

Hydrogel and its textile composite materials in the heavy metal removal research progress

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Abstract. With the rapid development of industrialization, global water resource shortages and heavy metal pollution problems occur frequently, seriously threatening ecological security and human health. This article expounds on the research status of heavy metal removal technology, analyzes in detail the characteristics and limitations of carbon-based materials, metal-organic frameworks, and biomass adsorbents. By focusing on hydrogel materials, it explains their three-dimensional network structure and physical/chemical cross-linking mechanisms, and summarizes the application progress of natural, synthetic, and composite hydrogels in heavy metal adsorption. Combined with the multidimensional structure and mechanical properties of textile materials, it discusses the functional modification strategies and adsorption efficiency of one-dimensional to three-dimensional textile materials. On this basis, it proposes the design of hydrogel textile composite materials, optimization of mechanical strength, improvement of selective adsorption, and enhancement of green preparation processes, in order to promote their large-scale application in heavy metal pollution control and provide innovative solutions for building a safe and sustainable water resource system.

Keywords: *Hydrogel textile composite materials; Heavy metal removal; Adsorbent materials*

Received on 02 March 2024, Accepted on 02 May 2024, Published on 15 July 2024

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1 Introduction

Water is an indispensable precious resource for human survival and social development. The earth is rich in water resources, about 75% of its area is covered by water, most of which is distributed in ocean areas, and only less than 0.3% of fresh water resources can be directly drunk by humans [1]. United Nations data shows that about a quarter of the global population is facing water shortage problems. In the past 40 years, global water usage has increased at an annual rate of about 1%, and it is expected that this growth trend will further increase by 2050. Water resource shortages not only affect people's daily lives but also have profound impacts on agriculture, industry, and other fields.

Heavy-metal contamination has become a silent thief of usable water, turning clean-source scarcity into an even tighter squeeze. Heavy metal pollution mainly comes from industrial emissions [2], agricultural activities [3], and urban life [4], and other aspects. Mining, smelting, chemicals and pharma all exhale metal-laden streams; if scrubbing is skipped, those effluents push river and groundwater concentrations past safe thresholds in a single discharge cycle. For example, in the mining process, after the ore is mined, crushed, and sorted, the selected ore and waste residue will be placed outdoors in the open air. When encountered rainwater washing, part of the heavy metals dissolve into the rainwater and penetrate into the soil and groundwater, causing harm to the local soil and water environment. In agricultural activities, excessive use of pesticides, chemical fertilizers, and sewage irrigation will also cause heavy metals to accumulate in plants and soil, endangering the environment and human health. Metal-laced water slows algal photosynthesis and skews fish reproduction; when people drink the same brew, the ions accumulate in organs, quietly eroding kidneys, bones and nerves [9–11]. Because metals climb

the food web without breaking down, each trophic step magnifies their load until dinner plates carry doses high enough to inflict permanent damage—making their removal a core task for safeguarding both ecosystems and public health.

Today's heavy-metal toolkit spans five broad lines: chemical precipitation, electrochemical plating, tight-knit membranes, microbe-assisted uptake, and surface adsorption. Precipitation swaps soluble ions for solid particles: lime, sulfide or carbonate reagents are dosed to nucleate metal hydroxides, sulfides or carbonates that settle out as sludge. However, the chemical precipitation method is not suitable for wastewater environments with low concentrations and is prone to produce sludge, which, if not treated, can easily cause secondary pollution to the environment. The electrochemical method uses the action of electric current to cause oxidation-reduction reactions of heavy metal ions on the electrode plate, and collect them near the electrode plate. However, electrochemical treatment has a high demand for electrical energy. For this reason, researchers have begun to explore the use of clean energy, such as photovoltaic power generation [16], air batteries [17], and other self-powered technologies, to achieve heavy metal removal while reducing energy consumption. The membrane separation method uses the selective permeability of semi-permeable membranes to heavy metal ions, and uses external pressure or an electric field to separate heavy metal ions from water molecules. Common methods include reverse osmosis [18], nanofiltration [19], and ultrafiltration [20]. This method has a simple operation process, does not require additional chemical reagents during the removal process, and is environmentally friendly, but the cost is high and the membrane is easily polluted. The biological method uses animals [21], plants [22-24], microorganisms [25-26], and plant-microorganism [27-28] combinations, etc., to absorb, transform, and enrich heavy metal ions. This method is environmentally friendly, using the natural metabolic process of organisms to remove heavy metal ions without adding chemical agents, but the removal time cycle is long and greatly affected by environmental conditions. Adsorption docks ions onto high-area solids whose surfaces are tailored to grab specific metals, trading capacity for selectivity without altering the water matrix. Captured heavy-metal ions can later be reclaimed by calcining the spent adsorbent [30] or by mild acid desorption [31], turning waste into a recoverable resource. Relative to competing techniques, adsorption offers straightforward operation and avoids secondary contamination, which explains its current popularity for heavy-metal clean-up.

Typical sorbents span activated carbons, metal-organic frameworks (MOFs) and a growing family of biomass-derived substrates. Carbon cousins—activated carbon, nanotubes or graphene—deliver vast, tailorable surfaces whose pore walls and π -electron clouds can be chemically scripted for high metal uptake. Yet flagship carbons such as graphene or carbon dots arrive through energy-intensive, reagent-heavy routes; slip-ups in waste handling can swap one pollutant for another. Metal-organic frameworks (MOFs) are crystalline sponges built from metal nodes and organic linkers that self-assemble into ordered, ultra-porous lattices [35–37]. Their cavities and window sizes can be blueprinted before polymerisation or re-tailored afterwards, letting chemists implant selective binding sites for chosen metal ions. Despite record capacities, MOF recipes are multi-step and solvent-hungry, keeping unit prices high and ton-scale use at arm's length. In contrast, biomass adsorption materials are widely used due to their wide source, environmental friendliness, and renewable material. Such materials are usually made from natural materials such as chitosan [38] and lignin [39], or natural waste materials such as waste sawdust [40] and waste marine algae [41]. At the same time, through optimization and modification, their adsorption capacity can be significantly enhanced, thereby playing a greater role in practical applications.

Among the many adsorption materials, hydrogel shows great potential in the field of heavy metal wastewater treatment due to its unique three-dimensional network structure, high hydrophilicity, rich modifiable functional groups (such as -COOH, -NH₂, -OH, -SH, etc.), and excellent adsorption capacity [42-43]. Hydrogel can efficiently capture heavy metal ions through various mechanisms such as electrostatic attraction, ion exchange, and chelation. Standalone hydrogels, however, are often hamstrung by weak mechanics, dwindling performance after a few reuse cycles and scale-up hurdles. To shore them up, scientists marry hydrogels to textiles; fabrics bring high surface area, flexibility, strength, stretch and 1-D to 3-D architectures that are easy to weave, knit or braid—perfect skeletons for gel infusion. Locking gel into fibre gaps boosts composite strength and shape integrity while preserving (often amplifying) the hydrogel's appetite for dissolved metals—offering a fresh route to cleaner water.

2 Research status of hydrogel adsorption materials in the field of heavy metal

removal

2.1 Preparation methods of hydrogel

2.1.1 Physical crosslinking

Physical cross-linking knits polymer chains through reversible forces—hydrogen bonds, ion pairing, hydrophobic pockets or van-der-Waals contacts—using routes such as freeze–thaw cycling, salt bridges or associative micelles.

Freeze-thaw method. A method of forming a hydrogel network structure through multiple freezing and thawing cycles, forming hydrogen bonds or other physical interactions in the polymer chains [44-45]. During the freezing process, water molecules in the material form conical ice crystals along the temperature gradient. As ice crystals advance they squeeze polymer segments together, expelling water and forcing chains into close register; each freeze–thaw cycle tightens the embrace, seeding new hydrogen bridges and micro-crystalline junction zones. Locked by a lattice of intra- and inter-chain hydrogen bonds, these crystalline patches act as physical net-points that hold the three-dimensional web together. Borrowing nature’s cross-link playbook, LIN et al. inserted tannic acid as a sticky bridge between cellulose nanocrystals and PVA; repeated freeze–thaw cycles welded the trio into a tough, ultra-strong, self-healing hydrogel laced with multiple hydrogen locks [46].

Ion crosslinking method. Using the electrostatic interaction or coordination interaction between metal ions and functional groups (such as carboxyl groups, hydroxyl groups, etc.) on the polymer chain to form crosslinking points to prepare hydrogel. SUN et al. selected chitosan and sodium alginate as materials, and through physical crosslinking, obtained a double-network hydrogel. The carboxyl groups in the sodium alginate molecules dissociate into negative charges in water. When they come into contact with Ca^{2+} in the solution, the calcium ions interact electrostatically with these negative charges, forming crosslinking points and constructing the first layer network of the hydrogel [47]. Likewise, protonated amino groups on chitosan lock onto alginate carboxylates via electrostatic handcuffs, building a second network that stiffens the gel without extra chemistry [47].

Hydrophobic association method. Introducing hydrophobic groups into the polymer chain, causing the polymer chains to aggregate through hydrophobic interactions, thus forming a hydrogel. LIU’s team grafted long C18 and short C8 acrylate tails onto DMAPMA and CNC, creating amphiphilic macromonomers that self-assemble into hydrophobic domains. These domains then associate—C18 pairing with C8 and cationic DMAPMA docking onto anionic CNC—building a reversible, hydrophobically stitched network that stiffens under stretch yet relaxes when stress is removed. This hydrogel exhibited excellent mechanical properties [48].

2.1.2 Chemical crosslinking

Chemical cross-linking welds polymer backbones together with covalent bonds—via condensation, radical chain growth or high-energy beams—locking in a permanent 3-D lattice.

Condensation reaction. Functional groups (such as hydroxyl groups, amino groups, carboxyl groups, etc.) on the polymer chain remove small molecules (such as water, alcohol, etc.), thereby forming covalent bonds and achieving hydrogel crosslinking. Hydrogels with specific structures and properties can be formed through different condensation reactions. LI et al. dialled in self-repair by letting dialdehyde hyaluronic acid (AHA) meet cysteine; the ensuing Schiff-base imine ties form within seconds, knitting a hydrogel that stitches itself whenever cut edges realign [49]. Similarly, JIAO et al. selected polyethylene glycol dicyanoacetate and polyvanillin acrylate as materials. Through Knoevenagel condensation, a dynamic covalent $\text{C}=\text{C}$ bond can be formed between the two raw materials. The reversibility of this reaction gives the hydrogel excellent self-healing performance [50].

Free radical polymerization. A method in which, under the action of an initiator, the double bonds in monomers or prepolymers are opened, generating free radicals, and then the free radicals combine with each other to form covalent bonds, thereby forming a hydrogel network. Using acrylamide, acrylic acid, chitosan and conductive MXene, LI triggered redox radicals with ammonium persulfate; chains grow simultaneously from every backbone, grafting MXene platelets into a tough, current-carrying nanocomposite mesh [51]. These free radicals can attack

the double bonds of monomer molecules, breaking them and forming new free radical active sites [51]. These active sites further react with other monomer molecules, initiating chain growth, and finally forming a polymer network.

High-energy irradiation. A method that uses electron beams, γ -rays, ultraviolet rays, etc., to irradiate polymer solutions or melts, generating free radicals, and then the free radicals combine to form covalent bonds, constructing a hydrogel network. Among them, electron beam radiation can achieve rapid crosslinking of hydrogels [52]. Compared with electron beam radiation, γ -ray irradiation has higher penetration and can achieve the preparation of highly crosslinked hydrogels [53], thereby improving the mechanical properties of the hydrogel. Ultraviolet irradiation has lower energy compared to the first two irradiation methods and usually requires the addition of photosensitizers to improve crosslinking efficiency [54], but it also increases the complexity of the preparation process.

In general, physically crosslinked hydrogels do not involve chemical reactions, have good biocompatibility, and are highly reversible and reusable, but the formed network structure is relatively weak. Chemically crosslinked hydrogels can form a three-dimensional network structure with excellent mechanical properties and high stability, and can precisely regulate properties to meet specific needs, but the preparation process is relatively complex and may produce toxic substances, causing environmental pollution. So, pick your cross-link strategy to fit the job: freeze–thaw for green simplicity, ionic handcuffs for self-healing, or covalent welds when permanence trumps remodelling.

2.2 Application of different types of hydrogels in heavy metals

Natural polymer hydrogels. Prepared from natural biomacromolecules, common materials such as chitosan, cellulose, etc. This kind of hydrogel material can degrade naturally and is very environmentally friendly.

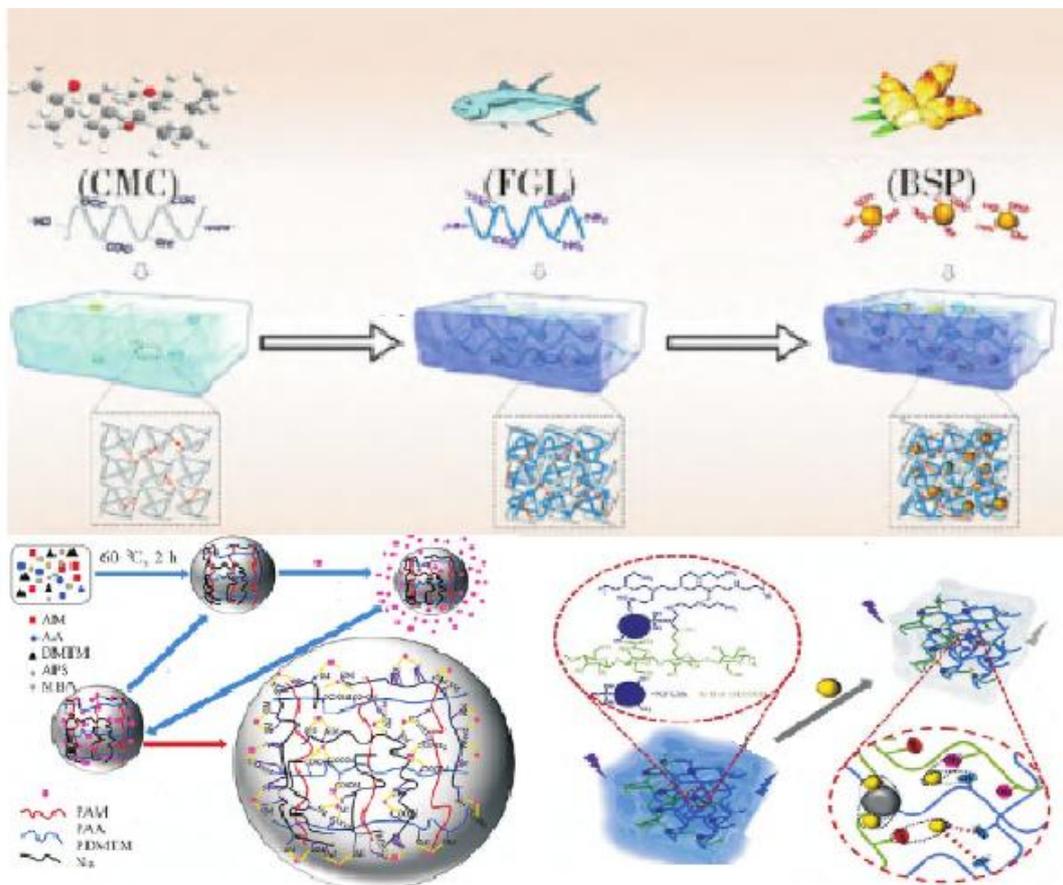


Figure 1 Application of different kinds of hydrogels in heavy metal removal

SHAN et al. brewed a one-pot gel straight from wheat-straw cellulose, lignin and hemicellulose; the lignin phenolics act as natural chelators, pulling Cu^{2+} out of solution without extra functionalisation. Cu^{2+} docks onto deprotonated $-\text{COO}^-$ pockets by electrostatic attraction, loading up to $1.421 \text{ mmol g}^{-1}$ [55]; the caveat is the same gel's modest modulus, a common weak spot for plant-polymer networks. To shore up the soft network, ZENG blended fish gelatin and bamboo-shoot fibres into carboxymethyl cellulose; the rigid cellulose crystallites and fibre bundles act as stress-transfer bridges, stiffening the gel without sacrificing its metal-chelating chemistry. As shown in Figure 1(a), based on hydrogen bonding, its critical strain value is as high as 214.68% [56]. Bamboo shoot particles have a large specific surface area, accelerating the adsorption of heavy metals in aqueous solution. Subsequently, the microchannels inside the microparticles promote the migration of metal ions, allowing heavy metals to quickly combine with the negatively charged carboxyl groups on CMC, relying on electrostatic interaction and coordination to achieve the removal of Cd^{2+} , Hg^{2+} , and Pb^{2+} , with maximum adsorption capacities of 147.7, 88.62, and $163.89 \text{ mg}\cdot\text{g}^{-1}$, respectively [56].

Synthetic gels—built from backbones such as acrylic acid or acrylamide—are stitched by covalent chemistry into 3-D nets whose stiffness, pore size and functional side-groups can be dialled in at will, delivering reliably higher moduli than their bio-based cousins. NIU polymerised acrylamide, acrylic acid and a triazine-thiol monomer into a sponge-like hydrogel (Fig. 1b) whose oversized pores and thiol-rich walls drink up water yet leave plenty of binding sites for incoming metal ions [58]. Its open, sponge-like lattice swells instantly, flooding the interior with metal-laden water; once inside, ions meet a cocktail of amide, $\text{C}=\text{N}$, carboxyl and thiol sites that snap them up through multidentate chelation. The gel clears Cu^{2+} , Cd^{2+} and Pb^{2+} with respective maxima of 92.33, 110.08 and 200.97 mg g^{-1} —capacities that sit in the top tier for single-network hydrogels [58].

Hybrid gels marry bio- and petro-worlds for one-plus-one performance. JIA, for example, knitted a poly(acrylic acid) network cross-linked with MBA around a β -cyclodextrin MOF; the sugar cages act as extra docking stations, boosting both swell and selectivity. This hydrogel not only exhibits excellent structural stability but also shows efficient adsorption performance for Au^{3+} , Ag^+ , and Pb^{2+} , with maximum adsorption capacities of $316.4 \text{ mg}\cdot\text{g}^{-1}$, $60.9 \text{ mg}\cdot\text{g}^{-1}$, and $414.2 \text{ mg}\cdot\text{g}^{-1}$, respectively [59]. The adsorption and removal of metal ions by this material are achieved through the chelation and electrostatic attraction between the $-\text{OH}$ and $-\text{COOH}$ groups and the heavy metal ions. Similarly, CHU et al. used carboxymethyl cellulose (CMC) and polyethyleneimine (PEI) biopolymers as materials to develop a new fluorescent composite hydrogel, see Figure 1(c) [60]. Among them, N, P-doped carbon dots (N, P-CDs) act as fluorescent probes, enabling the composite hydrogel to simultaneously detect and adsorb heavy metal ions. At pH 2, Cr(VI) sits mostly as HCrO_4^- ; the positively charged gel draws the anion in, then hydroxyls along the chain reduce part of it to Cr(III) , which is trapped by N- and O-donor coordination inside the matrix. Shifting to pH 4, deprotonated carboxylates pull Hg^{2+} inside; once captured, the ion is pinned by chelation to nearby amino and ether oxygens, locking it securely within the network. Meanwhile, N,P-doped carbon dots embedded in the gel donate electrons to bound Hg(II) and Cr(III) , quenching fluorescence through non-radiative transfer—turning the same patch into a dual-purpose sensor with sub-ppm limits (0.48 mg L^{-1} for Hg, 0.27 mg L^{-1} for Cr) while still loading 846.7 and 289.5 mg g^{-1} , respectively [60].

In general, composite hydrogels, through multi-component synergy, combine the environmental friendliness of natural polymer hydrogels and the structural tunability of synthetic hydrogels. Yet even these hybrids can tear under field handling and may still bleed competing ions into the binding sites—so the next task is to marry them with tougher scaffolds (textiles, foams, 3-D prints) that survive real wastewater while sharpening site selectivity.

3 Research progress of textile materials in heavy metal removal

Textile materials have the characteristics of high ductility, high specific surface area, and multi-group modification. Textile materials of different dimensions can be suitable for use in complex environments and have potential advantages for heavy metal removal, playing an important role in environmental management.

3.1 One-dimensional (1D) textile materials

1D textile materials, namely fibers, are the most basic unit of textile materials. After modification, they can be

used for the adsorption of heavy metal ions. NIU started with everyday cotton gauze, opened its glucose rings with periodate to expose aldehydes, grafted tetraethylenepentamine for multiple N-donor arms, and finally over-coated chitosan, yielding a fibre that chelates metals across a broad pH window [61]. At its sweet spot (pH 5) the triple-N cotton sequesters Cu^{2+} , Pb^{2+} and Cr^{3+} up to 81.97, 123.46 and 72.99 mg g^{-1} , binding each ion through lone-pair donation from secondary amines and primary $-\text{NH}_2$ groups. Likewise, JIAO grew MnO_2 nano-whiskers directly on cotton cellulose by a rapid ion-exchange/redox tandem, dressing each fibre with a catalytic oxide shell (Fig. 2a).

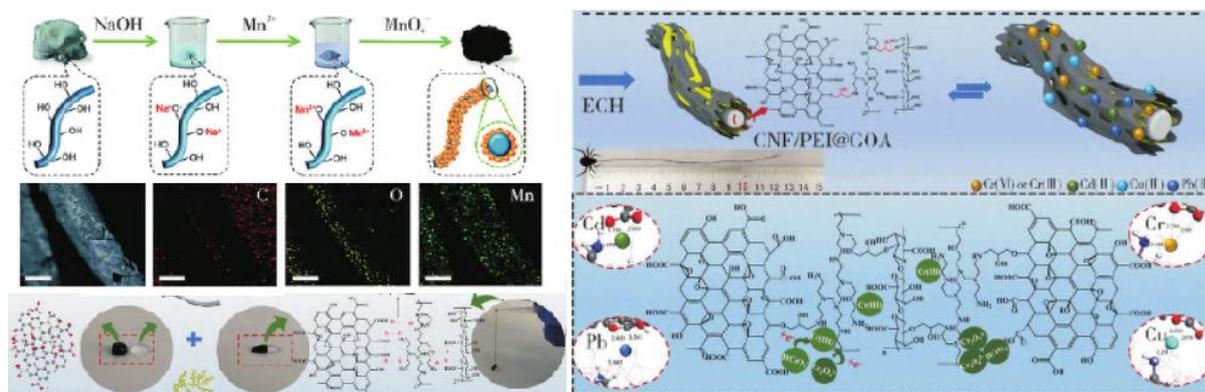


Figure 2 Application of 1D textile materials in heavy metal removal

It has good adsorption performance for Cu^{2+} and Pb^{2+} , with maximum adsorption capacities of 68.3 mg g^{-1} and 174.2 mg g^{-1} , respectively [62]. In order to solve the imbalance of amphoteric functional groups, researchers have also prepared bionic fiber materials based on bionic principles. Mimicking spider-silk layering, ZHOU wrapped a cellulose-nanofiber core with polyethylenimine and cloaked the bundle in graphene oxide sheets via electrostatic self-assembly, creating a core-shell CNF/PEI@GOA fibre (Fig. 2b) whose outer GO wall sieves ions while the PEI mid-layer chelates them [63]. Packed with 6.93 mmol g^{-1} amino and 5.81 mmol g^{-1} carboxyl sites, the silk-mimic fibre strips Cd^{2+} , Cr^{6+} , Cu^{2+} and Pb^{2+} to below detection within 40 min. While the fibre loads, $-\text{NH}_2$ and $-\text{COOH}$ work in concert: electrostatics pull Cd^{2+} through the GO sieve, then lone-pair chelation pins the ion between amine and carboxyl groups. The adsorption process of Cr^{6+} mainly depends on the amino group, and its adsorption mechanism includes electrostatic adsorption, chelation reaction, and redox reaction, while the adsorption of Cu^{2+} and Pb^{2+} is mainly attributed to the chelation of the carboxyl functional group [63].

3.2 Two-dimensional (2D) textile materials

Two-dimensional textile materials are planar structural materials made from 1D fibers or yarns through weaving, knitting, non-woven, and other processes. Compared with one-dimensional textile materials, two-dimensional textile materials have a larger specific surface area, giving them wide application potential in the field of heavy metal removal. HWANG et al. used waste silk fibroin as raw material and used a simple dip-coating method to mix silk fabric with tannic acid to make an adsorption material. Research shows that this material has a low adsorption capacity for Pb^{2+} , only 7.91 mg g^{-1} [64]. To push uptake further, SHI grew zirconium-MOF crystals directly on pre-carboxylated cotton cloth; the fabric acts as a flexible scaffold for the microporous framework, marrying textile handle with MOF-grade surface area and tunable porosity [65]. The cotton-MOF hybrid traps >99.99 % of Au^{3+} within minutes, plateauing at 190.98 mg g^{-1} (pH 3.25); under that acidity the framework's open Zr sites and cotton carboxyls reduce Au^{3+} to metallic $\text{Au}(0)$ while locking the newly formed clusters inside the pores.

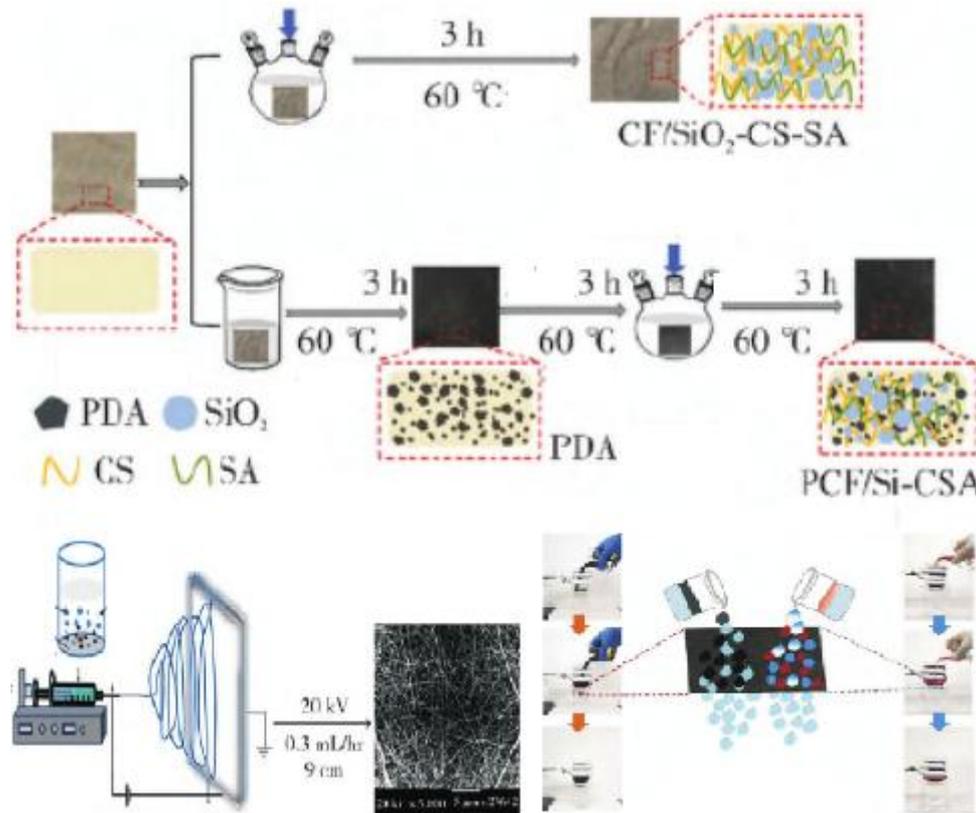


Figure 3 Application of 2D textile materials in heavy metal removal

To improve adsorption performance, researchers usually combine textile materials with other materials as substrates. SHI et al. prepared a bifunctional zirconium-based MOFs/cotton fabric composite by in-situ growth of MOFs on carbonylated cotton fabric [65]. This material has a high specific surface area, adjustable pore size, and strong adsorption capacity. The adsorption efficiency for Au^{3+} is as high as over 99.99%, and the saturated adsorption capacity at $\text{pH}=3.25$ is $190.98 \text{ mg}\cdot\text{g}^{-1}$ [65]. At low pH the cloth's $-\text{COOH}$ protonates to $-\text{COOH}_2^+$ while $\text{Zr}-\mu\text{-OH}$ groups pick up extra H^+ to form $-\text{OH}_2^+$; these cationic patches electro-statically haul in AuCl_4^- anions, after which redox chemistry deposits metallic gold inside the fibre. To survive oily effluents, LI rendered cotton simultaneously water-loving and oil-repelling: a silica nano-roughening step plus chitosan/alginate over-coat creates a surface that wicks water yet sheds oil underwater (Fig. 3a), letting the adsorbent work even when hydrocarbons are present [66]. The finished cloth posts an underwater-oil contact angle $>159.8^\circ$ and near-zero adhesion, so a gentle water rinse peels crude oil away. Beneath the oil screen, $-\text{COOH}$ and $-\text{NH}_2$ sites still chelate Cu^{2+} , delivering 91.3 % removal even from hydrocarbon-contaminated brine [66].

In addition to direct surface modification of the fabric, micro/nano structures can be constructed on the fabric surface to improve hydrophobicity. WANG et al. used nano-silica as a binder to coat natural zeolite powder on polyester fabric surface, synthesizing a natural zeolite-coated fabric with micro/nano structure [67]. After alkali treatment, natural zeolite has a high hydroxyl content, significantly improving the material's hydrophilicity, and it has a high cation exchange capacity, enhancing the material's heavy metal adsorption performance. The material has underwater superoleophobicity, with contact angles for kerosene and cyclohexane reaching 151.5° and 153.4° , respectively. At the same time, it can remove Cr and Mn ions, with removal rates up to 86.5% and 67.4%, respectively [67].

Compared to traditional fabric structures, electrospun membranes have a higher specific surface area and high porosity, showing broad application prospects in heavy metal removal. HAMAD et al. selected cellulose acetate nanofibers and hydroxyapatite as raw materials, and prepared nanocomposite fiber membranes using electrospinning. By adjusting electrospinning conditions, a uniform bead-free nanofiber structure was prepared,

as shown in Figure 3(b) [68]. Within 35 min and 40 min, the hybrid nanofiber composite can efficiently remove Pb^{2+} and Fe^{3+} , with removal rates up to 99.7% and 95.46%, respectively [68].

3.3 Three-dimensional (3D) Textile Materials

Three-dimensional textile materials refer to textile materials with three-dimensional structures manufactured through 3D weaving, 3D knitting, 3D non-woven, and other technologies. Compared with traditional two-dimensional textile materials, 3D textile materials have higher structural complexity and superior mechanical properties. GUO et al., inspired by mussel coatings, grafted thiol-terminated polyacrylic acid onto the surface of PP non-woven fabric to prepare a modified non-woven material with excellent heavy metal removal effect, as shown in Figure 4(a) [69]. A grafted polypropylene–poly(acrylic-acid) fabric (PP-g-PAA) binds Pb^{2+} , Cu^{2+} and Cd^{2+} at 123.38, 124.45 and 120.18 $mg\ g^{-1}$, respectively [69]. Meanwhile, YE etched TiO_2 onto non-woven cotton and ran a photo-bio hybrid: UV light splits copper–citrate complexes, free Cu^{2+} photoreduces to $Cu(0)$ on the fibre, and residual citrate is mineralised by immobilised microbes—achieving near-quantitative copper removal (Fig. 4b) [70]. Against a stand-alone photocatalytic reactor, the cotton/ TiO_2 /biofilm trio lifts Cu removal to 94 % by coupling photoreduction with microbial polishing [70].

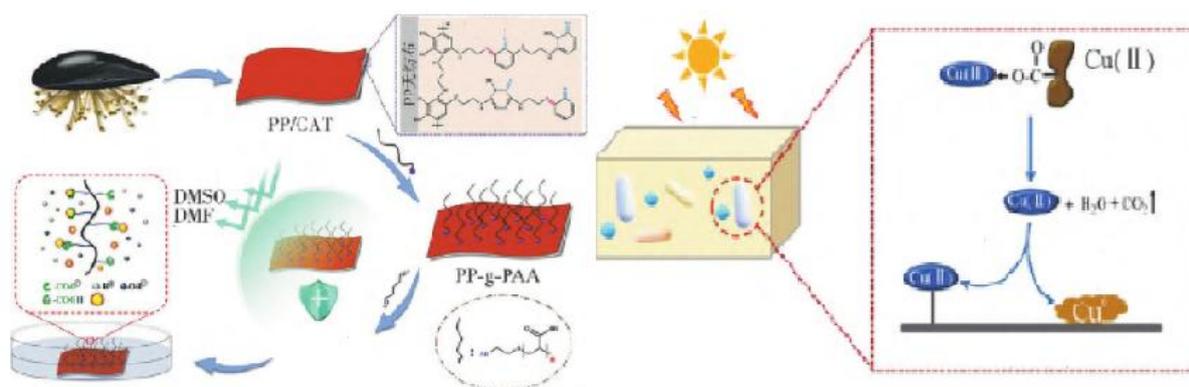


Figure 4 Application of 3D textile materials in heavy metal removal

In summary, the structural regulation of one-dimensional, two-dimensional, and three-dimensional fabrics in heavy metal removal has a significant impact on adsorption performance, as shown in Table 1. One-dimensional fabrics, with their linear structure and short mass transfer paths, are suitable for rapid filtration of low concentrations, but have low specific surface area and adsorption capacity; two-dimensional fabrics, by controlling weaving density and functional modification, achieve medium adsorption capacity, balancing permeability and active site distribution, but mass transfer efficiency is limited; three-dimensional fabrics, relying on multi-level pores and high specific surface area, significantly improve adsorption capacity, and the three-dimensional connected pores promote mass transfer, suitable for high-concentration wastewater treatment.

Table 1 Effect of Textile Material Structure on Adsorption Performance

Parameter	One-Dimensional (1D) Textile Materials	Two-Dimensional (2D) Textile Materials	Three-Dimensional (3D) Textile Materials
Structural Characteristics	Single fiber or fiber bundle, linear structure, simple structure	Planar network structure, fibers interwoven to form a two-dimensional layered or membrane-like structure	Porous three-dimensional network structure with complex pore hierarchy
Specific Surface Area	Low	Medium	High
Pore Structure	Few pores, mainly inter-fiber gaps	Controllable two-dimensional pores, adjustable by weaving density	Multi-level pore structure (micropores for adsorption, mesopores for mass transfer, macropores for rapid penetration)

Active Sites	Limited surface active sites, require functional modification (e.g., grafting functional groups)	Active sites distributed uniformly within the plane, can be increased by chemical modification	Three-dimensional network provides high-density active sites, and is easy to load with nanoparticles or polymer coatings
Mass Transfer Efficiency	Short mass transfer path, but low porosity limits diffusion	Long two-dimensional planar mass transfer path, but permeability can be improved by optimizing pore distribution	Three-dimensional connected pores promote rapid fluid diffusion, high mass transfer efficiency

4 Research Progress on Hydrogel-Based Textile Composite Materials in Heavy Metal Removal

Hydrogels and textile materials possess complementary advantages in heavy metal treatment. On one hand, hydrogels exhibit excellent adsorption performance due to their unique three-dimensional network structure. However, single-component hydrogels have certain limitations in mechanical strength and processability, which restricts their recyclability. On the other hand, textile materials demonstrate good recyclability owing to their excellent mechanical properties. Nevertheless, when used alone, their specificity and adsorption capacity for heavy metals are relatively insufficient. Therefore, combining the two through composite technology leverages the synergistic advantages of the multiple adsorption active sites of hydrogels and the high structural stability of textile substrates. This approach significantly enhances the adsorption performance and durability of the material, providing new research avenues for heavy metal removal.

4.1 Preparation of Hydrogel-Textile Composites

Dip-Coating Method. This method involves immersing the textile material into a hydrogel precursor solution. After the textile is fully impregnated, a stable bond is formed between the precursor solution and the textile through subsequent chemical crosslinking, UV irradiation, or heat treatment [71-72]. QIU et al. improved the hydrophilicity of ultra-high molecular weight polyethylene (UHMWPE) fabric through surface treatment and combined it with a double-network hydrogel featuring a multi-scale energy dissipation structure, developing a novel composite material. As shown in Figure 5(a), the composite exhibited significant impact resistance in both static and dynamic mechanical performance, with a tearing work nearly twice that of pure UHMWPE fabric [73].

Coating Method. Unlike the dip-coating method, the coating method involves uniformly applying the hydrogel precursor solution onto the surface of the textile material using tools such as rollers, brushes, or spray guns. The hydrogel is then bonded to the fabric through a subsequent cross-linking treatment [74]. Compared to dip-coating, this method allows for selective coating on the fabric surface, enhancing its multifunctionality. WANG et al. introduced a hydrogel with antioxidant and antimicrobial activity on one side of a medical fabric and rendered the other side hydrophobic with paraffin deposition, developing a multifunctional hydrogel-textile composite. As shown in Figure 5(b), this material possesses hemostatic properties, antimicrobial activity, and wound healing capabilities, making it suitable for medical dressings [75].

Lamination Method. This technique involves stacking and pressing layers of hydrogel and textile materials to prepare a composite. The mechanical properties of the composite are significantly enhanced through this layer-by-layer stacking process [76]. HUBBARD et al. used glass fiber fabric as a physical interfacial compatibilizer and prepared a three-layer composite via a two-step method, as illustrated in Figure 5(c) [77]. First, a PDMS mixture was poured onto a glass plate, followed by placing the glass fiber fabric. After curing, a polyampholyte (PA) hydrogel solution was injected into the gap between the glass fiber fabric and another glass plate and cured under UV irradiation in an argon atmosphere. The resulting PDMS-glass fabric-PA hydrogel composite achieved a tear energy of $(143 \pm 1.3) \text{ kJ}\cdot\text{m}^{-2}$, which is two orders of magnitude higher than that of the hydrogel $(5.6 \pm 0.2) \text{ kJ}\cdot\text{m}^{-2}$, PDMS $(2.5 \pm 1.1) \text{ kJ}\cdot\text{m}^{-2}$, and glass fabric $(3.2 \pm 0.6) \text{ kJ}\cdot\text{m}^{-2}$, while maintaining low flexural modulus and exhibiting excellent flexibility [77].

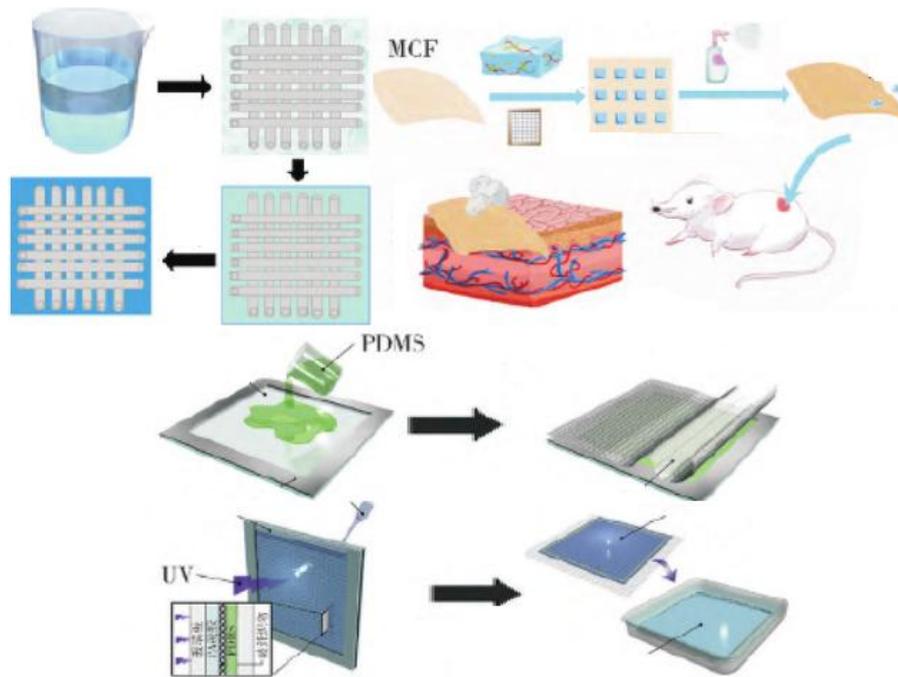


Figure 5 Hydrogel-textile composite preparation methods

4.2 Applications of Hydrogel-Textile Composites in Heavy Metal Removal

Hydrogel-textile composites combine the excellent mechanical properties of textiles with the efficient heavy metal ion adsorption performance of hydrogels, making them applicable in the field of heavy metal removal. However, related research is currently limited. LI et al. first pretreated polylactic acid (PLA) meltblown nonwoven fabric with plasma grafting. They then compounded it with a polyethylene glycol maleate double-network hydrogel to develop a hydrogel-textile composite with excellent mechanical properties and high adsorption capacity [78], as shown in Figure 6(a).

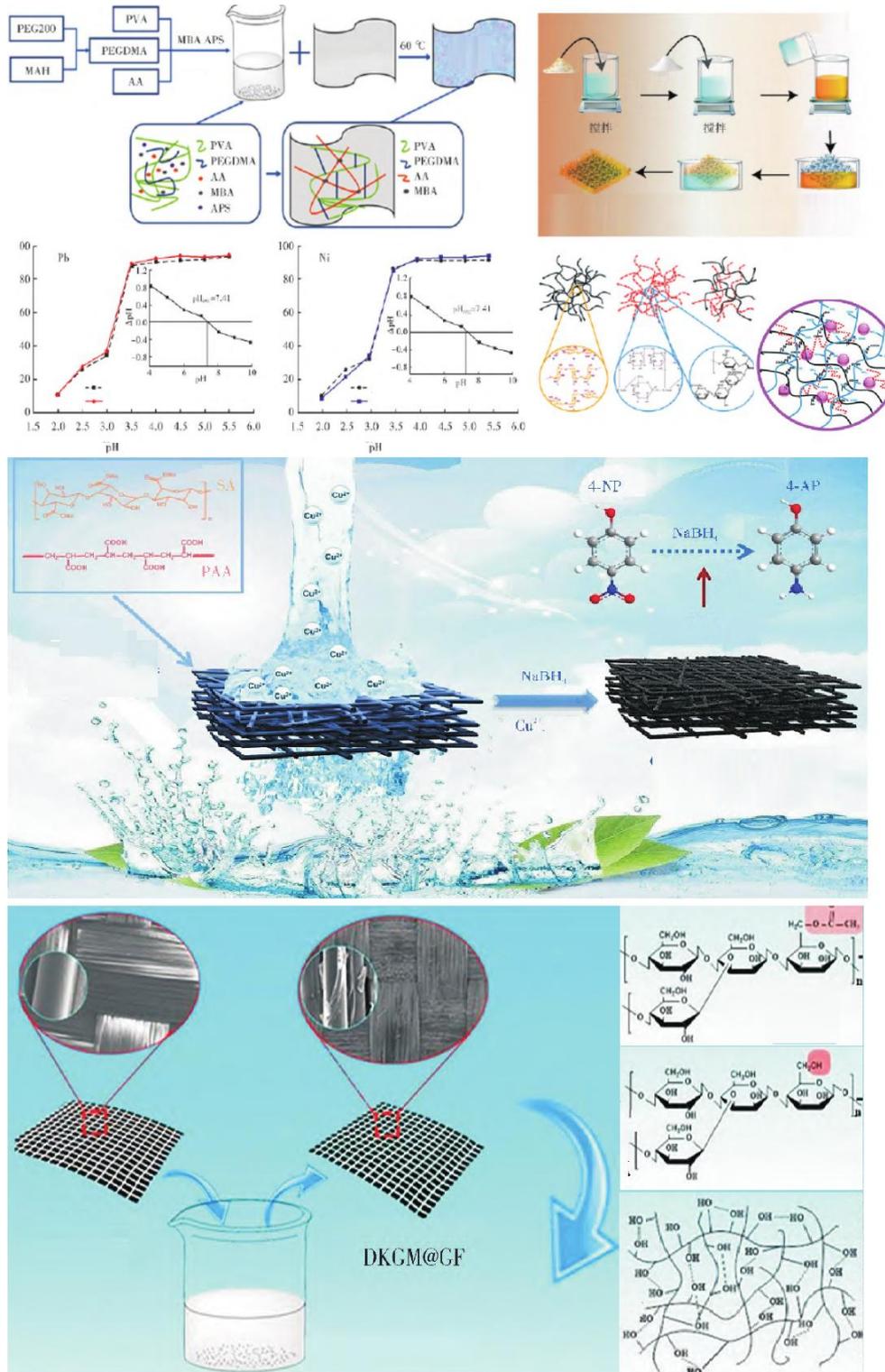


Figure 6 Application of hydrogel-textile composites in heavy metal removal

This material achieved a compressive strength of 40.6 kPa at 60% strain, representing a significant increase of 42.9% in compressive strength. At pH values between 3 and 3.5, the protonation effect is significant, giving the hydrogel surface a positive charge which creates electrostatic repulsion with Pb^{2+} and Ni^{2+} . Nonetheless, the removal efficiency for heavy metal ions can still reach up to 80%. The data show that even at low pH the

composite still loads metals—proof that coordination, not just Coulombic attraction, pins the ions; once the surface deprotonates at higher pH, electrostatics add extra pull and uptake climbs further. Between pH 3 and 3.5 the non-woven skeleton gives a modest edge: its macro-pores shorten diffusion paths, so metal ions reach binding sites faster than in the gel-only film. Carboxyl and amino side chains lock Pb^{2+} and Ni^{2+} through mixed chelation; Langmuir fits give saturation loads of 233.12 mg g^{-1} for lead and 165.06 mg g^{-1} for nickel—among the highest values yet reported for textile-reinforced hydrogels [78]. AZAM blended wool felt with sodium alginate, gum arabic and xanthan gum; the resulting sheet is crowded with $-\text{OH}$ and $-\text{COOH}$ groups that hydrogen-bond and electro-statically anchor Pb^{2+} , giving a cheap, fully bio-based sorbent. The wool–polysaccharide mat grabs 85.2 mg Pb^{2+} per gram and is kinetically greedy—88 % of full load is reached within the first hour, as shown in Figure 6(b) [79].

WANG electro-spun a 4:1 PAA/SA dope into continuous nanofibres, then oven-cured the mat to lock the chains; the resulting PAA-SA nanofibrous hydrogel (NFH) keeps a lace-like morphology that swells yet stays self-supporting [80]. Below pH 2 every $-\text{COO}^-$ is protonated, so the fibre surface turns cationic; mutual repulsion plus a swarm of competing H_3O^+ ions shuts Cu^{2+} out, slashing uptake. Once pH climbs to 5.5 the surface re-ionises; freed $-\text{COO}^-$ groups pull Cu^{2+} inside and the mat peaks at 591.7 mg g^{-1} —one of the highest copper capacities on record. A mild NaBH_4 rinse then reduces the bound ions in place, plating the fibres with antimicrobial $\text{Cu}(0)$ nanoparticles without losing the original nanofibre shape. The Cu-plated web doubles as a flow-through catalyst, converting 4-nitrophenol to 4-aminophenol in minutes with near-quantitative yield [80]. Similarly, YOU et al. prepared a natural polymer hydrogel using konjac glucomannan as the raw material and coated it onto an engineering material, glass fiber fabric, to create a hydrogel-glass fiber composite [81]. Beyond catalysis, the same membrane separates oil from water while stripping metals—delivering 27.7 % Pb, 32.3 % Cu, 34.5 % Cr and 48.3 % Cd removal in a single pass [81].

5 Summary and Outlook

Hydrogel and its textile composites show unique advantages and great potential in heavy metal removal. Hydrogels possess high water absorbency and abundant functional groups, enabling effective adsorption of heavy metal ions. Textile materials, characterized by high extensibility, high specific surface area, and multi-group modifiability, offer excellent mechanical properties while ensuring adsorption performance. Marrying gel and cloth thus lifts capacity and tear strength in one step; next-gen work will chase greener cross-linkers, trace-level selectivity, regenerability and low-energy manufacture—turning wearable filters into a practical weapon for cleaner water and circular economies.

Enhance Mechanical Strength and Durability. Improve the mechanical strength of hydrogel-textile composites through material modification and composite technologies, enabling them to withstand more complex industrial wastewater treatment environments.

Optimize Adsorption Performance. Enhance the selective adsorption capacity and adsorption capacity for specific heavy metal ions by adjusting the pore size and surface chemistry of the materials.

Ensure Environmental Friendliness and Sustainability. Develop hydrogel-textile composites based on natural or biodegradable materials to reduce the environmental burden and achieve sustainable development.

Enrich Intelligence and Multifunctionality. Develop hydrogel-textile composites capable of responding to environmental changes (e.g., pH, temperature) by incorporating smart material technologies, enabling visualization and intelligence in the heavy metal removal process.

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