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# Recent Advances in Water Quality, Functional Polymer-Supported Sorbents for Heavy Metal Determination, Preconcentration, and Removal from Water

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## Highlights

- Functional polymer-supported sorbents provide high selectivity and adsorption capacity for trace heavy metals in complex aqueous matrices.
- Polyamine–polyurea resins, Schiff base-functionalized polymers, magnetic composites, and bio-based adsorbents have significantly improved solid-phase extraction (SPE) and water purification.
- Polymer-supported SPE coupled with ICP-MS, ICP-OES, FAAS, and ETAAS enables sensitive and environmentally sustainable trace metal determination.
- Recent developments emphasize recyclable sorbents, multifunctional hybrid materials, and green analytical chemistry.
- Future research should focus on AI-assisted sorbent design, circular economy principles, and large-scale environmental applications.

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**Abstract:** Heavy metal contamination of aquatic environments has become a major environmental and public health concern due to rapid industrialization, mining activities, agricultural practices, and urban development. Toxic metals such as Pb(II), Cd(II), Hg(II), Cr(VI), Ni(II), Cu(II), As(V), and Zn(II) are persistent pollutants capable of bioaccumulating in aquatic ecosystems and entering the food chain, causing severe ecological and human health risks. Consequently, the development of highly selective, reusable, and environmentally friendly adsorbents has become an important research priority. Functional polymer-supported sorbents have emerged as one of the most promising material classes for both heavy metal preconcentration and water purification because of their tunable surface chemistry, high adsorption capacity, excellent regeneration ability, and compatibility with solid-phase extraction techniques. Recent advances in polymer chemistry have enabled the development of polyamine–polyurea resins, Schiff base-functionalized polymers, ion-imprinted polymers, magnetic polymer nanocomposites, and bio-based polymeric adsorbents exhibiting remarkable analytical performance and adsorption efficiency. This review summarizes recent progress (2020–2026) in the synthesis, adsorption mechanisms, analytical applications, and environmental performance of functional polymer-supported sorbents. Particular emphasis is placed on adsorption mechanisms, coordination chemistry, SPE applications, analytical determination of trace metals, and sustainable water treatment technologies. Current limitations, research gaps, and future perspectives related to multifunctional polymeric materials, green chemistry, artificial intelligence-assisted material design, and circular economy are also critically discussed.

## 1. Introduction

The contamination of aquatic environments by toxic heavy metals has become one of the most significant environmental problems worldwide because of rapid industrialization, mining activities, intensive agricultural practices, urbanization, and the continuous discharge of untreated industrial effluents. Toxic metals such as Pb(II), Cd(II), Hg(II), Cr(VI), Ni(II), Cu(II), Zn(II), Co(II), and As(V) are persistent pollutants that accumulate in aquatic ecosystems and pose serious ecological and public health risks (Ali et al., 2019; Alloway, 2013; Barakat, 2011; Kumar et al., 2023; Khan et al., 2023). Unlike many organic contaminants, heavy metals are non-biodegradable and may remain in aquatic environments for decades. Their bioaccumulation and biomagnification through food chains have been associated with neurological disorders, nephrotoxicity, endocrine disruption, reproductive toxicity, cardiovascular diseases, and various cancers. Consequently, reliable monitoring and efficient removal of heavy metals have become major priorities in environmental analytical chemistry and sustainable water treatment (Ali et al., 2019; WHO, 2022; IARC, 2023; Kumar et al., 2024). Several conventional treatment technologies, including chemical precipitation, coagulation–flocculation, membrane filtration, ion exchange, reverse osmosis, and electrochemical methods, have been developed for heavy metal removal. However, these techniques frequently suffer from high operational costs, sludge generation, membrane fouling, poor selectivity toward trace metals, and limited regeneration capability, particularly when complex environmental matrices are analyzed (Barakat, 2011; Fu & Wang, 2011; Wang et al., 2024). Among currently available approaches, adsorption has emerged as one of the most efficient and environmentally friendly technologies because of its simplicity, relatively low operating cost, high removal efficiency, and compatibility with green analytical chemistry. Functional polymer-supported sorbents have attracted considerable attention owing to their tunable surface chemistry, high ligand density, excellent chemical stability, and remarkable adsorption selectivity. The incorporation of amino, imine, hydroxyl, carboxyl, phosphonate, and thiol functional groups enables efficient coordination with dissolved heavy metal ions, thereby improving both analytical sensitivity and adsorption performance (Chen et al., 2023; Liu et al., 2024; Wang et al., 2024). Recent advances in polymer chemistry have enabled the development of polyamine–polyurea resins, Schiff base-functionalized polymers, ion-imprinted polymers, molecularly imprinted polymers, magnetic polymer nanocomposites, and bio-based polymeric adsorbents. These materials have demonstrated excellent analytical performance in solid-phase extraction (SPE) coupled with FAAS, ETAAS, ICP-OES, and ICP-MS while simultaneously exhibiting high adsorption capacities for water purification applications (Zhang et al., 2022; Chen et al., 2023; Kumar et al., 2024; Li et al., 2025). In addition to their analytical applications, polymer-supported sorbents have become increasingly important in sustainable water treatment. Their regeneration capability, mechanical durability, and compatibility with nanomaterials, metal–organic frameworks (MOFs), covalent organic frameworks (COFs), and renewable biopolymers have significantly expanded their practical applicability. Furthermore, recent developments involving artificial intelligence-assisted material design, computational chemistry, and green synthesis strategies are expected to accelerate the development of next-generation multifunctional sorbents capable of supporting both environmental monitoring and sustainable water purification (Liu et al., 2024; Wang et al., 2024; Li et al., 2025). This review summarizes recent advances in functional polymer-supported sorbents reported between 2020 and 2025, focusing on sorbent classification, adsorption mechanisms, coordination chemistry, solid-phase extraction, analytical applications, heavy metal removal efficiency, regeneration performance, and future research directions. Particular emphasis is placed on sustainable polymeric materials that combine high analytical performance with environmentally responsible water treatment technologies.

### 2.1. Water Quality and Its Importance in Heavy Metal Monitoring and Removal

Water quality is a fundamental indicator of environmental sustainability and public health, reflecting the physical, chemical, and biological characteristics of aquatic systems. Parameters such as pH, electrical conductivity (EC), total dissolved solids (TDS), dissolved oxygen (DO), turbidity, temperature, alkalinity, and hardness collectively determine the suitability of water for drinking, agricultural, industrial, and ecological applications. These physicochemical characteristics not only influence the overall quality of water but also govern the mobility, chemical speciation, bioavailability, and toxicity of dissolved heavy metals. For instance, acidic conditions generally enhance the solubility and mobility of toxic metal ions, whereas alkaline conditions may promote precipitation or adsorption onto suspended particles. Consequently, comprehensive water quality assessment requires the simultaneous evaluation of conventional water quality parameters together with trace metal concentrations to obtain a realistic understanding of contamination status and potential environmental risks (World Health Organization, 2022; Qasem et al., 2021; Li et al., 2023). The increasing deterioration of water quality resulting from rapid industrialization, mining, agricultural runoff, and urbanization has intensified the need for efficient monitoring and remediation technologies. Heavy metals released into aquatic environments may accumulate in sediments and living organisms, eventually entering the food chain and posing significant risks to ecosystems and human health. Therefore, advanced analytical methods combined with highly selective adsorbent materials have become indispensable for both accurate heavy metal determination and sustainable water treatment. Functional polymer-supported sorbents, particularly when integrated with activated carbon, magnetic nanomaterials, or bio-based polymers, provide high adsorption capacity, excellent selectivity, and remarkable regeneration performance, making them promising materials for improving drinking water quality and supporting sustainable water resource management (Ali et al., 2019; Alkhaldi et al., 2024; Kumar et al., 2025; Wang et al., 2025).

## 2. Functional Polymer-Supported Sorbents for Heavy Metal Separation and Water Treatment

Functional polymer-supported sorbents have become one of the most effective material platforms for the selective preconcentration, determination, and removal of heavy metals from aqueous media. Compared with conventional inorganic adsorbents, polymeric materials offer several advantages, including high chemical stability, adjustable porosity, tunable surface functionality, mechanical durability, and excellent regeneration capability. Their physicochemical properties can be tailored through molecular design, allowing selective interactions with specific heavy metal ions while maintaining high adsorption efficiency under complex environmental conditions (Barakat, 2011; Ali et al., 2019; Chen et al., 2023; Wang et al., 2024).

**Table 1.** Comparison of the major classes of polymer-based adsorbents used for heavy metal removal from aqueous systems.

| Polymer type | Main functional groups | Typical target metals | Main advantage |
|---|---|---|---|
| Polyamine–polyurea | –NH2, urea | Cu, Ni, Pb, Cd | High capacity |
| Schiff base | –C=N–, –OH | Cu, Ni, Fe | High selectivity |
| Ion-imprinted | Template cavities | Pb, Cd, Hg | Ultra-selective |
| Magnetic composite | Fe3O4 + polymer | Pb, Cr, As | Easy separation |
| Bio-based | –OH, –COOH, –NH2 | Pb, Cu, Cd | Sustainable |
| Hybrid | Mixed groups | Multi-metal | Multifunctional |

Recent advances in polymer chemistry have enabled the development of multifunctional sorbents containing nitrogen-, oxygen-, sulfur-, and phosphorus-based donor atoms capable of coordinating dissolved metal ions. Functional groups such as amino, imine, carboxyl, hydroxyl, phosphonate, and thiol moieties play a decisive role in adsorption performance because they

act as Lewis bases capable of forming stable coordination complexes with transition metals. Consequently, adsorption generally proceeds through a combination of chelation, ion exchange, electrostatic attraction, and surface complexation, leading to high adsorption capacities and excellent analytical recoveries (Pearson, 1963; Housecroft & Sharpe, 2018; Kumar et al., 2024). Modern polymer-supported sorbents can be classified into several major groups according to their chemical composition and adsorption mechanism.

**2.1 Polyamine–Polyurea Sorbents**

Polyamine–polyurea sorbents remain among the most extensively investigated polymeric adsorbents because of their high density of amino and carbonyl groups. These functional groups efficiently coordinate Cu(II), Ni(II), Pb(II), Cd(II), Co(II), and Zn(II), providing excellent adsorption capacity and selectivity. Their cross-linked polymeric structure also ensures remarkable mechanical stability and repeated adsorption–desorption performance, making them highly suitable for solid-phase extraction and continuous water treatment applications (Martell & Hancock, 1996; Khan et al., 2023; Kumar et al., 2024).

**2.2, Schiff Base-Functionalized Polymers**

Schiff base-functionalized polymers represent another important class of chelating sorbents. The azomethine (–C=N–) group together with adjacent oxygen donor atoms forms stable chelate complexes with transition metals. These polymers exhibit particularly high affinity toward Cu(II), Ni(II), Pb(II), Cd(II), and Fe(III). Their structural versatility allows immobilization onto silica, magnetic nanoparticles, graphene oxide, activated carbon, and bio-based polymer matrices, significantly improving adsorption selectivity and regeneration efficiency (Gupta & Sutar, 2008; Chen et al., 2023; Wang et al., 2024).

**2.3. Ion-Imprinted and Molecularly Imprinted Polymers**

Ion-imprinted polymers (IIPs) and molecularly imprinted polymers (MIPs) have attracted increasing attention because they provide highly selective recognition sites for target analytes. During synthesis, template ions are incorporated into the polymer matrix and subsequently removed, leaving cavities with complementary size, geometry, and functional groups. Such recognition sites provide excellent selectivity for trace heavy metal determination even in complex environmental matrices. Consequently, IIPs are increasingly employed in SPE procedures coupled with ICP-MS and ICP-OES for ultra-trace analysis (Chen et al., 2023; Liu et al., 2024).

**2.4. Magnetic Polymer Nanocomposites**

Magnetic polymer-supported sorbents have become one of the fastest-growing research areas because magnetic separation significantly simplifies sample preparation. Incorporation of $Fe_3O_4$ nanoparticles enables rapid recovery of adsorbents without filtration or centrifugation while maintaining high adsorption efficiency. Magnetic composites also exhibit improved regeneration capability and operational stability, making them promising candidates for wastewater treatment and environmental monitoring (Zhang et al., 2022; Wang et al., 2024).

**2.5. Bio-Based Polymeric Sorbents**

Growing environmental concerns have accelerated the development of renewable polymeric sorbents prepared from chitosan, cellulose, alginate, starch, lignin, and agricultural wastes. These materials possess abundant hydroxyl, amino, and carboxyl groups capable of binding heavy metals while offering biodegradability, low production cost, and reduced environmental impact. Chemical modification and surface functionalization have further improved their adsorption capacity and mechanical stability, enabling their application in sustainable water treatment technologies (Ali et al., 2019; Alsamman et al., 2020; Kumar et al., 2024).

### 2.6. Hybrid Polymeric Materials

The integration of polymers with graphene oxide, activated carbon, biochar, metal–organic frameworks (MOFs), covalent organic frameworks (COFs), silica, and carbon nanotubes has generated a new generation of multifunctional hybrid sorbents. These materials combine high surface area with abundant functional groups, resulting in rapid adsorption kinetics, excellent regeneration performance, and simultaneous removal of heavy metals and organic contaminants. Hybrid polymeric materials therefore represent one of the most promising directions for future environmental remediation technologies (Zhang et al., 2022; Liu et al., 2024; Wang et al., 2024).

### 2.7. Activated Carbon and Polymer–Activated Carbon Hybrid Sorbents

Activated carbon (AC) remains one of the most extensively employed adsorbent materials for water purification owing to its exceptionally high specific surface area (typically 500–2000 $m^2\ g^{-1}$), well-developed porous structure, excellent physicochemical stability, and broad adsorption spectrum. Although activated carbon has traditionally been used for the removal of organic pollutants, recent studies have demonstrated that appropriately modified activated carbon can also exhibit remarkable adsorption performance toward toxic heavy metals, including Pb(II), Cd(II), Hg(II), Cr(VI), Cu(II), Ni(II), Zn(II), and As(V) (Ali et al., 2019; Gupta et al., 2021; Upadhyay et al., 2021). The adsorption process is governed by a combination of pore filling, electrostatic attraction, ion exchange, surface complexation, and coordination interactions involving oxygen-containing surface functionalities such as hydroxyl, carbonyl, carboxyl, lactone, and phenolic groups (Vidu et al., 2020; Zhao et al., 2021). Despite these advantages, pristine activated carbon generally exhibits limited selectivity toward individual metal ions because its adsorption behavior largely depends on nonspecific surface interactions. Consequently, extensive research has focused on surface functionalization strategies aimed at introducing nitrogen-, sulfur-, phosphorus-, and oxygen-containing ligands capable of forming strong coordination complexes with dissolved metal ions. Surface oxidation, amination, thiolation, graft polymerization, and Schiff base immobilization have been shown to significantly enhance adsorption capacity, selectivity, and regeneration performance (Gupta et al., 2021; Jadoun et al., 2023; Pet et al., 2024). More recently, polymer–activated carbon hybrid adsorbents have emerged as one of the most promising material classes for advanced water treatment. In these systems, activated carbon provides extensive porosity and rapid mass transfer, whereas functional polymers introduce abundant reactive binding sites capable of selectively coordinating target metal ions. Polyamine–polyurea resins, polyethyleneimine (PEI), chitosan, alginate, cellulose derivatives, polyacrylic acid, and Schiff base-functionalized polymers are among the most frequently employed polymeric components. Their integration with activated carbon substantially improves adsorption kinetics, increases metal uptake capacity, and enhances resistance to mechanical degradation during repeated adsorption–desorption cycles (Alsamman et al., 2021; Alkhaldi et al., 2024; Khamis et al., 2024). The adsorption mechanism of polymer–activated carbon composites is considerably more complex than that of conventional activated carbon alone. Initially, dissolved metal ions diffuse through the porous carbon network before interacting with polymer-bound functional groups such as amino ($–NH_2$), imine (–C=N–), hydroxyl (–OH), carboxyl (–COOH), phosphonate ($–PO_3H_2$), and thiol (–SH). Stable coordination complexes are subsequently formed via Lewis acid–base interactions, while additional contributions from electrostatic attraction, ion exchange, and hydrogen bonding further enhance overall adsorption efficiency. This synergistic mechanism frequently results in substantially higher adsorption capacities than either activated carbon or polymeric sorbents used individually (Pearson, 1963; Housecroft & Sharpe, 2018; Wang et al., 2025). Numerous investigations published during the last five years have reported removal efficiencies exceeding 90–99% for Pb(II), Cd(II), Cu(II), Cr(VI), Hg(II), and As(V) using polymer-modified activated carbon under optimized experimental conditions. Furthermore,

these hybrid materials generally exhibit rapid adsorption kinetics, excellent regeneration capability over multiple cycles, reduced secondary waste generation, and compatibility with fixed-bed columns and continuous-flow treatment systems. Such characteristics make polymer–activated carbon composites particularly attractive for drinking-water purification, industrial wastewater treatment, mining effluents, and remediation of contaminated groundwater (Pet et al., 2024; Kumar et al., 2025; Wang et al., 2025). Recent advances have also incorporated magnetic nanoparticles, graphene oxide, biochar, metal–organic frameworks (MOFs), covalent organic frameworks (COFs), and electrospun nanofibers into polymer–activated carbon architectures. These multifunctional composites combine high adsorption capacity with simplified magnetic recovery, enhanced structural stability, and improved resistance to fouling. Consequently, polymer–activated carbon hybrid materials are increasingly regarded as next-generation adsorbents capable of simultaneously removing heavy metals and emerging contaminants while supporting the principles of green chemistry and sustainable water treatment (Singh et al., 2024; Qin et al., 2025; Kumar et al., 2025). Future research should focus on developing renewable activated carbons derived from agricultural residues and other biomass resources, integrating artificial intelligence-assisted material design, and evaluating long-term performance under realistic environmental conditions. Particular emphasis should be placed on pilot-scale validation, life-cycle assessment (LCA), techno-economic analysis (TEA), and circular economy approaches to facilitate the large-scale implementation of polymer–activated carbon technologies in sustainable drinking-water production and wastewater remediation (Alkhaldi et al., 2024; Kumar et al., 2025; Wang et al., 2025).

### 2.8. Comparative Assessment

Each polymer class possesses distinct advantages depending on the intended application. Polyamine–polyurea and Schiff base-functionalized polymers provide superior coordination capability, whereas ion-imprinted polymers offer exceptional analytical selectivity. Magnetic composites simplify sorbent recovery, while bio-based polymers contribute to sustainable and environmentally friendly water treatment. Hybrid materials combine these advantages, producing multifunctional adsorbents suitable for both analytical preconcentration and large-scale remediation. Consequently, future research should focus on integrating renewable polymer chemistry, nanotechnology, computational modelling, and artificial intelligence-assisted material design to develop highly selective, recyclable, and economically feasible sorbents for next-generation water purification systems (Chen et al., 2023; Liu et al., 2024; Wang et al., 2024).

## 3. Adsorption Mechanisms of Functional Polymer-Supported Sorbents

The outstanding performance of functional polymer-supported sorbents originates from the synergistic interaction of several adsorption mechanisms rather than from a single physicochemical process. In contrast to conventional adsorbents that mainly rely on nonspecific surface interactions, polymeric sorbents contain tailor-made functional groups capable of selectively binding heavy metal ions through coordination chemistry, ion exchange, electrostatic attraction, hydrogen bonding, and surface complexation. The relative contribution of each mechanism depends on the chemical structure of the sorbent, solution chemistry, and the physicochemical properties of the target metal ions (Pearson, 1963; Housecroft & Sharpe, 2018; Kumar et al., 2024).

### 3.1 Coordination and Chelation Mechanisms

Coordination chemistry is the primary mechanism responsible for heavy metal adsorption in most functional polymer-supported sorbents. Functional groups such as amino (–$NH_2$), imine (–C=N–), hydroxyl (–OH), carboxyl (–COOH), phosphonate (–$PO_3H_2$), and thiol (–SH) donate electron pairs to dissolved transition metal ions, forming stable coordination complexes. These interactions significantly improve adsorption selectivity and stability

compared with conventional ion-exchange materials. The adsorption affinity generally depends on the electronic properties of both the ligand and the metal ion. Multidentate ligands capable of forming five- or six-membered chelate rings exhibit higher thermodynamic stability than monodentate ligands because of the classical chelate effect. Polyamine–polyurea resins and Schiff base-functionalized polymers therefore display excellent adsorption capacities for Cu(II), Ni(II), Pb(II), Cd(II), Co(II), and Zn(II) (Martell & Hancock, 1996; Gupta & Sutar, 2008; Khan et al., 2023).

### 3.2 Hard–Soft Acid–Base (HSAB) Theory

The Hard–Soft Acid–Base (HSAB) theory provides a useful framework for understanding adsorption selectivity. According to this concept, hard metal ions preferentially coordinate with hard donor atoms, whereas soft metal ions form more stable complexes with soft donor atoms. Nitrogen-containing ligands exhibit strong affinity toward Cu(II), Ni(II), and Co(II), whereas sulfur-containing functional groups preferentially bind Hg(II), Ag(I), Cd(II), and Pb(II). Consequently, the rational selection of donor atoms represents one of the most effective strategies for designing highly selective polymer-supported sorbents (Pearson, 1963; Pearson, 1968; Wang et al., 2024).

### 3.3. Electrostatic Attraction and Ion Exchange

Electrostatic attraction facilitates the initial interaction between dissolved metal ions and charged polymer surfaces. Depending on solution pH, polymer-supported functional groups may become positively or negatively charged, thereby influencing adsorption efficiency. At the same time, polymers containing carboxylate, phosphonate, or sulfonate groups may remove heavy metals through ion-exchange reactions, replacing exchangeable ions with target metal ions. Although weaker than coordination chemistry, these mechanisms significantly contribute to adsorption kinetics and overall removal efficiency (Helfferich, 1995; Chen et al., 2023).

### 3.4. Surface Complexation and Hydrogen Bonding

Surface complexation involves the direct interaction of dissolved metal ions with reactive functional groups located on the adsorbent surface. Spectroscopic studies have confirmed that inner-sphere complexes dominate the adsorption of Cu(II), Pb(II), Cd(II), and Ni(II) onto nitrogen-rich polymeric sorbents. Hydrogen bonding also contributes to adsorption by stabilizing hydrated coordination complexes and facilitating pollutant transport within the polymer matrix. These interactions become particularly important in multifunctional hybrid materials designed for the simultaneous removal of heavy metals and organic contaminants (Sposito, 2008; Chen et al., 2023; Kumar et al., 2024).

### 3.5. Influence of Solution Chemistry

The adsorption behavior of heavy metals is strongly affected by environmental conditions. Solution pH determines both the protonation state of functional groups and the chemical speciation of dissolved metals. Acidic conditions generally reduce adsorption because amino and imine groups become protonated, whereas excessively alkaline conditions may induce metal hydroxide precipitation. In addition, ionic strength, competing metal ions, dissolved organic matter, and temperature influence adsorption equilibrium and kinetics. Therefore, optimization of solution chemistry is essential for reliable analytical applications and practical water treatment (Stumm & Morgan, 2012; WHO, 2022; Wang et al., 2024).

### 3.6. Adsorption Kinetics and Isotherms

Adsorption performance is commonly interpreted using pseudo-first-order and pseudo-second-order kinetic models, while adsorption equilibrium is generally described using Langmuir and Freundlich isotherms. In many polymer-supported sorbents, adsorption follows pseudo-second-order kinetics, indicating that chemisorption is the dominant rate-controlling mechanism. Langmuir isotherms frequently provide the best fit, suggesting monolayer adsorption on homogeneous active sites. Thermodynamic parameters ($\Delta G°$, $\Delta H°$, and $\Delta S°$) further indicate that heavy metal adsorption is generally spontaneous and, depending on the

polymer structure, may be either endothermic or mildly exothermic (Ho & McKay, 1999; Foo & Hameed, 2010; Kumar et al., 2024).

### 3.7. Implications for Sorbent Design

Modern polymer-supported sorbents are designed by integrating multiple adsorption mechanisms within a single material. Hybrid systems combining polymers with graphene oxide, biochar, activated carbon, $Fe_3O_4$ nanoparticles, MOFs, and COFs exhibit enhanced adsorption capacity, faster kinetics, improved regeneration, and broader applicability. Recent advances in computational chemistry, density functional theory (DFT), and artificial intelligence-assisted molecular design further enable the prediction of ligand–metal interactions before synthesis, thereby accelerating the development of highly selective and environmentally sustainable adsorbents (Liu et al., 2024; Wang et al., 2024; Li et al., 2025). Overall, adsorption by functional polymer-supported sorbents results from the cooperative action of coordination chemistry, electrostatic attraction, ion exchange, surface complexation, hydrogen bonding, and pore diffusion. Understanding these complementary mechanisms provides the scientific basis for designing next-generation multifunctional sorbents with improved selectivity, regeneration efficiency, and environmental sustainability.

## 4. Applications of Functional Polymer-Supported Sorbents in Solid-Phase Extraction and Water Purification

Functional polymer-supported sorbents have become indispensable materials in both environmental analytical chemistry and water treatment technologies because they simultaneously provide efficient trace metal preconcentration and high adsorption capacity. Their large specific surface area, abundant functional groups, excellent chemical stability, and regeneration capability make them attractive alternatives to conventional adsorbents. During the last decade, polymer-supported materials have been successfully integrated into solid-phase extraction (SPE), dispersive solid-phase extraction (dSPE), magnetic solid-phase extraction (MSPE), pipette-tip SPE, and online SPE systems, considerably improving analytical sensitivity while reducing solvent consumption and sample preparation time (Camel, 2003; Chen et al., 2023; Wang et al., 2024).

**Table 2**. Analytical Techniques Combining Solid-Phase Extraction with Instrumental Detection for Heavy Metal Analysis

| Technique | | | Detector | Advantages | Application |
|---|---|---|---|---|---|
| SPE | | | ICP-MS | Ultra-trace | Environmental water |
| SPE | | | ICP-OES | Multi-element | Routine analysis |
| MSPE | | | ETAAS | Fast separation | Wastewater |
| dSPE | | | FAAS | Low cost | Drinking water |
| Online SPE | | | ICP-MS | Automation | Monitoring |

### 4.1 Solid-Phase Extraction for Trace Heavy Metal Determination

Solid-phase extraction remains one of the most widely used sample preparation techniques for trace metal analysis because it combines efficient analyte enrichment with effective matrix removal. Functional polymer-supported sorbents containing amino, imine, carboxyl, phosphonate, and thiol groups selectively retain dissolved metal ions prior to instrumental determination. After adsorption, analytes are quantitatively eluted using dilute mineral acids or complexing agents and subsequently determined by highly sensitive analytical techniques. Among the available detection methods, ICP-MS provides the lowest detection limits and multi-element capability, whereas ICP-OES offers excellent analytical precision for routine monitoring. FAAS and ETAAS remain attractive alternatives because of their simplicity and lower operational costs. Coupling polymer-supported SPE with these instrumental

techniques substantially improves enrichment factors, minimizes matrix interferences, and enhances analytical accuracy for environmental water samples (Camel, 2003; Chen et al., 2023; Kumar et al., 2024).

### 4.2 Magnetic Solid-Phase Extraction

Magnetic solid-phase extraction (MSPE) has become one of the fastest-growing sample preparation techniques because magnetic nanoparticles eliminate the need for filtration or centrifugation. Polymer-coated $Fe_3O_4$ nanocomposites rapidly adsorb heavy metals and can be separated within seconds using an external magnetic field. This approach shortens analysis time, reduces solvent consumption, and improves analytical reproducibility. Magnetic polymeric sorbents have demonstrated excellent performance for the enrichment of Pb(II), Cd(II), Cu(II), Ni(II), Cr(VI), Hg(II), and As(V), particularly when coupled with ICP-MS or ETAAS. Their excellent regeneration capability further enhances their suitability for routine laboratory applications and continuous environmental monitoring (Zhang et al., 2022; Wang et al., 2024).

### 4.3 Heavy Metal Removal from Water

Beyond analytical applications, functional polymer-supported sorbents have been extensively investigated for wastewater remediation. Adsorption efficiencies exceeding 90% have frequently been reported for Pb(II), Cd(II), Cu(II), Cr(VI), Ni(II), Zn(II), and Hg(II), depending on solution pH, adsorbent composition, contact time, and initial metal concentration. Nitrogen-rich polymers generally exhibit superior affinity for transition metals because amino and imine groups readily form stable coordination complexes. Recent developments have focused on multifunctional hybrid sorbents prepared by combining polymers with graphene oxide, activated carbon, biochar, metal–organic frameworks (MOFs), covalent organic frameworks (COFs), and magnetic nanoparticles. These hybrid systems exhibit enhanced adsorption capacity, faster kinetics, improved mechanical stability, and excellent regeneration performance, making them suitable for large-scale water treatment (Ali et al., 2019; Alsamman et al., 2020; Liu et al., 2024).

### 4.4 Regeneration and Reusability

One of the principal advantages of polymer-supported sorbents is their excellent regeneration capability. Adsorbed heavy metals can generally be desorbed using dilute nitric acid, hydrochloric acid, or chelating agents without causing significant deterioration of the polymer matrix. Many polymeric sorbents maintain high adsorption efficiencies after multiple adsorption–desorption cycles, demonstrating their economic feasibility for long-term environmental applications. The regeneration performance depends on polymer cross-linking density, chemical stability, ligand structure, and operational conditions. Magnetic polymer composites and cross-linked polyamine resins generally exhibit superior long-term durability compared with non-cross-linked natural polymers (Kumar et al., 2024; Wang et al., 2024).

### 4.5 Comparative Performance of Representative Polymer-Supported Sorbents

**Table 3**. Classification and Comparative Characteristics of Functional Polymer-Based Sorbents for Heavy Metal Removal from Water

| Sorbent Type | Functional Groups | Target Metals | Major Advantages |
|---|---|---|---|
| Polyamine–polyurea | $–NH_2$, –NH–CO–NH– | Cu, Ni, Pb, Cd | High adsorption capacity, excellent regeneration |
| Schiff base polymers | –C=N–, –OH | Cu, Ni, Pb, Fe | Strong chelation and selectivity |
| Ion-imprinted polymers | Template cavities | Pb, Cd, Hg | Exceptional analytical selectivity |
| Magnetic polymers | $Fe_3O_4$ + polymer | Pb, Cr, As, Hg | Rapid magnetic separation |
| Chitosan-based sorbents | $–NH_2$, –OH | Pb, Cu, Cd | Renewable and biodegradable |
| Hybrid polymer composites | Mixed functionalities | Multi-metal systems | High capacity and multifunctionality |

### 4.6 Current Challenges and Emerging Trends

Despite significant progress, several challenges remain before polymer-supported sorbents can be implemented on an industrial scale. Many laboratory studies are performed under ideal experimental conditions using synthetic solutions, whereas real environmental waters contain competing ions, dissolved organic matter, and variable physicochemical properties that may reduce adsorption performance. In addition, long-term mechanical stability, large-scale production costs, and regeneration efficiency require further optimization. Future developments are expected to focus on renewable polymer sources, green synthesis strategies, multifunctional hybrid materials, continuous-flow adsorption systems, and computationally guided sorbent design. The integration of artificial intelligence, machine learning, and molecular simulation into polymer development is anticipated to accelerate the discovery of highly selective and economically sustainable adsorbents for environmental remediation and analytical chemistry (Liu et al., 2024; Wang et al., 2024; Li et al., 2025).

## 5. Advantages, Current Limitations, and Future Perspectives

### 5.1 Advantages of Functional Polymer-Supported Sorbents

Functional polymer-supported sorbents have emerged as one of the most promising material platforms for heavy metal preconcentration, determination, and removal from aqueous environments. Their primary advantage lies in the ability to tailor their physicochemical properties through molecular design. Unlike conventional adsorbents, polymer-supported materials can be functionalized with amino, imine, thiol, phosphonate, hydroxyl, and carboxyl groups that provide highly selective binding sites for metal ions through coordination and chelation mechanisms (Ali et al., 2019; Alkhaldi et al., 2024). Another important advantage is their excellent compatibility with analytical sample preparation techniques. Functional polymers significantly improve solid-phase extraction performance by increasing enrichment factors, minimizing matrix interferences, and enhancing detection sensitivity when coupled with ICP-MS, ICP-OES, ETAAS, and FAAS. These characteristics make polymer-supported sorbents indispensable in trace metal analysis for environmental monitoring and drinking water quality assessment (Camel, 2003; Li et al., 2023). Compared with conventional adsorbents, polymer-supported materials also exhibit superior regeneration capability and mechanical stability. Cross-linked polymer matrices generally tolerate repeated adsorption–desorption cycles with only minor reductions in adsorption capacity, reducing operational costs and supporting sustainable water treatment strategies (Crini et al., 2019; Kumar et al., 2025). Recent developments in hybrid polymer nanocomposites have further improved adsorption efficiency by combining polymers with graphene oxide, magnetic nanoparticles, biochar, MOFs, COFs, and cellulose-based materials. These multifunctional systems provide higher adsorption capacities, faster adsorption kinetics, and broader applicability for complex environmental matrices (Caixeta et al., 2025; Qin et al., 2025).

### 5.2 Current Limitations

Despite significant progress, several limitations continue to restrict the widespread application of polymer-supported sorbents. Most published adsorption studies are still performed using synthetic laboratory solutions under controlled conditions, whereas natural waters contain competing ions, dissolved organic matter, suspended particles, and fluctuating physicochemical properties that may considerably reduce adsorption efficiency (Qasem et al., 2021). Economic considerations also remain important. Many advanced polymeric sorbents require multi-step synthesis procedures, expensive functional monomers, or nanomaterial additives that increase production costs. Simplifying synthesis while maintaining adsorption performance is therefore a key objective for future research (Alkhaldi et al., 2024). Long-term regeneration and durability also require further investigation. Although many sorbents maintain high adsorption efficiencies after repeated regeneration, gradual degradation of functional groups and incomplete desorption of strongly coordinated metal ions may reduce long-term

performance. Consequently, pilot-scale and continuous-flow studies remain essential before industrial implementation.

### 5.3 Future Perspectives

Future research should emphasize the development of environmentally sustainable, economically feasible, and highly selective polymer-supported sorbents. Renewable biopolymers such as chitosan, cellulose, alginate, starch, and lignin are expected to become increasingly important because of their biodegradability, low toxicity, and wide availability.

Artificial intelligence (AI), machine learning (ML), molecular dynamics (MD), and density functional theory (DFT) are anticipated to accelerate the rational design of new sorbent materials by predicting ligand–metal interactions and adsorption performance before experimental synthesis. These computational approaches may substantially reduce development costs while improving material optimization. Another promising direction involves integrating polymer-supported adsorption with complementary technologies such as membrane filtration, photocatalysis, electrochemical treatment, and advanced oxidation processes. Such hybrid systems may enable simultaneous removal of heavy metals, pharmaceuticals, pesticides, dyes, and emerging contaminants from complex water matrices.

Finally, future studies should increasingly include life-cycle assessment (LCA), techno-economic analysis (TEA), and circular economy principles to evaluate not only adsorption efficiency but also environmental impact, resource recovery, and long-term sustainability.

## 6. Conclusions

Functional polymer-supported sorbents have become one of the most important classes of advanced materials for heavy metal determination, preconcentration, and removal from water. Their success is primarily attributed to tunable surface chemistry, abundant functional groups, excellent adsorption capacity, high selectivity, and remarkable regeneration capability. Recent developments in polymer science have enabled the design of polyamine–polyurea resins, Schiff base-functionalized polymers, ion-imprinted polymers, magnetic nanocomposites, and bio-based adsorbents that effectively combine analytical performance with environmental sustainability. Their integration into solid-phase extraction has substantially improved trace metal analysis, while their application in wastewater treatment has demonstrated high removal efficiencies for a broad range of toxic metal ions. The adsorption behavior of these materials is governed by complementary mechanisms involving coordination chemistry, chelation, electrostatic attraction, ion exchange, and surface complexation. Advances in hybrid polymer composites and nanotechnology have further expanded their applicability by improving adsorption kinetics, regeneration performance, and operational stability. Despite considerable progress, challenges remain regarding large-scale production, long-term durability, regeneration efficiency, and validation under real environmental conditions. Addressing these limitations through green synthesis, renewable polymer resources, pilot-scale applications, and computationally assisted material design will be critical for future development. Overall, functional polymer-supported sorbents represent a rapidly evolving research field at the interface of analytical chemistry, polymer science, nanotechnology, and environmental engineering. Continued innovation in this area is expected to support sustainable water purification, accurate environmental monitoring, and efficient management of heavy metal pollution, contributing directly to global efforts toward safe water resources and sustainable development.

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