

Research Progress on the Treatment of Heavy Metals in Water Using Agricultural and Forestry Waste Adsorbent Materials

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Abstract:

Agricultural and forestry waste, as adsorbent materials, offers numerous advantages such as wide availability, low cost, and environmental friendliness, demonstrating broad application prospects. In recent years, the adsorption performance of these materials has been significantly improved through optimization and modification. This review systematically classifies agricultural and forestry waste adsorbent materials, thoroughly summarizes their modification methods, adsorption performance for heavy metals, and factors influencing heavy metal adsorption. It also explores the adsorption mechanisms and the effects of desorption and regeneration, and finally proposes future trends in the research and application of agricultural and forestry waste, providing references for heavy metal pollution control.

Keywords: Agricultural waste, Forestry waste, Heavy metals, Adsorption methods

Introduction

Agricultural and forestry wastes are widely available, inexpensive, and rich in a variety of active functional groups, exhibiting excellent adsorption performance. They represent a highly promising class of green adsorbent materials. This paper reviews recent research progress on the application of agricultural and forestry waste-based adsorbents in the treatment of heavy metal-containing wastewater, covering aspects such as material classification, modification methods, adsorption performance, influencing factors, mechanisms of action, and regeneration and reuse. The aim is to provide theoretical support and technical reference for future research and practical applications.

With the rapid development of industrialization and urbanization, large amounts of heavy metal-contaminated wastewater generated from production are discharged into water bodies, causing severe environmental pollution issues [1-2]. Heavy metals are highly toxic, non-degradable, and accumulate continuously in the food chain [3-4], posing serious threats to human health [5]. When the concentration of heavy metals in the human body exceeds critical levels, their toxicity may damage or impair the central nervous system and mental activities, while also causing harm to the lungs, liver, kidneys, blood components, and other vital organs, leading to various diseases, including cancers [6].

Current technologies for treating heavy metal wastewater include ion exchange, chemical precipitation, membrane separation, adsorption, and electrochemical methods. Among these, adsorption is advantageous due to its simplicity, environmental friendliness, cost-effectiveness, energy efficiency, and reusability [7]. It also offers practicality and flexibility in design, making it one of the preferred methods for heavy metal

removal [8]. Among various conventional and unconventional adsorbent materials, agricultural and forestry waste adsorbents have distinct advantages: they are widely available, low-cost, and have a large specific surface area, making them highly effective for removing heavy metal ions from polluted water. Additionally, agricultural and forestry waste is rich in lignin, cellulose, lipids, and active functional groups such as hydroxyl, carboxyl, and amino groups, which effectively promote complexation with heavy metal ions, offering broad application prospects [9]. This paper reviews and summarizes recent studies on the adsorption behavior of agricultural and forestry waste materials for heavy metals in wastewater, aiming to provide references for addressing heavy metal pollution in water bodies.

1. Removal of Heavy Metals Using Agricultural and Forestry Waste Adsorbent Materials Agricultural and forestry waste is divided into agricultural waste (such as peanut shells, straw, sugarcane bagasse, etc.) and forestry waste (such as bark, wood chips, sawdust, etc.) [10]. Commonly used agricultural and forestry waste is shown in Figure 1.



Figure 1

Agricultural waste refers to the residues and byproducts generated during agricultural production that lack direct economic value to farmers and require processing or disposal. The most widely utilized types of agricultural waste materials include fruit peels, straw, and nutshells [11]. Forestry waste primarily encompasses residues and byproducts generated during forest resource cultivation, processing, and natural regeneration, with commonly used materials including bark and sawdust [12]. The surface characteristics of various agricultural and forestry wastes exhibit significant differences, primarily due to variations in their chemical composition and structure [13]. For instance, rice husks, wheat straw, and similar wastes are rich in cellulose, hemicellulose, and lignin, which contain a variety of functional groups in their chemical structures, such as hydroxyl (-OH), carboxyl (-COOH), carbonyl (-C=O), and ether (-C-O-C-) groups [14]. Some of these functional groups can interact with heavy metal ions through mechanisms such as ion exchange and complexation, thereby facilitating adsorption. The type and quantity of functional groups directly influence the adsorption efficiency and selectivity of agricultural and forestry waste for heavy metal ions.

To enhance the adsorption performance of agricultural and forestry waste for heavy metal ions, modifications are often applied to increase the content or exposure of specific functional groups. Common modification methods include acid-base modification, carbonization, metal ion modification, oxidant modification, and organic grafting [15]. For example, oxidant modification can increase the presence of oxygen-containing functional groups on the material's surface, thereby improving its adsorption capacity. Grafting can alter the surface functionality of the adsorbent and introduce new functional groups [16]. These modification techniques enhance the performance of agricultural and forestry waste adsorbents by increasing adsorption sites or improving the material's pore structure.

(1) Adsorption Performance of Agricultural Waste Adsorbents

Jahin et al. [17] modified banana peel using a NaOH solution and investigated its efficacy in removing Cu(II) from wastewater. Experimental results demonstrated that under optimal conditions (initial concentration of 50 mg/L, adsorbent dosage of 10 g/L), the modified banana peel achieved a Cu(II) removal efficiency of 72%. Muhaisen et al. [18] employed sodium hydroxide for the chemical modification of orange peel. The modified orange peel exhibited significantly enhanced removal efficiencies for Cd(II) and Ni(II), reaching 91.0% and 93.44%, respectively, compared to the 40–50% removal rates of unmodified orange peel. Jin et al. [19] prepared biochar from grape pomace to evaluate its adsorption performance for Pb(II) in two types of wastewater. The results indicated that the prepared biochar exhibited excellent Pb(II) adsorption performance at both high and low concentrations, particularly in drinking water at low concentrations (ppb level), where it reduced Pb(II) levels well below the safe drinking water limit, achieving a removal efficiency of 97.9%. This notable enhancement highlights its potential for practical applications.

Jong [20] prepared sesame straw biochar to investigate its adsorption behavior for single and multi-metal systems. In single-metal adsorption isotherms, the maximum adsorption capacities followed the order: Pb > Cd > Cr > Cu > Zn. In multi-metal systems, the order was Pb > Cu > Cr > Zn > Cd. The adsorption capacity for Pb was least affected by competitive interactions, while Cd was the most affected. Lan Tian et al. [21] examined the adsorption characteristics of corn straw biochar for Cu(II) and Pb(II), revealing that the adsorption capacity for Pb(II) (9.84 mg/g) was significantly higher than for Cu(II) (4.66 mg/g). Wang Yi et al. [22] modified corn straw biochar (BC) using KOH and polyethyleneimine to produce two novel adsorbents, KBC and PBC, and studied their removal efficiencies for Cu(II) and Pb(II) in aqueous solutions. The modified biochars demonstrated significantly improved heavy metal removal, with maximum adsorption capacities in the order PBC > KBC > BC. Notably, all three biochars exhibited a preference for Pb(II) adsorption, though modification enhanced the competitive adsorption capacity of Cu(II) in composite systems.

Guan Wei [23] prepared a modified biochar composite from walnut shells to investigate its competitive adsorption performance for Ni(II) and Cr(VI) in water. The results showed a stronger selective adsorption for Cr(VI) compared to Ni(II). Yiyi Deng [24] studied the adsorption behavior and mechanisms of rice husk biochar for Cd(II) and Ni(II) in single and binary metal systems. In the binary system, the biochar exhibited a greater adsorption preference for Ni(II) over Cd(II).

Table 1.1 Adsorption effect of common agricultural waste adsorption materials on heavy metals

Adsorbents	Modification method	Heavy metals	Initial concentration mg/L	Dosage g/L	Adsorption capacity mg/g	Removal rate%	References
banana peel	NaOH soak	Cu(II)	50	10	3.20	72.0	Error! Reference source not found.
watermelon rind	Ammonium sulfide and carbonization	Pb(II)	1000	2	97.63	96.5	Error! Reference source not found.
orange peel	NaOH soak	Ni(II)	50	25	1.96	93.4	Error! Reference source not found.
		Cd(II)	50	30	1.53	91.0	
grape pomace	carbonization	Pb(II)	300	1	107.00	71.7	Error! Reference source not found.
Bagasse	Carbonation and oxalic acid	Cr(VI)	50	0.6	73.90	99.1	Error! Reference source not found.

walnut shells	carbonization	Cr(V I)	100	1.1	94.50	93.0	Error! Reference source not found.
peanut shells	Potassium permanganate modification after carbonization	Pb(II)	250	0.3	27.80	97.1	Error! Reference source not found.
wheat straw	carbonization	Cr(V I)	200	2	125.60	80.5	Error! Reference source not found.
		Cr(III)			68.9	45.7	
corn stalks	carbonization	Pb(II)	400	2	9.84	96.1	Error! Reference source not found.
		Cu(II)			4.66	78.5	
corn stalks	KOH and polyethyleneimine modification after carbonization	Pb(II)	30	2	54.51	93.0	Error! Reference source not found.
		Cu(II)			35.21	99.0	
rice straw	None	Cr(V I)	20	1	65.40	96.1	Error! Reference source not found.
		Ni(II)			54.60	88.4	
rice straw	Calcium thioglycolic acid modified after carbonization	Pb(II)	100	0.8	124.92	98.1	Error! Reference source not found.

(2) Adsorption Performance of Forestry Waste Adsorbents

Wang Lei et al. [31] modified sycamore bark through impregnation with a zinc chloride solution followed by carbonization to investigate its adsorption performance for Cr(VI). Under conditions of an adsorbent dosage of 8 g/L, pH 2, and static adsorption for 3 hours, the removal efficiency for a 100 mg/L Cr(VI) solution reached 99.8%. Gonzalo et al. [32] chemically activated pine bark using a sulfuric acid solution. At an initial Cr(VI) concentration of 100 mg/L and an adsorbent dosage of 1.5 g/L, the removal efficiency reached 96.4% within 7 hours and increased to 97.5% after 24 hours. Paradelo et al. [33] studied the competitive adsorption of Cd, Cu, Ni, Pb, and Zn by pine bark, demonstrating that pine bark is an effective adsorbent for retaining heavy metals in multi-metal contaminated media. The retention capacity of pine bark followed the sequence Pb > Cu > Zn > Cd > Ni. The presence of a second metal affected the migration of all studied elements except Pb, confirming the strong influence of Pb and Cu on the retention of other metals. Cu and Pb could displace other metals from adsorption sites, thereby reducing the removal efficiency of pine bark for these elements. Cu could be partially displaced by Pb, but Pb was not desorbed by Cu.

Aline et al. [34] used modified pine sawdust to remove Cr(III) and Ni(II) from solution, finding that chemically modified pine sawdust (MPB) exhibited high adsorption capacities for both Cr(III) and Ni(II).

The adsorption of Cr(III) was minimally affected by Ni(II) concentration, whereas the adsorption capacity for Ni(II) significantly decreased with increasing Cr(III) concentration. In real electroplating industrial wastewater, the adsorption capacities of MPB for Cr(III) and Ni(II) were notably reduced, likely due to the presence of numerous other ions in the wastewater. Ofomaja [35] investigated the adsorption of Cu and Pb ions by *Mansonia sycamore* sawdust, demonstrating good adsorption capacities for both ions. In competitive adsorption studies, the competition for biosorption sites in the Cu-Pb binary metal system was stronger than in the Pb-Cu binary system.

Table 1.2 Adsorption effects of some forestry waste adsorption materials on heavy metals

Adsorbents	Modification method	Heavy metals	Initial concentration mg/L	Dosage g/L	Adsorption capacity mg/g	Removal rate%	References
Sycamore bark	carbonization	Cr(VI)	50	8	7.89	99.8	Error! Reference source not found.
pine bark	H ₂ SO ₄ activation	Pb(II)	100	1.5	93.70	97.5	Error! Reference source not found.
pine bark	NaOH	Cd(II)	10	4	26.08	94.8	Error! Reference source not found.
hickory bark	none	Cu(II)	100	5	26.90	89.0	Error! Reference source not found.
cedar bark	None	Pb(II)	200	5.5	16.39	93.9	Error! Reference source not found.
Eucalyptus sawdust	None	Pb(II)	150	30	4.80	96.1	Error! Reference source not found.
Poplar sawdust	carbonization	Cd(II)	100	2.5	49.32	82.4	Error! Reference source not found.
		Pb(II)			62.68	85.3	
pine bark	NaOH	Cr(III)	50	3	31.40	87.0	Error! Reference source not found.
		Ni(II)			23.70	70.0	

pine bark sawdust	None	Pb(II)	200	1.5	13.48	99.0	Error! Reference source not found.
		Cu(II)			9.59	96.0	
Manson Sycamore Sawdust	None	Pb(II)	100	2	51.81	90.3	Error! Reference source not found.
		Cu(II)			42.37	51.3	

2. Factors Influencing Heavy Metal Adsorption by Agricultural and Forestry Waste Adsorbents

The adsorption of heavy metals by agricultural and forestry waste adsorbents is influenced by multiple factors. On one hand, the adsorption capacity of the adsorbent is related to its pore structure and the quantity and type of surface functional groups. Additionally, factors such as solution pH, adsorption temperature, ionic strength, adsorbent dosage, initial concentration of the adsorbate, contact time, and coexisting ions significantly affect adsorption performance.

(1) pH Value

The pH of the solution influences the charge state of functional groups on the adsorbent surface and the speciation of metal ions, thereby affecting heavy metal adsorption efficiency. Studies have shown that both excessively low and high pH values are unfavorable for the adsorption of heavy metal ions by agricultural and forestry waste materials. At low pH, H⁺ ions compete with heavy metal cations for active sites on the adsorbent surface. Conversely, at high pH, OH⁻ ions compete with heavy metal ions for these active sites, similarly hindering adsorption. Ippolito et al. [42] investigated the adsorption of Cu²⁺ from wastewater using KOH-activated walnut shell biochar and found that the removal efficiency was highly pH-dependent. The maximum adsorption capacity of 42.3 mg/g was achieved at pH 6.0, with adsorption capacity decreasing as pH increased to 9. Liu [43] prepared modified walnut shell biochar (FWNS) to study its adsorption of Pb(II). The adsorption capacity for Pb(II) significantly increased as pH rose from 2 to 6, reaching its maximum at pH 6. However, at pH values above 6, the formation of metal hydroxide precipitates led to a decline in adsorption efficiency.

(2) Reaction Time

Reaction time is closely related to adsorption efficiency. Typically, during the initial stage of adsorption, the adsorbent surface exposes a large number of active sites, allowing rapid adsorption of heavy metal ions. As time progresses, the number of available adsorption sites decreases as they become occupied, leading to adsorption saturation, after which the process stabilizes and reaches equilibrium. Chen [44] prepared modified biochar from spinach waste activated with KMnO₄ and investigated its adsorption performance for Cd(II), Pb(II), Cu(II), and Zn(II). The adsorption rate was rapid within the first 10–30 minutes, achieving adsorption efficiencies of 93.5%, 90.0%, 92.0%, and 95.7% for Cd(II), Pb(II), Cu(II), and Zn(II), respectively. After 60 minutes, the adsorption efficiency of heavy metal ions stabilized, indicating that the adsorption process had reached equilibrium.

(3) Adsorbent Dosage

Adsorbent dosage is a critical parameter influencing adsorption performance. Generally, increasing the adsorbent dosage results in a larger total surface area and more adsorption sites, thereby enhancing the removal rate of heavy metal ions. However, as the dosage continues to increase, the removal rate may peak and then decline. Zhang Yumin et al. [45] used modified orange peel bioadsorbent to remove Pb(II) and found that the adsorption capacity for heavy metal ions increased with adsorbent dosage up to 15 g/L, after

which it gradually stabilized. However, excessive adsorbent dosage may lead to agglomeration [46], reducing the number of effective adsorption sites and consequently decreasing the removal efficiency of heavy metal ions.

(4) Initial Heavy Metal Ion Concentration

The initial concentration of heavy metal ions determines the utilization rate of active sites on the adsorbent surface. At lower initial concentrations, agricultural and forestry waste adsorbents typically exhibit higher adsorption performance. Dan [47] functionalized bamboo activated carbon (BAC) with EDTA through direct grafting, using TEOS as a cross-linking agent to form the BAC@SiO₂-EDTA composite material. The study investigated the adsorption behavior of Pb(II) and Cu(II) at different initial concentrations. It was found that as the initial concentration increased, the adsorption capacity initially increased and then stabilized, indicating that the active sites on the adsorbent surface were gradually saturated.

(5) Temperature

Temperature is another critical factor influencing the adsorption performance of heavy metal ions, as it affects the surface chemical structure and particle diffusion rate of agricultural and forestry waste adsorbents. Numerous studies have shown that the adsorption efficiency of these materials for heavy metals either increases or rapidly decreases with rising reaction temperature. Classical thermodynamic parameters, such as enthalpy change (ΔH), entropy change (ΔS), and Gibbs free energy change (ΔG), are commonly used to investigate the impact of temperature on adsorption behavior. Darweesh et al. [48] studied the adsorption of Cu(II) by banana leaf (BL) and banana leaf biochar (BLAC), finding that the removal efficiency of Cu(II) by both bioadsorbents increased with rising reaction temperature, indicating an endothermic adsorption process. When the temperature was increased from 25 °C to 40 °C, the Cu(II) removal efficiency of BL and BLAC improved by 22%, which can be attributed to enhanced effective collisions between Cu(II) ions and the active sites on the adsorbent surface at higher temperatures. Conversely, Owalude et al. [49] observed that when the temperature was raised from 30 °C to 70 °C, the adsorption capacity of peanut shells and modified peanut shells for Cr(VI) in simulated wastewater decreased, indicating an exothermic adsorption process.

(6) Coexistence of Multiple Ions

In wastewater treatment, the adsorption behavior of heavy metals is often significantly influenced by the presence of coexisting ions. The coexistence of multiple ions may interfere with the removal efficiency of target heavy metals through mechanisms such as competitive adsorption and electrostatic shielding. Competitive adsorption effects are commonly observed during adsorption processes. For instance, when multiple cations (e.g., Ca²⁺, Mg²⁺, Na⁺, K⁺) or other heavy metal ions are present, they compete for active sites on the adsorbent surface, thereby reducing the adsorption efficiency for the target heavy metal [50]. Additionally, electrostatic interactions can influence adsorption behavior. The presence of background electrolytes (e.g., NaCl) may alter the electrical double-layer structure on the adsorbent surface, shielding electrostatic attractions and weakening the adsorption of positively charged heavy metals onto negatively charged adsorbents, such as biochar [50].

Moreover, pH-dependent synergistic or antagonistic effects can also impact adsorption behavior [51]. Under acidic conditions (pH < 5), H⁺ ions may compete with heavy metal ions (e.g., Cu²⁺, Ni²⁺) for adsorption sites. In contrast, under neutral to alkaline conditions, multivalent anions (e.g., CO₃²⁻, OH⁻) may promote the precipitation of heavy metals, thereby enhancing the apparent adsorption capacity.

3. Mechanisms of Heavy Metal Adsorption by Agricultural and Forestry Waste Adsorbents

The removal of heavy metal ions by agricultural and forestry waste adsorbents typically involves the synergistic interplay of multiple mechanisms. These mechanisms may include ion exchange, complexation, chelation, redox reactions, electrostatic attraction, chemical precipitation, and physical adsorption [52].

Broadly, these can be categorized into three main types: ion adsorption, chemical adsorption, and physical adsorption. The relative contribution of each mechanism is influenced by factors such as the properties of the heavy metal ions, the pH of the solution, and the type and structure of the agricultural and forestry waste adsorbent [53].

(1) Ion Exchange Mechanism

The surfaces of agricultural and forestry waste adsorbents are typically rich in oxygen-containing functional groups, which confer significant ion exchange capabilities with heavy metal ions. Jiawen [54] utilized magnesium-modified coconut shell biochar (MgBC400) as an adsorbent to remove lead (Pb) and cadmium (Cd) from wastewater. The magnesium modification significantly enhanced the ion exchange and precipitation capacities of the biochar, with studies indicating that MgBC400 exhibited strong adsorption of Pb and Cd through a cation exchange mechanism. EI-Shafey et al. [55] investigated the adsorption of Cd(II) and other heavy metal ions using flax fiber biochar, finding that ion exchange reactions between acidic functional groups and base cations on the biochar surface with Cd(II) were a primary mechanism for heavy metal adsorption. Mohan et al. [56] used biochar derived from rapid pyrolysis of wood or bark to adsorb Pb(II), Cd(II), and As(III), demonstrating that lignocellulosic biochar possesses high cation exchange capacity, with ion exchange being the dominant mechanism for metal ion adsorption.

(2) Chemical Adsorption Mechanism

The chemical adsorption mechanism of agricultural and forestry waste adsorbents primarily involves complexation. This process occurs through the formation of covalent bonds between metal ions and functional groups (e.g., —COOH, —O—) on the adsorbent surface, resulting in the removal of metal ions via complex formation. Gilbert et al. [57] observed that during the removal of heavy metal ions using defatted papaya seeds, functional groups on the biochar surface formed complexes with the heavy metal ions. Chen et al. [58] employed KMnO₄-modified walnut shell biochar (MWSC) as an adsorbent, finding that Cu²⁺, Pb²⁺, Cd²⁺, and Zn²⁺ were adsorbed by substituting Mn²⁺ on the MWSC surface. Additionally, these heavy metal ions formed complexes with functional groups (e.g., —OH and —COOH) on the MWSC surface. Shuo Ai et al. [59] studied the adsorption behavior of HNO₃-modified sugarcane bagasse (NTB) for Cd(II), achieving an adsorption capacity of 119.30 mg/g. FTIR, XPS, and DFT analyses revealed that the —COO⁻ groups in NTB coordinated with Cd(II) in aqueous solution through chelation. Wang Weizhen et al. [60] investigated the adsorption mechanisms of Cd(II) in aqueous solution using biochar derived from sycamore bark, branches, and leaves. Despite the leaf-derived biochar having the highest specific surface area, it exhibited the lowest adsorption capacity for Cd(II), indicating that the adsorption process was not dominated by a single mechanism. ATR and XRD analyses confirmed that electrostatic attraction and chelation were the primary mechanisms for Cd(II) removal.

(3) Physical Adsorption Mechanism

Physical adsorption mechanisms primarily encompass physical precipitation and electrostatic interactions. Dong et al. [61] studied the adsorption of Cr(VI) by sugarcane bagasse biochar, demonstrating that electrostatic attraction played a role under acidic conditions. Initially, negatively charged Cr(VI) ions migrated toward the positively charged biochar surface (where carboxyl, alcohol, and hydroxyl functional groups lost protons). Subsequently, the biochar acted as an electron donor, reducing Cr(VI) to Cr(III) under the influence of H⁺ ions. Finally, some Cr(III) ions formed complexes with functional groups on the biochar surface. Ruzhen Xie et al. [62] investigated activated carbon prepared from walnut shells, finding that the adsorption of Cu(II) was driven by physical forces (van der Waals forces). The biochar absorbed Cu(II) and Pb(II) through physical diffusion mechanisms.

4. Desorption and Regeneration of Heavy Metals from Agricultural and Forestry Waste Adsorbents

In evaluating the performance of adsorbent materials, the reusability of adsorbents is a valuable practice. Multiple adsorption-desorption cycles can not only minimize the economic costs of the process but also reduce environmental impacts [63]. For agricultural and forestry waste adsorbents, their adsorption and regeneration performance directly determine their potential for industrial applications. Therefore, selecting an appropriate eluent is critical in desorption studies. The eluent should exhibit metal selectivity, economic feasibility, and high desorption efficiency. Commonly used eluents for recovering metal ions from loaded adsorbents include sodium carbonate, potassium cyanide, EDTA, nitric acid, sulfuric acid, and hydrochloric acid [64-65].

Liu Xuemei et al. [66] used HCl to desorb Pb(II) from modified orange peel adsorbents. The study found that after five cycles, the adsorption efficiency for Pb(II) decreased from 97.66% to 91.57%, indicating that the regenerated adsorbent retained high adsorption performance. Bhagat et al. [67] demonstrated that banana peel adsorbents loaded with Cu(II) and Zn(II) could be effectively regenerated using H₂SO₄ solution. After five desorption-reabsorption cycles, the removal efficiency for Cu(II) decreased from 98.03% to 81.75%, and for Zn(II) from 94.18% to 59.75%. Ezeonuegbu et al. [68] treated metal-loaded sugarcane bagasse with 0.1 M nitric acid, achieving an effective desorption efficiency of 85.2%. This suggests that sugarcane bagasse can be reused without significant loss of adsorption efficiency. However, further multi-cycle experiments were not conducted, leaving the practical application potential uncertain. Bayuo [69] used 0.1 M H₂SO₄ and HCl to recover Cr(VI) and Pb(II) ions from peanut shell adsorbents, achieving desorption efficiencies of 76.1% for Cr(VI) and 82.1% for Pb(II). After five consecutive reuse cycles, the removal efficiencies for Cr(VI) and Pb(II) in the third cycle were 53.5% and 54.6%, respectively. These results indicate that peanut shell-derived adsorbents show promise for heavy metal remediation in aqueous environments. However, some agricultural and forestry waste adsorbents exhibit limitations during repeated use, including low mechanical strength, small particle size, significant mass loss after regeneration, and difficulty in separation from the aqueous phase. Therefore, future research should focus on improving their solubility, biodegradability, and stability.

5. Summary and Outlook

In summary, adsorbents should ideally possess high adsorption capacity, ease of separation from aqueous solutions, low cost, and recyclability. Agricultural and forestry waste adsorbents are cost-effective, widely available, and highly effective for heavy metal ion removal, making them a promising novel adsorbent material worthy of further research and development. Moreover, utilizing these wastes for heavy metal treatment achieves the goal of "treating waste with waste," providing an effective pathway for their comprehensive resource utilization. This approach offers significant economic and ecological benefits for future development.

In adsorption studies, priority should be given to multi-component systems, as water systems often contain multiple metal ions as pollutants, and interactions between different metal ions significantly affect adsorption efficiency. Beyond understanding the competitive adsorption strength and changes in adsorption capacity, research on the adsorption of multiple heavy metals and complex pollutants should focus on how these interactions influence the relationships between ions and adsorbates. Efforts should aim to address the reduced adsorption efficiency caused by competitive interactions or to develop methods for achieving high-efficiency adsorption of specific ions, thereby providing more practical solutions for real-world applications. For agricultural and forestry waste adsorbents, future research can focus on the following areas:

- (1) Develop new agricultural and forestry waste adsorbents and further explore methods and mechanisms for heavy metal adsorption to provide a theoretical basis for developing additional functional applications.
- (2) Seek more efficient and environmentally friendly modification agents and methods, while ensuring that production and preparation costs remain reasonable.
- (3) Investigate desorption mechanisms and develop more efficient and green eluents. Explore the preparation of composite adsorbents by combining agricultural

and forestry waste materials with other materials to achieve synergistic effects, thereby enhancing adsorption and regeneration performance. (4) Current research on the adsorption of complex multi-pollutant wastewater is limited. Future studies should focus on investigating the effects of varying ion concentrations and the coexistence of multiple ions to address the complexities encountered in practical wastewater treatment scenarios.

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