# Recent Advances in Adsorbent Materials for Hexavalent Chromium Removal from Aqueous Solutions

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# Recent Advances in Adsorbent Materials for Hexavalent Chromium Removal from Aqueous Solutions

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**Abstract:** *Chromium contamination in aqueous systems poses serious environmental and public health risks due to the toxicity of its hexavalent form, Cr(VI). Among various remediation strategies, adsorption has emerged as the most viable technique owing to its simplicity, cost-effectiveness, and eco-friendliness. This mini-review critically examines recent advancements in chromium adsorption technologies, with emphasis on adsorbent innovations. Diverse categories such as carbon-based materials (activated carbon, CNTs, graphene), bio-based adsorbents (biochar, agricultural waste), nanomaterials, natural polymers, clays, zeolites, metal-organic frameworks, and functionalized hydrogels are systematically analyzed for their removal efficiencies, mechanisms, and practical applicability. The review also contrasts real-world performance versus laboratory conditions and identifies critical factors such as pH, surface functionalization, and regeneration potential that govern adsorption capacity. Despite significant progress, challenges remain regarding selectivity, scalability, and complete removal efficiency. This study highlights the need for future research focused on hybrid and smart adsorbents with enhanced performance in complex wastewater matrices.*

**Keywords:** Chromium removal; Adsorption; Bio-based adsorbents; Surface modification; Nanomaterials.

## 1. INTRODUCTION

Chromium (Cr) is a hard, grey transition metal that primarily exists in trivalent [Cr(III)] and hexavalent [Cr(VI)] forms [1]. It occurs naturally in soil, rocks, volcanic dust, and gases, often as chromite or in compounds like crocoite and bentorite [2]. Although largely geogenic comprising over 83% of the earth's crust [3] chromium contamination arises significantly from anthropogenic sources. Key industrial contributors include chromium electroplating, leather tanning, cement production, and textile dyeing [4]. Additionally, natural activities like volcanic eruptions and forest fires contribute to its environmental spread.

Cr(VI) is notably toxic, with multiple studies confirming its role in immune suppression and disruption of enzymatic functions such as oxidative phosphorylation [5]. It poses severe health risks including DNA damage, carcinogenicity, and respiratory ailments like bronchitis [6]. Cr(III), while less toxic and essential in trace amounts, may still contribute to metabolic disorders if dysregulated [7].

To control exposure, various regulatory bodies have imposed limits on chromium levels in water. The U.S. Safe Drinking Water Act of 1974 mandates a maximum of 0.1 mg/L [8], while the European Union and WHO impose stricter limits of 0.05 mg/L for surface and potable waters [9]. However, these standards alone cannot eliminate chromium's health hazards, necessitating effective removal strategies.

Conventional chromium remediation techniques include chemical precipitation, ion exchange, membrane filtration, coagulation-flocculation, electrochemical treatments, and bioremediation [10], [88]. Among these, adsorption stands out for its efficiency, cost-effectiveness, simplicity, and environmental compatibility. It involves the binding of chromium ions onto adsorbent surfaces through redox reactions, ion exchange, or electrostatic forces. Activated carbon and other advanced materials have enhanced adsorption efficiency [11]. Recent research highlights significant progress in adsorption technologies using bio-based, carbonaceous, and nanostructured adsorbents confirming their improved effectiveness, environmental sustainability, and operational simplicity [12-14]. This paper reviews these advancements and evaluates their implications for practical wastewater treatment.

## 2. CHROMIUM SPECIES AND ADSORPTION MECHANISM

As noted, Cr(III) and Cr(VI) are the chromium's dominant species. In aqueous solutions, the concentration of Cr (III) depends largely on the potential of hydrogen (PH). Bat-Amgalan et al. [15] point out that this chromium species exists mainly as $Cr^{3+}$ when the PH ranges from one to three. However, when the PH reaches four to six, it changes to $CrOH_2^{+}$. If the PH increases beyond six, Cr(III) precipitates, depicting increased adsorption capacity. Similarly, Cr(III) mobility depends on the PH of the aqueous media. Specifically, soluble Cr(III) mobility is higher when the PH is high [16]. Another characteristic of soluble Cr(III) is that it is less toxic than Cr(VI). Like Cr(III), Cr(VI) exists in different forms at different PH levels [17]. When the PH is at acidic levels (1-3), Cr(VI) changes to chromic acid ($HCrO_4^{-}$) and can be adsorbed via electrostatic attraction [18]. At alkaline levels (PH greater than 7), chromate ($CrO_4^{2-}$) becomes the most dominant. This form competes with most compounds containing OH for binding spaces, which interfere with the adsorption process. In addition, compared with Cr(III), Cr(VII) is highly soluble in aqueous solutions, implying that its mobility and toxicity are higher.

Due to their ability to exist in different forms, these chromium species can be removed via different adsorption methods. Physical adsorption relies on natural forces rather than temperature to remove atoms, ions, or chromium particles from an aqueous media [19]. This method often employs multiple layers of the adsorbent to capture chromium particles. Chemical adsorption removes chromium from an aqueous solution through a chemical reaction, such as a redox process in which electrons move from one species (compound) to another. Thus, this process reduces Cr(VI) to less toxic forms. Ion exchange is another chromium removal method. This involves passing wastewater through resin beads that attract chromium ions [20]. The resin is usually discriminatory when handling the ions from different compounds. The chromium ion properties allow the resin to hold chromium particles but release ions from other compounds coexisting with chromium, such as potassium. Electrostatic attraction is an adsorption mechanism that involves charging a surface so that it has positive charges and then passing water through this positively charged surface [21]. This surface attracts negatively charged chromium ions, forming an insoluble complex, which facilitates precipitation. Surface complexation is not a specific adsorption mechanism, but it is helpful in predicting the relevant equilibrium for chromium removal. Specifically, it guides equilibrium estimation by assuming resin beads have a planar surface containing evenly distributed ions. This assumption allows professionals to estimate how chromium particles will be dispersed in the resin.

## 3. RECENT ADVANCES IN ADSORBENTS FOR CHROMIUM REMOVAL

### 3.1 Carbon-Based Adsorbents

Liu et al. [22] explain that carbon is a fundamental material in chromium removal because it is a primary medium for some widely applied adsorbents. Examples of carbon materials employed as adsorbents include active carbons, carbon nanotubes (CNTs), biochar, graphene, and graphene oxide. Investigating the broad carbon-based adsorbents can help clarify how they work and their advantages or disadvantages (shortcomings). The following subsections describe these adsorbents further.

**Activated Carbon and Its Modifications**

Activated carbon (AC) is a porous material derived from carbon-rich sources such as wood, coconut shells, lignite, or coal, widely used for removing contaminants from air and water. Its use dates back to 1773 for gas purification and later for liquid decontamination in the 1780s [23]. The term "activation" refers to the enhancement of its internal surface area and porosity via chemical, physical, or biological modifications. Chemical activation typically involves oxidizing agents like sulfuric or hydrochloric acid, or impregnation with metal ions to improve surface reactivity. Another strategy is nitrogen enrichment, which introduces electron-releasing functional groups, enhancing adsorption efficiency and redox capability [24].

Physical activation methods include high-temperature treatments that develop pore structures, while biological methods such as bio-regeneration use microorganisms to metabolize pollutants, aiding desorption. Functionally, AC contains various surface groups such as carboxyl, lactones, phenols, carbonyls, and quinones. These are composed of elements like sulfur, nitrogen, oxygen, and hydrogen, enabling interactions with a broad range of pollutants. However, despite its effectiveness, AC production and modification often require intensive chemical processes, which can elevate cost and environmental risk.

Several factors influence the adsorption efficiency of AC. According to Bhatnagar et al. [23], pH is a key determinant, as Cr(III) and Cr(VI) exhibit different behaviors at varying pH levels. Proper pH conditions optimize precipitation and adsorption. Surface area is another crucial factor-larger areas with more pores enhance adsorption capacity [25]. Temperature also impacts performance. Higher temperatures increase particle kinetic energy, potentially reducing adsorption efficiency by promoting desorption [26]. Finally, the type of AC-based on precursor material and activation method affects pore structure, functional group composition, and overall adsorption behavior.

This comprehensive understanding of AC's properties and influencing factors is essential for optimizing its application in chromium removal and enhancing its environmental sustainability.

**Biochar and CNTs**

Biochar, a carbon-based adsorbent, is produced by pyrolyzing organic waste under limited oxygen conditions. This thermal process drives off volatile compounds while concentrating carbon, forming a porous structure suitable for adsorption. Its high electronegativity enables biochar to attract electrons from metal contaminants, thereby supporting ion exchange and redox reactions critical for reducing toxic Cr(VI) to the less harmful Cr(III) [27-29]. These multiple adsorption mechanisms enhance biochar's effectiveness. Economically, biochar is advantageous due to the low cost or free availability of its raw materials. However, its reliance on non-recyclable organic waste raises sustainability concerns. Moreover, the production process may emit greenhouse gases (GHGs), which could offset its environmental benefits [30]. In particular, biochar activated with NaOH and treated at 700°C demonstrated significantly enhanced Cr(VI) adsorption, attributed to enriched surface functional groups like alkenes that facilitate redox conversion to Cr(III) [31].

Carbon nanotubes (CNTs), another carbon-based material, are cylindrical nanostructures rich in oxygen-containing functional groups such as carboxyl. These groups provide strong sites for adsorption, enabling reduction of Cr(VI) and promoting ion exchange and electrostatic interactions. CNTs also exhibit high surface area and porosity, which allows for increased adsorption capacity over time [32]. Their performance can be further enhanced through physical or chemical modification. Liu et al. [22]. highlight that treatment with oxidants or high temperatures improves adsorption efficiency by approximately 13% [32]. Thus, identifying optimal modification agents is essential to maximizing CNT performance in treating chromium-contaminated solutions.

**Graphene-Based Materials**

Graphene is a two-dimensional, all-carbon material derived from graphite, widely applied in environmental remediation due to its exceptional surface chemistry. Graphene-based adsorbents such as graphene oxide (GO) and GO-coated silica nanoparticles possess oxygen-rich functional groups that enable chromium removal via electrostatic interaction [33]. GO, in particular, also supports hydrogen bonding, enhancing Cr(VI) adsorption. These materials additionally remove chromium through redox reactions, ion exchange, and surface complexation. Notably, the high oxygen content allows GO to chemically reduce toxic Cr(VI) to the less harmful Cr(III), improving environmental safety.

GO synthesis can occur via dry or wet methods. Dry preparation involves oxidizing graphene with oxygen and ultraviolet light, while the wet approach uses acidic media [33]. However, certain acids like nitric acid release harmful $NO_x$ gases (e.g., nitrogen dioxide), which can aggravate respiratory conditions such as bronchitis and asthma. To mitigate such risks, researchers advocate for safer oxidants like potassium permanganate.

To enhance chromium removal efficiency, graphene adsorbents are often functionalized with metal oxides such as goethite, gadolinium, or ferrihydrite. These modifications significantly boost adsorption capacity. For example, GO combined with such functional groups has demonstrated chromium uptake levels up to 342 mg/g [33]. Similarly, Nirmala et al. [34] found that graphene composites could remove approximately 90% of heavy metals from contaminated water. Additionally, Tadjenant et al. [35]. synthesized rGO/PEI-KOH nanocomposites, achieving an outstanding Cr(VI) adsorption capacity of 398.9 mg/g at low pH. Despite their high performance, the synthesis and functionalization of graphene materials can be time-consuming. Therefore, further research is recommended to streamline production processes and improve the scalability of graphene-based adsorbents.

### 3.2 Natural and Modified Materials

#### Clay Minerals and Zeolites

Clay minerals, widely found in rocks and soils, are effective adsorbents for chromium removal due to their small particle size (<2 μm), large surface area, and porous structure [36]. Typically classified as crystalline or amorphous, the most functional crystalline clays, such as kaolinite, illite, attapulgite, and sepiolite-possess layered structures composed of silica tetrahedra and hydroxyl-rich octahedral sheets, which enable high adsorption capacity[36] Their structural framework, enriched with hydroxyl groups and metal cations, facilitates hydrogen bonding, ion exchange, electrostatic interaction, and surface complexation. Due to isomorphic substitution within layers, these clays maintain a net negative charge, making them highly reactive toward positively charged chromium species [36].

The dual ionic nature of clays containing both cations and anions further supports Cr(VI) and Cr(III) adsorption through diverse mechanisms, primarily ion exchange and electrostatic attraction [37, 38]. The adsorption performance of clay materials is influenced by several factors, including pH, temperature, contact time, and mixing speed. Lower pH and temperature generally improve Cr(VI) removal, as do increased adsorbent dosages and mixing speeds, which enhance surface interaction with the contaminant.

Modified clays, such as surfactant-treated bentonite, show improved efficiency. Castro-Castro et al. [39] demonstrated that bentonite modified with surfactants exhibits optimal Cr(VI) adsorption at pH 3 an acidic condition favoring the presence of hydrogen chromate, which binds more effectively to the clay surface. In contrast, elevated pH leads to species less readily adsorbed, reducing efficacy[40]. Higher stirring speeds improve contact between the adsorbent and chromium ions, while increased adsorbent quantity provides more active sites, further improving removal rates [39]. Bentonite's advantages also include low cost, wide availability, and environmental compatibility[41].

Despite their long-standing use, clays remain relevant due to their chemical versatility. Ashour and Tony (2020) emphasized that their modifiability via thermal or chemical treatment significantly enhances functional group reactivity and adsorption capacity.

In contrast, zeolites another class of naturally occurring aluminosilicates primarily rely on their extensive porosity and electrochemical activity for contaminant removal. Their crystalline framework contains abundant micro- and mesopores, which facilitate high adsorption capacities, reportedly exceeding 90% in some cases [42, 43]. Additionally, zeolites contain reactive functional groups that support ion exchange processes with metal ions like Cr(VI), contributing to their effectiveness in aqueous remediation[44].

#### Natural Polymers

Natural polymers such as cellulose, lignin, and chitosan are abundant, biodegradable, and non-toxic materials derived from plants and animals, making them suitable for removing contaminants from aqueous solutions. Their chemical and biological reactivity allows them to interact effectively with various pollutants. Studies by Majigsuren et al.[45], Samani and Toghraie [46] and Zhang and Tian [47] have highlighted their capacity for ion exchange and redox-based removal of heavy metals like chromium.

Cellulose, for example, possesses both reductive and non-reductive functional groups, along with crystalline and amorphous regions bearing hydroxyl groups. Although its ion exchange capacity is relatively low, it has demonstrated efficacy in redox-mediated contaminant removal [47]. Lignin, a major component of wood, features a complex structure composed of hydroxyl-rich monomers such as dimethoxycinnamyl and hydroxycinnamyl alcohols [18]. These structures provide acidic sites that enable lignin to effectively adsorb metal ions, primarily through ion exchange.

To improve performance, natural polymers can be chemically or physically modified. Majigsuren et al. [45] reported enhanced Cr(VI) and Cr(III) adsorption when chitosan was combined with clay, particularly under acidic conditions. Similarly, Samani and Toghraie [46] observed that the adsorption capacity of polyaniline-based composites depended significantly on pH, contact time, and dosage. These findings underscore the importance of structural enhancement and environmental conditions in optimizing natural polymer-based adsorbents for chromium remediation.

**Agricultural Waste-derived Adsorbents**

Agricultural materials have also become some of the most useful adsorbents in treating contaminated water. Indeed, agricultural remains may have unique adsorption capabilities because they contain virtually all the features needed to neutralize or remove contaminants. Besides, adsorbents obtained from agricultural remains are abundant and may not cost anything [48-50]. Studies in this area have utilized experimental approaches to determine the ability of adsorbents to remove contaminants. In one experiment based on Cucumis melo, El Kassimi et al.[50] adsorbents from agricultural remains have carboxyl and other functional groups, which enhance their adsorption. They also contain pores and electrostatic sites, which facilitate contaminant adsorption. Amir et al. [48] clarify this point by indicating that agricultural adsorbents use their functional groups to remove Cr(VI) through ion exchange.

### 3.3 Synthetic and Functionalized Adsorbents

Synthetic adsorbents come from a combination of polymers that link to form structures of multiple pores [51]. Functionalized adsorbents are chemically modified materials that can remove contaminants from water. This section focuses on these materials.

**Metal-Organic Frameworks**

The metal–organic frameworks (MOFs) are among the most widely studied synthetic adsorbents for water treatment applications. Structurally, MOFs consist of metal ions or clusters coordinated with organic ligands to form highly porous, crystalline polymers [52]. Common MOF types such as UiO-66, ZIF-67, and MIL-53 exhibit several advantageous properties for adsorption, including large surface areas, tunable pore sizes, and chemical flexibility. These characteristics make MOFs particularly effective in removing hexavalent chromium Cr(VI) from aqueous media.

As reported by Lin et al. [52], the adsorption performance of MOFs is strongly influenced by environmental parameters such as pH, contact time, and adsorbent dosage. Maximum Cr(VI) uptake is typically observed under acidic conditions, with performance improving with longer contact times and higher MOF dosages, though this enhancement plateaus beyond optimal thresholds.

Importantly, the presence of positively charged metal sites, such as magnesium, facilitates Cr(VI) removal through mechanisms such as physical sorption and ion exchange [53]. Additionally, MOFs possess unique photocatalytic properties that contribute to their versatility. García et al.[54] highlighted the capacity of MOFs to reduce Cr(VI) to the less toxic Cr(III) via photocatalytic processes, enabled by their hybrid composition of metal oxides and organic linkers. This redox transformation further enhances the environmental safety and efficacy of MOF-based remediation strategies.

***Functionalized Nanomaterials***

Nanomaterials, characterized by their ultra-small particle size and high surface-area-to-volume ratio, exhibit unique photocatalytic properties that enable them to transfer charges and catalyze chemical reactions efficiently [55]. These materials encompass a broad range of structures, including nanofibers, nanoparticles, nanocomposites, nanowires, nanotubes, nanohorns, and nanorods. Their intrinsic surface reactivity allows for interaction with various chemical species, making them highly suitable for environmental remediation.

Functionalization of nanomaterials typically achieved through chemical processes such as covalent bonding or surface modification further enhances their physicochemical properties and broadens their application potential. This process improves surface functionality, promotes selectivity, and significantly increases adsorption or catalytic performance.

In the context of chromium-contaminated water, functionalized nanomaterials are particularly effective due to their ability to facilitate photocatalytic reduction processes [56]. For instance, nano zero-valent iron (nZVI) rapidly reduces Cr(VI) to Cr(III), precipitating and immobilizing it on its surface, making it a promising nanomaterial for chromium removal [57].

Owing to their wide bandgap conduction structures, these materials are easily photoactivated under light exposure, generating electron-hole pairs that drive redox reactions [58, 59]. Specifically, Cr(VI) is reduced to the less toxic Cr(III) species during these processes. Since light is a readily available and sustainable energy source, the use of photoactive nanomaterials represents a promising and environmentally friendly strategy for hexavalent chromium remediation.

**Hydrogels and Aerogels**

Hydrogels are materials consisting of polymer chains linked together in an aqueous medium [60]. Some natural hydrogels are fibrin, gelatin, and hyaluronic acid. An aqueous solution and cations in hydrogels enable them to remove Cr(VI) through precipitation and floatation [61]. Precipitation involves allowing the metal to settle at the bottom of the solution, while floatation is causing the metal to float on the solution's surface. Hydrogels also utilize their polymer characteristics, such as oxides and positive and negative charges, to remove hexavalent chromium through ion exchange and reduction processes [62, 63].

Aerogels are ultralight, highly porous materials formed by replacing the liquid phase of a gel with gas. Typically composed of silica, oxides, or carbon, they possess high surface area, electrical conductivity, and thermal stability [64]. These properties make them highly effective for environmental applications, particularly in removing hexavalent chromium Cr(VI) from aqueous solutions. Chromium removal occurs via redox reactions, ion exchange, and electrostatic attraction, facilitating the reduction of Cr(VI) to the less toxic Cr(III) form [65].

### 3.4 Bioadsorbents

**Algae, Fungi, and Bacterial Biomass**

Bioadsorbents are adsorption materials based on biological processes. Indeed, most contain biomass from bacteria, fungi, algae, and other biological organisms [66]. Besides being abundant and harmless to the environment, this adsorbent category has several qualities that make it suitable for chromium adsorption, such as cations and reactive elements [67]. That is why microbial materials have gained popularity in the water treatment field [68, 69].

**Modified Bioadsorbents**

Usually, modification alters the physical and chemical qualities of a material, making it capable of functioning better. When microbial biomass undergoes this process, it can adsorb more contaminants than the natural material [70]. Saravanan et al.[71] reveal that modified biological materials remove 25% more contaminants than natural materials. That means modification can help with the limitations depicted by these adsorbents with respect to the amount of contaminants they can remove within a particular time.

## 4. COMPARATIVE PERFORMANCE AND REAL-WORLD APPLICATIONS

### 4.1 Comparison of Adsorbent Performance

Table 1 summarizes the key performance metrics and operating conditions of the various chromium adsorbents discussed throughout this review, providing a comparative perspective on their efficiency and regeneration potential.

Table 1. Comparison of adsorbent performance

| Adsorbent Name | Adsorbent Type | Max.Ads. Capacity (mg/g) | Optimum Conditions | Regeneration Cycles | Ref |
|---|---|---|---|---|---|
| Activated carbon | Carbon-based | 75 | Low PH, large surface area, low temperature | Drying, vaporization, and heating at high temperatures | [23] |
| Biochar | Carbon-based | 157.9 | High temperatures | Freezing, drying, and subjecting to oxides or microorganisms | [31] |
| CNTs | Carbon-based | 168.5 | High temperatures | Two main phases: heating at high temperatures and treating using chemicals like hydrochloric acid | [32] |
| Graphene-based Materials | Carbon-based | 342 | Higher PH and temperatures | Oxidation or heating at high temperatures | [33] |
| Clay minerals | Natural | 136 | Low PH and temperature | Main method is treating the used clay using chemical reagents | [37] |
| Zeolites | Natural | 13.5 | Low PH and temperature | The main phases are treatment using ultraviolet photolysis, oxidation, and increasing temperatures | [42] |
| Natural polymers Cellulose | Natural | 40 | Low PH and temperature | Three phases: treating using chemical reagents and high temperatures and adjusting the PH | [47] |
| Agricultural waste-derived adsorbents | Natural | 50 | Medium PH, low temperature (some), and high temperature (some) | Two phases: treating with chemical reagents and high temperatures | [18] |
| MOFs | Synthetic | 333 | Low PH, low temperatures | One phase: exposing used MOFs to high temperatures | [52] |
| Functionalized nanomaterials | Synthetic and functionalized | 398 | Low PH and temperature | Three phases: heating at high temperatures, treating with chemical reagents, and oxidation. | [35] |
| Hydrogels | Synthetic | 13 | Medium PH level and low temperature | Two phases: adjusting the PH and applying a chelating agent | [62] |
| Aerogels | Synthetic | 289 | Low PH and high temperature | Two phases: heating and treating with sodium hydroxide and hydrochloric acid | [64] |
| Algae, fungi, and bacteria biomass | Bioadsorbent | 58 | Medium PH Level | One phase: treating with chemical reagents or heating | [66] |

### 4.2 Applications in Real Wastewater

**Studies That Test Adsorbents Using Industrial Effluents Instead of Synthetic Solutions**

An experiment by Rao et al.[72] examined the extent to which fly ash, AC, sawdust and other materials could treat wastewater from industries operating in Hyderabad, India. The findings show that the adsorbents significantly reduced the effluents' physicochemical parameters, such as chlorides, calcium, and phosphates. However, the effectiveness is different across the adsorbents. For instance, AC achieved the highest impact on chloride reduction, while sawdust had an insignificant effect. Amuda and Ibrahim [73] compared the effectiveness of adsorbing organic matter from beverage plant wastewater between coconut shell-based AC and calgon carbon (commercial carbon). Ultimately, the coconut-derived AC removed far greater organic matter compared to the commercially available form of the AC. Based on this finding, beverage manufacturers or communities may not have to incur costs purchasing commercial AC materials. Instead, they may collect coconut shells and prepare an adsorbent from it, given that this AC has been proven to be effective in treating wastewater from beverage plants. Rana et al.[74] conducted another project to clarify the usefulness of agricultural materials in eradicating industrial wastewater contaminants. The results confirm that adsorbents from agricultural remains effectively treat wastewater discharged from industries, especially when they act in favorable PH, temperature, and dosage conditions[75].

**Overcoming Practical Limitations in Real Wastewater Treatment**

Most emerging adsorbents show promise in removing heavy metals like chromium; however, several challenges still hinder their effectiveness. One key issue is the limited adsorption capacity no current material has demonstrated complete removal of Cr(VI) or Cr(III). This can be mitigated by optimizing adsorbent properties such as surface area, pore size, and porosity to enhance performance over time [76]. Another important challenge is the lack of selectivity, as many adsorbents indiscriminately interact with both harmful contaminants and essential water constituents. This non-specific uptake can lead to the removal of beneficial minerals such as calcium and magnesium, which are important for health and water quality. To overcome this, adsorbents can be engineered with functional groups such as thiol, amine, or carboxyl that promote selective binding to target contaminants. These modifications enhance electrostatic interactions, redox activity, and complexation, thereby improving specificity and overall adsorption performance [76-78].

### 4.3 Challenges and Future Perspectives

Recent advancements in chromium removal have led to the development of a wide range of adsorbent materials, including carbon-based, natural, synthetic, functionalized, and bio-based adsorbents. These materials have demonstrated improved adsorption capacities, environmental compatibility, and operational simplicity. However, despite notable progress, no single adsorbent has yet achieved complete and selective removal of chromium species across diverse environmental conditions. Many existing materials lack the specificity required to differentiate between target contaminants and essential constituents, occasionally leading to the unintended removal of benign or beneficial molecules, such as vital minerals or water itself. This lack of selectivity and consistency limits their practical applicability in real-world scenarios. To overcome these limitations, multidisciplinary collaboration is essential to drive the rational design of next-generation adsorbents. Hybrid systems that combine multiple functional materials or integrate adsorption with complementary treatment processes may provide synergistic advantages. Furthermore, the incorporation of emerging technologies such as machine learning, high-throughput screening, and data-driven material optimization offers a transformative pathway for designing smart adsorbents with tunable surface chemistries and enhanced target specificity. In parallel, future research should prioritize field-scale validation, lifecycle assessments, and regulatory compliance to ensure that these materials are not only technically effective but also scalable, safe, and aligned with long-term environmental sustainability goals.

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