

HEAVY METAL EXTRACTION FROM WASTEWATER USING POLYVINYL ALCOHOL- BASED SUPERABSORBENTS: A NARRATIVE REVIEW

Muskan Salaria
Lalita Chopra
Carlo Santulli¹
Cristiano Fragassa

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ABSTRACT

Industrial activities contribute significantly to environmental pollution, particularly through the release of hazardous contaminants into water bodies. Water treatment is essential for reusing it in agriculture, industry, and services, and, in its purest form, for food production and human use. Heavy metals, such as Ni(II), Cr(III) and Cr(VI), Pb(II), Hg(II), and Zn (II), are among the major industrial contaminants in water. Several innovative methods and technologies can contribute to wastewater treatment, including ion exchange, chemical reduction and oxidation, precipitation, and membrane filtration techniques, such as reverse osmosis. In the case of contamination from heavy metal ions, their adsorption from aqueous medium can be considered a highly efficient method. Among polymer-based adsorbents, such as chitosan, starch, and cellulose, poly(vinyl alcohol) (PVA) has attracted considerable attention for its water solubility, non-toxicity, biodegradability, and high potential for chemical modification via grafting and crosslinking. Although PVA presents limitations such as low mechanical properties and limited intrinsic functionality, its adsorption performance can be significantly improved through copolymerization and other modification strategies. This review provides an overview of PVA modification approaches to enhance the adsorption capacity of hydrogel-based PVA polymers for heavy metal sorption. Particular attention is given to the use of monomers such as 2-hydroxyethyl methacrylate (HEMA), acrylic acid, and acrylamide, as well as crosslinkers such as *N,N'*-methylenebisacrylamide (MBA), boric acid, and citric acid. Finally, the prospects of modified PVA-based hydrogels in terms of efficiency, affordability, and sustainability for water treatment are discussed.



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¹ Corresponding author: Carlo Santulli
E-mail: carlo.santulli@unicam.it

1. INTRODUCTION

Although water plays a fundamental role in sustaining life on Earth, only about 2.5% of the planet's water is freshwater, over 68% of which is locked in ice and glaciers, so that surface freshwater in rivers and lakes represents only a very small fraction of the total water supply (Shiklomanov, 1993; U.S. Geological Survey). Water contamination can occur naturally, owing to phenomena such as soil erosion, volcanic activity, and geogenic processes, or anthropogenically through industrial discharge, mining activities, agricultural runoff, and the accumulation of waste. The continuous release of untreated wastewater into aquatic environments has therefore become a major global concern (Akhtar et al., 2021). The anthropogenic contamination of water from distinct industrial activities like electroplating, battery manufacturing, and food processing becomes a threat to potable water as it discharges various heavy metals into the aquatic system. Heavy metals such as mercury, lead, chromium, zinc, and cadmium are among the most concerning environmental contaminants because of their toxicity and adverse effects on ecosystems (Vardhan et al., 2019). In aquatic environments, these elements are commonly present as dissolved ionic species, whose removal from wastewater represents a crucial challenge in environmental remediation. Indeed, heavy metal ions are non-biodegradable, persistent, and capable of accumulating in living organisms even at low concentrations (Fu & Wang, 2011). In this context, adsorption has attracted considerable attention because of its operational simplicity, relatively low cost, high efficiency, and suitability for treating dilute metal-contaminated effluents (Barakat, 2011). Furthermore, the environmental relevance of heavy metal contamination is amplified by the fact that several metals may exert toxic effects through multiple mechanisms, including oxidative stress, interference with cellular functions, and disruption of physiological processes (Jaishankar et al., 2014). V. Singh et al. (2024) conducted research on the removal of toxic metal ions from contaminated water using eco-friendly methods. Chronic exposure to polluted water can lead to various health problems, such as damage to the liver and kidneys, nervous system impairment, and increased abnormalities in newborn children.

Among pollutants, heavy metal ions have attracted considerable attention because of their high toxicity, persistence, and non-biodegradability. Z. Zhang et al. (2025) recently reviewed the relevance of heavy metal contamination in wastewater and the potential of cellulose-based hydrogels for their removal. Hama Aziz et al. (2023) reported that metal ions such as nickel, lead, chromium, and arsenic can be released into water bodies through industrial effluents, mining activities, and other waste streams, causing harmful effects on aquatic ecosystems and human health. Unlike organic pollutants, heavy metals are not degraded in the environment and

may progressively accumulate in living organisms, as discussed by Nnaji et al. (2023). Moreover, Saidon et al. (2024) highlighted that their transfer along aquatic food chains can lead to biomagnification, increasing the exposure risk for higher trophic levels. Naz et al. (2025) explained in their study how metal ions move into the food chain and affect human health. It explains the concept of biomagnification, which indicates an increase in metal ion concentration at higher trophic levels in a food chain and can lead to various health issues, including neurological disorders, kidney and liver damage etc. These poisonous metal ions not only give severe effects to human health but also disrupt the ecological balance. These heavy metal ions can change the physical and chemical properties of water and reduce the oxygen level, which has a severe effect on both plants and animals, along with humans. Sanusi et al. (2025) in their study examined the ecotoxicological consequences of heavy metal bioaccumulation, which causes oxidative stress and disruption of enzymatic and metabolic processes, hence negatively impacting the existence, growth, and reproduction of living organisms. This study also emphasized the remediation potential of hybrid systems, based e.g., on macroalgae structured in a carbon nanotube composite.

More generally, several technologies have been investigated for the removal of toxic metal ions from contaminated water, including chemical precipitation, electrochemical treatments, ion exchange, adsorption, and membrane-based processes. Xu et al. (2023), for instance, investigated combined chemical–microbial reduction strategies for Cr(VI) stabilization, while Xu et al. (2020) developed graphene oxide-based membranes for textile wastewater treatment. Biodegradable polymers have also attracted increasing attention in this field. In the field of biopolymers, Sun et al. (2019) proposed novel chitosan-based flocculants for the removal of Cr and Ni ions from chromic acid lotion and electroplating wastewater through integrated chelation and flocculation. In adsorption, pollutants from the aqueous phase accumulate onto the surface of a solid adsorbent. This process has proven effective at removing heavy metal ions from contaminated water, even at very low concentrations. Rajendran et al. (2022) provided a broad overview of recent developments in adsorption-based techniques for heavy metal removal from wastewater. More specifically, Sui et al. (2026) focused on biomass-based adsorbents, Ezzeddine et al. (2025) reviewed organically modified mesoporous silica, Upadhyay et al. (2021) discussed chitosan-based adsorbents, and Rani et al. (2020) examined metal–organic framework adsorbents for the elimination of toxic heavy metals from aqueous solutions. However, this advantage is generally less evident in other treatment methods. Qasem et al. (2021) highlighted that conventional technologies such as chemical precipitation, ion exchange, and membrane filtration may involve high operational costs and complex process management. In contrast, adsorption using microalgal biomass was identified as a sustainable

and effective alternative for the removal of heavy metals, particularly at low contaminant concentrations. The main adsorbent properties affecting heavy metal removal include surface area, porosity, and the presence of functional groups. Ijagbemi et al. (2009) investigated the role of montmorillonite surface properties in the sorption of heavy metals from aqueous solutions. Selvakumar et al. (2023) highlighted the importance of three-dimensional porous adsorbent structures, such as hydrogels and aerogels, for water treatment applications. Liu et al. (2019) showed that functional groups can also be introduced through biomimetic strategies, as in the case of SiO₂-chitosan composites for heavy metal removal from drinking water. Overall, a wide range of adsorbent materials has been explored for removing heavy metal ions from water, including activated carbon (M. Zhang et al., 2023), clays, polymer-based materials, and, more recently, agricultural waste-derived adsorbents (Arthi et al., 2021). Chemically modified agricultural residues have also been investigated as low-cost adsorbents for heavy-metal uptake. Senthil Kumar et al. (2012) reported the adsorption of Cu(II), Cd(II), Zn(II), and Ni(II) from aqueous solutions, showing that surface modification of polysaccharidic biomass-derived materials can improve metal-ion binding, providing a useful benchmark for the potential use of biopolymers in this field.

Since then, polymeric adsorbents have attracted increasing attention because of their structural flexibility, chemical stability, and possibility of introducing functional groups able to enhance adsorption capacity. In this context, poly(vinyl alcohol) (PVA) is particularly interesting because it is a synthetic, non-toxic, biodegradable, and water-soluble polymer bearing hydroxyl groups distributed along its backbone. These groups can interact with metal ions through hydrogen bonding, electrostatic interactions, and coordination mechanisms, making PVA a versatile platform for water remediation. Its potential has already been explored in the treatment of textile dye-contaminated wastewater (Mushtaq et al., 2022). Moreover, PVA can be processed into different geometries and architectures, including hydrogels (Liang et al., 2024) and hierarchical composite structures (Dhiman et al., 2020), nanocomposite films e.g., in combination with carbon nanotubes (Youssef et al., 2019), and aerogels. In particular, engineered PVA aerogels have recently shown promising performance for mercury removal from wastewater, supported by their chemical stability and hydrophilic nature (Sun et al., 2024).

However, native PVA employed in water treatment also presents some limitations, including limited adsorption capacity toward metal ions, mainly due to the insufficient density of specific binding functional groups, and the need for improved structural stability in aqueous environments (Kloknicer et al., 2025). Also, as deemed necessary for further use, PVA and related polymers have been discussed in terms of their biodegradability (Amann

et al., 2011), while PVA-based composite systems have been developed to overcome these limitations. For example, Chen et al. (2023) prepared multifunctional PVA/chitosan hydrogel membranes for the purification of emulsified oil wastewater containing Pb(II) ions, reporting a Pb(II) removal efficiency of 97.44%. Crosslinking and grafting strategies can further enhance the water stability, surface area, and density of active functional groups in PVA-based adsorbents. In this respect, Tian et al. (2019) showed that electrospinning PVA with suitable crosslinkers can produce stable nanofibrous adsorbents for heavy metal removal. More broadly, crosslinked PVA-based membranes have been widely investigated for water treatment applications because the formation of a three-dimensional network improves their resistance to dissolution in aqueous media (Choudhury et al., 2021).

Another important feature of PVA is its swelling behavior, which plays a significant role in adsorption processes. Due to its hydrophilic nature, PVA can absorb water, swell, and form a porous network, thereby facilitating the diffusion of metal ions into the polymer matrix and promoting stronger adsorbate-adsorbent interactions. This behavior can be further improved by blending PVA with other polymers, such as alginate. For instance, Zhang et al. (2022) developed alginate-PVA double-network hydrogels using a biomass-resource strategy and demonstrated their effectiveness in adsorbing heavy metals.

In recent years, numerous studies have focused on the development of advanced PVA-based adsorbents for the treatment of contaminated water. Accordingly, this review provides a comprehensive overview of PVA-based superadsorbents for the removal of heavy metal ions from aqueous media, highlighting their potential as effective, sustainable materials for environmental remediation.

2. METHODOLOGY

2.1. Literature search strategy

A literature search was conducted to identify relevant studies on poly(vinyl alcohol)-based adsorbents for the removal of heavy metal ions from contaminated water. The search was performed using major scientific databases, including Scopus, Web of Science, ScienceDirect, SpringerLink, Wiley Online Library, ACS Publications, MDPI, and Google Scholar. The literature search focused mainly on papers published between 2000 and 2026, with particular attention to recent studies published in the last five years.

The main keywords and combinations used during the search included: “poly(vinyl alcohol)”, “PVA”, “PVA hydrogel”, “PVA composite”, “PVA adsorbent”, “PVA membrane”, “PVA nanofiber”, “PVA aerogel”, “heavy metal adsorption”, “metal ion removal”, “wastewater

treatment”, “water remediation”, “Pb(II) removal”, “Cd(II) removal”, “Cr(VI) removal”, “Ni(II) removal”, “Cu(II) removal”, “Zn(II) removal”, and “Hg(II) removal”. Additional terms such as “crosslinking”, “grafting”, “functionalization”, “chitosan”, “cellulose”, “alginate”, “graphene oxide”, “biochar”, and “magnetic adsorbents” were also used to refine the search.

The selected literature included original research articles and review papers dealing with heavy metal contamination, adsorption mechanisms, conventional water-treatment technologies, and the development of PVA-based materials for environmental remediation. Particular attention was given to studies reporting adsorption capacity, removal efficiency, adsorption mechanisms, regeneration ability, and structural or chemical modification strategies of PVA-based adsorbents.

2.2 Selection Criteria and Scope of the Review

The literature collected through the search process was screened for relevance to the objectives of this review. Priority was given to peer-reviewed journal articles reporting the synthesis, characterization, modification, and application of poly(vinyl alcohol)-based materials for the adsorption of heavy metal ions from aqueous media. Both experimental studies and review papers were considered.

Studies focusing on PVA hydrogels, composite adsorbents, nanofibers, aerogels, membranes, and chemically modified PVA systems were included. Particular attention was paid to investigations reporting adsorption mechanisms, adsorption capacity, removal efficiency, kinetic and isotherm models, regeneration performance, and the influence of material composition and structure on adsorption behavior.

The review also includes selected studies on the environmental impacts of heavy metal contamination, conventional wastewater treatment technologies, and adsorption fundamentals to provide the necessary scientific background and to contextualize the role of PVA-based adsorbents within the broader field of water remediation.

Conference abstracts, patents, non-peer-reviewed documents, and studies not directly related to heavy metal removal or PVA-based adsorption systems were generally excluded unless they provided essential background information or historical context. The scope of this review is therefore focused on the development of advanced PVA-based adsorbents and their application in the removal of heavy metal ions from contaminated water, with particular emphasis on Pb(II), Cd(II), Cr(III)/Cr(VI), Ni(II), Cu(II), Zn(II), and Hg(II).

2.3 Review Framework

The methodological framework adopted in this review is schematically illustrated in Figure 1 (see Appendix). The review was structured according to a progressive and problem-driven approach, connecting the broader environmental challenge of heavy metal contamination with the design and application of advanced poly(vinyl alcohol) (PVA)-based adsorbents for water remediation.

The framework first considers the global context of water scarcity and the increasing demand for clean water, emphasizing how limited freshwater availability makes contamination control a critical priority. The main sources of water contamination are then identified, including industrial effluents, agricultural activities, and urban or domestic wastewater. Within this context, heavy metals are considered particularly relevant because of their persistence, non-biodegradability, toxicity even at low concentrations, and tendency to accumulate in environmental and biological systems.

The review then examines the risks associated with heavy metal contamination, including bioaccumulation, biomagnification, and pollution of soil, water, and air. Specific attention is given to the main sources of heavy metals, such as mining, smelting, electroplating, battery production, tannery and textile industries, agricultural inputs, waste disposal, irrigation, and natural or geogenic contributions. Their environmental impacts are discussed in relation to soil degradation, reduced fertility, microbial imbalance, plant uptake, food-chain transfer, water-quality deterioration, aquatic toxicity, and atmospheric contamination through metal-containing particulates.

After defining the environmental problem, the framework compares conventional remediation methods, including chemical precipitation, ion exchange, membrane filtration, coagulation–flocculation, electrochemical treatments, solvent extraction, biological treatment, and constructed wetlands. Their established effectiveness is acknowledged, but their practical limitations are also considered, especially high operational costs, process complexity, sludge or secondary pollution generation, and reduced efficiency at low contaminant concentrations. These limitations justify the need for more sustainable and efficient removal technologies.

From this perspective, adsorption is a promising solution due to its high efficiency, operational simplicity, cost-effectiveness, and suitability for removing metal ions even at low concentrations. The review therefore analyzes adsorption mechanisms, distinguishing between physical adsorption, mainly based on van der Waals forces, hydrogen bonding, and electrostatic interactions, and chemical adsorption, involving coordination, ion exchange, and stronger chemical interactions.

Building on this background, the review focuses on PVA as an adsorbent platform. PVA is discussed in terms of its key properties, including hydrophilicity, abundance of hydroxyl groups, high water affinity, swelling behavior, film-forming ability, biodegradability, and non-toxicity. The interaction between PVA-based materials and heavy metal ions is then examined through hydrogen bonding, electrostatic attraction, and coordination complex formation. Different PVA forms and structures, such as hydrogels, beads, membranes, nanofibers, and porous systems, are considered for their role in increasing surface area, porosity, adsorption capacity, kinetics, recovery, and reuse.

The framework also highlights the development of PVA-based composite adsorbents, where performance can be enhanced by incorporating magnetic materials, inorganic fillers, carbon-based materials, biopolymer blends, and natural or low-cost fillers. These combinations can improve recovery, mechanical strength, functionality, surface area, conductivity, sustainability, and cost-effectiveness. In parallel, crosslinking and chemical modification strategies are discussed as key routes to obtain three-dimensional networks with controlled swelling, improved mechanical and chemical stability, increased active-site density, and better adsorption performance.

Finally, the performance of PVA-based materials for heavy metal removal is critically discussed in relation to adsorption capacity, mechanisms, kinetics, thermodynamics, regeneration, and practical applicability. Overall, the framework provides a logical pathway from environmental need to material design, showing how PVA-based adsorbents may contribute to the efficient, sustainable, cost-effective, and environmentally friendly removal of heavy metals from contaminated water.

2.4. Review Overview

Following the methodological framework described above, the review is organized according to a progressive and interconnected structure that guides the reader from the general context of heavy-metal contamination to the specific role of poly(vinyl alcohol)-based adsorbents in water remediation.

The discussion begins with an overview of heavy-metal pollution, including its principal sources, environmental consequences, and potential impacts on human health. Conventional remediation technologies are subsequently introduced to provide a broader technological background and to highlight the advantages and limitations of currently available treatment approaches. The review then moves to adsorption processes, presenting the fundamental adsorption mechanisms and the main factors influencing adsorption performance. This section establishes the theoretical basis necessary

for understanding the interaction between heavy metal ions and adsorbent materials.

Building on these concepts, the focus shifts to poly(vinyl alcohol), whose physicochemical characteristics, adsorption-related properties, and suitability for environmental applications are examined. The different strategies adopted to improve the performance of PVA-based materials are subsequently presented, including structural modification, functionalization, and the development of composite systems incorporating additional organic, inorganic, or carbon-based components.

The following sections discuss the operational parameters affecting adsorption efficiency and illustrate the application of PVA-based materials in various water-treatment scenarios. Finally, the review concludes with an analysis of the main advantages and current limitations of PVA-based superadsorbents, followed by considerations on future research directions and their potential contribution to sustainable wastewater-treatment technologies.

3. HEAVY-METAL POLLUTION: SOURCES, IMPACTS AND REMEDIATION STRATEGIES.

3.1 Heavy metal sources

Heavy metals, such as Pb (II), Cr (VI), Zn (II), Hg (II), etc., are naturally occurring and highly toxic elements. These metallic elements have high density and atomic mass, generally exceeding 5 g/cm³. Although these metals are found naturally in the Earth's crust, human activities make their persistence more hazardous and toxic to ecosystems. Industrial activities are among the major sources of heavy metal discharge into potable water, as summarized in Table 1. Wu et al. (2024) studied groundwater quality by analyzing the concentrations of cadmium, nickel, lead, and arsenic in an industrial area in southwest China, revealing high non-carcinogenic and carcinogenic risks to residents and indicating rapid contamination of drinking water. In that case, cadmium and arsenic originated from packaging and printing industry, bioengineering, and pharmaceutical industry, while iron was obtained from wine and beverage manufacturing, and the cement and concrete industry, and chromium more specifically derived from the innovative materials industry. However, the origins can be multifarious: Mokarram et al. (2020) studied the effects of toxic metal ions in the Kor River in southern Iran, particularly due to industrial discharges from petrochemical industries and sugar mills, with heavy metal discharges affecting both potable water and soil. Nasim et al. (2026) revealed the effect of cadmium, chromium, nickel, and lead on agricultural soil for different cultivations, namely cucumber, wheat, green chili, potato, ladyfinger (S5), and tomato, specifically concentrating on crop productivity and soil fertility.

Table 1. Sources and harmful impacts of most diffused and dangerous heavy metal ions

Heavy Metal Ions		Major sources	Harmful effects
Lead	Pb ⁺²	Mining industries, battery industries	Kidney disorders and neurological damage (Lentini et al., 2019)
Cadmium	Cd ⁺²	Fertilizers, electroplating industries, dyes and pigments	Skeleton deformities, lung and kidney disorders (Reyes-Hinojosa et al., 2019)
Nickel	Ni ⁺²	Refining industries, mining, steel industries, batteries	Skin problems, memory loss, damage to the nervous system (Rafati Rahimzadeh et al., 2025)
Hexavalent chromium	Cr ⁺⁶	Paint industries, dyes, and electroplating factories	Respiratory disorders, skin allergies, liver and kidney disorders (Chatterjee, 2015)
Mercury	Hg ⁺²	Coal combustion, pharmaceutical industries	Brain dysfunction and development problems in children (Chamoli & Karn, 2024)

3.2 Environmental impacts

Due to their persistence and bioaccumulation potential, heavy metals have a considerable impact on the environment. Unlike many organic pollutants, they do not readily degrade and can remain for long periods in soil, water, and sediments. Their prolonged presence may alter the physicochemical properties of water and negatively affect aquatic ecosystems, and therefore, specifically planning and tailoring their removal is essential (Xia et al., 2019). In the specific case of mercury, Kayani and Mohammed (2025) highlighted additional concerns related to its transformation into methylmercury in aquatic environments, which can significantly increase its toxicity. This is a point for its selective removal, which was attempted by Zhao and Zhang (2025) through PVA/chitosan composites. More generally, chronic heavy metal contamination is associated with several environmental issues, including degradation of water quality, soil contamination, and broader ecological impacts (P. Zhang et al., 2023). Human exposure may also increase the risk of severe health effects, including carcinogenic outcomes and neurological disorders (Singh et al., 2023). Such

exposure can occur through different routes, mainly inhalation, ingestion, and dermal absorption (Xu et al., 2024).

Some points need to be further detailed, in particular:

a. Soil degradation: Significant amounts of discharged metals, such as cadmium, nickel, and lead, can reduce soil quality, productivity, and crop yield. When metal concentrations exceed regulatory threshold values, they may reduce microbial diversity and alter nutrient cycling; affecting the soil biota and the ecological functions it supports (Adagunodo et al., 2018). Tian et al. (2025) showed that heavy metal contamination can alter soil microbial diversity and disrupt biological functions associated with the cycling of carbon, nitrogen, phosphorus, and sulfur. In particular, changes were observed in microbial taxa such as Bradyrhizobium, Nitrospira, Steroidobacter, and Luteitalea. As depicted in Figure 2, heavy metals present in contaminated agricultural soils, although generally nonessential or toxic to crops at elevated concentrations, may impair crop health and pose a significant environmental risk (Rashid et al., 2023).

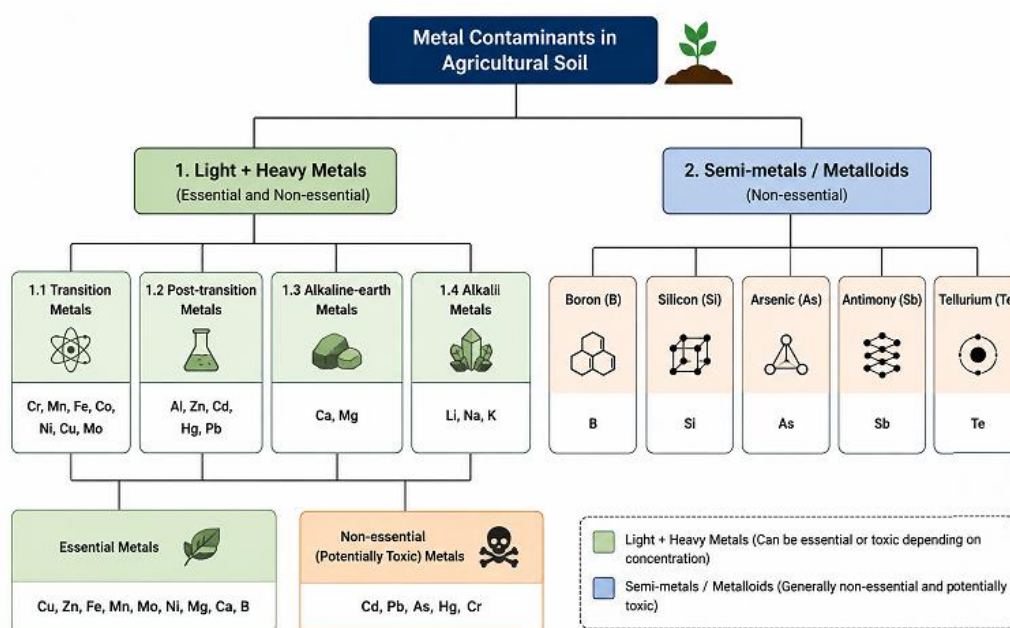


Figure 2. Classification of metals and metalloids in soil (adapted from authors)

b. Aquatic pollution: Excessive industrial discharge into water bodies can cause several ecological problems, including changes in species composition, food-web disturbances, and broader ecosystem imbalance. Although this topic still requires further investigation, Zahran et al. (2025) reviewed heavy metal accumulation in fish and reported oxidative stress and histopathological alterations across different aquatic habitats. Tuska et al. (2025) further showed that heavy metal contamination, particularly involving Cd and Fe, can impair the physiological and reproductive health of female Nile tilapia (*Oreochromis niloticus*).

c. Atmospheric contamination: Particulates containing heavy metals are mainly released into the atmosphere through mining activities, industrial emissions, combustion processes, and traffic-related sources, representing a serious health concern. Prolonged inhalation of air contaminated with toxic metals such as cadmium, nickel, and lead can affect different organs and systems, including the respiratory, nervous, and renal systems (Jomova et al., 2025). Chen et al. (2025) recently monitored PM_{2.5}-bound metals and metalloids in Wuxi, China, from 2020 to 2023, showing that fine particulate matter can act as a carrier of potentially toxic elements and may contribute to non-carcinogenic and carcinogenic health risks.

3.3 Removal Methods

To prevent the bioaccumulation of heavy metals in living tissues, more tailored and effective removal methods are

required. Several conventional physicochemical technologies have been used to remove toxic metal ions from contaminated water, as summarized in Figure 3, including ion exchange, membrane filtration, coagulation–flocculation, reverse osmosis, chemical precipitation, and electrochemical treatments. Among them, chemical precipitation is widely used because of its relative simplicity, accessibility, and affordability. Benalia et al. (2022) investigated this approach for the removal of Cu(II) and Zn(II) from industrial wastewater using lime, caustic soda, and soda ash, also characterizing the resulting sludge. In precipitation-based treatments, chemical reagents are added to convert dissolved metal ions into poorly soluble hydroxides or related solid phases, which can then be separated by sedimentation and filtration. However, Haas et al. (2019) showed that filtration may also remove insoluble metal oxides and hydroxides, potentially affecting the interpretation of metal removal mechanisms.

Although conventional methods can reduce metal concentrations in polluted water, they may have limitations, including reduced effectiveness at low metal concentrations, high operating costs, secondary pollution, and the generation of sludge that requires further management (Camargo et al., 2016). Among recovery-oriented alternatives, Kumar et al. (2021) reviewed biogenic sulfide precipitation as an emerging strategy for heavy metal recovery from wastewater, although this approach remains distinct from adsorption-based polymer systems.

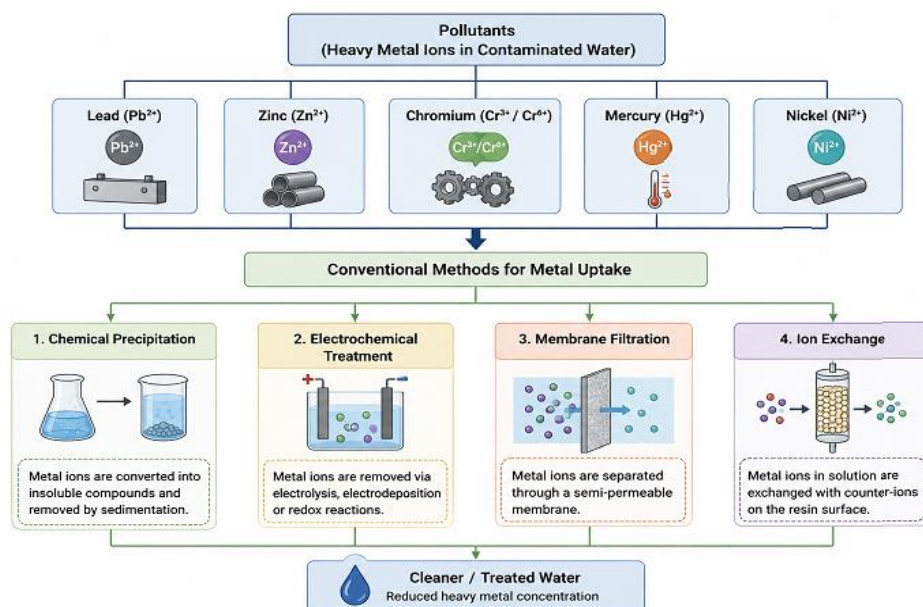


Figure 3 Flow chart representing conventional methods for metal uptake (from authors)

Ion exchange is another widely used method for removing metal ions from aqueous media (Dąbrowski et al., 2004). This technique is based on the reversible exchange of toxic metal ions with less harmful counter-ions bound to a solid ion-exchange resin or matrix.

Hubicki and Kołodyńska (2012) described ion exchange as an effective approach for the selective removal of heavy metal ions from water and wastewater, also highlighting the possibility of resin regeneration and reuse. Despite its high selectivity and efficiency, its

practical application may be limited by operating costs, resin fouling, and the need for repeated regeneration. Similarly, membrane filtration and reverse osmosis have shown high effectiveness for metal ion removal, but their large-scale industrial application can be constrained by high energy demand, membrane cost, fouling, and complex operating conditions (Fei et al., 2023). More recently, Joshi et al. (2026) reviewed a broad range of heavy metal removal technologies from water, including adsorption, membrane-based processes, ion exchange, and electrochemical treatments, discussing their mechanisms, recent advancements, and implementation challenges.

4. ADSORPTION PRINCIPLE AND MECHANISM

4.1 Principle of Adsorption

In recent years, adsorption has been considered one of the most sustainable, eco-friendly, and effective methods for removing toxic metal ions from polluted water, owing to its high efficiency, commercial viability, and operational simplicity. Adsorption is generally defined as the accumulation of ions, molecules, or atoms from liquid or gas phases onto the surface of a solid material. It can be interpreted through different theoretical models and surface-interaction mechanisms, which help explain the affinity between adsorbates and active sites on solid adsorbents (J. Wang & Guo, 2020; L. Wang et al., 2020; Ahmed Alsharif, 2025). In this context, the adsorbate is the species retained on the solid surface, while the adsorbent is the material that provides the active surface sites.

Toxic metals such as lead, cadmium, nickel, and arsenic can enter water bodies through industrial effluents, posing serious risks to ecosystems and human health. Although several technologies are available for their removal, adsorption is widely considered particularly advantageous because it can effectively capture metal ions even at low concentrations (Qasem et al., 2021; Shrestha et al., 2021). Its performance is influenced by several parameters, including surface area, pore-size distribution, surface chemistry, functional groups, temperature, contact time, pH, and initial metal-ion concentration. In particular, adsorbents with large surface areas and high densities of active sites generally exhibit greater adsorption capacities, as they provide more available sites for metal-ion binding (Chakraborty et al., 2022).

4.2 Adsorption types

Adsorption is generally divided into two major types based on the type of interaction between the adsorbate and the adsorbent surface: (i) physisorption, also called physical adsorption, and (ii) chemisorption, also called chemical adsorption.

a. Physical Adsorption

The adsorption occurs between the adsorbent surface and adsorbate molecules through weak intermolecular forces, such as van der Waals interactions, hydrogen bonding and electrostatic interactions called physical adsorption. The limited strength of these interactions makes them reversible and more applicable at low temperatures, thereby allowing easy desorption of adsorbed molecules from the surface. This can occur through an increase in temperature, whether or not subsequent to pressurization, thereby increasing kinetic energy, while the adsorption process does not require the formation of new chemical bonds between adsorbate and adsorbent (Crini & Lichtfouse, 2019). Therefore, physical adsorption generally occurs at high pressure and low temperature and may lead to the formation of numerous layers of adsorbate molecules on the adsorbent surface. After the formation of the initial layer, additional layers accumulate due to intermolecular attractions among adsorbate molecules. This form of adsorption has a low energy requirement, in the order of 5-40 kJ/mol, and typically has a relatively low activation barrier (Aljamali et al., 2021). Physisorption processes are the most effective and suitable for materials with large surface areas and porous structures. Some of the commonly and frequently used adsorbents for this process are activated carbon, also from biochar, silica gel, zeolites and polymer-based materials (Shakoor et al., 2020). These materials offer an extensive range of adsorption sites where adsorbate molecules can interact weakly. In wastewater treatment applications, physical adsorption plays a significant role in removing harmful and toxic contaminants, including dyes, organic matter, and heavy metal ions.

b. Chemisorption (Chemical adsorption)

Chemical adsorption, or chemisorption, involves stronger interactions between adsorbates and surface sites, often including coordination or the formation of chemical bonds. In metal-ion removal, complexation with hydroxyl, amine, or carboxyl groups and ion exchange may contribute to uptake. The relative contributions of these mechanisms depend on the adsorbent, metal species, and solution conditions (Shakoor et al., 2020).

In wastewater treatment, adsorption processes are widely used because of their simplicity, versatility, and ability to remove different classes of contaminants (Aljamali et al., 2021). Materials with large surface areas and porous structures, such as activated carbon, biochar-based sorbents, silica-based materials, zeolites, and polymer-based adsorbents, can provide numerous sites for pollutant retention. In the specific case of heavy metal removal, Shakoor et al. (2020) also showed that biochar-based sorbents can retain metal ions through multiple mechanisms, including physical binding, electrostatic interactions, ion exchange, surface precipitation, and

complexation. Therefore, although physical adsorption contributes to heavy metal uptake, the overall removal mechanism often involves both physical and chemical interactions.

5. PVA AS AN ADSORBENT

PVA is a synthetic, non-toxic, biodegradable, and water-soluble polymer widely investigated in water-treatment applications because of its chemical stability, film-forming ability, hydrophilicity, and ease of processing. Its structure contains repeating vinyl alcohol units bearing numerous hydroxyl groups, which can contribute to interactions with pollutants through hydrogen bonding, electrostatic interactions, and coordination-related mechanisms.

Matabola et al. (2023) reviewed PVA-based nanofibrous materials for azo-dye adsorption, while Mok et al. (2020) discussed PVA and PVA-based polymer composite adsorbents for dye removal. Although these studies mainly concern organic pollutants rather than heavy metal ions, they demonstrate the versatility of PVA-based materials in wastewater treatment. More broadly, Ahmaruzzaman et al. (2023) reviewed polymeric hydrogel-based materials for wastewater treatment, showing that their porous structure, tunable chemistry, and high-water affinity make them suitable for removing both organic and inorganic contaminants.

The hydroxyl groups distributed along the PVA chain are important for its sorption behavior, as they can interact with dissolved pollutants and facilitate water uptake. Due to its hydrophilic nature, PVA-based structures can swell in aqueous media, increasing the accessibility of internal adsorption sites and improving diffusion within the polymer matrix. Parameters such as molecular weight, degree of hydrolysis, and crosslinking density can further affect the stability and adsorption performance of PVA-based materials. Although not specifically focusing on PVA, Williams et al. (1998) compared different biosorbents for the removal of metal ions from aqueous solutions, supporting the broader relevance of functional polymeric and biopolymeric materials for metal-ion uptake.

5.1 PVA-Based Composite Adsorbents

PVA has become an important polymer matrix for the development of composite adsorbents in environmental remediation, particularly for the removal of heavy metal ions from contaminated water. The adsorption capacity and structural stability of pure PVA can be enhanced by incorporating natural or synthetic polymers, inorganic fillers, and nanomaterials. For instance, Areal et al. (2018) proposed PVA-based magnetic gels for heavy metal removal, combining the adsorption capability of PVA networks with easier material recovery after treatment.

PVA can also be blended with inorganic components to improve selected physical properties. For example, Pingan et al. (2017) developed transparent silica/PVA hybrid materials with enhanced thermal stability and mechanical strength, although this study was not directly focused on wastewater treatment. In water-remediation applications, PVA matrices have been combined with graphene oxide and kaolinite clay in aerogel form, as reported by Joshi et al. (2022), or structured with magnetic GO-Ni-Fe₂O₄ nanoparticles for heavy metal removal, as shown by Moustafa et al. (2022).

PVA has also been blended with polysaccharides to obtain composite hydrogel adsorbents. Wang and Wang (2016) prepared PVA/carboxymethylcellulose hydrogels for heavy metal ion removal, while Trikkaliotis et al. (2022) reviewed chitosan/PVA adsorbents for wastewater treatment. Similarly, W. Wang et al. (2021) reported a reusable porous semi-IPN hydrogel based on alginate and PVA for fast and efficient Pb(II) adsorption. In addition, Zhou et al. (2022) prepared a PVA/waste oyster shell powder composite for heavy metal adsorption from wastewater, highlighting the possibility of combining PVA with low-cost mineral waste to obtain more sustainable adsorbent systems.

5.2 Functionalization of PVA

a. Three-Dimensional Crosslinked PVA Matrix

To improve the mechanical stability and chemical resistance of PVA materials, crosslinking and chemical modification play significant roles. Many crosslinking agents, including MBA, boric acid, and citric acid, are used to form a three-dimensional network structure with controlled swelling, an essential feature for water treatment (M. Zhang et al., 2024). In practice, more adsorption sites are available for greater adsorption, while also preventing polyvinyl alcohol from dissolving in water. For example, in the MBA-crosslinked PVA adsorbent, the modified polymer has ester groups that interact with pollutants through hydrogen bonding and electrostatic interactions and has better adsorption capacity as compared to native polyvinyl alcohol (Atta & El-Ghazawy, 2003). Composite hydrogels based on sodium alginate, PVA, kaolin, and polyacrylamide have been reported as effective for Cu(II) adsorption; the multicomponent network improved water retention, structural stability, and copper-ion uptake, highlighting how low-cost fillers and crosslinked polymer matrices can work synergistically in heavy-metal removal (Ullah et al., 2020). Likewise, crosslinked PVA-acrylamide hydrogels have been investigated for Cr(III) and Pb(II) removal, further demonstrating the role of PVA 3D networks in improving adsorption performance toward heavy-metal ions (Li et al., 2012). Similarly, metal-coordinated PVA composites have also been studied lately for the sorption of dyes and heavy metal ions, such as copper-coordinated PVA composites, which are used where coordination interaction occurs between the metal

ions and oxygen atoms of the hydroxyl groups in the PVA polymer structure. Wan et al. (2024) examined the potential of synergistic crosslinking to increase the structural and mechanical strength of polyvinyl alcohol. According to the study, crosslinking minimizes the dissolution of polymer in aqueous solution by improving intermolecular interactions and altering the chemical structure of the PVA chain. Aljar et al. (2023) also synthesized PVA-chitosan adsorbent for heavy metal sorption from contaminated water. The addition of a small amount (0.5%) of cellulose in the polymer blend shows the effective removal of almost 100% lead, cobalt, cadmium, and zinc ions from aqueous media (Aljar et al., 2023). The crosslinking of PVA provides a three-dimensional network and abundant functional groups, including hydroxyl and amine groups, which increases the sorption capacity of adsorbents through electrostatic attraction and hydrogen bonding, indicating the effectiveness of PVA-based adsorbents. Similarly, Zulfiqar et al. (2020) reported PVA hydrogel composites reinforced with oil palm bio-waste and MWCNTs for Pb(II) removal, showing that crosslinked PVA-based networks can be effectively combined with carbonaceous fillers to improve adsorption performance, as also confirmed by kinetic, isotherm, and thermodynamic analyses. In line with this, W. Wang et al. (2021) developed a reusable porous semi-IPN hydrogel based on alginate and PVA, achieving fast and efficient Pb(II) adsorption through the combination of porosity, polymer-network stability, and metal-binding sites (Wang et al., 2021).

b. Grafting Modification of PVA Matrix

Grafting polymer chains onto the poly(vinyl alcohol) backbone is an important approach for functionalizing PVA (Vu et al., 2025). Through grafting modification, many new polymer segments are integrated, incorporating various functional groups that can interact with environmental contaminants, thereby increasing the number of active adsorption sites and improving the material's stability. During the grafting process, many monomers like acrylic acid, acrylamide or methacrylic acid are introduced onto the PVA backbone via radical polymerization as described by F. S. Wang et al. (2017). The resulting grafted copolymers exhibit enhanced adsorption capacity for metal ions due to the additional functional groups incorporated by grafting. Grafted PVA exhibits better permeability and swelling behavior, making it easier for contaminants to diffuse into the polymer matrix than native PVA. Cyclic desorption process of PVA/chitosan resins, carried out with simple eluents, strong acids and alkalis, allows the simultaneous removal of lead, copper and iron, as reported by Patel et al. (2023). In general, as discussed by Sharma et al. (2023), the presence of carboxylic acids is known to ease the complexation of heavy metal ions. This occurs especially in view of multiple cycles of functioning, therefore providing higher levels of absorption, namely in the case of mercury, as reported by Abo et al. (2025).

Zhao and Zhang (2025) prepared a carboxylic-acid functionalized PVA-Chitosan composite. In this study – COOH functional group increases the sorption capacity of the adsorbent for mercury ions selectively. The prepared adsorbents showed 90% adsorption of mercury ions and 20 adsorption-desorption cycles, indicating the effectiveness of the grafted polymer. In Ozbas et al. (2018), thermosensitive PVA-based polymers obtained by grafting N-isopropylacrylamide onto crosslinked PVA have also been investigated for Cu(II), Ni(II), and Cd(II) removal; their temperature-responsive swelling behaviour highlights how grafting can introduce additional responsiveness and improve metal-ion extraction from aqueous media.

c. Polymer Hybrids

The forms and applications of PVA-based adsorbents are summarized in Table 2. PVA is combined with either natural or synthetic polymers, not only in the case of chitosan but also more generally, e.g., with cellulose and polyacrylic acid, to exploit the co-presence of functional groups, such as carboxyl, amine, and hydroxyl, thereby increasing the physicochemical strength and adsorption capacity. In this context, Shirazi et al. (2022) incorporated amine-grafted halloysite nanotubes into electrospun chitosan/PVA nanofibrous membranes, obtaining a functional hybrid adsorbent for Cd(II) and Pb(II) removal, where the amine groups and the nanofibrous morphology contributed to enhanced metal-ion binding. Similar concepts are also found by Ling et al. (2025) in next-generation alginate-based hydrogels, where dynamic adsorption-desorption behavior and sustainable reusability are key aspects for heavy-metal ion removal. M. Zhang et al. (2024) reported porous PVA/xanthan gum hydrogels, which showed adsorption capability toward both methylene blue and Pb(II); the improved swelling behaviour and porous structure of the hybrid network confirmed the usefulness of polysaccharide-PVA systems for mixed-contaminant wastewater treatment. The co-polymerization between PVA and acrylic acid can also be obtained by gamma irradiation, in which case it was demonstrated that the absorption of zinc, cobalt, and manganese ions is pH-dependent, and maximum sorption of these ions has been found to be 388, 245 and 152 mg/g, respectively (Al-Qudah et al., 2014). Sopanrao and Sreedhar (2024) prepared a PVA-chitosan hybrid resin for multi-metal removal, such as copper, nickel, and zinc. In that case, the adsorbents showed high adsorption capacities of 303.90 mg g⁻¹ for copper, 9209.08 mg g⁻¹ for nickel, and 173.39 mg g⁻¹ for lead and exhibit high stability and reusability.

d. PVA Aerogels

PVA aerogels are a class of highly porous, lightweight materials produced by separating the aqueous phase from a poly(vinyl alcohol) gel while preserving its three-dimensional network and are often modified with

cellulose and chitosan to enhance mechanical strength and absorption capacity (Abdolazizi et al., 2024). Due to their large specific surface area, low density, and high porosity (more than 90%), they become very effective for the adsorption applications, especially for the removal of toxic metal ions and organic pollutants. With their porous structure, PVA aerogels absorb maximum water without shedding their dimensional stability, making it easier for the pollutants to reach the active sites. PVA aerogels are generally made by freeze-drying after gelation, forming a highly porous network by removing the solvent while preserving the internal structure. An example was developed by Zhou et al. (2019), where PVA was freeze-dried with cellulose nanofibers and bio-based gelatin, although combinations with other polysaccharides are also possible, such as in Jang et al. (2025), where

carrageenan and sodium alginate are used. The interconnected pore structure facilitates the diffusion of pollutants into the aerogel matrix. Related PVA aerogels have also been investigated for CO₂ capture (Song et al., 2018). Hydrogen bonding, electrostatic interactions and coordination interactions provide numerous active adsorption sites, which can interact with the contaminants for better adsorption of metal ions (Franco et al., 2021). Recent evidence further supports this approach: Yin et al. (2025) developed an ultra-light chitosan/PVA/MXene double-crosslinked aerogel with high structural robustness and efficient adsorption of Cr(VI) and Pb(II), confirming the potential of PVA-based aerogels for advanced water purification applications. Different works on PVA-water adsorbents are summarised in Table 2.

Table 2 Different forms of PVA-based adsorbents for metal uptake.

PVA-based material	Preparation	Key properties	Application
PVA-based hydrogel beads	Formed by crosslinker including boric acids, MBA, or hardener, such as calcium carbonate	Maximum hydroxyl groups, good mechanical stability, and swelling capacity	Heavy metals like lead, cadmium, copper, and rare earth, are effectively removed (Wei et al., 2026; Mallakpour & Khadem, 2017)
PVA films	Thin polymeric films prepared by solvent evaporation also in combination with ceramic binders	Good chemical stability, flexible structure	Sorption of metal ions and dyes (Moradi et al., 2026)
PVA nanocomposites	Formed by the integration of nanomaterials, including metal oxides or carbon nanotubes into PVA chain	Improved active adsorption sites by increasing the surface area	Due to the synergistic effect and nano particles, effectively removed organic pollutants, dyes or metal ions (Yu et al., 2022)
PVA-biopolymer composites	Formed by combining natural polymers like cellulose or chitosan with polyvinyl alcohol	Reusable, high sorption capacity, better dimensional stability	Good metal binding ability due to additional functional groups. (Yin et al., 2025)
Polymer Hybrid Materials	Prepared by blending polymers with either natural or synthetic polymers	Better porosity and mechanical ability	With multiple adsorption mechanisms, adsorb metal ions and organic pollutants (Zulfiqar et al., 2020)
PVA aerogels.	Formed by the gelation process using the freeze-drying method	High porosity, more than 90%, and low density	With a large adsorption ability shows excellent adsorption capacity (Yin et al., 2025)

5.3 Factors affecting adsorption behavior

a. Solution's pH

One of the most important factors affecting adsorption is the solution pH. It regulates the speciation of toxic metal ions and the surface charge of the PVA-based hydrogel. At low pH levels, adsorbent efficacy may decrease due to the presence of excessive H⁺ ions, which compete with metal ions for active binding sites. In contrast, a high pH can cause metal hydroxides to precipitate. In general, an ideal pH range is required for effective adsorption of metal ions.

b. Time of Contact

Contact time plays a significant role in determining the duration of interaction between adsorbent and adsorbate. Initially, there are many active sites present, due to which adsorption happens quickly, but as the sites fill up, the adsorption rate decreases with time. At the equilibrium point, the net adsorption rate approaches zero. To get the most removal of metal ions, there must be enough contact

time, as insufficient time can lead to incomplete adsorption. Understanding adsorption kinetics also supports the process, as reflected in the adsorption capacities and removal efficiencies compared in Table 3.

c. Temperature effect

Temperature has an impact on the adsorption process by affecting the diffusion rate and interaction between the adsorbate and metal ions in contaminated water. Higher temperatures can increase ion mobility, although their effect on adsorption capacity depends on the system. Temperature also influences the swelling behavior of PVA-based hydrogel by affecting pore size and active site accessibility. Overall, it has a great impact on practical applications for the eco-friendly removal of metal ions from wastewater.

d. Adsorbent functional groups

The adsorption capacity of a PVA-based adsorbent is highly dependent upon the functional groups present in it. Functional groups such as hydroxyl, amine, and

carboxyl groups can interact more strongly with metal ions in wastewater. Functionalization can improve the adsorption strength and selectivity of the material. Different groups can interact with different metal ions,

increasing efficiency by increasing the number of active sites. In general, the overall performance of adsorption can be improved by functionalization.

Table 3 Adsorption performance of different PVA-based adsorbents.

Materials	Specific metal ions	Adsorption capacity	Removal Efficiency	Sorption Mechanism
PVA-Chitosan hydrogel beads	Lead (Pb^{+2})	210 mg/g	95%	Complexation and electrostatic interaction
PVA-Chitosan composites	Copper (Cu^{+2})	303.3 mg/g	96%	Coordination interaction with amine groups
Cross-linked hydrogel PVA	Nickel (Ni^{+2})	180 mg/g	90%	Surface adsorption and ion-exchange method
PVA-Graphene oxide nano composites	Lead (Pb^{+2})	420 mg/g	98%	Electrostatic interaction with metal ions
PVA aerogel	Chromium (Cr^{+6})	546.9 mg/g	99%	Through Redox interactions
PVA-based porous super adsorbents	Nickel (Ni^{+2})	380 mg/g	95%	Pore diffusion and coordination interactions

5.4 Applications of PVA-based Absorbents for the Removal of Heavy Metal Ions

a. Treatment of Industrial Waste

The release of heavy metals such as lead, cadmium, arsenic, chromium, and nickel into aquatic environments has increased with industrial activity. The manufacturing industries, including electroplating, mining, battery production, and textile processing, release highly toxic metal ions that are nonbiodegradable and tend to accumulate in living things, posing severe risks to the environment and human health. To overcome this, PVA-based adsorbents have become highly efficient materials for wastewater treatment because of their superior hydrophilicity, mechanical stability and flexible chemical structure. Polyvinyl alcohol has hydroxyl groups, which promote hydrogen bonding and provide active sites for further functionalization. Introducing functional groups such as carboxyl, amine, and sulfonic acid groups can improve PVA stability and metal uptake through ion exchange, chelation, and electrostatic interactions. Additionally, with their good reusability capacity, PVA-based materials may be suitable adsorbents for a continuous wastewater treatment system. Their widespread use is further supported by their cost-effectiveness and simplicity of synthesis.

b. Groundwater Remediation

Heavy metal contamination of groundwater is an enduring environmental problem caused by industrial discharge, inappropriate waste disposal, and agricultural runoff. It has become difficult to clean up contaminated groundwater because pollutants move slowly and interact intricately within soil matrices. PVA-based materials can be used in groundwater remediation through methods such as injecting hydrogel systems and installing permeable reactive barriers. As shown in Figure 4, the adsorbent materials are placed in the path of contaminated groundwater flow within permeable reactive barriers, where they immobilize and adsorb

heavy metal ions to prevent their migration. The direct incorporation of PVA hydrogel into wastewater enables it to swell and form a reactive network that adsorbs toxic metal ions such as cadmium, nickel, lead, and arsenic. Various adsorption mechanisms, including complexation, ion exchange, and physical confinement, are employed to adsorb as many metal ions as possible by reducing their mobility and bioavailability.

c. Purification of drinking water

Trace levels of toxic metal ions in potable water have become a major global concern, as chronic exposure may lead to various health problems like cancer, kidney damage and neurological disorders. Strict permissible limits for heavy metals in drinking water have been set by regulatory bodies like WHO, which require effective purification technologies. PVA-based sorbents play a significant role as they are non-toxic, biocompatible and eco-friendly. These materials are highly recommended to generate hydrogel beads, membranes, or nanocomposites that effectively remove metal ions from wastewater while improving water quality. Furthermore, the adsorption capacity and selectivity are enhanced by incorporating nanomaterials into the PVA matrix, such as metal oxides, carbon nanotubes, or graphene oxides. The PVA-based adsorbents include many advantages like high efficiency, low maintenance and easy handling. Their ability to remove heavy metal ions at low concentrations may be useful for potable-water treatment (Qasem et al., 2021).

d Treatment of Biomedical and Pharmaceutical Wastewater

Along with organic pollutants, many hazardous heavy metals are frequently found in wastewater discharged by the pharmaceutical and hospital sectors (as represented in Figure 5). Different techniques are used to prevent pollutants from contaminating the environment. One of the most frequent techniques is PVA-based adsorption, as these super adsorbents can interact with a variety of contaminants and are effective in treating such complex

wastewater. PVA adsorbents, combined with catalytic or antimicrobial agents, can support the removal of organic pollutants and selectively absorb heavy metal ions. They are considered most appropriate for environmental applications because of their non-toxicity and biocompatibility. Although most PVA-based adsorbents

are discussed for heavy-metal uptake, PVA composites have also been explored for removing pharmaceutical contaminants, including antibiotics; this confirms their broader applicability in complex biomedical and pharmaceutical wastewater streams, where organic pollutants and metal ions may coexist (Çifçi et al., 2025).

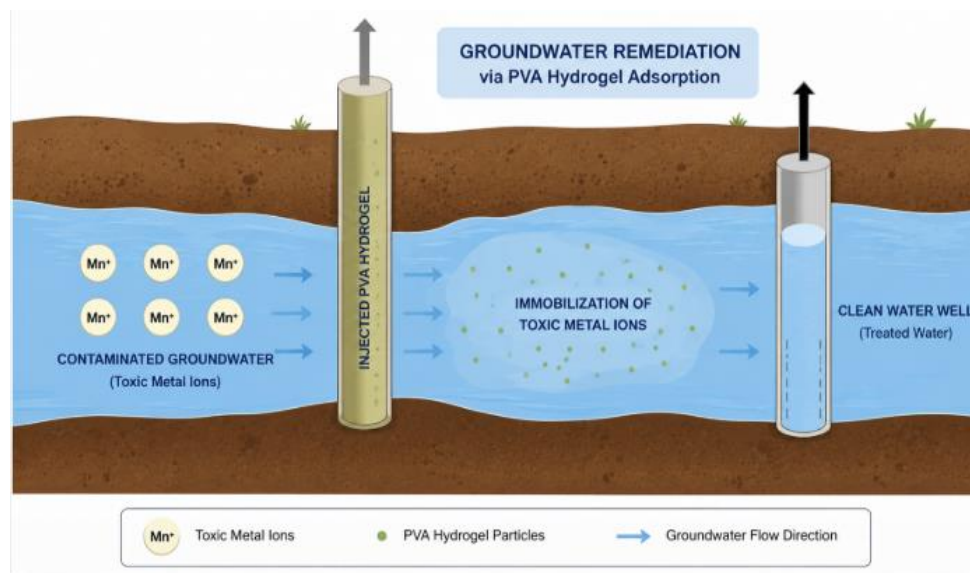


Figure 4 Ground water remediation through adsorption (adapted from authors)

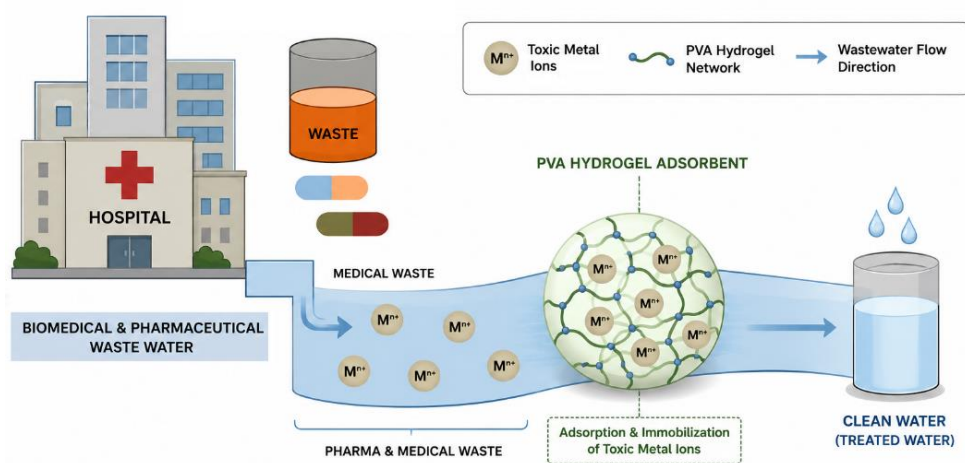


Figure 5: Application of adsorption in the biomedical and pharmaceutical field (from authors)

5.5 Advantages of PVA-based Super Adsorbents

a. Maximum Adsorption Capacity

Due to their three-dimensional crosslinked network structure, PVA-based super adsorbents have high adsorption capacity. The 3D structure gives many active sites and a large surface area where heavy metal ions can be bound. The hydroxyl group and additional functional groups, such as amine and carboxyl groups, improve chemical stability and adsorption capacity through chelation or ion-exchange interactions, thereby making this method more applicable even at low concentrations. Additionally, the porous nature of hydrogels allows better diffusion of ions into the matrix, which contributes to better adsorption capacities.

b. Swelling Behaviour and Hydrophilicity

Polyvinyl alcohol structure includes hydroxyl groups, which make it highly hydrophilic in nature. When it meets water, it swells drastically and absorbs the maximum amount of water. The swelling produces a hydrated network that makes heavy metal ions enter the polymer matrix more easily. The contact between adsorbate and adsorbent can be improved by diffusion, which results in the improvement of adsorption kinetics. In dilute solutions, these characteristics play a significant role because they support the effective removal of heavy metal ions in aqueous media even at low concentrations. In general, swelling behaviour significantly influences the adsorption performance.

c. Simple Tunability and Functionalisation

The chemical versatility of polyvinyl alcohol is one of its major advantages. It can be readily altered by a variety of physical and chemical approaches. New functional groups can be introduced by modification to target the particular heavy metal ions, thereby enhancing selectivity and adsorption efficiency. Additionally, it makes it possible to create sophisticated hybrid materials for better adsorption. Due to its tunability and adaptability, PVA is considered the most useful adsorbent in wastewater treatment.

d. Eco-friendliness and biocompatibility

Among various polymers, PVA is regarded as one of the most widely used environmentally friendly polymers because of its safe and non-toxic nature. When it is used as an adsorbent for the adsorption of toxic metal ions, no hazardous byproducts are released. It is biodegradable under specific conditions, which reduces its long-term environmental impact and can be used to purify water, unlike other synthetic polymers. Polyvinyl alcohol supports many eco-friendly remediation technologies as it follows green chemistry principles and can be easily handled and disposed of, which makes it more applicable for the adsorption process.

e. Availability and Cost-Effectiveness

As compared to many other advanced polymeric materials, PVA is more affordable and commercially available. Their production can use readily available raw materials and relatively simple procedures; due to this, PVA-based adsorbents are financially feasible for widespread applications. Additionally, they can be produced by relatively simple methods such as crosslinking or adding nanoparticles, which lower their production costs and can facilitate material reuse. It is mainly used in developing regions where cost is the major concern. As a result, it provides a balance between cost and performance.

f. Regeneration and Reusability

After the adsorption process, PVA-based adsorbents can be regenerated with the desorbing agents for reuse. Different techniques, such as treatment with acids or chelating agents, are used to get rid of bound metal ions for further use. Reusability lowers the operating cost and waste production of the material and makes the treatment process more sustainable. Research indicates that PVA adsorbents continue to function well even after several cycles. Eventually, though, a small loss in capacity occurs. Double-network gels have been proposed by Chu et al. (2015) as low-cost, easily recyclable adsorbents for Cd(II) and Pb(II); their high adsorption efficiency and reusability demonstrate that network design is a key strategy for improving both removal performance and material recovery in wastewater treatment. Overall, this supports cost-effective and environmentally friendly usage.

5.6 Limitations of PVA-based Super Adsorbents

a. Poor Mechanical strength

Although PVA has good mechanical strength in dry form, in the swollen state, its strength is drastically reduced. Excessive absorption of water can weaken the polymer network, which results in deformation or structural failure. This becomes a significant constraint in a high-flow system. As the absorption increases, the material may become less effective and lose its shape and reduce its durability for maximum adsorption. Recent work (Xiang et al., 2024) on woven hydrogels fabricated from water-soluble PVA yarns also suggests that textile-like architectures may provide a route to improve the mechanical robustness, flexibility and handling of PVA-based hydrogel systems, addressing one of the main practical limitations of highly swollen adsorbents.

b. Limited stability

PVA-based materials are susceptible to extremely acidic or alkaline conditions, as these conditions can break down the polymer structure and affect the adsorption efficiency of the materials. At extreme pH levels, many functional groups in the polymeric material become less active, which restricts its use in some industrial wastewater. Different chemical modifications can address this limitation and enhance the chemical stability and adsorption capacity of the materials at different pH levels, as shown by Ling Felicia et al. (2025).

c. Low selectivity

In native PVA, strong binding sites for the selective adsorption of specific metal ions are scarce, so adsorption may depend on weaker interactions like hydrogen bonding. Comparatively modified adsorbents have higher selectivity than pure PVA adsorbent materials. However, material modifications can increase both the cost and the number of preparation steps, which is one of the major disadvantages of PVA-based materials for the adsorption process.

d. Less efficiency

Although PVA-based adsorbents can be regenerated multiple times, their efficiency may decrease with increasing cycle number due to incomplete desorption of metal ions. This problem is also exacerbated by structural damage sustained during regeneration. Active sites of adsorbent material become blocked, and this results in a gradual reduction in the adsorption. Despite having drawbacks, reuse is still advantageous over single-use adsorbents, as reported by Areal et al. (2018) or Van Tran et al. (2018). Despite their potential, it was highlighted that hydrogel-based adsorbents still face relevant challenges, including mechanical instability, limited selectivity, regeneration losses and scale-up constraints; these issues have been identified as central barriers for practical heavy-metal removal and should guide future development of PVA-based systems (K. Zhang et al., 2021).

6. CONCLUSIONS

The removal of hazardous metal ions from wastewater is an environmental challenge due to increasing industrialization. In this review, the potential of PVA-based adsorbents as a practical, affordable, and eco-friendly wastewater treatment solution is highlighted. Due to its hydrophilic, non-toxic and biodegradable nature, PVA is a promising adsorbent platform for nickel, cadmium, mercury and lead uptake. Different chemical modifications, such as crosslinking or introducing other functional groups, can enhance the chemical stability and adsorption capacity of native PVA for better adsorption. Adsorption with modified PVA has several advantages, including simplicity, affordability, high efficiency and reusability. Despite limitations such as low mechanical strength under swollen conditions and low efficiency under highly alkaline conditions or after multiple recycling steps, PVA-based adsorbents remain among

the most widely used super adsorbents for the adsorption of heavy metal ions by addressing these limitations through various modifications. In general, PVA-based hydrogel systems show potential for the removal of toxic metal ions. Additionally, future research can focus more on developing more durable, selective and eco-friendly modifications. Their performance can further be improved by combining cutting-edge nanomaterials with green synthesis methods. Therefore, PVA-based hydrogel offers a viable path towards effective, sustainable, and scalable water purification methods. Future studies on PVA-based adsorbents should concentrate more on increasing adsorption efficacy and mechanical stability for wastewater applications. To enhance sustainability, environmentally friendly crosslinkers and nanocomposites could be incorporated into PVA using green synthesis techniques. Overall, it is anticipated that additional development should make PVA-based materials a more effective and long-lasting method for water purification.

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Muskan Salaria

Department of Chemistry,
Chandigarh University,
Gharuan, Mohali, 140413,
(Punjab) India
muskansalaria12@gmail.com
ORCID 0000-0003-0496-6294

Cristiano Fragassa

Department of Industrial
Engineering,
University of Bologna,
Bologna, 40136
Italy
cristiano.fragassa@unibo.it
ORCID 0000-0003-0046-8810

Lalita Chopra

Department of Chemistry,
Chandigarh University,
Gharuan, Mohali, 140413,
(Punjab) India
lalita.e2341@cumail.in
ORCID 0000-0003-1803-667X

Carlo Santulli

School of Science and
Technology,
University of Camerino,
Camerino, 62032
Italy
carlo.santulli@unicam.it
ORCID 0000-0002-1686-4271

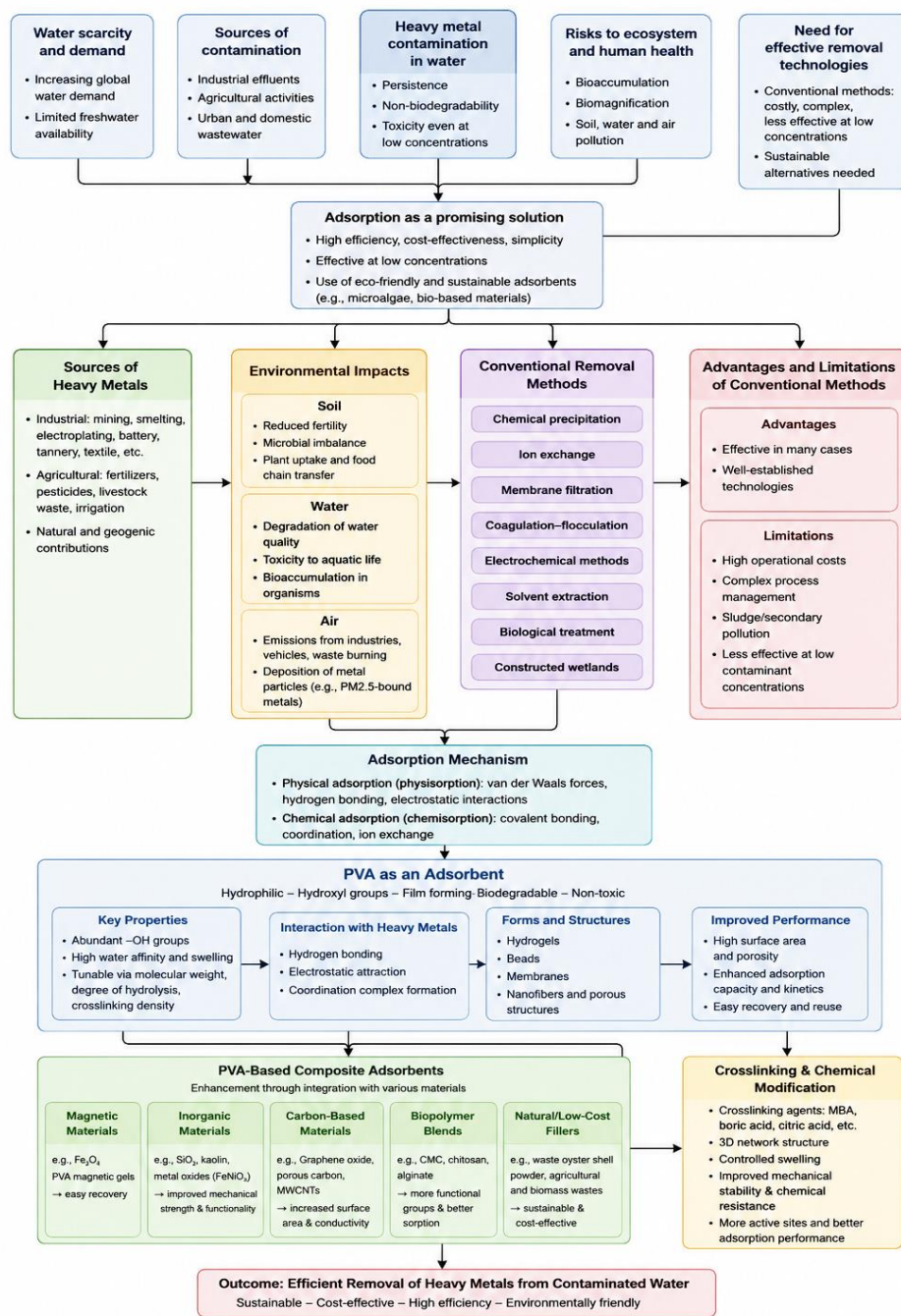


Figure 1. Conceptual framework of the review, illustrating the relationship between heavy-metal contamination, environmental impacts, conventional remediation technologies, adsorption mechanisms, and the development of advanced PVA-based adsorbents for water treatment