anions (including  $\text{Cl}^-$ ,  $\text{NO}_3^-$ ,  $\text{HPO}_4^{2-}$ , and  $\text{SO}_4^{2-}$ ). The pseudo-secondary kinetic model more closely approximates, which suggests that the adsorption is chemisorption. The Freundlich model fit the adsorption isotherm data well, indicating that the adsorption process was monolayer adsorption.

For the synthesized material, not only the characterization is studied, but also the optimization of the adsorption conditions. After the preference, the characteristics of the adsorption kinetics and isotherms are explored. Carbon hydroxyapatite was synthesized by the hydrothermal method using waste eggshell as the raw material, and its structure was characterized by XRD (X-ray diffraction), SEM (scanning electron microscopy), and EDS (energy dispersive spectrum). Carbon hydroxyapatite was used as an adsorbent for chromium-containing wastewater to investigate the effects of pH, initial Cr (VI) concentration, and adsorption time on Cr (VI) adsorption behavior. The results showed that the initial concentration of 50 mg/L of Cr (VI) solution at room temperature ( $22 \pm 2$ ) °C, pH 3.0, and a carbon hydroxyapatite dosage of 5 g/L for 30 min reached the adsorption equilibrium with a Cr (VI) removal rate of 98.3%, and the saturated adsorption capacity was 29.85 mg/g. The adsorption behavior of carbon hydroxyapatite on Cr (VI) conformed to the Langmuir–Freundlich adsorption isotherm, and the correlation coefficients were 0.9984 and 0.9226, respectively [94]. The hydrothermal carbonization method was used to prepare the adsorbent for the hydrochar of grapefruit peel. The functional groups and pore structures on the surface of the hydrochar were determined by an infrared spectrometer and a nitrogen adsorption instrument. The authors have studied the effect of relevant test conditions, such as adsorbent dosage, liquid pH, Cr (VI) content in solution, and adsorption time, on the adsorption of Cr (VI). The results showed that the adsorption effect was better when the pH value of the solution was less than 7. When the initial concentration of Cr (VI) in solution was 50 mg/L, pH = 6, the adsorbent dosage was 5 g/L, the adsorption time was 90 min, and the adsorption rate and adsorption capacity of hydrochar for Cr (VI) were 99.03% and 6.19 mg/g, respectively. The adsorption process of Cr (VI) on pomelo peel hydrochar conformed to the pseudo-second-order kinetic model, and the isothermal adsorption process is in accordance with the Freundlich model [95].

If the hydrochar is modified, the resulting material is more useful for adsorption than the original material. Gong et al. [96] used laminated double hydroxides to modify waste wood chips by a hydrothermal method. Hydrochar was prepared from pine sawdust and modified with different concentrations of ammonium dihydrogen phosphate as an activator. Characterization of the obtained hydrochar, the results showed that the surface area of hydrochar modified by a low concentration activator increased, and the surface nitrogen functional groups increased. Similarly, Yao et al. [97] prepared cyanobacteria-based hydrochar adsorption materials by hydrothermal carbonization with phosphoric acid activation and found that the cyanobacteria-based hydrochar was rich in oxygen-containing functional groups, which facilitated the removal of hexavalent chromium with an adsorption capacity of 1.982 mg/g. Liu et al. [98] used bagasse-derived hydrochar in

sulfuric acid to simulate the adsorption of chromium-containing wastewater. The maximum adsorption capacity of Cr (VI) was 3.871 mg/g. Langmuir's isothermal adsorption model and pseudo-second-order kinetic model can well reflect the adsorption process.

#### 4.1.2. Application of Hydrochar with High Adsorption Capacity of Cr (VI)

The authors have studied the influence of the pH of the solution, the amount of material used, the time of the experimental reaction, and the initial level of the solution on the an adsorption of hydrochar (Table 5). In terms of the amount of material used, some experiments have shown that the unit adsorption capacity of 5% ammonium dihydrogen phosphate modified hydrochar > 10% modified hydrochar > unmodified hydrochar; the results of adsorption kinetics and adsorption isotherm showed that the adsorption processes of the three adsorbents all followed the second-order kinetic model. At the same time, the Langmuir model can better describe the adsorption process of the three adsorbents [99]. The N-doped hydrochar was synthesized by the hydrothermal reaction of  $\text{NH}_4\text{Cl}$  and bamboo to investigate the adsorption of Cr (VI) by the added element.  $\text{NH}_4\text{Cl}$  can be used as a source of nitrogen to increase the nitrogen content of the hydrochar. Not only that, the decomposition of  $\text{NH}_4\text{Cl}$  under N-doped hydrochar can produce HCl, which acts as a catalyst to accelerate the decomposition of certain components of the bamboo and enhance the adsorption qualities of the material. Cr (VI) is highly dependent on pH value, and the adsorption capacity decreases with the increase in pH value. The optimum pH is 2, and the Freundlich isotherm simulated curve better fitted the testing data [100]. Based on the Langmuir isotherm model, the nitrogen-doped hydrochar material with a Schiff base structure reached a sorption capacity of 349.6 mg/g of Cr (VI) at 298 K and pH 2.0. The adsorption of Cr (VI) on nitrogen-doped hydrochar with a Schiff base structure is largely due to electrostatic attraction, redox, and chelation between nitrogen-containing groups and Cr (VI) [44,101].

In terms of the adsorption mechanism, the hydrochar adsorption mechanism varies. The co-aluminate-layered double hydroxide of three-dimensional porous carbon nanofibers containing hematite was prepared by a hydrothermal method by Poudel et al. and investigated. The adsorption performance of Cr (VI) was investigated. The results showed that the maximum adsorption of Cr (VI) by the super hydrophilic porous carbon nanofibers loaded with hematite was 400.40 mg/g. The adsorption process was accompanied by precipitation, surface complexation, isomeric substitution, and electron transfer [102]. When modifying the material, Sun et al. [103] prepared porous carbon adsorbents from microalgae for Cr (VI) adsorption by hydrothermal charring and KOH or  $\text{NH}_3$  activation reactions. The adsorption capacity of KOH-activated porous carbon for Cr (VI) was higher than that obtained by  $\text{NH}_3$  modification (370.37 > 95.70 mg/g). The modified hydrochar has a mesoporous and macroporous structure and a larger specific surface area ( $1784 \text{ m}^2/\text{g}$ ) and pore volume, giving it a better Cr (VI) adsorption capacity. Its results for Cr (VI) adsorption fit well with the Langmuir model, indicating that the removal of Cr (VI) by the modified hydrochar material is due to the monolayer adsorption of the active center on the carbon surface. The resultant amine-modified black liquor and pure lignin-derived biocoal materials were synthesized by a hydrothermal carbonization method with the addition of hexamethylenebis. The results showed that the hydrochar modified by black liquor had a better adsorption effect. The maximum adsorption amount of black liquor-180 (hydrothermal temperature  $180 \text{ }^\circ\text{C}$ ) was 741.74 mg/g, while that of pure lignin-150 was only 165.16 mg/g, as calculated by the Langmuir model at  $45 \text{ }^\circ\text{C}$  [104]. In terms of experimental temperature, Shen et al. [105] found that temperature is a key factor in the hydrothermal carbonization process and that by increasing the temperature, more energy is available to break down the intermolecular bonds in chitosan. Raising the temperature will release more volatiles, resulting in more gaseous and liquid products than solid ones.

**Table 5.** Preparation conditions of hydrochar and Cr (VI) in adsorption wastewater.

Raw Materials	Synthesis Conditions	Material Usage	pH	Kinetics	Isotherm	Absorption Time	Adsorption Capacity	References
Pine wood chips	240 °C, 4 h	10 g/L	1–3	Pseudo-second-order	Langmuir	24 h	—	[99]
Chitosan powder	180 °C, 12 h	1.34 g/L	1–3	Pseudo-second-order	Freundlich	0.5 h	42.50 mg/g	[93]
Chitosan	180 °C, 10 h	0.5 g/L	4	Pseudo-first-order	Langmuir	12 h	388.6 mg/g	[105]
Blue algae	240 °C, 1 h	5 g/L	7	Pseudo-second-order	—	4 h	1.982 mg/g	[97]
Bagasse	190 °C, 12 h	14 g/L	2	Pseudo-second-order	Langmuir	1.5 h	3.871 mg/g	[98]
Pomelo peel	190 °C, 2 h	5 g/L	6	Pseudo-second-order	Freundlich	1.5 h	6.19 mg/g	[95]
Lignin	180 °C	1 g/L	2	Pseudo-second-order	Freundlich	72 h	859.43 mg/g	[104]
Bamboo powder	200 °C, 24 h	1 g/L	2	Pseudo-second-order	Freundlich	7 h	195.76 mg/g	[100]
Hemicellulose	220 °C, 12 h	4 g/L	2	Pseudo-second-order	Langmuir	12 h	349.6 mg/g	[101]

#### 4.2. Application of Hydrochar in the Adsorption of Cd (II)

The investigation of Cd (II) in water adsorbed by hydrochar, such as the studies on Cr (VI) in water, divided the material into two groups, one with an adsorption capacity over 100 mg/g and the other with an adsorption capacity below 100 mg/g, which should provide some food for thought for the reader. We chose cadmium for our study because Cd is a toxic metal that is widely distributed in water and soil and occurs in the oxidized form as 0 or +2 according to its valence state. By compound form, it occurs in nature as Cd(OH)<sub>2</sub>, CdCO<sub>3</sub>, and CdSO<sub>4</sub>. According to the presence of precipitates, Cd also precipitates as arsenate, phosphate, chromate, sulfide, etc. Ecosystems are not only contaminated by the direct production of cadmium but also by secondary contamination from sources of cadmium, which has been found to have chronic effects on animals and humans, even when exposure is minimal [106].

What is very concerned about is the harm of Cd to the human body. According to incomplete statistics, when the human body absorbs a certain amount of Cd, it will cause damage to various organs to varying degrees. In the respiratory system, the mucous membrane, causing shortness of breath, severe pneumonia, due to Cd toxicity, beyond the threshold, urinary protein, glomeruli, and tubular damage, in the reproductive system, breast cancer, testicular necrosis, progesterone and testosterone disorders, such as pain, osteoporosis, and low bone density. Table 6 summarizes the Cd concentration standards of some regions and countries. We can see that Australia has the lowest Cd concentration requirement of 2 ug/L, China requires that its maximum threshold concentration should not exceed 5 ug/L, and Canada requires that it should not be higher than 7 ug/L. Therefore, the removal of Cd (II) in water is also of great concern [107]. In this part, the adsorption conditions and effects of hydrochar on Cd (II) in water will be investigated, bringing some reference for researchers studying related contents (Table 7).

**Table 6.** Control standard of Cd in different areas and harm of Cd.

Metal	Region	Standard	Harm	References
Cd	China	5 ug/L	Pneumonitis;	GB 5749-2022
	Canada	7 ug/L	Mucous membrane destruction;	[86]
	WHO	3 ug/L	Proteinuria;	[87]
	NZ	4 ug/L	Glomerular and Tubular damage;	[88]
	AUS	2 ug/L	Itai-Itai disease;	[89]
	USEPA	5 ug/L	Progesterone and Testosterone disturbance;	[90]
	UK	5 ug/L	Testicular necrosis.	[91]

Note: WHO, World Health Organization; NZ, New Zealand; AUS, Australia; USEPA, US Environmental Protection Agency; UK, United Kingdom.

##### 4.2.1. Application of Hydrochar with Low Adsorption Capacity of Cd (II)

The adsorption of Cd (II) in water by hydrochar has been studied. From the point of view of multiple adsorptions, increasing the magnetic properties of the material allows for the experimental study of its multiple adsorptions and increases the utilization of the

material. The adsorption efficiency of Cd (II) in an aqueous solution was evaluated by batch equilibrium experiments using magnetic graphene oxide and Mg-Al layered double hydroxide nanocomposites. The results showed that magnetic graphene oxide and Mg-Al layered double hydroxide nanocomposites had good adsorption capacity for Cd (II) [108]. Liu et al. [109] found that triethylenetetramine was used to modify the surface of bagasse. Because triethylenetetramine had an active group of aminos, it could chelate with heavy metal ions to adsorb Cd (II) heavy metal ions in water, and the adsorption effect was good. Saeed et al. [110] prepared red hemp and magnetic biochar composites for Cd<sup>2+</sup> adsorption and found that the magnetic biochar complexes also showed a higher affinity for Cd<sup>2+</sup> than the pristine biochar. Zhang et al. [73] prepared the adsorbent by a hydrothermal method and then combined it with lignin sulfonate to form a carbon-lignin sulfonate adsorbent. Firstly, the authors have characterized the materials by using field emission scanning electron microscopy, Fourier transform infrared spectroscopy, X-ray diffractometry, and Raman spectroscopy. Further, the effect of pH value at the time of reaction, initial concentration of pollutants, time, and temperature of the reaction on the adsorption effect of the adsorbent was investigated. It was found that experimental conditions at 25 °C, pH 7, usage of 0.01 g and a heavy metal ion concentration of 40 mg/L, and an adsorption time of 60 min resulted in a removal rate of 100%. Finally, the experimental data were modeled, and the second-order kinetic model and the Langmuir model were found to be closer to the adsorption effect. Moreover, the carbon-lignosulfonate adsorbent had good reusability, with the adsorption rate remaining above 80% after five times of adsorption resolution. Hydrochar carries surface functional groups such as -COOH and -OH, which can interact with Cd (II) to form complexes on the surface of biochar. With the increase in solution pH, the dissociation of these organic functional groups increases, so the ability to form complexes with Cd (II) will be enhanced.

After further modification of the material, the properties of the material change again in different ways. Li et al. [111] aged pristine hydrochar with nitric acid (HNO<sub>3</sub>) at mass fractions of 5%, 10%, and 15%, and the resulting material was used to remove Cd (II). The experimental results revealed that the adsorption ability of the hydrochar with a nitric acid concentration of 15% was 19.99 mg/g, which was a 7.4-fold increase compared to the pristine hydrocarbon. After chemical aging, the specific surface area, and oxygen-containing functional groups of the hydrochar increased, which helped the adsorbent to bind to Cd (II) through physical adsorption and surface complexation. In addition, there is also ion exchange occurring during the adsorption of Cd (II). Zhou et al. [112] synthesized carbon microspheres by using monosaccharide biomass in combination with a hydrothermal method, followed by chemical co-precipitation to immobilize magnetic iron oxide nanoparticles on the surface of the material. It was found that the hydrothermal method resulted in high material yields, and the carbon microspheres were relatively homogeneous in quality and rich in oxygen-containing functional groups. Magnetic-rich Fe<sub>3</sub>O<sub>4</sub> nanoparticles (10–20 nm) were produced by alkali addition treatment and chemical precipitation processes, uniformly dispersed on the surface of the carbon microspheres. Magnetic carbon microspheres exhibited effective adsorption of Cd (II) ions, which was in good agreement with the proposed second-order kinetics and Langmuir isotherm. Immediately after the adsorption has stabilized, the magnetic carbon microspheres can be completely separated from the liquid phase due to the external magnetic field gradient.

Finally, adsorption isotherms, kinetics, and adsorption mechanisms are investigated. A new magnesium silicate hydrochar composite was synthesized by the hydrothermal method and used for the removal of Cd (II) from wastewater by Xiong et al. [113]. Sun et al. [114] used KOH to modify the hydrochar and found that the number of aromatic and oxygen-containing functional groups, such as carboxyl groups, increased in the modified carbon, resulting in an approximately 2–3-fold increase in Cd (II) adsorption (30.40–40.78 mg/g) compared to the unmodified (13.92–14.52 mg/g). The kinetics of cadmium adsorption on modified hydrochar can be explained by proposed secondary kinetics, and the adsorption isotherms can be modeled using the Langmuir adsorption

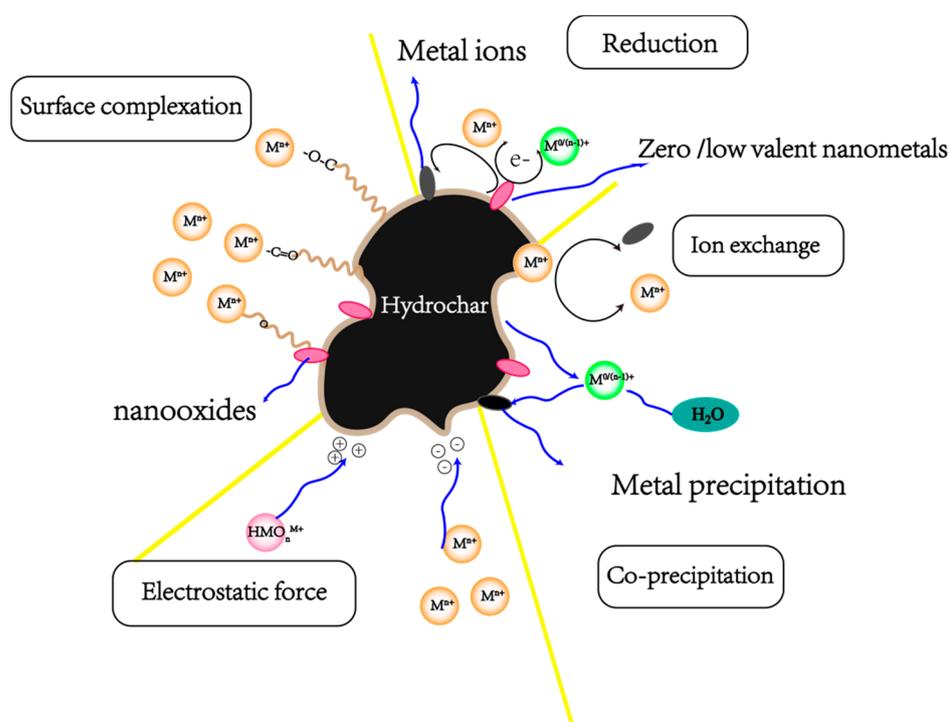
model. The uptake of cadmium on the modified hydrochar was higher in the pH range of 4.0–8.0. The thermodynamic parameters indicate that the adsorption process is spontaneous and that the adsorption reaction is a heat absorption process. In total, 66.6 mg/g of Cd (II) was adsorbed by the MoS<sub>2</sub>/multi-walled carbon nanotube nanocomposite, and the adsorption mechanism was ion exchange and electrostatic interactions. Among them, the formation of metal-sulfur complexes was the key factor for the adsorption of heavy metal ions, followed by multilayer adsorption by electrostatic interactions. Gusain et al. [115] explored the ability of molybdenum sulphide/thiol functionalized multi-walled carbon nanotube nanocomposites to remove Cd (II) from wastewater generated from industrial mines. Using sodium molybdate and sodium diethyl dithiocarbamate as MoS<sub>2</sub> precursors, MoS<sub>2</sub>/multi-walled carbon nanotube nanocomposites were synthesized by acid treatment and sulphidation of multi-walled carbon nanotubes, followed by a simple hydrothermal reaction. The authors' study of kinetics and isotherms showed that the reaction followed the secondary kinetic model and the Freundlich adsorption isotherm model proposed by their predecessors. The results showed that the porous bulk magnesium silicate was modified by polyhydrochar through C-O-Si covalent bonding. In addition, the adsorption behavior of Cd (II) based on magnesium silicate, polyhydrochar, and magnesium silicate hydrochar composite was systematically investigated. Equilibrium data for Cd (II) were under the Langmuir model. The sorption capacity of the composites was significantly higher compared to pure magnesium silicate and polyhydrochar, with a maximum sorption capacity of 108 mg/g for Cd (II), where the mechanism for the removal of Cd (II) is ion exchange and electrostatic attraction.

#### 4.2.2. Application of Hydrochar with High Adsorption Capacity of Cd (II)

Firstly, the influence of the physical properties of the material on the adsorption effect is explored. Xiong et al. [116] synthesized titanate nanotubes with a specific surface area of 272.31 m<sup>2</sup>/g and a pore volume of 1.264 cm<sup>3</sup>/g by an alkaline hydrothermal method and studied their ability to remove heavy metals. As a new effective adsorbent, titanate nanotubes can effectively remove Cd (II) from an aqueous solution. Nitrogen adsorption-desorption isotherms analysis showed that mesoporous titanate nanotubes had a larger specific surface area and higher pore volume. In addition, Fourier transform infrared spectroscopy showed that the hydroxyl groups in the titanate nanotubes play a role in the adsorption of Pb (II) and Cd (II). The batch adsorption tests showed that a number of factors influence the adsorption effect, such as the mixing time of the adsorbent with the solution, the pH of the solution, and the grams of adsorbent. The adsorption of each metal ion was rapid during the first 5 min and reached a steady state of adsorption after 180 min. In the pH range of 5.0–6.0, the adsorbed Cd (II) reached its maximum adsorption capacity. Kinetic studies showed that the adsorption of Cd (II) on titanate nanotubes was most consistent with the pseudo-second-order kinetic model. The equilibrium adsorption studies showed that the Langmuir model was the most suitable model to describe the adsorption behavior of Pb (II) and Cd (II). The maximum monolayer adsorption capacities of Pb (II) and Cd (II) were 520.83 and 238.61 mg/g, respectively. The titanate nanotubes were investigated as adsorbents for the removal of Pb (II) and Cd (II) from aqueous solutions. Adsorption-desorption results showed that titanate nanotubes could be easily regenerated after 0.1 M HCl adsorption. Therefore, in engineering practice, titanate nanotubes have great potential for removing Pb (II) and Cd (II) from wastewater. High-temperature carbonization treatment is conducive to the generation of a large specific surface area.

We also explore the reaction mechanism and the reaction process. Zhang et al. [117] successfully prepared layered double hydroxides by a simple hydrothermal method. The resulting material has a typical an-double hydroxides peak, good crystallinity, and a hexagonal lamellar structure. The adsorption of Cd (II) in an aqueous solution by the layered double hydroxides is short and efficient, with a theoretical maximum removal capacity of 1035.4 mg/g. Within the first hour, Cd (II) is rapidly adsorbed, and the mechanism of the adsorption reaction is an isomeric substitution, surface complexation, and ionic pre-

precipitation. Nworie et al. [118] prepared double (salicylaldehyde) ethylenediamine grafted multifunctional nanocomposite biochar by hydrothermal method. When the optimum pH value was 5, the maximum adsorption capacity was 8220 mg/kg and the initial metal ion dosage was 4480 ppm, the removal rate was 99.30%. The data simulated by the adsorption model and kinetic model were well-fitted in the Freundlich isotherm, which included the multi-layer adsorption chemical adsorption process. Internal sphere complexation, ion exchange, co-precipitation, and electrostatic attraction are the main factors in the mechanism of interaction of nanocomposite biochar functionalized with Schiff base  $N_2O_2$  surfaces with cadmium. The presence of abundant O and N atoms on the hydrocarbon surface facilitates the immobilization of Cd. This also suggests, from another perspective, which the adsorption mechanism is linked to surface complexation and electrostatic attraction (Figure 5). Besides, the content of sodium ions was also found to decrease significantly after the adsorption reaction, which indicates that ion exchange has an important influence on the adsorption of cadmium [119].



**Figure 5.** Mechanism of heavy metal ion adsorption by hydrochar.

By modifying the material, we have conducted an in-depth study of it. Deng et al. [120] used polyacrylic acid to modify hydrochar to adsorb Cd (II), and the adsorption effect was improved to varying degrees. The adsorption performance of layered double hydroxide/carbon nanosheets for Cr (VI) and Cd (II) was much better than that of layered double hydroxide, and the maximum adsorption capacities increased by 4.4 and 6.7 times, respectively [121]. Zhang et al. [122] constructed the sulfide-modified hydrochar described as the target hydrochar by grafting  $Fe_3O_4$  nanoparticles and sulphur-containing groups onto a pinealite-derived hydrocarbon, which was synthesized by the reaction. The hydrochar was effective in adsorbing Cd (II) over a wide pH range and reached rapid uptake equilibrium within 25 min. The maximum monolayer uptake of Cd (II) was 62.49 mg/g in a monolayer system. The hydrochar-bound Cd (II) is mainly bound through electrostatic interactions, ion exchange, and complexation. Magnetic-rich  $Fe_3O_4$  nanocarbon materials were synthesized by hydrothermal carbonization using the Fe-rich plant acinosa Roxb as a raw material, and the synthesis was used for the removal of Cd from water. By means of material characterization, the results show that the average size of the synthesized magnetic nanoparticles is  $(2.62 \pm 0.56)$  nm and that the element N is doped into the magnetic nano-

Fe<sub>3</sub>O<sub>4</sub> hydrochar. The adsorption process was explored using the model and was found to fit the Langmuir isotherm and pseudo-second-order kinetic model, where a maximum of 246.6 mg/g of Cd (II) could be achieved for Cd (II) in water. CdCO<sub>3</sub> crystals can be formed after adsorption, indicating that surface precipitation plays an important role in Cd adsorption.

Both physical and chemical modifications are widely used in the modification process (Table 7). Chen et al. [123] prepared hydrochar from lettuce waste at a low temperature (200 °C) using H<sub>3</sub>PO<sub>4</sub> as an acid activator. Batch adsorption experiments showed that the biochar reached adsorption equilibrium within 30 min with optimum adsorption of 195.8 mg/g of Cd (II), which was significantly increased from ca. In total, 20.5 mg/g at a solution pH of 6.0 of the original biochar without activator. The prepared biochar adsorption data fit results were consistent with the pseudo-secondary kinetic and Sips isotherm models, with Cd (II) adsorption being a spontaneous exothermic process. Zhang et al. [124] used a hydrothermal method to synthesize carbon spheres and layered double hydroxides composite adsorbents and then calcined them at a temperature range of 300–800 °C to change their surface properties. After testing, the number of oxygen-containing functional groups in the composite is closely related to the calcination temperature and has a negative correlation, with higher temperatures resulting in fewer oxygen-containing functional groups. Conversely, the specific surface area of the material was positively correlated with temperature, increasing with increasing temperature. The final results show that the carbon spheres and layered double hydroxide composite adsorbent obtained after calcination are more favorable for the adsorption of metal ions when the experimental temperature is 400 °C, and the maximum sorption of Cd (II) was 475 mg/g. The complexation reaction between the Langmuir model complex and the metal ions was considered to be the main adsorption mechanism (Figure 5). Due to a large number of oxygen-containing functional groups, such as hydroxyl and carboxyl groups, on the surface of the hydrochar, it can adsorb metal ions very well. Metals can be well dispersed in hydrochar. Iron nanoparticles loaded on mesopore-rich hydrocarbons reduce the agglomeration of metal nanoparticles, thus improving catalytic activity and stability [39].

**Table 7.** Preparation conditions of hydrochar and Cd (II) in adsorption wastewater.

Raw Materials	Material Usage	pH	Kinetics	Isotherm	Absorption Time	Adsorption Amount	References
<i>Strain P. chrysogenum</i>	1 g/L	5	Pseudo-second-order	Langmuir	5 h	203 mg/g	[120]
Hydrotalcite	50 g/L	—	Pseudo-second-order	—	1 h	1035.4 mg/g	[117]
Titanate nanotubes	0.2 g/L	5–6	Pseudo-second-order	Langmuir	3 h	238.61 mg/g	[116]
MgAl-LDH/chitosan	1 g/L	7	Pseudo-second-order	Langmuir	1 h	39.7 mg/g	[125]
Hydrotalcite, glucose	0.4 g/L	5	—	Langmuir	6 h	475 mg/g	[124]
Sawdust	1.65 g/L	8	Pseudo-second-order	Langmuir	24 h	19.99 mg/g	[111]
Graphene Oxide	3.5 g/L	6	Pseudo-second-order	Langmuir	4 h	45.1 mg/g	[108]
Glucose	0.67 g/L	6	Pseudo-second-order	Langmuir	24 h	72.63 m/g	[112]
Sawdust	2 g/L	4–8	Pseudo-second-order	Langmuir	24 h	40.78 mg/g	[114]

## 5. Conclusions

The main focus of this paper is a review of the preparation of carbon materials from biomass waste by hydrothermal methods, which in turn deals with environmental pollution in water. There has been a lot of research on carbon-neutral technology for biomass waste recycling, and we focus on the study of heavy metal pollutants in water adsorption from waste biomass by hydrothermal methods. This research approach addresses both the treatment of biomass waste and the pollution problem. In-depth, the adsorption method is efficient, economical, and simple, and the biochar material is a low-polluting and low-cost material. In addition, biochar, as a composite adsorption material, contributes to the goal of carbon neutrality. Among these, hydrochar is a new type of oxygenated carbon material that will become a new direction for future carbon material research due to its environmentally friendly preparation method and tunable surface chemistry.

However, there are some difficulties with the use of hydrochar. Firstly, the process of preparing hydrochar takes a long time, and the test conditions are demanding, and expensive. Secondly, the reagents used in the preparation process may cause environmental pollution, and the disposal of the adsorbent after the adsorption of metals is also a great challenge; some of the hydrochar are not very stable, which poses an obstacle to recycling. Thirdly, powdered adsorbents prepared by traditional methods have dust contamination and are easily lost. Formed adsorbents have great advantages in terms of storage, transportation, and use, and can meet a wide range of needs in different industries. However, there is little research into the formation of functionalized carbonaceous materials, resulting in their inability to be used in large quantities in practical applications.

## 6. Further Prospects

As single biochar materials tend to agglomerate and have a small number of functional groups on their surface, the introduction of appropriate functional groups on the surface of the material can increase its dispersion in water and reduce the appearance of agglomerates, and also effectively reduce the influence of other unwanted factors on adsorption, and the surface functional groups can also selectively adsorb heavy metal ions through electrostatic interaction and complexation to achieve the purpose of removing heavy metal ions from water.

At present, some progress has been made in the application of hydrochar in the fields of water pollution treatment, catalysts, porous carbon material preparation, and clean energy. How to prepare highly functional hydrothermally activated carbon materials with high specific surface area, adjustable porosity, and surface chemistry by optimizing the preparation process and the activation process will become a hot research spot in the field of carbon materials in the future. Meanwhile, grafting organic functional groups onto hydrochar to prepare retarders, phase change surface activators, and specific catalysts will also become an important research direction.

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