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Review

Research Progress on Physical and Chemical Remediation Methods for the Removal of Cadmium from Soil

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Abstract: Soil cadmium contamination is a global environmental issue, threatening ecosystem health and human safety. Common remediation strategies, including phytoremediation and soil replacement, are typically hampered by their lengthy processes or high costs. The aim of this review is to explore and evaluate innovative physical and chemical remediation techniques to address cadmium pollution effectively. This review focuses on three promising approaches: the co-application of phosphate fertilizers and sepiolite, CaAl-layered double hydroxide (LDH) immobilization, and hydrochar treatments. The primary methodologies involved evaluating the adsorption capacity, ion exchange mechanisms, and remediation efficiency under varying environmental conditions. Results indicate that these techniques significantly enhance cadmium immobilization, with the co-application of phosphate fertilizers and sepiolite demonstrating up to 72.6% removal of HCl-extractable cadmium. The review concludes that these techniques offer superior cost-effectiveness and scalability for large-scale applications and recommends future research to optimize amendment formulations and develop renewable adsorbents to further improve sustainability.

Keywords: cadmium ion remediation; sepiolite based; hydrochar; CaAl-LDH

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1. Introduction

Soil cadmium pollution has caused significant harm to the environment, and controlling it has been a critical issue that scientists have been striving to solve [1]. Cadmium ions are harmful to crops, because excessive absorption causes root poisoning and reduces yield [2]. Cadmium ions ingested through the food chain can lead to osteomalacia, osteoporosis, cancer, and various other diseases in humans [3–6]. Cadmium pollution is caused by various activities, including mining cadmium-containing minerals, discharging cadmium-laden wastewater from chemical plants, and manufacturing or disposing of batteries, all of which can introduce cadmium ions into the soil [7–10].

Soil cadmium pollution in China, especially in Hunan and other areas south of the Yangtze River, is very common [11]. About 16.7% of China's crop planting area is contaminated by various heavy metals, with around 40% being cadmium-contaminated soil [12,13]. Unlike organic matter [14], cadmium ions in soil cannot be degraded or destroyed; they can only be remedied or transferred [15]. Soil contaminated with cadmium cannot self-repair; even after many years, cadmium levels in contaminated soil and crops hardly change significantly [16–18].

Previously, hydrated lime or limestone was added to the soil to neutralize cadmium ions, forming $CdCO_3$ or Cd $(OH)_2$ [19]. However, this method required large amounts of lime or limestone and could lead to soil compaction [20–22]. Soil replacement also has disadvantages, such as high costs and large engineering workloads. Moreover, the excavated contaminated soil requires further treatment, and improper handling may lead to more widespread pollution [23]. Phytoremediation is a lengthy process with relatively low plant uptake efficiency, making it less effective for soils with high cadmium concentrations.

Furthermore, the cadmium-enriched plant biomass requires careful management after remediation to prevent secondary pollution [24–26].

In situ remediation, a promising method for remediating cadmium-contaminated soils, involves adding specific modifying agents to the soil, which convert Cd^{2+} into less bioavailable and less mobile forms [27–30]. Among the various in situ soil-remediation methods in recent years, the co-application of phosphate fertilizer and sepiolite method, the CaAl-layered double hydroxide (CaAl-LDH) method, and the hydrochar method have emerged as effective treatments for Cd^{2+} remediation. Sepiolite, a naturally occurring fibrous clay mineral, facilitates Cd^{2+} adsorption and stabilization through its high specific surface area and structure [31–34]. The co-application of phosphate fertilizer and sepiolite in Cd-contaminated soils has shown a more promising effect in reducing Cd^{2+} bioavailability than using sepiolite alone through adsorption and ion exchange mechanisms. CaAl-LDH, synthetic layered materials with remarkable anion exchange capacities and structural stability, remedies Cd^{2+} through surface complexation and intercalation processes, forming stable CdAl-LDH complexes that minimize Cd leaching and bioavailability [35–38]. Hydrochar, derived from the pyrolysis of biomass with modifying agents, increases the surface functional groups and enhances porosity, thereby improving its metal binding capacity, which effectively reduces the migration rate and plant uptake of Cd^{2+} by increasing its adsorption and precipitation capacity [39–41].

This review offers a detailed analysis of three in situ methods for remediating cadmium ions in soil: the co-application of phosphate fertilizer and sepiolite method, the CaAl-LDH fixation method, and the hydrochar method, thoroughly analyzing their underlying mechanisms and remediation effects. Additionally, the review also supplements some promising but still developing remediation methods, such as the modified steel slag method. Combing with the mechanism of factors influencing the efficiency of cadmium ion remediation in soil, it provides valuable guidance for future engineering applications and scientific research. Future cadmium ion remediation methods should aim to optimize remediation amendment compositions to enhance buffering capacity against pH fluctuations, ensuring stable remediation outcomes. And developing recyclable adsorbents and a comprehensive recycling system will facilitate resource reutilization.

2. Typical Remediation Methods and Mechanisms for Cadmium Pollution in Soil

2.1. Study on the CaAl-LDH Remediation Method and Mechanism

2.1.1. CaAl-LDH Remediation Method

In situ soil immobilization reduces the solubility and fluidity of cadmium ions, minimizing their harm to soil and crops. LDH, an anionic clay with excellent catalytic, photochemical, and electrochemical properties, is widely used to remove anions, but its potential for removing metal cations is often overlooked [42,43]. Kong et al. [44] conducted experiments on remedying cadmium ions in soil using LDH and synthesized CaAl-LDH samples with a co-precipitation method using quicklime and hydroxyapatite (Figure 1b). The synthesized samples were analyzed by XRD and SEM to study their crystal structure (Figure 1c–e). The results indicate that all diffraction peaks of the synthesized samples align with the standard CaAl-LDH pattern (Figure 1a, Curve I), showing no significant impurities and confirming the successful preparation of the CaAl-LDH sample.

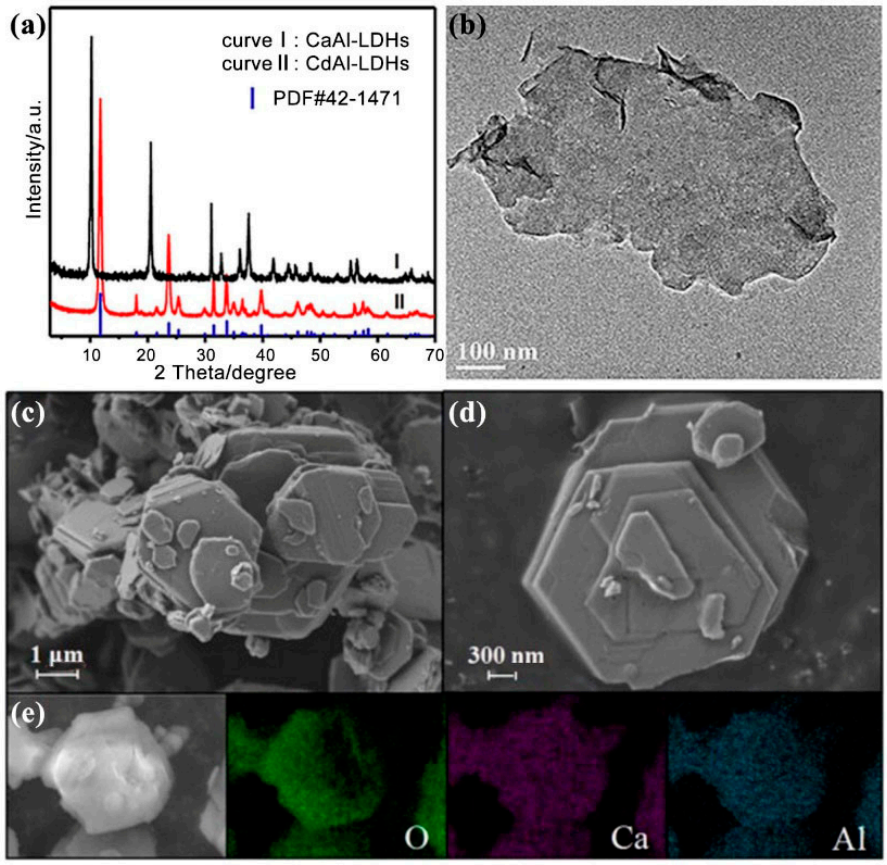


Figure 1. (**a**) XRD pattern of samples before and after removal of Cd^{2+} [44]; (**b**) TEM image of CaAl-LDH [44]; (**c**) SEM image of CaAl-LDH at 1 μm [45]; (**d**) SEM image of CaAl-LDH at 300 nm [45]; (**e**) SEM image of CaAl-LDH [45].

Cd^{2+} in soil is replaced with Ca^{2+} using an isomorphous method, enabling CaAl-LDH to react with Cd^{2+} to form CdAl-LDH (Figure 1a, curve II) [46]. Experiments have demonstrated that after 7 days of treatment using CaAl-LDH, the concentration of extractable Cd^{2+} in the soil significantly decreased and continued to decline over time. CdAl-LDH exhibits superior thermal stability compared to CaAl-LDH. In a field experiment where CaAl-LDH was applied only once over 3 years, the level of $CaCl_2$-extractable Cd^{2+} in the soil was reduced from 0.018 mg/kg to 0.007 mg/kg. And the remediation efficiency is not inhibited by environmental ions such as nitrate and sulfate; rather, it is promoted. Additionally, the presence of elements like zinc, magnesium, and potassium in the environment does not affect the remediation capacity for cadmium ions [44].

CaAl-LDH has economic advantages for soil remediation. For example, the raw materials for CaAl-LDH preparation can be substituted with by-products such as desulfurization gypsum, calcined lime, and aluminum ash. And the entire production process generates less wastewater. Using biochar as a stabilizer at a dosage of 22.5 t/ha has a market price of approximately 8250 RMB/ha per year. However, the cost of using CaAl-LDH, which employs the aforementioned raw material substitutions, is significantly lower, with treatment costs for Cd-contaminated soil being less than 4000 RMB/ha per year [44]. These results suggest that this method has great potential for widespread application in large-scale soil-remediation projects.

2.1.2. Mechanism of CaAl-LDH Remediation Method

The mechanism of Cd^{2+} removal by CaAl-LDH involves the reaction of CaAl-LDH with Cd^{2+} in the soil to generate CdAl-LDH, where Cd^{2+} and Ca^{2+} can be fixed by isomorphic substitution. Specifically, CaAl-LDH dissolves in the soil, releasing Ca^{2+} and Al^{3+}

as well as NO_3^- and OH^-, and the OH^- in the system will trigger the co-precipitation reaction between Cd^{2+}, Al^{3+}, OH^-, and CO_3^{2-} to form CdAl-LDH. Simultaneously, Cd^{2+} replaces Ca^{2+} in the LDH layer, fixing the isomorphic substitution as CdAl-LDH (Figure 2). This process was ultimately verified through morphological evolution via TEM measurements, HRTEM images of selected electron diffraction patterns, and density functional theory calculations [44].

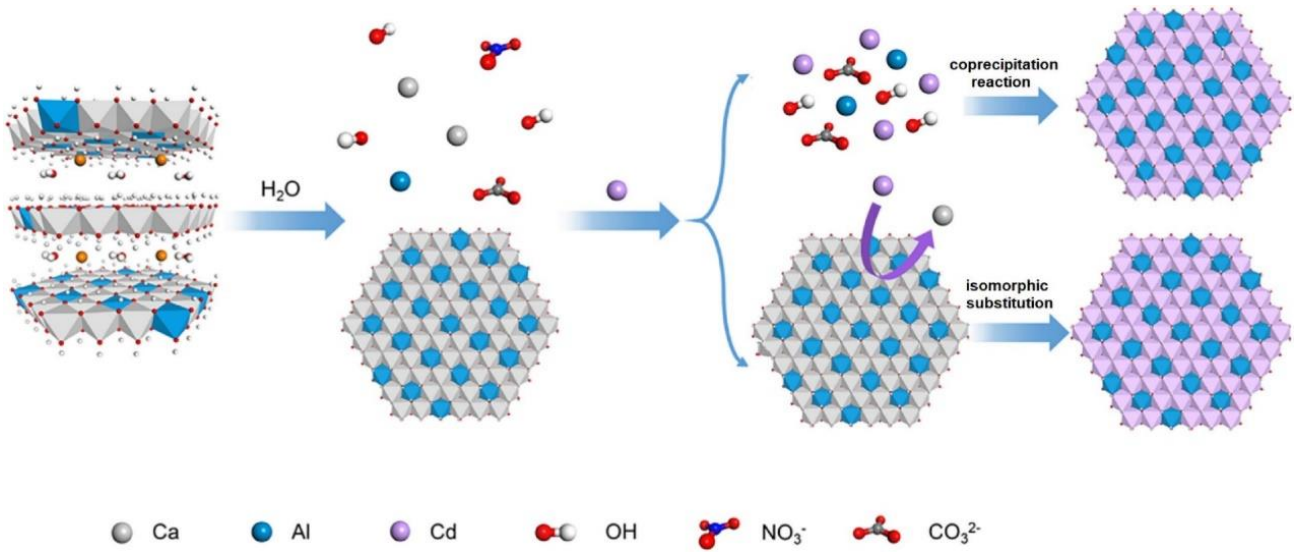


Figure 2. Schematic diagram of CdAl-LDH formation mechanism [44].

2.2. Study on the Hydrochar Remediation Methods

2.2.1. Remediation Methods Based on Hydrochar

Carbon-based materials have gained popularity due to their effectiveness in minimizing cadmium accumulation [47,48]. Hydrochar, a porous material with adsorptive properties, has demonstrated high affinity and adsorption capacity for metal ions in wastewater, yet their effectiveness in remediation of metal-contaminated soil remains underexplored [49,50]. Due to the impact of biochar acidity on the formation of metal precipitates, modifying these materials is crucial for the effective remediation of metal ions [51].

Hydrochar, enriched with surface reactive oxygen functional groups such as hydroxyl/phenolic, carbonyl, and carboxyl groups, possesses a higher number of deprotonated oxygen-containing functional groups (OFGs) compared to traditional hydrochar. This increase enhances its capacity to bind heavy metal ions (HMs) through surface interactions [52]. Xia et al. [53] use a simple pot of lime water through hydrothermal carbonization (HTC) to modify the traditional hydrochar. The results show that the efficacy of hydrochar in fixing Pb and Cd is significantly enhanced due to increased surface functionality, amorphous structure, higher pH, and enhanced electronegativity.

Furthermore, hydrochar modified with clay minerals such as attapulgite and montmorillonite has shown efficacy in reducing cadmium content in rice and enhancing rice yield [49]. Experimental findings revealed that the cadmium concentration in soil treated with hydrochar progressively declined over time [41] (Figure 3a). The greatest decrease was noted with the hydrochar modified by 1% attapulgite (Figure 3b–d). The cadmium content in soil treated with CA-1% was significantly lower than that in soil treated with CA-0.5% on the day of rice transplanting. After 30 days, soil treated with CA-1% showed a reduction in cadmium content by 12.3% and 10.2% compared to soil treated with CK and CA-0.5%, respectively. The ion-exchangeable cadmium content in soil continued to decrease over time, with iron and manganese oxide-bound cadmium content reaching 18.7–34.5% at 30 days across all treatments. At 90 days, the residual cadmium content in the

soil of the CK group was several times higher than that of the other groups (Figure 3f–h), indicating effective remediation of cadmium ions.

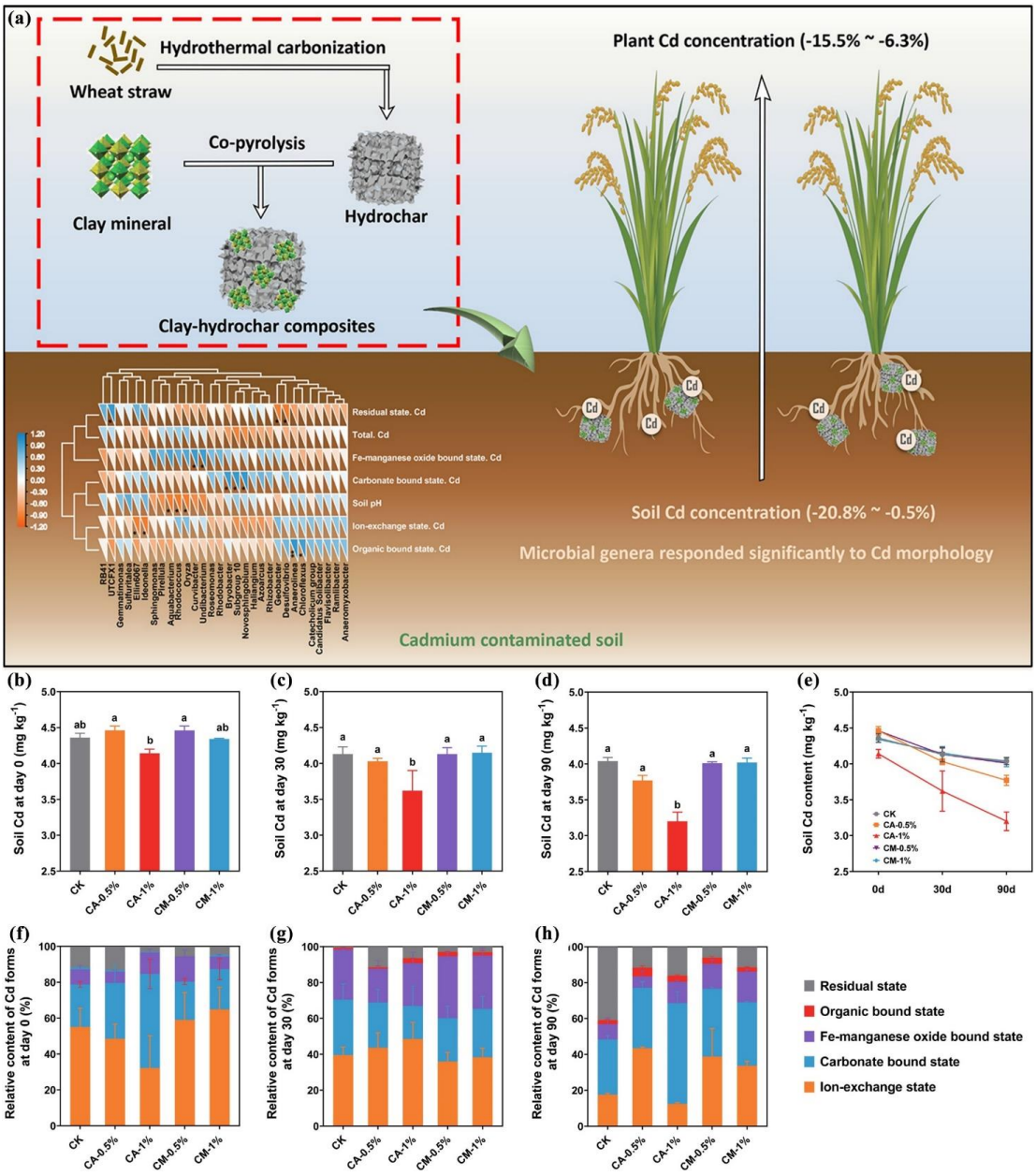


Figure 3. (**a**) Hydrochar can effectively reduce cadmium content in rice; (**b**) Cadmium in soil on Day 0; (**c**) Cadmium in soil on day 30; (**d**) Cadmium in soil on day 90; (**e**) Cd concentration in soil under different treatments; (**f**) Relative content of cadmium on day 0; (**g**) Relative content of cadmium on day 30; (**h**) Relative content of cadmium on day 90 (0 d: rice transplanting day; 30 d: the 30th day after rice transplantation; 90 d: 90 days after rice transplantation) [41].

Anaerobic fermentation technology is commonly used in the decomposition of organic pollutants and the biogas production process [54]. However, Hua et al. [55] used this method to enhance the adsorption capacity of traditional hydrochar through experimental anaerobic fermentation. The Figure 4. (Figure 4) indicates that the number of surface sites on hydrochar increases with the microbial aging process during anaerobic fermentation [56]. Furthermore, over time, the pore quantity and volume of hydrochar will increase, and numerous organic and inorganic components on the carbon skeleton's surface will continue

to dissolve, leaving cavities and thereby increasing its specific surface area and adsorption sites (Figure 4) [57]. Finally, XPS results show that the number of carboxyl (–COOH) and carbonyl groups (C=O) on the hydrochar surface increases, enhancing its oxidation degree and increasing its adsorption capacity by up to 3.8 times, while also strengthening its functional group and complexation capabilities.



Figure 4. Modified hydrogen carbon aging adsorption of cadmium ion diagram [55].

Previously, the production of traditional hydrochar involved multiple washings with deionized water and acetone, making the process cumbersome and prone to generating wastewater, which could cause secondary pollution. The above three modified methods use inexpensive and readily available raw materials and have simple operation processes. These processes do not produce secondary pollution, eliminating the need for subsequent pollution management, making them suitable for industrial applications.

2.2.2. Mechanism of Hydrochar Remediation Methods

Hydrochar attracts heavy metals from the soil solution to the surface soil through electrostatic attraction and polarization. Adding lime increases system alkalinity, accelerates the decomposition of cellulose in the raw material, creates amorphous regions, and increases the available surface area, as confirmed by FT-IR and Raman spectroscopy [58]. The addition of lime also promotes the deprotonation of OFGs and enhances the electronegativity of hydrochar, facilitating the coordination of metal cations with anions and their adsorption onto active sites on both inner and outer surfaces [59–61]. The remediation of Cd^{2+} is achieved through surface complexation (OFGs), precipitation, and canal-cation interactions [62,63] (Figure 5).

The clay-hydrochar composites (CHC) play a pivotal role in the remediation of Cd^{2+} in soil, primarily due to their highly efficient adsorption and complexation capabilities of oxygen-containing functional groups. The oxygen-containing functional groups in CHC, such as –COOH and carbonyl groups (CO), can chemically react with Cd^{2+} in the soil, forming stable complexes [64]. Particularly, the –COOH in CHC exhibit high affinity and can engage in strong complexation reactions with Cd^{2+}, resulting in the formation of stable Cd-carboxyl complexes. The formation of these complexes significantly reduces the concentration of soluble Cd^{2+} in the soil. Through this mechanism, CHC can markedly improve the quality of contaminated soil without altering its fundamental properties. The

reduction in soil Cd^{2+} concentration directly alleviates the Cd stress on rice plants during their growth.



Figure 5. Schematic diagram of the mechanism of cadmium remediation by hydrogen carbon [53].

And in cadmium-contaminated soils, different microorganisms such as *Acidobacteria*, *Chloroflexi*, and *Gemmatimonadetes* exhibit sensitivity to cadmium and show various response patterns [65]. For instance, *Bryobacter* (belonging to *Acidobacteria*) shows a significant positive correlation with carbonate-bound Cd, potentially promoting the binding of cadmium to carbonate minerals through its metabolic activities [66,67]. Within the *Chloroflexi* phylum, *Anaerolinea* is associated with Cd remediation, and *Chloroflexus* is potentially enriched due to contamination and is significantly positively correlated with organically bound Cd. In contrast, UTCFX1 is significantly negatively correlated with residual Cd, suggesting its role in reducing residual Cd in the soil [68,69]. Certain genera within the *Proteobacteria* phylum are sensitive to soil pH and Cd, showing negative correlations with ion-exchangeable and residual Cd and positive correlations with Fe-Mn oxide-bound Cd, highlighting their roles in regulating the soil cycling of cadmium [70].

2.3. Methods and Mechanisms of Co-Application of Phosphate Fertilizer and Sepiolite

2.3.1. Co-Application of Phosphate Fertilizer and Sepiolite Method

Sepiolite, a natural clay mineral, can significantly reduce the mobility of cadmium ions in soil and inhibit their transfer from soil to plants [71,72]. Sepiolite can undergo isomorphic substitution and surface complexation in soil, which enhances its ability to remedy cadmium ions [73]. Experiments results showed that applying sepiolite at a rate of 2.25 $kg \cdot m^{-2}$ resulted in an 18% increase in the above-ground biomass of maize and a 63% reduction in the extractable Cd^{2+} in the soil [71]. Sun et al. [31] confirmed that sepiolite could significantly reduce the cadmium concentration in the edible parts of spinach. When 5% sepiolite is applied, the cadmium content in spinach is reduced to a safe level (Figure 6a). This effect is largely due to sepiolite's ability to raise soil pH, which rapidly decreases the bioavailable cadmium in the soil. As a result, soil quality improves, along with enhanced microbial activity, contributing to healthier crop growth. The adsorption isotherm curve for sepiolite and Cd ions was determined experimentally, where X/M represents the mass of solute retained per unit mass of adsorbent, and Ce represents the equilibrium concentration of the solute remaining in the solution. The curve for cadmium shows a steady increase in X/M as the Ce increases. This suggests that sepiolite has a good capacity for adsorbing cadmium, with a strong relationship between the concentration of cadmium in the solution and the amount adsorbed by the sepiolite. The curve seems to level off as it reaches higher

concentrations, indicating that the adsorption sites on sepiolite may become saturated as Ce increases (Figure 6b).

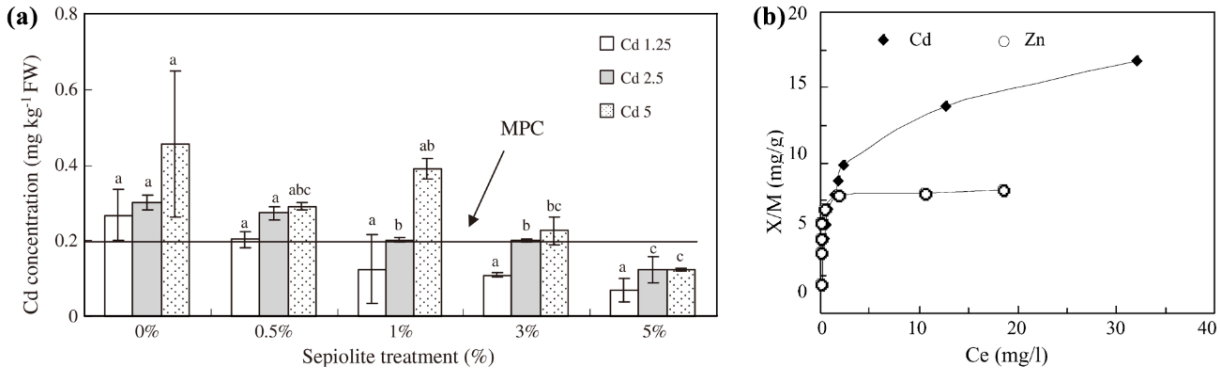


Figure 6. (**a**) Cd concentration in the edible parts of spinach under different treatments. MPC refers to the maximum permissible concentration [31], Letters above the bar diagram refer to the difference at significance level $p < 0.05$ among different treatments of sepiolite, and letters under the *x*-axis refer to the difference at significance level $p < 0.05$ among different concentrations of Cd. (**b**) sorption isotherms of Cd and Zn on sepiolite [74].

Phosphate fertilizers, as shown in Figure 7, play a critical role in immobilizing heavy metals in soil through various mechanisms, including adsorption, precipitation, acidification, and liming effects. These mechanisms effectively reduce the mobility of toxic metals like cadmium [75,76]. Seshadri et al. [77] experimentally demonstrated that the addition of reactive phosphate (SPR) containing phosphorus compounds significantly decreases cadmium concentrations in soil leachate and reduces cadmium accumulation in soil-dwelling organisms such as earthworms. The phosphorus compounds in SPR contribute to enhanced metal immobilization, as illustrated in the figure by the interaction between these compounds and the soil environment. The combination of these mechanisms ensures the stabilization of cadmium and other heavy metals, thereby minimizing their environmental and biological impacts.

Huang et al. [78] investigated the effects of sepiolite combined with calcium magnesium phosphate fertilizer (CMP) and single superphosphate (SSP) on the concentration of Cd in soil. The experimental design employed the combined application of sepiolite with CMP or SSP to evaluate their effectiveness in reducing the concentration of extractable cadmium ions in the soil. According to Table 1, sepiolite has shown particular efficacy in reducing Cd concentrations in soil, with treatment groups utilizing sepiolite demonstrating a decrease of 32.21% and 10.50% in cadmium concentrations extractable by hydrochloric HCl and DTPA, respectively, compared to CK. Additionally, both CMP and SSP exhibited significant pollution-reduction effects. Specifically, the application of CMP reduced the HCl-extractable cadmium concentrations by 21.85% to 46.06%, while SSP application led to reductions ranging from 31.21% to 44.83%. The results indicate that combining sepiolite with either calcium CMP or SSP markedly decreased the levels of extractable cadmium (including both HCl-extractable and DTPA-extractable Cd) in the soil, compared to using sepiolite alone. When sepiolite was used in combination with CMP, the reduction in HCl-extractable cadmium ranged from 40.57% to 72.60%, and DTPA-extractable cadmium decreased by 7.05% to 14.53%. When used with SSP, the corresponding reductions were 37.68% to 59.66% and 20.71% to 25.07%, respectively. Moreover, with increasing doses of CMP and SSP, the Cd extracted from soil by HCl and DTPA gradually decreased (Table 1) [78,79]. These findings indicate that the combined use of sepiolite with CMP or SSP significantly enhances the reduction of extractable cadmium in soil, providing an effective strategy for the environmental remediation of cadmium-contaminated soil by leveraging the synergistic effects of these amendments [78].

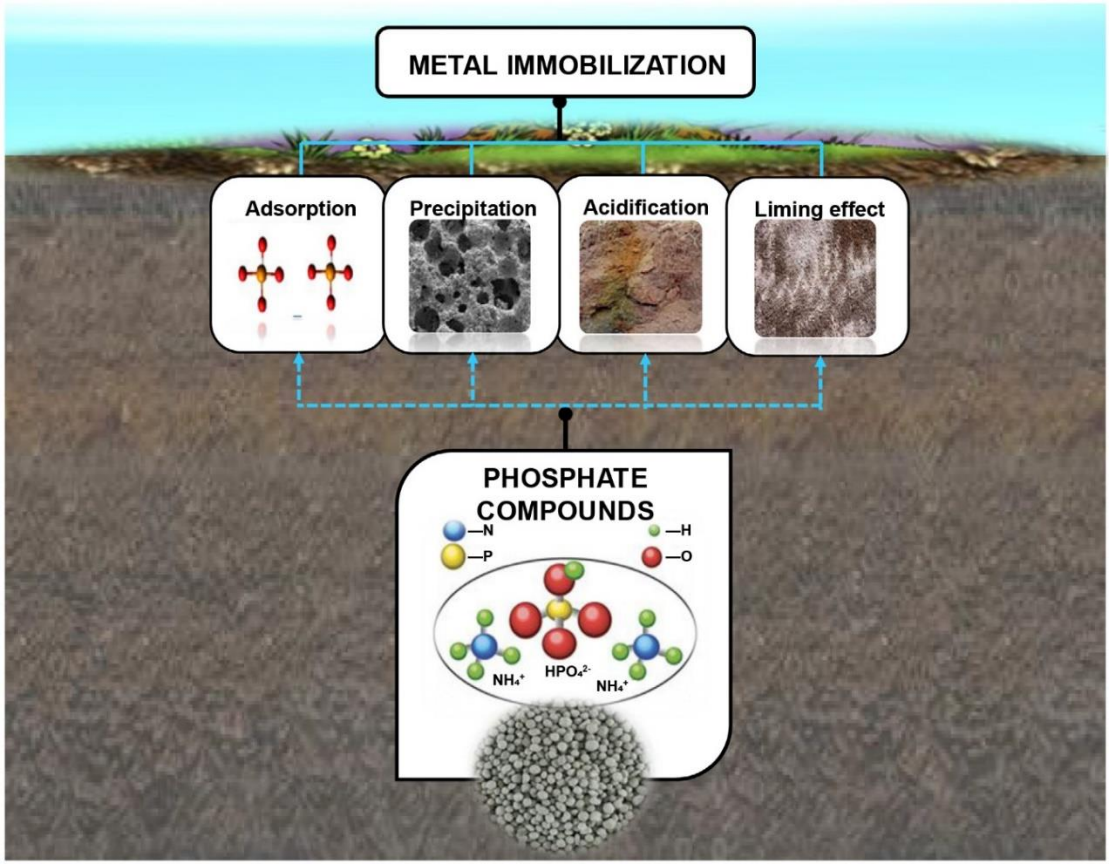


Figure 7. Phosphorus containing compounds can remedy heavy metal elements in soil [77].

Table 1. The extractable Cd concentration of soil in different methods [78].

	0.025 mol·L^{-1} HCl	DTPA		0.025 mol·L^{-1} HCl	DTPA
Methods	**mg·kg^{-1}**		**Methods**	**mg·kg^{-1}**	
CK	0.65 ± 0.09 a	0.42 ± 0.02 a	S	0.44 ± 0.09 b	0.38 ± 0.01 bc
P1.L	0.51 ± 0.08 b	0.42 ± 0.02 a	S.P1.L	0.26 ± 0.06 cd	0.35 ± 0.02 bc
P1.M	0.49 ± 0.05 b	0.41 ± 0.02 a	S.P1.M	0.17 ± 0.01 de	0.32 ± 0.07 c
P1.H	0.35 ± 0.06 c	0.39 ± 0.02 ab	S.P1.H	0.12 ± 0.03 e	0.35 ± 0.02 bc
P2.L	0.45 ± 0.04 bc	0.40 ± 0.02 ab	S.P2.L	0.27 ± 0.04 de	0.29 ± 0.01 d
P2.M	0.38 ± 0.05 c	0.36 ± 0.01 c	S.P2.M	0.19 ± 0.05 e	0.28 ± 0.01 d
P2.H	0.36 ± 0.03 cd	0.38 ± 0.03 bce	S.P2.H	0.18 ± 0.02 e	0.30 ± 0.01 d

Data are meant ± SE (n = 3). Different letters of the same vertical forms indicate significant differences among methods ($p < 0.05$).

2.3.2. Mechanisms of Co-Application of Phosphate Fertilizer and Sepiolite Method

In addition to soil environmental factors, soil available cadmium concentration is primarily influenced by soil pH and Eh [30,80]. Therefore, Huang et al. [78] monitored the changes in pH and Eh levels throughout the entire process. The results showed that the combined use of sepiolite with CMP or SSP could effectively raise soil pH. The alkaline nature of sepiolite is derived from its $CaCO_3$ content, which reacts with H^+ in the soil to produce CO_2, H_2O, and HCO_3^-, thereby enhancing soil alkalinity. Additionally, phosphate ions specifically adsorbed to clay particles, releasing OH^- groups and further raising pH levels [81]. As pH increases, Eh typically decreases, increasing the negative charge of soil particles and enhancing their Cd adsorption capacity [33]. Under high pH conditions, Cd^{2+} is more likely to hydrolyze to $CdOH^+$, aiding the fixation of cadmium ions and soil remediation. Experimental data show that using CMP and SSP alone can reduce extractable

cadmium concentrations by 21.85% to 46.06% and 31.21% to 44.83%, respectively [78]. It is mainly due to the increased pH, which lowers the concentration of cations in the soil, reducing competition with cadmium ions and facilitating their remediation [82,83]. Notably, SSP reduces soil pH and increases soil Eh, while reducing HCl-extractable and DTPA-extractable cadmium in soil, indicating that soil is a complex system. The three types of acid radicals in SSP ($H_2PO_4^-$, HPO_4^{2-}, and PO_4^{3-}) may aid in the adsorption of Cd or co-precipitation in the form of metal phosphates. The influence of these acid radicals and accompanying soil cations (Ca^{2+}, Mg^{2+}) on soil cadmium is greater than that of pH [7,80].

By regulating soil pH and Eh, the concentration of extractable cadmium can be effectively reduced, promoting the environmental remediation of contaminated soils [84].

The performance of the three main methods is summarized as follows (Table 2).

Table 2. The performance of different remediation methods.

Method	Advantage	Disadvantage	Economic Performance
CaAl-LDH remediation	The treatment cost with CaAl-LDH is less than 4000 RMB/ha per year, significantly lower than biochar (8250 RMB/ha per year). CdAl-LDH demonstrates superior thermal stability compared to CaAl-LDH, ensuring long-term remediation effects.	There is still room for improvement in the repair effectiveness time.	Cost-effective, as raw materials are easy to access, resulting in treatment costs as low as 4000 RMB/ha per year, which is 50% less than conventional biochar remediation
Hydrocar remediation	Simple preparation process, environmentally friendly, and pollution-free	Poor heat resistance and low porosity; needs to be adjusted depending on soil quality	2000–4000 RMB/ha for initial treatment, but additional costs may be incurred for modifications, potentially raising the cost to 6000–7000 RMB/ha depending on the soil requirements.
Co-application of phosphate fertilizer and sepiolite remediation	The combination of sepiolite with CMP or SSP demonstrated greater cadmium-removal efficiency than sepiolite alone, emphasizing their synergistic effect.	Limited application range; more effective in acidic soils	The cost of combining sepiolite with phosphate fertilizers (CMP/SSP) is approximately 3000–4500 RMB/ha, which is cost-effective due to the easy availability of both materials.

2.4. Other Treatment Techniques for Cadmium Pollution in Soil

Ordinary Portland cement (OPC) can also be used as a binder to reduce the leaching rate of cadmium ions in soil. The study by Li et al. [85] found that adding cement binders can convert soluble metal salts into their hydroxides and complexes, thereby remedying cadmium. However, the treatment effect is easily influenced by changes in soil acidity and alkalinity. Future improvements in this technology can focus on optimizing the composition of cement binders to enhance their buffering capacity against pH fluctuations. For instance, incorporating stable components such as coal fly ash and slag can significantly improve the performance and durability of the binders. These additions can help increase the chemical stability and physical robustness of the cement-based stabilization method.

In addition, adding biochar and alkali residue can also remedy cadmium in soil and reduce its accumulation in crops [86]. As shown in (Figure 8), biochar has a large specific surface area (SSA) due to its irregular shape and is rich in carbonyl, carboxyl, and hydroxide groups [87,88]. Consequently, cadmium adsorption can be enhanced through physical adsorption, ion exchange, and electrostatic attraction [89]. When biochar is added, a large number of active groups is introduced, creating new adsorption surfaces, which remedy Cd^{2+} in the soil and increase soil fertility [90,91]. Alkali residue, rich in common lime, significantly promotes the transformation of Cd from its active state to a residual state, thereby reducing its transfer to above-ground plant parts. These additives can also be combined with sepiolite to alter the microbial community structure in soil, increase the

number of soil microorganisms, enhance soil enzyme activity, improve the physical and chemical properties of contaminated soil, boost leaf photosynthesis, and increase crop resistance to Cd [92–94].

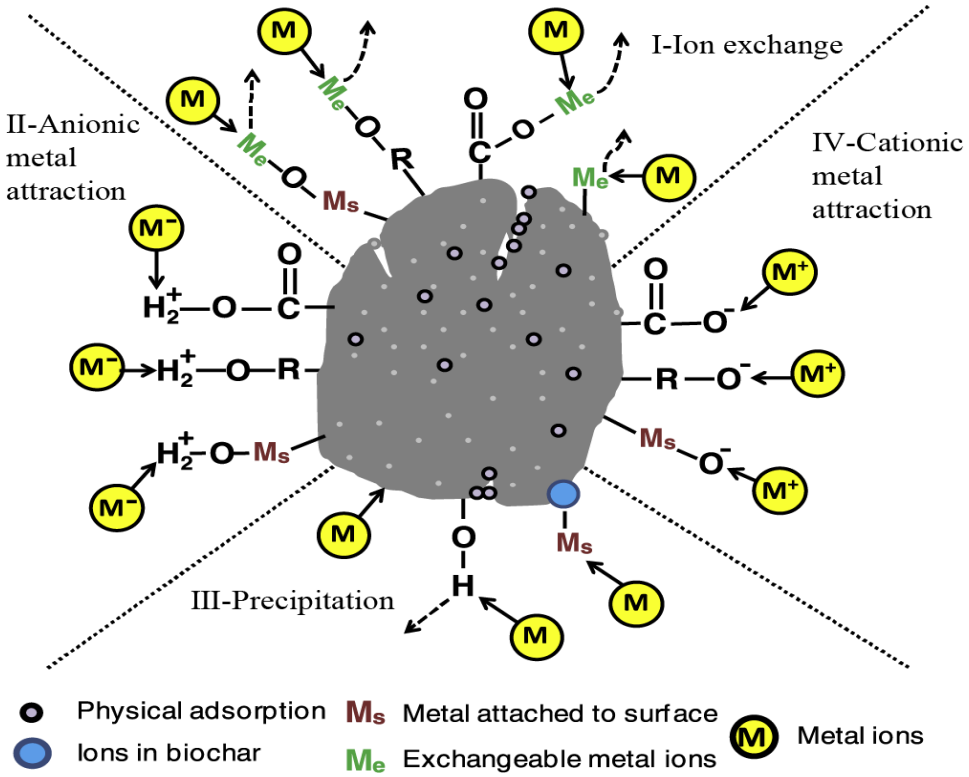


Figure 8. A hypothesized mechanism of interaction between biochar and inorganic pollutants. The circles on the biochar particles appear as physical adsorption. I—Ion exchange of target metal with exchangeable metal in biochar, II—Electrostatic attraction of anionic metals, III—precipitation of target metal, IV—electrostatic attraction of cationic metal [87].

Finally, recent studies have shown that steel slag and its modified products can also be used as additives to remedy cadmium ions in soil through adsorption and precipitation [95,96]. Additionally, the strong binding of Cd with steel slag increases the concentration of oxidizable Cd, which can combine with anions in the soil to form carbonate and complex precipitates [97,98].

3. Factors That May Affect the Stabilization of Cadmium Fixation in Soil

3.1. Soil pH

Typically, pH is a critical factor affecting the available cadmium content in soil [99]. The general affinity order of heavy metals for organic matter is: $Cu^{2+} > Cd^{2+} > Fe^{2+} > Pb^{2+} > Ni^{2+} > Co^{2+} > Mn^{2+} > Zn^{2+}$. pH alters the form of cadmium in soil by affecting its adsorption sites, coordination properties, and surface stability. The adsorption of Cd^{2+} increases in an S-shaped manner with pH. When the pH value is between 4 and 8, the adsorption of cadmium ions by soil minerals increases rapidly. Nevertheless, once the pH value surpasses 8, Cd^{2+} adsorption diminishes owing to competitive interactions between the formation of organometallic complexes and surface adsorption [100,101]. Therefore, pH can affect the remediation efficiency of cadmium ions in soil through various mechanisms, such as adsorption effects, the availability of adsorption sites, and by indirectly influencing the extraction ability of cadmium-removing plants [102,103]. In addition, Karlsson et al. [104] used X-ray absorption near edge structure (XANES) spectroscopy to confirm that S_8 in soil can be oxidized by sulfur-oxidizing bacteria to produce hydrogen ions, increasing environmental acidity and enhancing the extraction ability of cadmium ions by certain

plants [105]. Furthermore, an acidic environment makes it more difficult for heavy metal sediments to reach a saturated state [106]. In engineering applications, it is essential to continuously monitor soil pH and supplement with soil amendments and pH-adjusting additives to maintain optimal conditions for in situ Cd^{2+} remediation.

3.2. Organic Matter in Soil

Organic fertilizers contain numerous microorganisms and various organic substances, which can alter the physical and chemical properties of soil and affect the mobility of Cd^{2+} within it [107,108]. Shan et al. [109] used straw and pig manure to regulate cadmium in soil. The results showed that over time, the content of exchangeable Cd^{2+} in soil decreased, the content of iron-manganese oxide and carbonate-bound Cd first increased and then decreased, and the content of residual cadmium gradually increased, indicating that cadmium had been remediated into a stable form. The increase in organic matter can influence the complexation and chelation of Cd^{2+} in soil, promote the formation of chemically or biologically stable Cd^{2+} compounds, and lead to the decomposition of organic matter into smaller inorganic molecules, affecting the migration and transformation of heavy metals in soil [110–112].

3.3. Soil Bacteria

Soil hosts a large number of effective soil-heavy metal-adsorbing bacteria, including *sulfate-reducing bacteria* (*SRB*), *iron-reducing bacteria* (*FRB*), *iron-oxidizing bacteria* (*FOB*), *Pseudomonas aeruginosa* (Figure 9a), *Arthrobacter* (Figure 9b), and *Candida* (Figure 9c). The type, concentration, and growth conditions of bacteria influence the composition, quantity, and structure of crystals formed during the remediation of heavy metals [113].

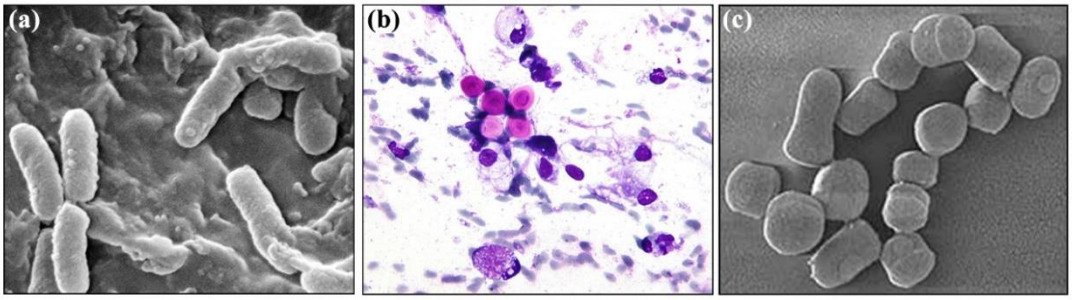


Figure 9. (**a**) Image of *Pseudomonas aeruginosa*, (**b**) image of *Arthrobacter*, (**c**) image of *Candida*.

First, higher bacterial cell concentrations generally promote the production of more and larger biocrystals. Cheng et al. [114] observed the morphology of biocrystalline calcium carbonate and found that at low bacterial concentrations, the crystals were mostly diamond-shaped and cubed (Figure 10b,c). However, at high bacterial concentrations, the crystals were spherical, agglomerated, and overlapped (Figure 10a), with bacterial cells flocculating due to high density. The concentration and species of bacteria in soil affect the formation and aggregation of biocrystals [115]. Additionally, bacteria cultivated in enriched nutrient media demonstrate enhanced mineralization performance and higher precipitation amounts compared to those in fresh natural environments [116]. This is because the bacteria release additional free urease, which promotes the breakdown of nutrients, and the medium contains sufficient nutrients to support bacterial activity. Therefore, the physical and chemical properties of soil are key factors affecting the soil bacterial community [117]. In engineering applications, we should integrate and optimize the soil microbial community and adjust its physicochemical properties, such as organic matter content and mineral composition, to further enhance heavy metal remediation.

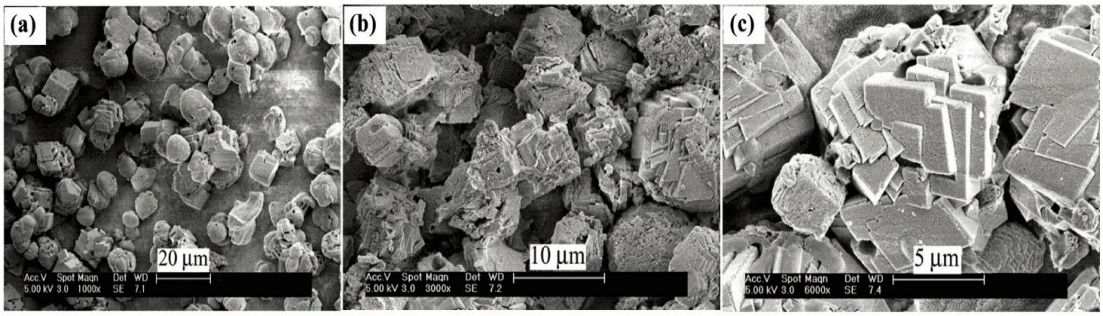


Figure 10. SEM images of $CaCO_3$ crystals formed in 100% (**a**) 50%; (**b**) 25%; (**c**) concentration bacteria solution (20 °C) [118].

3.4. Other Factors

Some non-metallic elements in soil, such as phosphorus (P) and silicon (Si), also affect the remediation of cadmium [114]. For example, SiO_2 in some soils can be hydrated to form calcium silicate hydrate [119]. Calcium silicate hydrate is crucial for the remediation of cadmium ions. In this process, Cd^{2+} in the soil is exchanged with Ca^{2+} in calcium silicate hydrate, leading to its even distribution within the crystal's Ca^{2+} positions. However, to achieve the desired remediation effect, the proportion of Cd^{2+} must not surpass 30% of the combined total of Ca^{2+} and Cd^{2+}. P can also form stable phosphate compounds with Cd^{2+} to help remediate cadmium ions [120,121]. Yin and Shi [122] found that modified low-grade phosphate ores containing soda slag can remediate cadmium in soil. The soda residue provides an alkaline environment, which promotes the binding between Cd and P. Additionally, Bhattacharya [123] discovered that the efficiency of cadmium removal by Serratamar clay varied with the concentration of Cd^{2+}. At a cadmium concentration of 5 mg/L, the removal rate was 98%, but it decreased to 79% at 10 mg/L and to 65% at 15 mg/L. This variation in efficiency can be explained by two factors: high metal concentrations may inhibit the growth of specific mineralizing cells, and the scarcity of available nucleation sites within cells may limit the precipitation of metal carbonates.

The factors affecting the remediation efficiency of cadmium ions are numerous and complex [123,124]. In future studies, we can develop mathematical models to simulate the dynamic processes of cadmium remediation under various conditions involving non-metallic elements. This will help elucidate the mechanisms by which different non-metallic elements influence cadmium remediation.

The impact of various factors and their mechanism of influence are summarized as follows (Table 3).

Table 3. The impact of each factor and its impact mode.

Factor	The Impact of Factor	Impact Mode
pH	The adsorption of cadmium is influenced by pH value and exhibits an "S" curve.	The acidic environment makes it difficult for the sediment of Cd^{2+} to reach saturation state. When the pH is between 4–8, the adsorption of cadmium by the soil increases.
Organic matter	The microorganisms and organic matter in organic fertilizers affect the properties of soil.	The increase in organic matter affects the recombination and chelation reactions of cadmium, and its decomposition products also affect the remediation of cadmium.
Microbiota matter	Microorganisms in the soil have an adsorption effect on heavy metals.	The concentration and type of bacteria in soil affect the composition and size of biocrystals in the soil, thereby affecting the efficiency of cadmium remediation.
Non-metallic element	The influence of non-metallic elements such as phosphorus and silicon on the fixation of cadmium	Silicon can form calcium silicate hydrates, promoting the remediation of cadmium. Phosphorus can form stable phosphate compounds, which help fix cadmium.

4. Problems and Future Prospects of Remediation of Soil Cadmium Pollution

4.1. Main Problems to Be Faced

Firstly, the diversity and complexity of soil composition present challenges in the process of Cd^{2+} remediation [125–127]. The mineral composition, organic matter content, pH, and other chemical properties of the soil can all impact the effectiveness of cadmium remediation, potentially leading to significant differences in remediation outcomes across different sites. Secondly, the production costs of some highly effective soil amendments are prohibitively high, limiting their large-scale application. Finally, the use of these amendments can result in secondary pollution, such as wastewater discharge and residual chemicals, posing environmental safety concerns.

4.2. Future Prospects

4.2.1. Material Innovation

A comprehensive understanding of the mechanisms behind heavy metal ion immobilization is crucial for developing more effective remediation agents. Future research should aim to optimize the structure and surface properties of these materials to improve their stability under complex environmental conditions. For instance, new materials consisting of composite or nanocomposite materials with higher stability and higher adsorption capacity for the superior Cd^{2+} ion could be applied in remedial engineering [128]. Many adsorbents are difficult to regenerate after use, leading to resource waste and increased costs [129]. It is imperative to research and develop efficient regeneration technologies that allow adsorbents to be easily restored to their original adsorption capacity through simple chemical or physical methods. Besides, utilizing regenerated adsorbents with other treatment technologies in constructing a recycling treatment system also enhances economic performance [130].

4.2.2. Original Technological Improvement

Since some of the efficient remediation methods tend to be expensive to implement, they cannot be adopted on a large-scale application. Optimizing production processes to improve material efficiency, reduce energy consumption, and lower raw material costs is a key direction for future development. This involves refining manufacturing techniques and potentially using waste or by-products as raw materials to reduce overall costs and enhance sustainability [131].

4.2.3. Policy Guidance

Governments should continue to make policies and regulations for supporting the treatments to remediate the soils. Providing financial subsidies and technical support can promote the research and application of various soil amendments. This policy-driven approach can encourage the integrated use of these amendments to achieve comprehensive management of soil-heavy metal pollution [132].

5. Conclusions

This review has analyzed three main remediation methods: CaAl-LDH immobilization, hydrochar, and the co-application of phosphate fertilizer with sepiolite. These methods were chosen due to their ability to minimize secondary pollution, improve in situ remediation, and offer economic advantages over conventional methods. Each method presents unique strengths, but the comparison of their effectiveness reveals that no single method is universally superior. For instance, the co-application of phosphate fertilizer with sepiolite demonstrated the highest cadmium-removal efficiency, achieving up to 72.6% for HCl-extractable cadmium, making it highly suitable for acidic soils. However, CaAl-LDH offers enhanced long-term stability due to its superior thermal properties, which may render it more effective in sustaining remediation over time, especially in alkaline environments. Hydrochar, while environmentally friendly and easy to produce, may require further opti-

mization to improve its adsorption efficiency and heat resistance, potentially making it a viable option for regions where low-cost production is critical.

Future research should focus on developing regenerative adsorbents and refining production processes to enhance material efficiency and reduce costs. Furthermore, continued exploration of heavy metal ion remediation mechanisms will be crucial in developing composite or nanomaterials with greater stability and higher adsorption capacities. This will help improve the overall sustainability and economic viability of large-scale cadmium-remediation efforts.

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