

Review Article

Sorption mechanisms and materials for mitigating heavy metal contamination in soil and water systems - A review

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Abstract

Heavy metal contamination in soil and water systems represents a persistent environmental challenge due to the non-degradable nature, toxicity, and bioaccumulative behavior of metallic pollutants. Sorption-based remediation has emerged as a widely applied and adaptable approach for reducing metal mobility, bioavailability, and ecological risk across diverse environmental settings. This review critically examines recent advances in sorption mechanisms, materials, modeling approaches, and field applications for minimizing heavy metal contamination. Key sorption processes, including ion exchange, surface complexation, electrostatic attraction, precipitation, and redox transformations, are discussed in relation to metal speciation and environmental conditions. The performance of natural sorbents, biochar and carbon-based materials, and engineered and nanostructured sorbents is evaluated, with emphasis on their advantages, limitations, and suitability for soil and water remediation. Progress in sorption modeling and kinetics is reviewed to highlight the role of equilibrium isotherms, kinetic models, and mechanistic frameworks in predicting system behavior and supporting scale-up. Field applications demonstrate the practical potential of sorption technologies but also reveal challenges associated with material stability, competitive sorption, long-term effectiveness, and economic feasibility. Finally, future research directions are outlined, focusing on sustainable material development, integration of sorption with complementary remediation strategies, and improved translation of laboratory findings to real-world conditions. Overall, this review underscores the continued importance of sorption-based technologies in achieving effective and sustainable management of heavy metal contamination in soil and water environments.

Keywords: Heavy metals, Sorption mechanisms, Soil and water remediation, Biochar, Natural sorbents, Nanostructured sorbents, Adsorption modeling, Environmental sustainability

Introduction

Heavy metal contamination of soil and water has become a critical global environmental issue as a consequence of rapid industrialization, mining operations, fossil fuel combustion, agricultural intensification, and improper disposal of industrial and municipal wastes (Alloway, 2018). Toxic metals such as lead (Pb), cadmium (Cd), chromium (Cr), arsenic (As), and mercury (Hg) are particularly problematic due to their persistence, non-biodegradability, and ability to bioaccumulate in food chains, leading to long-term ecological and human health risks (Tchounwou *et al.*, 2019).

Soil and aquatic environments contaminated with heavy metals pose serious threats to agricultural productivity, groundwater quality, and ecosystem stability. Elevated metal concentrations adversely affect soil microbial communities, enzymatic activities, and nutrient cycling, ultimately reducing soil fertility and crop yield (Kumar *et al.*, 2021). In aquatic systems, heavy metals can remain dissolved or adsorbed onto suspended particles and sediments, facilitating their transport and entry into drinking-water supplies (Briffa *et al.*, 2020).

Conventional remediation methods, including soil excavation, solidification–stabilization, chemical precipitation, and membrane filtration, are often limited

by high operational costs, incomplete metal removal at low concentrations, and the generation of secondary pollutants or sludge (Fu & Wang, 2019). These limitations have encouraged the development of alternative remediation approaches that are more cost-effective, environmentally sustainable, and suitable for large-scale or in situ applications (Song *et al.*, 2022).

Sorption-based remediation has emerged as one of the most promising strategies for minimizing heavy metal contamination in soil and water. Sorption processes enable the immobilization or removal of metal ions through physicochemical interactions between contaminants and solid surfaces, offering simplicity, high efficiency, and operational flexibility (Ismail *et al.*, 2024). The effectiveness of sorption is governed by multiple mechanisms, including electrostatic attraction, ion exchange, surface complexation, chelation, pore filling, surface precipitation, and redox transformations, depending on metal speciation and environmental conditions (Li *et al.*, 2022).

Recent advances have led to the development of a wide variety of sorbent materials with enhanced metal uptake capacities. Natural materials such as clays, zeolites, and agricultural residues have been widely studied due to their abundance and low cost, particularly

for soil remediation applications (Ismail *et al.*, 2024). Engineered sorbents, including activated carbon, metal-oxide-based materials, graphene oxide, carbon nanotubes, and metal–organic frameworks (MOFs), exhibit superior sorption performance owing to their high surface areas, tunable pore structures, and functionalized surfaces (Hua *et al.*, 2020).

Among emerging materials, biochar has attracted considerable attention as a sustainable sorbent because of its low production cost, environmental compatibility, and ability to immobilize heavy metals while improving soil physicochemical properties (Ahmad *et al.*, 2019). Surface modification of biochar and other sorbents using metal oxides or functional groups has further enhanced metal selectivity and binding strength (Gao *et al.*, 2022). However, the performance of sorbents in real environmental systems is often affected by competitive sorption in multi-metal systems, pH variability, and long-term stability issues (Lin *et al.*, 2024).

Therefore, a comprehensive understanding of sorption mechanisms, material properties, and environmental interactions is essential for optimizing sorbent design and ensuring long-term remediation effectiveness. This review critically examines recent advances (2018-2025) in sorption mechanisms and materials for minimizing heavy metal contamination in soil and water, with emphasis on performance, sustainability, and future research needs.

Heavy metal contamination in soil and water systems

Heavy metal contamination in soil and water systems has become an increasingly urgent environmental concern due to anthropogenic activities such as industrial discharge, mining, waste disposal, and wastewater irrigation (Xu *et al.*, 2024). Metals such as cadmium (Cd), lead (Pb), chromium (Cr), arsenic (As), mercury (Hg), and zinc (Zn) are persistent environmental pollutants that accumulate in soils and aquatic sediments, posing long-term risks to ecosystem health and human well-being (Mustapha *et al.*, 2025). These pollutants have high toxicity even at trace concentrations and can enter the food chain through crops irrigated with contaminated water or grown on polluted soils (Rashid *et al.*, 2023). A less conventional but increasingly noted source is pharmaceuticals themselves, which can introduce metals such as platinum, gadolinium, and arsenic into soil and water; this contribution is considered in a later section.

In soil environments, heavy metals alter physicochemical properties and disturb soil microbial communities, which can suppress enzyme activity and degrade soil fertility (Angon *et al.*, 2024). Soil pH and organic carbon levels also influence heavy metal mobility and bioavailability, affecting their potential to migrate into groundwater or surface water systems (Adnan *et al.*, 2025). Contaminated soils near abandoned smelting sites often show high levels of cadmium and arsenic, indicating that historical industrial activities continue to affect current soil quality (Adnan *et al.*, 2025).

Heavy metals in water originate from point sources such as industrial effluents and non-point sources including agricultural runoff. Once in water, metals may remain dissolved or adsorb onto suspended particles, increasing their transport potential across watersheds (Madjar & Scăteanu, 2025). Chronic exposure to heavy metal-contaminated water is associated with serious health risks including carcinogenic and non-carcinogenic effects in humans (Tripathi *et al.*, 2025). Addressing heavy metal contamination therefore requires integrated monitoring, risk assessment, and remediation strategies that account for both soil and water pathways.

Fundamentals of sorption processes

Sorption is a broad term encompassing physisorption and chemisorption processes that control how solutes partition between liquid/soil phases and solid surfaces; these processes underpin many remediation strategies for heavy metals in soil and water (Alkhaldi *et al.*, 2024). Physisorption is driven by weak, non-specific forces (van der Waals, hydrogen bonding, dipole interactions) and is typically reversible and fast, whereas chemisorption involves formation of specific chemical bonds (coordination, covalent or ionic) and is usually slower but more permanent (Pourhakkak *et al.*, 2021). Experimental characterization of sorption commonly uses equilibrium isotherms (Langmuir, Freundlich, Temkin and newer multi-component extensions) to represent capacity and surface heterogeneity, and kinetic models (pseudo-first/second order, intraparticle diffusion) to describe rate-controlling steps (Murphy *et al.*, 2023). Surface complexation models link molecular binding (functional groups, surface sites) to macroscopic sorption behavior and are particularly useful for predicting pH- and ionic-strength dependence of metal uptake (Cojocaru *et al.*, 2024). Ion exchange, electrostatic attraction, surface precipitation (including hydroxide/carbonate formation), and redox transformations are distinct but often concurrent mechanisms that determine metal fate; their relative importance depends on metal speciation, pH, competing ions, and sorbent chemistry and texture (El Jery *et al.*, 2024). Biosorption and polymeric sorbents add biologically or synthetically derived functional groups (amine, carboxyl, thiol) that enhance selectivity and capacity for target metals (Jadoun *et al.*, 2023). Traditional natural sorbents such as clays and zeolites remain relevant because of low cost and ion-exchange capability, often serving as benchmarks for engineered materials (Ismail *et al.*, 2024). A mechanistic, multi-scale understanding — from site-level binding to column- and field-scale behavior — is essential for rational sorbent design and reliable performance prediction.

Factors influencing heavy metal sorption

Sorption of heavy metals in soils and waters is controlled by a combination of soil/water chemistry, mineralogy and sorbent properties that together determine metal speciation, mobility and bioavailability. Soil and solution pH is often the single most important control: increasing pH generally increases negative surface charge and promotes cation sorption and metal precipitation, while acidic conditions

mobilize many metals (Palansooriya *et al.*, 2020). Organic matter and humic substances supply complexing functional groups (carboxyl, phenolic, thiol) that both enhance metal retention through complexation and sometimes increase apparent mobility via soluble organo-metal complexes (Welikala *et al.*, 2021). Clay mineralogy and metal (hydr) oxide content set the density of high-affinity sorption sites and cation-exchange capacity (CEC), so soils rich in illitic/kaolinitic clays or iron oxides typically show higher retention of Pb, Cu and As (Liu *et al.*, 2023). Competing cations, ionic strength and dissolved anions (e.g., sulfate, phosphate) alter site occupancy and complexation equilibria and can suppress or enhance sorption in multi-metal systems (Yang *et al.*, 2018). Sorbent texture — surface area, porosity and particle size — determines access to internal sites and affects kinetics; fine, high-surface-area biochars and modified clays show faster uptake and higher capacities (Bayar *et al.*, 2024). Temperature and redox conditions control redox-sensitive metals (Cr, As), with reducing environments favoring less mobile species in some cases (Peel *et al.*, 2022). Finally, aging, microbial activity and field-scale processes (leaching, wet–dry cycles) modify sorption over time and can either stabilize or remobilize sorbed metals, so lab results must be validated under local field conditions (Palansooriya *et al.*, 2020).

Natural sorbent materials

Natural sorbent materials have been extensively studied in Europe and Australia as sustainable, low-cost options for mitigating heavy metal contamination in soil and water systems. These materials, which include natural zeolites, clay minerals, peat, and biochar derived from agricultural or biosolid wastes, are attractive due to their abundance, minimal processing requirements, and environmental compatibility (Belviso, 2020). Their sorption performance is governed by inherent physicochemical properties such as surface area, cation-exchange capacity, mineral composition, and the presence of reactive functional groups.

Natural zeolites, particularly clinoptilolite, are among the most widely applied sorbents in European remediation studies. Their high cation-exchange capacity and structural stability enable effective removal of metal ions such as Pb^{2+} , Cd^{2+} , and Zn^{2+} from aqueous systems, while mild chemical activation further enhances selectivity and capacity (Velarde *et al.*, 2023). Clay minerals such as bentonite and montmorillonite also exhibit strong affinity for heavy metals due to their layered structures and negatively charged surfaces, which promote ion exchange and surface complexation mechanisms (Wang *et al.*, 2024).

Organic natural sorbents, including peat and Sphagnum moss, have been widely investigated in northern and central Europe. Their high content of humic substances provides abundant carboxylic and phenolic groups capable of forming stable metal complexes, although sorption performance may vary with pH and redox conditions (Astolfi *et al.*, 2024). In Australia, unmodified and minimally processed biochars derived from biosolids and agricultural residues have shown considerable potential for immobilizing heavy metals in

soils, simultaneously improving soil structure and reducing metal bioavailability (Aktar *et al.*, 2024).

Despite their advantages, natural sorbents often exhibit variability in performance due to source heterogeneity and environmental conditions. Consequently, recent European and Australian research emphasizes careful characterization and targeted modification to ensure reliable, long-term remediation outcomes (Senila & Cadar, 2024). Beyond the divalent metals that dominate this literature, natural sorbents of this kind have occasionally been applied to less conventional targets. Waste plant biomass, for example, has been used to take up gadolinium of the sort released by magnetic resonance imaging (MRI) contrast agents (Ogata *et al.*, 2025), a connection taken up in the section on pharmaceutical-derived metals below.

Biochar and carbon-based sorbents

Biochar and other carbon-based sorbents have emerged across South Asia and the Middle East as affordable, scalable options to immobilize or remove heavy metals from soils and waters, while simultaneously improving soil physical properties and crop resilience (Faizan *et al.*, 2024). Field and pot studies from Pakistan show that biochar amendments can significantly reduce plant uptake and soil mobility of cadmium and other toxic metals, with effectiveness depending strongly on feedstock and application rate (Murad *et al.*, 2024). Regional work demonstrates that pyrolysis temperature and feedstock selection control biochar pH, surface area and cation-exchange capacity — key predictors of metal sorption and liming potential in alkaline soils common in arid parts of the Middle East (Murtaza *et al.*, 2024).

In India, nano- and modified-biochars are gaining attention for enhanced sorption and plant-protective effects under heavy-metal stress, with several studies reporting improved crop growth and lower shoot metal concentrations following nano-biochar or functionalized biochar application (Faizan *et al.*, 2024). Middle-Eastern research has also focused on value-added carbon sorbents: date-seed-derived activated carbons and chemically modified carbons (e.g., thiourea functionalization) show high Pb and Cd uptake from water, offering locally sourced, low-cost adsorbents for wastewater treatment (AlShahrani *et al.*, 2024). Novel feedstocks such as camel dung or water-hyacinth biochar have been evaluated regionally and show promising adsorption capacities, further expanding locally available sorbent options (Wilson *et al.*, 2024; Ullah & Rahman, 2024).

Engineered and nanostructured sorbents

Engineered and nanostructured sorbents have gained considerable attention over the past decade due to their high surface areas, tunable pore structures, and customizable surface chemistries, which enable superior performance in heavy-metal remediation compared with conventional sorbents (Deshwal *et al.*, 2023). These materials include graphene-based sorbents, magnetic nanoparticles, metal–

organic frameworks (MOFs), metal-oxide nanomaterials, and multifunctional nanocomposites, all of which are designed to enhance sorption capacity, selectivity, and kinetics under complex environmental conditions (Karnwal & Malik, 2024).

Graphene oxide (GO) and reduced graphene oxide (rGO) are among the most widely studied nanostructured sorbents because of their high specific surface area and abundance of oxygen-containing functional groups that facilitate electrostatic attraction and surface complexation with metal ions (Mokoena & Mofokeng, 2023). Recent studies report high removal efficiencies for Pb(II), Cd(II), and Cr(VI), particularly when GO is incorporated into polymeric or metal-oxide composites to prevent aggregation and improve mechanical stability (Melchor-Durán *et al.*, 2024). Functionalization with amine, thiol, or carboxyl groups further enhances selectivity toward specific metals (Deshwal *et al.*, 2023).

Magnetic nanoadsorbents, typically based on Fe₃O₄ or Fe₂O₃ cores, have been extensively explored because their magnetic properties allow rapid and efficient separation after treatment (Sibiya *et al.*, 2025). Surface modification with silica, biopolymers, or chelating ligands improves chemical stability and metal affinity, while enabling multiple regeneration cycles with minimal capacity loss (Barozzi *et al.*, 2022). These materials have shown promising performance for Cu, Ni, Pb, and As removal in aqueous systems (Naseer, 2024).

Metal-organic frameworks (MOFs) represent another advanced class of engineered sorbents characterized by extremely high porosity and well-defined binding sites. Recent non-Chinese reviews emphasize the development of water-stable MOFs and MOF-derived carbons that maintain structural integrity under aqueous conditions while providing high metal uptake (Alsehli, 2023). Composite approaches, such as MOF-carbon or MOF magnetite hybrids, aim to overcome limitations related to hydrolytic stability and cost (Yang *et al.*, 2023).

Metal-oxide nanomaterials, including TiO₂, ZnO, MnO_x, and CeO₂, have also been engineered for heavy-metal sorption through surface complexation, redox reactions, and precipitation mechanisms (Olawade *et al.*, 2024). These oxides are particularly effective for redox-sensitive metals such as chromium and arsenic. However, concerns regarding nanoparticle release, ecotoxicity, and life-cycle impacts remain significant challenges for large-scale application (Karnwal & Malik, 2024).

Overall, while engineered and nanostructured sorbents demonstrate exceptional laboratory-scale performance, future research focuses on scalable synthesis, long-term stability, regeneration, and environmental safety to support real-world implementation (Naseer, 2024).

Sorption modeling and kinetics

Quantitative description of sorption processes is essential for translating laboratory batch results into

predictions of field behavior and for designing treatment systems. Kinetic models are used to interpret rate data and to infer rate-controlling steps: the pseudo-first-order and pseudo-second-order (PSO) models remain the most commonly applied empirical rate laws, with PSO often giving superior fits for many metal-adsorbent systems; however, critics point out that PSO is largely descriptive and can lack mechanistic predictive power unless linked to mass-transfer limitations or sorbate concentration dependence (Bullen *et al.*, 2020; Revellame *et al.*, 2020). Recent work has therefore focused on making kinetic models more predictive — for example by modifying PSO to include explicit dependences on initial sorbate and sorbent concentrations or by separating external film diffusion, intraparticle diffusion and surface reaction steps through multi-step rate formulations (Bullen *et al.*, 2020; Revellame *et al.*, 2020; Tran, 2023).

Interpreting kinetic fits correctly requires careful experimental design: early-time sampling, appropriate mixing, and consideration of sorbent particle size and agitation are critical because poor practice can cause misleading rate constants and mis-assignment of mechanisms (Tran, 2023). Mechanistic discrimination is best achieved by coupling rate models with complementary diagnostics — e.g., intraparticle diffusion plots, estimation of film-mass transfer coefficients, and evaluation of how rate constants scale with particle radius or solution concentration — rather than relying solely on goodness-of-fit metrics (Revellame *et al.*, 2020; Tran, 2023).

Equilibrium isotherm modeling remains central to sorption studies. Classical isotherms (Langmuir, Freundlich, Temkin) are widely used to estimate capacities and heterogeneity, but modern practice recognizes their limitations for predictive multi-component systems. Work since 2018 has emphasized advanced and multicomponent isotherms (Sips, Redlich-Peterson and recent multicomponent frameworks) that can describe competitive adsorption and surface heterogeneity more accurately; newly proposed multicomponent models (e.g., JAMM and related formulations) improve fitting across binary and ternary systems and support mechanistic interpretation of competition and site-blocking effects (Acharya *et al.*, 2023; Amrutha *et al.*, 2023; Chu *et al.*, 2024).

For environmental prediction (soils, sediments, aquifers), surface complexation models (SCMs) bring more mechanistic rigor by representing discrete surface sites, site protonation equilibria and explicit ion-pairing/complexation constants; SCMs (constant-capacitance, diffuse-layer, triple-layer models) have been successfully applied to metal sorption on oxides, clays and biochars and are indispensable when pH-dependence and specific ion effects must be captured (Shi *et al.*, 2021; Sun & Li, 2021). SCMs also form the chemical kernel for reactive-transport models used to simulate coupled advection-dispersion and sorption in porous media (Stolze & Rolle, 2022; Samborska-Goik & Pogrzeba, 2024).

Reactive-transport modelling platforms (e.g., PHREEQC, HYDRUS, TOUGHREACT) integrate SCM or kinetic sorption modules with hydrodynamic transport and geochemical reactions to predict long-term metal fate and remediation outcomes; recent reviews highlight best practices for parameterization (use of batch and column experiments to constrain site densities, binding constants and rate parameters) and stress the need for uncertainty analysis and validation against field data (Samborska-Goik & Pogrzeba, 2024; Zhao *et al.*, 2024). Meanwhile, data-driven approaches — neural networks and machine-learning models — are proving useful to predict adsorption capacity and kinetics when mechanistic parameterization is infeasible, although they should complement rather than replace mechanistic models for risk-sensitive decisions (Fiyadh *et al.*, 2023).

Field applications and limitations

Field application of sorption-based remediation technologies has increased over the past decade, particularly for in situ stabilization of heavy metals in contaminated soils and for ex situ treatment of industrial and municipal wastewaters. Natural and engineered sorbents such as biochar, clays, zeolites, iron-based materials, and carbon composites have been applied at pilot and field scales to reduce metal mobility, bioavailability, and ecological risk (Ahmad *et al.*, 2019; Song *et al.*, 2022). In soil systems, sorbents are commonly incorporated through mixing or amendment strategies to immobilize metals and limit plant uptake, while in water treatment they are used in fixed-bed columns, permeable reactive barriers, or batch reactors (Song *et al.*, 2022).

Despite demonstrated effectiveness, several limitations constrain large-scale deployment. Field performance often deviates from laboratory results due to soil heterogeneity, variable pH and redox conditions, competing ions, and organic matter interactions that reduce sorption efficiency (Yang *et al.*, 2023). Long-term stability is a major concern, as aging, wet–dry cycles, and microbial activity may alter sorbent structure and promote gradual metal remobilization (Chen *et al.*, 2023). In aqueous systems, fouling, hydraulic clogging, and pressure losses can limit operational lifespan of sorbent beds.

Economic and environmental considerations also influence feasibility. High-performance nanomaterials and engineered sorbents often face cost, scalability, and regulatory barriers, while regeneration and disposal of metal-laden sorbents require careful management to avoid secondary pollution (Deshwal *et al.*, 2023). Consequently, recent field studies emphasize hybrid approaches, combining sorption with phytoremediation, chemical stabilization, or biological treatments to enhance robustness and sustainability. Overall, while sorption technologies are promising, their successful field application requires site-specific design, long-term monitoring, and integration with complementary remediation strategies.

Pharmaceutical derived heavy metals as an emerging sorption challenge

Industrial, mining, and agricultural activity accounts for most of the contamination discussed so far, but it is not the whole picture. Metal-bearing pharmaceuticals are a smaller and less familiar contributor, and a growing one. The concern is not the organic drug molecules that dominate most micropollutant studies, but the metal each compound carries (Li *et al.*, 2021). These reach soil and water in forms that have little in common with the free divalent cations most sorbents are built to capture, which is exactly why they belong in a review of sorption.

Consider platinum (Pt) first. The cytotoxic drugs cisplatin, carboplatin, and oxaliplatin are only partly metabolised, so a fraction leaves the body unchanged and moves through sewage, most concentrated in hospital effluent, into surface water (Li *et al.*, 2021). Among anticancer agents they fare badly for aquatic toxicity: cisplatin is one of the most hazardous compounds in the class, and platinum complexes as a group show the highest acute toxicity (Li *et al.*, 2021). Platinum is genuinely scarce in natural waters, yet medical and automotive use keep adding to it, leaving an accumulating burden whose recovery happens to carry real economic value (Suzuki Mashio *et al.*, 2019).

Gadolinium (Gd) tells a similar but better-documented story. Now treated as a heavy metal and rare-earth element of environmental concern (Inoue *et al.*, 2025), it enters water through magnetic resonance imaging (MRI) contrast agents. Patients excrete these complexes within hours, and conventional treatment lets them through almost untouched, producing the anthropogenic gadolinium anomaly recorded in rivers, groundwater, and tap water (Brünjes & Hofmann, 2020; Inoue *et al.*, 2025). The trend is not trivial: Berlin tap water saw roughly a thirty-fold rise between 2009 and 2021 (Krohn *et al.*, 2024). Mostly the metal stays bound in its original chelate rather than releasing free gadolinium (Gd^{3+}), although some degradation under particular treatment conditions is now recognised (Brünjes & Hofmann, 2020).

Arsenic (As) arrives by a different and largely agricultural route. Roxarsone, an organoarsenical fed to poultry, passes almost entirely into the litter, with mass-balance studies recovering something like 86-108% of what the birds ingest, and that litter is then spread on fields as fertiliser (Gupta *et al.*, 2018). In the soil, microbes break it down into inorganic arsenic that is both more mobile and more toxic, so the path runs cleanly from a veterinary drug to soil and, with runoff, to surface water (Wu *et al.*, 2024).

Speciation is the thread tying the three together, and the reason they matter to sorption. None appears as the free divalent cation, lead (Pb^{2+}), cadmium (Cd^{2+}) or copper (Cu^{2+}), that most sorbents reviewed here are tuned to capture. Platinum moves as chloro- and related anionic complexes, arsenic as the oxyanions arsenate and arsenite, and gadolinium stays wrapped in a stubbornly stable chelate

(Suzuki Mashio *et al.*, 2019; Wu *et al.*, 2024; Inoue *et al.*, 2025). A material built to bind cations will do little with any of them, so removal turns on chemical form rather than on the amount of metal present.

The sorbent families surveyed in this review offer plausible starting points, though work on these particular metals remains preliminary. Functionalised chitosan, crown-ether sorbents, and layered double hydroxides have been explored for platinum-group recovery (Grad *et al.*, 2021; Cochechi *et al.*, 2022), and a small number of biomass- and framework-based adsorbents have been tested for gadolinium (Ogata *et al.*, 2025). One mismatch keeps surfacing: gadolinium adsorbents are usually demonstrated against the free gadolinium (Gd^{3+}) ion, whereas the gadolinium actually present in the environment is the intact chelate that resists adsorption (Brünjes & Hofmann, 2020; Ogata *et al.*, 2025). Pharmaceutical-derived metals, with their assortment of chemical forms, thus remain an open challenge for sorbent design and a worthwhile direction for future work.

Conclusions and future perspectives

Sorption-based approaches have emerged as effective and versatile strategies for mitigating heavy metal contamination in soil and water systems. Advances in understanding sorption mechanisms, material design, and process modeling have significantly improved the ability to immobilize or remove toxic metals under a wide range of environmental conditions. Natural sorbents such as clays, zeolites, and biochar offer cost-effective and environmentally compatible options, while engineered and nanostructured sorbents provide enhanced capacity, selectivity, and kinetics. Together, these developments highlight sorption as a central component of sustainable remediation frameworks.

Despite substantial progress, several challenges remain that limit large-scale and long-term implementation. Variability between laboratory and field performance, uncertainties in sorbent aging and stability, and the influence of complex, multi-contaminant environments continue to affect reliability. In addition, economic constraints, scalability of advanced materials, and management of spent sorbents require careful consideration to avoid secondary pollution. Addressing these limitations is essential for transitioning sorption technologies from controlled experiments to widespread field application.

Future research should prioritize the integration of mechanistic understanding with realistic field conditions, emphasizing long-term performance, regeneration strategies, and life-cycle assessment. The development of hybrid remediation systems that combine sorption with biological, chemical, or physical treatments holds promise for improving robustness and sustainability. Advances in modeling, data-driven optimization, and monitoring technologies are expected to enhance predictive capability and support site-specific design. Ultimately, continued interdisciplinary efforts will be critical to advancing

sorption-based remediation toward reliable, scalable, and environmentally responsible solutions for managing heavy metal contamination.

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