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Role of Nano-Hydrogel Based Materials for Water Purification: A Comprehensive Review

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ABSTRACT

The escalating global challenge of aquatic contamination, predominantly attributed to industrial discharge, agricultural runoff, and domestic effluents, necessitates the development of innovative and sustainable remediation technologies. Nano-hydrogels have emerged as promising candidates for water purification applications due to their unique physicochemical properties, including exceptional water retention capacity, tunable porosity, and the capability to incorporate multifunctional moieties. This comprehensive review investigates the fundamental principles governing hydrogel behavior, elucidates their contaminant removal mechanisms, encompassing adsorption, ion exchange, catalytic degradation, and size exclusion filtration, and underscores their efficacy in targeting diverse pollutants, including heavy metals, organic contaminants, pharmaceutical residues, synthetic dyes, and microplastics. The classification of hydrogels according to their source materials (natural, synthetic, composite) and architectural configurations (crosslinked networks, macroporous structures) is thoroughly examined, emphasizing their tunable characteristics for addressing specific environmental challenges. Furthermore, contemporary advances in hydrogel engineering, particularly the integration of nanoscale reinforcements and stimuli-responsive functionalities, are explored. Comparative analyses with conventional treatment methodologies demonstrate the superior advantages of hydrogel-based systems regarding cost-effectiveness, selectivity, recyclability, and ecological compatibility.

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INTRODUCTION

Accelerated urbanization processes and intensive industrial development have been observed to result in unprecedented releases of heterogeneous pollutants into essential aquatic systems, thereby causing substantial disruption to both marine and terrestrial ecological networks [1]. The escalating dependence on fossil fuel consumption, combined with environmental deterioration resulting from extractive mining

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operations and uncontrolled waste incineration practices, has been demonstrated to further exacerbate the contamination of critical natural resources, particularly freshwater systems [2]. Throughout the preceding century, industrial activities have been shown to substantially intensify human exposure to an extensive array of contaminants, particularly persistent organic pollutants (POPs) and microplastic particles, alongside heavy metal species, all of which have been identified to present considerable toxicological risks even at trace concentrations [3]. In addressing these pressing environmental challenges, advanced materials have been recognized to attract considerable attention for their applications in environmental remediation, specifically within the essential field of aquatic purification [4, 5]. In comparison to all other materials, hydrogels and their nano form are widely employed and functionalized materials for use in water treatment applications [6, 7] (Fig. 1). The main features of these materials including high swelling property, presence of ionic functional groups and promising adsorption potential for all types of pollutants make them effective as an adsorbent [8, 9].

In contrast to previous reviews that have primarily concentrated on conventional hydrogel compositions, this study incorporates recent advances in areas such as stimuli-responsive characteristics (including pH and temperature responsiveness), sophisticated methods for controlling porosity, and the integration of nanomaterials to enhance functional capabilities. Furthermore, the importance of sustainably developing biodegradable hydrogels derived from natural polymers and agricultural byproducts is underscored, thereby addressing the environmental concerns associated with synthetic materials. The inclusion of computational methods for the design of intelligent hydrogels and the optimization of their performance further distinguishes this work, providing novel perspectives on future research directions. Through synthesizing information across various pollutant types, hydrogel categories (natural, synthetic, and composite), and real-world applications, this review establishes a comprehensive framework that highlights the transformative potential of hydrogels in achieving sustainable and efficient water purification on a global scale.

HYDROGELS

A hydrogel is a biphasic material, representing an intricate mixture of a water-insoluble, three-dimensional network of polymers and a substantial quantity of water or other interstitial fluid, typically comprising at least 10% of its total volume [7]. The exceptional water absorption capacity of hydrogels facilitate intermolecular interactions with water

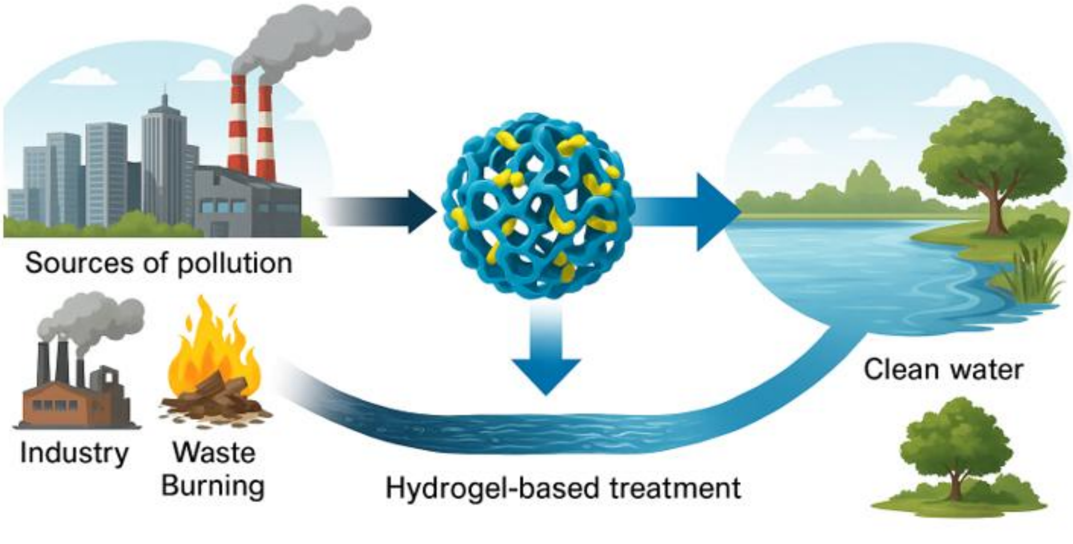

Fig. 1. Hydrogels used for water treatment.

molecules [10]. Two types of interactions are there in hydrogels structure and these include physical and chemical interactions that develop by weak and strong ionic forces correspondingly [7]. Further, another remarkable property of hydrogels is their capacity to absorb water. This exceptional water uptake capability is primarily ascribed to their hydrophilic character, by polar functional group presence within polymer chains, and their porous three-dimensional network architecture [7, 11, 12].

Characteristics of hydrogel

Several factors have been identified to influence the swelling degree of hydrogels. The hydrophilicity of the polymer's pendant groups has been demonstrated to play a crucial role in this process. The nature of the surrounding swelling media, including its ionic strength and composition, has also been shown to affect swelling behavior. Furthermore, the cross-linking density of the polymer network has been recognized as a key determinant; a higher degree of cross-linking typically results in a tighter network structure with reduced capacity to expand and accommodate water molecules. Certain hydrogels have been demonstrated to exhibit responsiveness to environmental stimuli, such as pH variations. Generally, pH-sensitive hydrogels contain acidic or basic functional groups that can be ionized depending on the pH of the surrounding solution [13-16]. Temperature has also been demonstrated to significantly impact the swelling behavior of hydrogels. Temperature-sensitive hydrogels, such as those based on poly(N-isopropylacrylamide) (PNIPAm), have been shown to exhibit phase transitions at specific temperatures, transitioning from a swollen gel state at lower temperatures to a collapsed sol state at higher temperatures [17]. This property can be exploited in water treatment processes where temperature fluctuations occur or can be controlled to enhance pollutant removal or facilitate hydrogel regeneration. Interestingly, the concentration of polymer utilized to form the hydrogel has also been observed to influence its swelling capacity. These properties need to be considered during the design of hydrogels with required water uptake capacity for efficient pollutant removal [18-21].

Classification of hydrogels

Hydrogels can be broadly categorized based on the origin of polymers that constitute their network structure: natural, synthetic, or hybrid

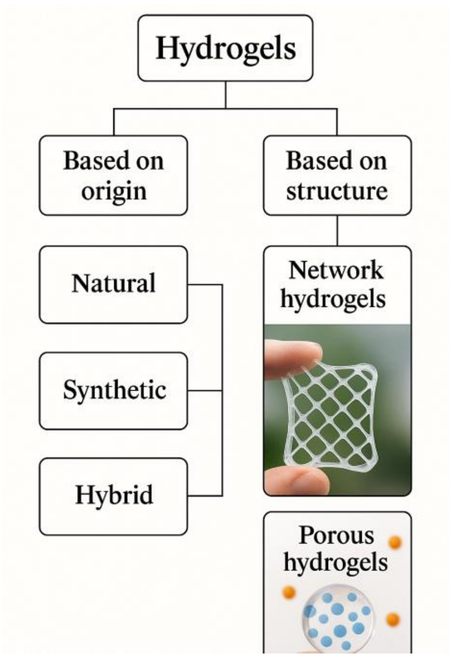

Fig. 2. Classification of hydrogels.

(Fig. 2). Natural hydrogels are derived from polymers that occur in nature, as polysaccharides and proteins. Common polysaccharides that find uses for preparation of hydrogels are alginate, cellulose, starch, gum, pectin, agarose, and hyaluronic acid [22-27]. Natural hydrogels have good biocompatibility and low toxicity with presence of numerous inherent functionalities as hydroxyl, carboxyl, and amine groups that play an important role in water treatment [10]. However, natural hydrogels often show less stability and strength in comparison to their synthetic counterparts, that limit their use for required purposes. Synthetic hydrogels are typically fabricated from artificially manufactured polymers, with commonly employed synthetic polymers in hydrogel synthesis encompassing polyvinyl alcohol (PVA), polyethylene glycol (PEG), polyacrylic acid (PAA), polyacrylamide (PAAm), and poly(2-hydroxyethyl methacrylate) (PHEMA). These materials can be engineered to exhibit desired properties, including enhanced structural stability and mechanical strength, while being designed with specific functionalities to target diverse contaminant categories [10]. By carefully selecting and combining different types of polymers, it is possible to create synergistic effects, where the resulting material possesses properties that are superior to those of its individual components [28]. Hybrid hydrogels have been recognized as a promising approach for developing advanced water purification materials that provide an optimal balance between performance and environmental sustainability [29]. Hydrogels may also be categorized according to their physical structure, predominantly into network hydrogels and porous hydrogels. The three-dimensional network of hydrogels establishes the structural foundation for water retention and solute interaction [30]. Porous hydrogels are distinguished by the presence of interconnected pores within the polymer network, which substantially enhances mass transport and environmental interaction. The extent and nature of porosity, classified as microporous, mesoporous, macroporous, or super-porous, determine their applicability for applications and dimensions of pollutants that can be effectively targeted [31]. The physical configuration of hydrogel as a matrix, film, or microsphere can be customized based on the polymerization methodology employed [32].

WATER CONTAMINANTS

Water sources worldwide are increasingly subjected to contamination by a diverse array of pollutants derived from industrial, agricultural, and domestic activities [33, 34]. These contaminants present significant risks to both environmental integrity and human health, thereby necessitating the development of effective removal technologies. Heavy metals, encompassing elements as lead (Pb), mercury (Hg), chromium (Cr), copper (Cu), nickel (Ni), and zinc (Zn), constitute a major class of inorganic pollutants encountered in aquatic systems [12, 35]. These metallic species are introduced through various pathways, including industrial discharges from mining operations, electroplating facilities, and tanneries, alongside agricultural runoff and natural mineral deposits [36]. Heavy metals have been demonstrated to exhibit high toxicity even at low concentrations and demonstrate a tendency toward bioaccumulation in living organisms that lead to their removal as a critical priority in water purification endeavors. Organic compounds represent an extensive category of aquatic pollutants, encompassing pesticides, herbicides, pharmaceuticals, solvents, industrial chemicals, and volatile organic compounds (VOCs) [37, 38]. Further, dyes, also termed as one of the major water pollutants. Numerous synthetic dyes and their degradation products have been identified as potentially toxic and carcinogenic, thereby posing risks to both environmental and human health [39]. The distinctive coloration associated with dye pollution serves as a visible indicator of industrial impact on water quality [40].

Pesticides, including herbicides, insecticides, and fungicides extensively employed in agricultural practices, constitute another major category of aquatic contaminants [41]. These chemical agents enter water systems predominantly through agricultural runoff from treated fields, as well as through accidental spills and improper disposal practices [42]. The environmental and human health effects of pesticides have been extensively documented, encompassing acute toxicity and immediate health complications to chronic effects including cancers, birth defects, reproductive harm, and disruption of ecological equilibrium [43]. The widespread application of pesticides in agricultural systems establishes their removal from water sources as a critical concern for safeguarding both drinking water supplies and ecosystem health [44].

Residues of both prescription and over-the-counter pharmaceutical compounds are increasingly being detected in water bodies worldwide. These contaminants originate from various sources, including human excretion, landfill leachate, the disposal of unused medications, hospital effluents, and discharges from pharmaceutical manufacturing facilities. Even at low concentrations, pharmaceuticals have been demonstrated to exert significant ecological effects, such as endocrine disruption in aquatic species, and contribute to the alarming rise of antibiotic-resistant bacteria [38]. Potential long-term human health effects from exposure to these compounds have also been identified as an emerging area of concern [45]. The biological activity inherent in pharmaceuticals, designed to elicit specific effects in living organisms, poses unique challenges when these compounds persist in environmental systems [46].

Microplastics, defined as plastic particles measuring less than five millimeters in length, have become a pervasive environmental pollutant within water sources [46]. They originate from various sources, including the degradation of larger plastic debris, microbeads utilized in personal care products, synthetic fibers from textiles, and industrial activities. Microplastics can enter water bodies through wastewater treatment plant effluent, urban runoff, and direct disposal mechanisms [47]. In environmental systems, microplastics can be ingested by aquatic organisms, potentially leading to physical harm, toxin transfer, and bioaccumulation throughout food chains [48]. Emerging research also suggests potential human health concerns associated with microplastic exposure, including associations with vascular disease, cancers, and other disorders. The widespread presence and potential impacts of microplastics represent a relatively recent but rapidly escalating environmental challenge [49].

Main sources of pollution

The principal origins of the aforementioned aquatic contaminants have been attributed to industrial, agricultural, and domestic activities. Industrial processes have been demonstrated to contribute substantially to heavy metal contamination, whereas agricultural practices represent a primary source of pesticides, herbicides, and nitrate compounds. Domestic effluents and inappropriate disposal of household chemicals have been shown to contribute to organic pollutant and pharmaceutical residue accumulation within aquatic systems. Furthermore, atmospheric deposition, urban stormwater runoff, and extractive mining operations have been identified to play considerable roles in introducing diverse contaminant species into water resources. The occurrence of these contaminants, both as individual compounds and within complex mixtures, has been observed to exert severe adverse effects on aquatic ecosystems, terrestrial environments, and human health [50].

HYDROGELS FOR POLLUTANTS REMOVAL

Hydrogels and their nano forms are used several mechanisms for pollutant removal from aquatic systems, establishing them as versatile materials for water purification [30]. These mechanisms principally encompass adsorption, absorption and filtration processes. Adsorption represents a surface-based phenomenon whereby pollutants are retained on the hydrogel material surface. Hydrogels have been demonstrated to function as particularly effective adsorbents due to their elevated porosity and extensive surface area [51]. Nano-hydrogels functionalized with ionic groups can facilitate the removal of charged pollutants, such as heavy metal ions, through ion exchange processes. Through this mechanism, less harmful ions are released from the hydrogel into the aqueous phase while pollutant ions are simultaneously captured, effectively achieving ion exchange within the material's structure. Both cation exchange hydrogels, designed for positively charged ion removal, and anion exchange hydrogels, engineered for negatively charged ion elimination, can be synthesized by incorporating appropriate ionic functional groups into the polymer network [52]. This mechanism provides a selective approach for targeted charged pollutant removal from aquatic systems. Hydrogels can also function as matrices for immobilizing catalytic nanoparticles or enzymes that facilitate pollutant degradation into less harmful substances. This catalytic mechanism has been demonstrated to be particularly effective for organic pollutant and dye degradation, where immobilized catalysts facilitate chemical reactions that transform pollutants into less toxic forms [53].

The inherent porous structure of hydrogels can also facilitate the removal of larger pollutants, including microplastics and suspended solids, through physical filtration mechanisms. The pores within the hydrogel network function as physical barriers, preventing particles exceeding specific size thresholds from passage. Furthermore, hydrogels can be fabricated into membrane configurations with precisely controlled pore dimensions to enhance filtration capabilities for targeted pollutant removal applications. This mechanism complements chemical removal processes including adsorption, absorption, and ion exchange, thereby providing a comprehensive approach to water purification systems [30].

HYDROGELS: TYPES AND THEIR TARGET POLLUTANTS

Hydrogels have been classified to natural, synthetic and composite hydrogels based on their source of origin and synthesis.

Natural hydrogels

Alginate has been proved to exhibit effectiveness in removing various heavy metals as well as organic dyes. Alginate hydrogels used to immobilize microalgal cells, which has been shown to further enhance the removal of pollutants including palm oil, ammonium, and phosphate from water [53]. Calcium alginate hydrogels employed for removing cyanide and heavy metals from industrial electroplating effluents, thereby highlighting their uses in treating wastewater [54]. Chitosan, obtained from chitin, show remarkable adsorption capacity for heavy metals, organic pollutants and microorganisms. Its effectiveness has been extended to removal of various metal ions, dyes, anions, and phenolic compounds from aqueous solutions [55]. Cellulose is termed as the basis for hydrogels to remove various water contaminants including dyes, heavy metals, oils, pharmaceutical and pesticides [56, 57]. Cellulose-based hydrogels can be modified to enhance their adsorption capacity for pollutants, thereby improving their overall performance characteristics [58]. Further, composite hydrogels (generally pH responsive materials) that are generally fabricated from cellulose, pectin, and starch also employed for dye adsorption [59].

Synthetic hydrogels

Polyacrylamide (PAAm) hydrogels used for removal of pollutants from water as PAAm hydrogels showed good capacity for adsorbing methylene blue dye from water [60]. They have also been applied in industrial settings for the removal of total metal ions and total organic acid anions from industrial lean amine solvents used in gas sweetening processes [61]. Nanocomposites fabricated from polyacrylamide and sodium montmorillonite shown to demonstrate effectiveness in water treatment [62]. Polyvinyl alcohol (PVA) represents a versatile synthetic polymer used in hydrogel fabrication due to its excellent biocompatibility [63]. PVA-based hydrogels have been proven effective in removing heavy metal ions when used in composite materials with carboxymethyl cellulose [64]. Functionalization of PVA hydrogels with graphene oxide has also been shown to significantly improve their adsorption capacity for methylene blue [65]. Moreover, anisotropic composite hydrogels fabricated from PVA and MXene have been developed for efficient solar-driven water evaporation and comprehensive wastewater purification applications [66].

Composite hydrogels

Composite hydrogels, which combine natural and synthetic polymers or incorporate additional materials such as nanoparticles and activated carbon, are increasingly being investigated to enhance performance in water purification applications [51]. The incorporation of nanomaterials into chitosan-based hydrogels demonstrated to significantly improve their adsorption capacity [30]. Anisotropic composite hydrogels such as PVA/MXene showed improved solar-thermal conversion efficiency for water purification [66]. Gum acacia is also used for synthesizing nanocomposites for water treatment [67].

HYDROGELS AS ADSORBENT VS. TRADITIONAL WATER TREATMENT MATERIALS

Hydrogels have several benefits over traditional adsorbents for water treatment. In many cases, the production of hydrogels can be more cost-effective compared to traditional synthetic adsorbents such as activated carbon, especially when utilizing low-cost natural or waste-derived materials [68]. For instance, hydrogels employed in agricultural applications have been shown to demonstrate potential for reducing the need for frequent irrigation and the amount of fertilizer required, leading to significant economic benefits [69]. The potential for utilizing abundant and inexpensive starting materials makes hydrogel technology more accessible, particularly in resource-limited settings. Hydrogels often exhibit high adsorption capacities for a wide range of pollutants, including heavy metals, organic compounds, and dyes. Some hydrogels have been demonstrated to show rapid removal rates for specific pollutants and can be specifically designed through functionalization to target contaminants of concern with high selectivity. Notably, certain hydrogels have shown superior efficiency in removing micropollutants compared to traditional methods like activated carbon, especially in terms of speed (Fig. 3) [53]. A significant advantage of many hydrogel-based adsorbents is their ability to be regenerated and reused multiple times. Regeneration can be achieved through various methods such as pH modification, magnetic separation, and UV irradiation, depending on the type of hydrogel and the nature of the adsorbed pollutants [70]. This reusability reduces waste generation and lowers the overall cost of water treatment, contributing to the sustainability of the process. Additionally, hydrogels have the potential to be more environmentally friendly than some traditional methods. They can be synthesized from biodegradable natural polymers, reducing the environmental footprint of the material itself. The reusability of hydrogels also minimizes waste generation compared to single-use adsorbents. Furthermore, the synthesis of some hydrogels can be achieved under milder conditions than those required for the production of traditional materials like activated carbon, leading to lower energy consumption (Table 1) [71].

CHALLENGES AND FUTURE OUTLOOK

Despite the significant potential of nano-hydrogels in water purification, several challenges need to be addressed to facilitate their widespread adoption and effectiveness. While hydrogels exhibit versatility in removing a wide range of pollutants, they may not be equally effective for all types [51, 75]. The performance of a particular hydrogel can be observed to vary depending on the specific pollutant and the complexity of the water matrix, which may contain interfering substances. Therefore, ongoing research has been identified as crucial for optimizing hydrogel design and functionalization for the removal of a broader spectrum of contaminants, including emerging pollutants that may not be effectively targeted by existing hydrogel materials. Some natural hydrogels have been demonstrated to possess limited mechanical strength [76] that can affect their long-term performance and reusability, particularly in continuous flow or large-scale water treatment systems where they may be subjected to mechanical stress conditions. Enhancing the mechanical properties of hydrogels through advanced cross-linking techniques, the development of composite materials, and innovative structural designs has been identified as crucial for their practical application in water purification processes [29]. Furthermore, transitioning the successful performance of hydrogels from laboratory-scale experiments to industrial-scale water treatment has been recognized to present significant engineering and economic challenges. Developing cost-effective and efficient methods for producing large quantities of hydrogels with consistent quality has been established as essential for their widespread

Table 1. Comparison of hydrogels with traditional methods.

Feature	Hydrogels	Traditional methods (activated carbon, membrane filtration, chemical precipitation)
Cost	Potentially lower production cost, especially with natural/waste materials	Can be expensive (e.g., activated carbon production, membrane replacement)
Efficiency	High adsorption capacity, tunable for specific pollutants	Variable efficiency depending on the pollutant and method
Reusability	Often regenerable and reusable	Can generate waste (e.g., saturated activated carbon, sludge)
Environmental Impact	Potential for biodegradability, reduced waste	Can generate hazardous byproducts (e.g., sludge), high energy consumption in some cases
Selectivity	Can be highly selective through functionalization	May lacks selectivity for emerging contaminants
Operational Complexity	Can be simple (e.g., single-step adsorption)	Can involve multiple steps and complex infrastructure

implementation in water treatment facilities [76]. Additionally, engineering considerations related to the integration of hydrogel-based systems into existing water treatment infrastructure have been identified as requiring attention [77]. The degradation of hydrogels over extended use or under certain environmental conditions has been observed to potentially release byproducts into the treated water. It has been established as essential to thoroughly evaluate the nature and toxicity of these degradation products to ensure the overall safety and sustainability of hydrogel utilization for water purification applications. Research into the long-term stability of hydrogels and the development of biodegradable hydrogels that degrade into environmentally benign products are important aspects of ensuring their effective application [78]. The field of hydrogels for water purification is dynamic, with ongoing research and development focused on addressing current limitations and enhancing their performance. Future study must be focused on developing novel hydrogel materials that posses high potential for adsorption of variety of pollutants even under dynamic conditions [6]. Furthermore, use of different techniques as molecular imprinting can lead researchers in this field to synthesize hydrogels that can target specific pollutants with higher efficiency [79].

CONCLUSION

For the purpose of treating polluted water, recent studies have been reported on development of some highly efficient and promising adsorbents that show better performance to nearly all kinds of water pollutants. One of the materials is nano-hydrogel material that possess high water absorption ability that lead to swelling in its structure. This swelling property of hydrogels is their key feature that make them widely employed adsorbing material in modern society. Another property of hydrogel that mainly relates with their reusability and less cost associated with their processing further make it a promising material. Nowadays, research is focusing on the use of hydrogels for the treatment of polluted water that contains variety of contaminants including dyes, metals, pathogens, drugs, and others. Although, in many studies, it was observed that the hydrogels-based materials find limitations in water treatment in terms of high efficiency, regeneration, easy availability, cost and stability, however, the use of modified forms of hydrogels (in form of composites or nanocomposites) is increasing day by day. Further research is focused on addressing the limitations of nano-hydrogel

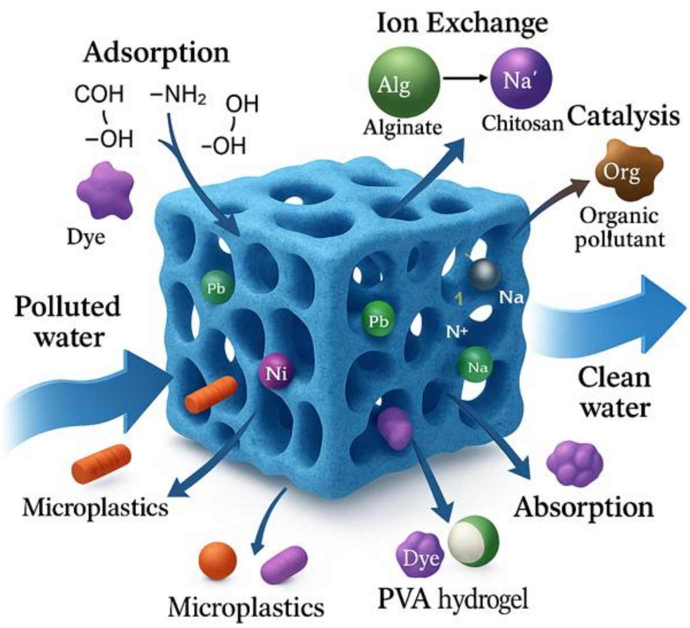

Fig. 3. Applications of hydrogels for the removal of different water contaminants.

based materials with significant trends focusing on improving adsorption efficiency and selectivity, developing sustainable materials for performance enhancement.

CONFLICT OF INTEREST

The authors declare that there is no conflict of interests regarding the publication of this manuscript.

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