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Emerging Hydrogel Technologies and Mechanistic Insights for Adsorptive Removal of Heavy Metals and Organic Dyes: A Systematic Review

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Abstract:
Water pollution from heavy metals and synthetic dyes poses a serious environmental threat due to their toxicity and persistence. Conventional wastewater treatment technologies often suffer from limitations such as high operational costs, secondary pollution, low selectivity, and reduced efficiency in complex effluents. In this context, hydrogel-based adsorbents have emerged as promising materials for sustainable water purification. This review critically examines recent advances in hydrogel technologies for the adsorptive removal of heavy metals and organic dyes from aqueous systems. Emphasis is placed on the evolution of hydrogel materials, including natural, synthetic, composite, nanocomposite, and stimuli-responsive hydrogels, and their structural and functional design strategies. The review highlights adsorption mechanisms such as electrostatic attraction, ion-exchange, hydrogen bonding, surface complexation, and chelation, demonstrating how synergistic interactions enhance removal efficiency. Comparative analysis shows that composite and nanocomposite hydrogels exhibit superior adsorption capacities and reusability compared to conventional adsorbents. Additionally, the influence of environmental parameters such as pH, temperature, ionic strength, and contaminant concentration is discussed. Despite significant laboratory-scale progress, challenges remain regarding real wastewater application, regeneration efficiency, scalability, and economic feasibility. This review provides mechanistic insights and design principles to guide the development of next-generation hydrogel adsorbents for efficient and sustainable wastewater treatment.

Keywords: Hydrogel-based adsorbents, Heavy metal removal, Organic dye removal, Composite hydrogels, Nanocomposite hydrogels.

I. Introduction

Water pollution has mainly had emerged as one of the most critical environmental challenges of the twenty-first century, driven by largely the rapid industrialization, urban expansion, as well as intensified agricultural activities.. One of the worst marine contaminants that can cause a lot of damage to the people is a heavy metal and synthetic organic dye because it is toxic, persistent and cannot instead decompose naturally as compared to the others. Then the heavy metals such as lead, cadmium, mercury, chromium and copper are non-biodegradable and obtained in the biological system causing chronic diseases including neurological damage, kidney failure, cancerous condition and body defects. Similarly organic dyes that are released by industries of textile, leather, paper, pharmaceutical and plastic are mutagenic, carcinogenic and aesthetically detrimental at extremely small levels as they reduce light penetration and destabilize the dissolved oxygen balance.

The common traditional methods of water purification such as chemical precipitation, coagulation-flocculation, membrane filtration, ion exchange, electrochemical treatment and advanced oxidation process have been widely applied in removing pollutants(Ogutu *et al.*, 2023). However, these techniques are normally consumed with severe weaknesses of character that encompass high operating and upkeep cost, secondary sludge, selectivity, membrane foul and ineffective execution due to existence of slight pollutant concentrations. Therefore, adsorption has also been developing into the growing popularity as a new inexpensive and eco-friendly approach to wastewater treatment.

Nevertheless, over the recent years the best type of adsorbents that has gained the most potential to be deployed in the process of eliminating heavy metals and organic dyes in the contaminated water are the hydrogel-based materials(Zhu *et al.*, 2023). Hydrogels Hydrogel- crosslinked polymeric network Hydrogel is a polymeric network that can absorb and hold huge quantities of water at the same time. They are also remarkably tunable surface chemistry besides the fact that they are highly porous, possess a large number of functional groups and are mechanically flexible, and thus useful in applications that involve adsorption. Additional application of polymer chemistry, nanotechnology, and materials engineering also ensured that smart, multifunctional, and nanocomposite hydrogels having high adsorption capability, selectivity, and reusability could be developed.

Even though more research work is currently underway in this field, the synthesis of all hydrogel adsorption systems in terms of comprehensive and mechanically oriented manner is still needed to result to rational material design and scale model. This review journal aims at critically analyzing the development and evolution of the hydrogel technology in adsorption of the heavy metals and organic dyes keeping in check the variation in focus on the principle that drives the process of adsorption, materials utilized, and the factor that drives the functioning of the gel, and the way ahead in research work. However, several problems still exist. Many studies are at laboratory-level research using synthetic wastewater because this is not a real test of the complexity that may encompass actual industrial effluents. It should be explored more on regeneration efficiency and longevity when it comes to repeated adsorption-desorption cycles. Large-scale production and economic viability that have not been delved upon are also present.

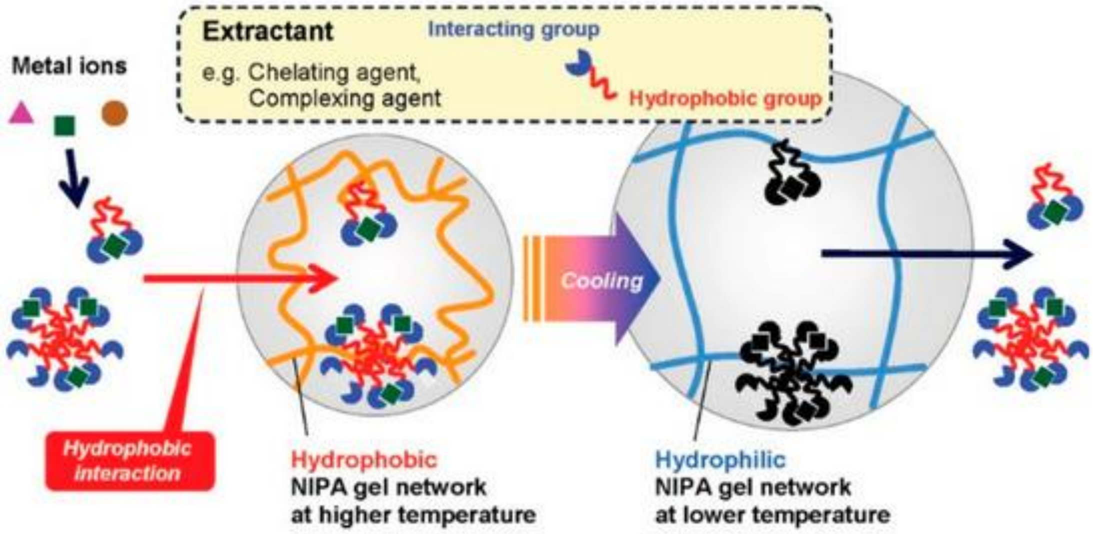

Figure: 1 Emerging Hydrogel Technologies and Mechanistic Insights for Adsorptive Removal of Heavy Metals(adapted from Zhang et al., 2017)

As shown in Figure 1, the newly forming hydrogel system demonstrates the temperature sensitive adsorption-desorption behaviour of metal ions in a NIPA gel network. On increase in temperature, the gel forms a hydrophobic network, which allows the extractant and the metal ions to be attracted more through a hydrophobic interaction. When cooled, the hydrogel structure changes to a hydrophilic network, weakening such interactions, releasing metal-extractant complexes out of the gel matrix--a reversible binding performance and higher selectivity in the extraction of heavy metals (Zhang et al., 2017).

The review is an in-depth analysis of the fast emerging hydrogel technologies in the adsorptive removal of heavy metals and synthetic organic dyes of water systems. The peculiarities of the structures have made hydrogel adsorbent materials highly promising because they possess the following characteristics: high retention capacity of water, can be created in form of interconnected porous networks, surface chemistry is controllable, and functional groups are abundant. Those properties allow hydrogels to react well with contaminants by a combination of adsorption forces, such as electrostatic attraction, ion exchange, hydrogen bonding, chelation, and surface complexation. Specifically, the flexibility and versatility of hydrogel structures can be applied to selective extraction of particular pollutants, which is a definite advantage over more traditional adsorbents such as activated carbon, clays, and synthetic resins. Regardless of the high level of improvement achieved, a number of critical issues need to be tackled before adsorbent made of hydrogel can be adopted by mass treatment processes. Existing studies have been based on laboratory experiments involving synthetic wastewater, which might not be representative of the complexities of industrial effluents that include mixed pollutants, variable pH, and elevated ionic strength. The future work should focus on the real wastewater validation, long-term durability test and life-cycle analysis in order to consider the environmental safety and cost-effectiveness. Another notable hindrance to commercialisation is the scaling up of production of materials with proper material uniformity and low costs of synthesis.

II. Research Trends and Developments

2.1 Water Pollution by Heavy Metals and Organic Dyes

One of the most effective and the most appealing water contaminations that takes place all over the world particularly owing to the discharge of the heavy metals, the synthetic organic dyes into the water system is the industrial effluents (Zhang *et al.*, 2025). The major causes of the increased release of such harmful pollutants into rivers, lakes as well as ground water include; the high rate of industrialization and the absence of wastewater treating plants in most regions. The industries that cause this form of pollution to a great extent include mining, electroplating, batteries, metal finishing, pigment production, textile dyeing, printing and finishing. Such sectors normally end up with the wastewater that is highly pollutant in terms of toxic compounds that are not only harmful to the sustainability of the environment but also the health of the people.

Of particular interest are the heavy metals because of the reason that they are not biodegradable and because they are highly toxic even at levels of trace. The types of metals that are generally used in the industry processes due to their attracting chemical and physical properties are Lead, cadmium, mercury, chromium, copper and nickel. However when they are discharged into the water bodies, these metals are long lasting and undergo very complex reactions with the sediments, water life and such dissolved organic substances(Darban*et al.*, 2022). The heavy metals are unable to be deteriorated to harmless end products through chemical and biological degradation processes like most of the organic pollutants. Instead they accumulate in water bodies and get transferred to the food web through bio accumulation and bio magnification. This ultimately leads to increased metal and other trophic species like fish and other organisms that man is consuming hence becoming an ecological risk as well as health risk in the long run.

The consequences of exposure to heavy metals have turned out to be having very different unfavorable health outcomes as well. There is also demonstration of lead causing neurological disorders particularly in children and through exposure of cadmium damage of kidneys and skeletal disorders(Zanbili*et al.*, 2025). Mercury can cause harm to the nervous system and cognitive development as hexavalent chromium has been described as being a strong agent of carcinoma. Their presence on the waters is especially dangerous because its toxicity is chronic due to the possibility of the irreversible damage inflicted by the long-term exposure to their presence on the organs of man and on the ecosystems. Besides, heavy metals can destroy microbial communities and biodiversity of the aquatic ecosystems to alter the ecosystem functionality as well as reduce its resilience.

Alongside with the pollution with heavy metals, synthetic organic dyes is one more important category of water contaminants with the help of which the environmental impact is especially destructive(Ling Felicia *et al.*, 2025). The dyes are hugely used in the textile, paper, leather, plastic, pharmaceutical, and cosmetic industries to give their products color and aesthetic beauty. During the dyeing and finishing processes, a high level proportion of such dyes fail to be bonded with the material, and are discharged into sewage wastes. Low-concentration dyes make the water have a vivid colour which reduces penetration of light that deactivates photosynthetic processes in water plants and algae. This can lead to shortage of oxygen and imbalance in aquatic life due to such interference with main productivity.

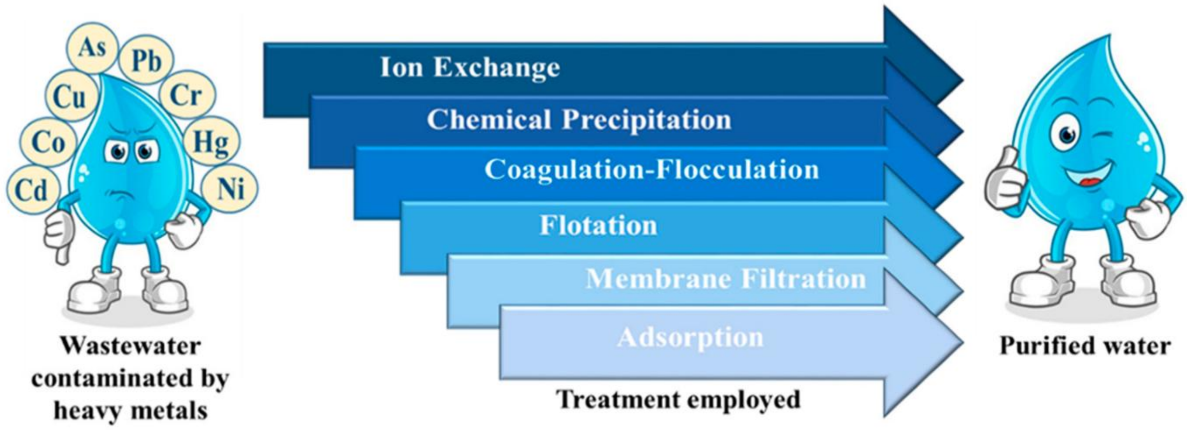

Figure: 2 Hydrogel-Based Adsorbent Materials for the Effective Removal of Heavy Metals from Wastewater(adapted from Fu & Wang, 2011)

As shown in Figure. 2, the wastewater that is polluted with heavy metals that have toxic properties is subjected to numerous treatment procedures to attain the necessary purification. Starting with traditional methods like ion exchange, chemical precipitation, coagulation-flocculation, flotation, and membrane filtration, the sequence of treatment shows how sequential removal of metal pollutants is achieved. The last step is the emphasis on adsorption as an effective and selective technique to extract heavy metals in aqueous systems especially by use of hydrogel based adsorbent material. The method increases purification efficiency and encourages conversion of polluted wastewater to clean and safe water that can be reused (Fu and Wang, 2011).

The capacity of dyes to remain in water bodies is limited to the fact the dyes possess complex molecular structures and many chemical resistance. The synthetic dyes are mostly aromatic rings, azo fixation and heterocyclic to make sure that they are not affected by the photodegradation, biodegradation, and chemical oxidation. They therefore can remain relatively long in water bodies without degrading much(Zhang *et al.*, 2021). Other dyes and their degradation products are also toxic, mutagenic or carcinogenic and have a direct impact (life-threatening) which directly impacts aquatic organisms and human health. The skin exposure to the dye chemical contaminated water has been associated with long term effects such as skin irritation as well as difficulty in breathing and the possibility of cancer in human beings.

The heavy metals are present with organic dyes in the industrial wastewater and make the treatment processes even more difficult. These pollutants exist in a combination in majority of effluents that we find in real world and they interact with each other in addition to interacting with the rest of the dissolved substances. Mixed contaminating systems are complicated systems that are likely to reduce the effectiveness of water treatment methods that are traditional(Raji *et al.*, 2023). They include classic ways or treatment like chemical precipitation, coagulation-flocculation, membrane filtration and advanced oxidation processes that treatment usually uses in order to treat heavy metals and dyes. Such methods, however, have various limitations, particularly in cases where the concentration of the pollutants is very low or in the case of a multi-component wastewater. The adverse features of the methods are that operations are expensive, energy and sludge generated membrane encroachment and incomplete removal.

The ineffective nature of the traditional treatment technologies when handling the stubborn pollutants such as heavy metals and dyes to the high standards placed by the regulatory bodies has never been underemphasized in the prior researches. Such limitations have brought up the need to find other effective and successful treatment processes, capable of achieving considerable degree of elimination effectiveness, kinetics and environmental response. Adsorption is one of the potential solutions that have emerged as a promising solution to problems since it is extremely easy, has a wide range and can treat a large variety of contaminants(Chan *et al.*, 2021). This has created an increase pressure on the necessity to refine adsorbent materials to take away heavy metals and dyes in the complex wastewater systems in a selective and efficient manner.

This augmented ecological issue has pushed the world to undertake immense studies on the nature and outcomes into the developing of new adsorbent material with high performance properties(Akhtar *et al.*, 2024). More precisely, hydrogel adsorbents have gained significant attention since they have a variety of structural features in addition to tunable surface chemistry and the ability to react with diverse pollutants. The nature and the source of water contamination with heavy metals and organic dyes are very important to be known to create appropriate remediation strategy in addition to educate the next generation of materials that will serve on the principle of sustainable water purification.

2.2 Evolution of Adsorbent Materials

The conventional adsorbents such as activated carbon, zeolites, clays and agricultural by-products have been observed to have varied degrees of effectiveness in the removal of the pollutant. Activated carbon is quite effective but very expensive and regeneration is not easy. Natural materials can be economical and could possess low adsorption capacity and selectivity. The adsorption of synthetic polymeric adsorbents has also offered increased serviceability with issues relating to sustainability as well as safety to the environment. The development of adsorbents is not the last in the use of hydrogels where the gel is given a hybrid character since it is not only flexible by nature as a polymer but it is also solid by nature as a solid(Alhajri *et al.*, 2025). Hydrogel early research was predominantly on the biomedical grounds although, the prospect of hydrogel in the healing of the environment is currently a widespread trend in the past two decades. So-called functionalized hydrogels have been functionalized with carboxyl, amino, hydroxyl and sulfonate moieties with unmatched affinity with metal ions and dye molecules.

2.3 Hydrogels as Advanced Adsorbents

There exists a growing trend in the literature which argues towards the development of multifunctional systems of hydrogel which are able to use several simultaneous mechanisms of adsorption(Sahoo *et al.*, 2025). Hydrogel composite products with chitosan, cellulose and alginate as the natural polymers combined with synthetic polymers or inorganic nanomaterials have shown good adsorption capacity. Graphene oxide, nanoparticles of magnets, metal oxides and clay minerals have also enhanced the surface area, mechanical strength and recovery ease.
More recent studies are now directed towards stimuli-responsive hydrogels that are responsive to stimuli in the environment, such as pH, temperature and light, enabling product adsorption and desorption to be regulated(Chame*et al.*, 2025). The progress mentioned above can underpin the fact that hydrogel-based adsorbents are becoming more advanced and can contribute to the emergence of the new generation of water treatment systems.

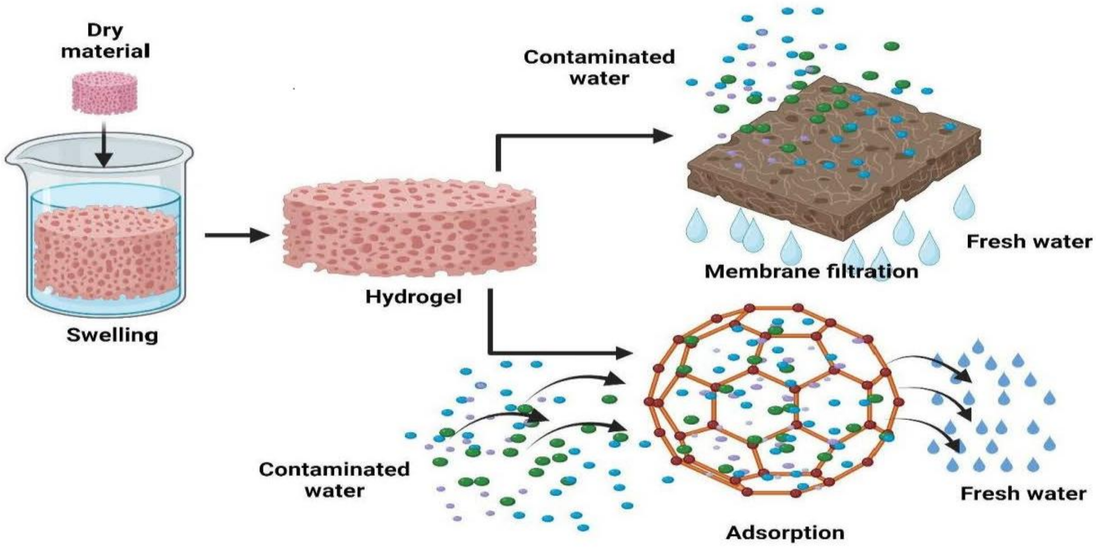

Figure: 3 Hydrogels as Advanced Adsorbents(adapted from Liu et al., 2023)

The hydrogels are also advanced adsorbent materials as in Figure. 3 hence their porous structure and capacity to swell to a large size. As the dry hydrogel substance takes on water, it expands to a three-dimensional network that is able to react with contaminants. The polluted water may then be subjected to certain treatment methods which include membrane filtration or adsorption whereby the hydrogel matrix selectively absorbs the heavy metal ions and pollutants. This process leads to the discharge of clean water, which proves the usefulness of hydrogels in water treatment and their possible use in sustainable wastewater treatment (Liu et al., 2023).

III. Methodological Approach

The present research employs systematic study review method employed in a critical analysis of the emerging hydrogel technologies and their mechanism of action in adsorptive removal of the heavy metals and organic dyes in aqueous environment (Mondal *et al.*, 2025). The systematic review methodology has been selected to offer transparency, reproducibility and multidimensional coverage of the rapidly increasing pool of literature related to this branch of interdisciplinary research which encompasses polymer science, environmental engineering, materials chemistry as well as water treatment technology. Such an approach minimizes the selection bias by compensating the structured review protocols and, therefore, a meticulously structured synthesis of the existing research findings as a foundation of credible findings concerning the establishment of trends, gaps, and future research areas.

The methodological paradigm of this review was set so as to be aligned to the best practices that are mostly considered in the high impact journals listed in Scopus. It incorporates a clearly mentioned review design, intensive literature search scheme, clear inclusion and exclusion eligibility and formal method of data extraction and study (Alsaka*et al.*, 2025). Mechanistic knowledge, material innovation, adsorption performance indicators, practical functionality were paid special attention, and it was ensured that the review overviews the works of other researchers, but first of all, critically examines the scientific contributions and limitations of their works.

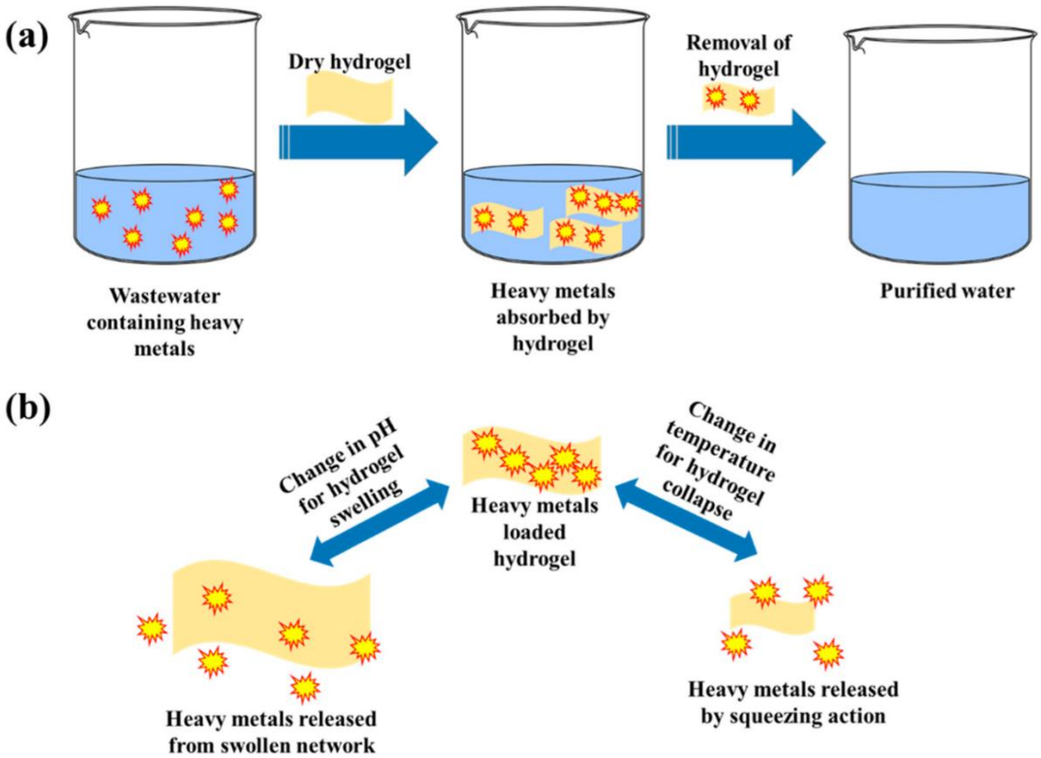

Figure: 4 Hydrogel-Based Adsorbent Materials for the Effective Removal of Heavy Metals from Wastewater(adapted from Li et al., 2020)

Figure. 4 demonstrates that hydrogels are useful adsorbent material in the elimination of heavy metals in wastewater. In part (a), the dry hydrogel is placed in contaminated water whereby the porous network of the hydrogel absorbs the dissolved metal ions. After the removal of the hydrogel, the water is purified, which also shows a single and efficient treatment route. Part (b) indicates the regeneration process: it is possible to release heavy metals which are loaded to the hydrogel network by changing environmental parameters pH or temperature. The release of ions by the swelling at certain pH values and the release by the collapse at the temperature effects allow discharging by mechanical squeeze. This reversible behaviour emphasizes reusability and sustainability of hydrogel-based treatment systems (Li et al., 2020).

3.1 Analytical Framework Study

The proposed study will be presented in the form of qualitative systematic review study which will involve synthesizing and critical review of the peer reviewed articles on the use of hydrogel based adsorbents in the removal of the heavy metals and organic dyes in water(Tsauria*et al.*, 2025). When compared to meta-analytical procedures that are extremely contingent on quantitative incorporation of information, the existing review theme is more interested in the conceptual integrative and mechanistic elucidation, which is central in understanding of the complex processes that govern the phenomena of adsorption in hydrogel systems.

The common principles of systematic reviews determined the design of the review through the determination of clarity in scope, reproducibility of the search processes, and systematic analysis of the findings(Chen *et al.*, 2024). The reason why its scope was set was to ensure that either one of the basic or applied research was not overlooked in giving a holistic view of hydrogel materials such as naturally occurring biopolymer hydrogels and the state of the art nanocomposite and stimuli- responsive hydrogels. The special attention was given to papers that address the mechanisms of adsorption, in particular, electrostatic interactions, hydrogen bonding, ion exchange, surface complexation, and chelation, as a mechanistic understanding is a key to the rational designing of materials and the enhancement of their performance.

In addition to the mechanistic studies, the review design included the study of the hydrogel production methodologies, functionalization methodologies or strategies and network modifications because it is known that the adsorption performance is closely related to polymer chemistry, crosslinking density and crosslinking network structure(Zhao *et al.*, 2021). The personalities of the review designs integrate the material science and the worlds of thought of environmental engineering, and thus provided the possibility of a multidisciplinary evaluation of the hydrogel-based technologies.

Instances of adsorption performance under variant experimental conditions are also brought to the fore in the review including pH, variation, temperature, variation, ionic strength and variation in contaminant concentration, respectively. This aspect of the structure into consideration is the reality that the behavior of adsorption is highly situational, and the laboratory findings are only supposed to be taken care of when considering the application to the real world(El Messaoudi *et al.*, 2025). Regeneration and reusability research was included to establish the long term nature of adsorbents on hydrogel which is an innovative and increasing demand of sustainable wastewater treatment technologies.

3.2 Study Identification and Selection

A comprehensive and systematic literature search was conducted to make relevant peer review articles that handle the hydrogel adsorption of heavy metals and organic dyes. The major scientific databases (including Scopus, Web of Science, ScienceDirect and SpringerLink) were selected as all of them have a broad scope of the high-quality research papers that are published in the area of materials science as well as environmental engineering, polymer chemistry, and applied nanotechnology(Yin *et al.*, 2024). Such a mixture of databases allows locating not only the first work but also the ongoing research in the sphere of hydrogel.

The search of the literature was more specific to articles that were published within the last decade to reflect on recent events but at the same time covered some of the older articles that made significant contribution to the discipline. The search strategy incorporated the use of both controlled vocabulary and free-text keywords since it was necessary to obtain the highest level of accuracy and coverage(Akhter *et al.*, 2025). The keywords were selected according to preliminary scoping searches and background knowledge and included keywords according to hydrogel, adsorption processes, heavy metal, and organic dyes, nanocomposites, and stimuli-responsive materials.

It has been carried out with the use of a number of keyword phrases to accommodate the disparity in disciplines. On one of the examples, where words such as, hydrogel adsorbents, polymeric hydrogels and crosslinked polymer networks were collated with certain words used to denote the pollutants, such as, but not restricted to, heavy metal removal, dye adsorption and wastewater treatment. The mechanism orientation keywords, i.e.,adsorption mechanisms, electrostatic interaction, ion exchange, and chelation were searched to reduce the search results to those studies that provide the explanation of the mechanism rather than the data on the performance that were attained empirically.

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Relevant subject areas were eliminated by use of Boolean operators and database specific filters in order to eliminate irrelevant search results(Akhter *et al.*, 2025)
(Tan *et al.*, 2025). The filter options of the documents type were set to select a preference to the research articles and review papers that would be published in any peer-reviewed journal articles where possible. Non-peer reviewed sources such as editorials, proceedings of the conferences were generally not looked at unless they included an exceptionally remarkable information that was otherwise unavailable in the journal articles.

Introduction Reference lists of significant review articles and highly accessed researches were also read manually to ensure that other significant research was also discovered which could have been overlooked by search databases collectively(Al-Gethami*et al.*, 2024). It is a citation tracking method, but it is reverse by nature and thus it helped to minimize the likelihood of missing the significant studies along with the overall quality of the literature search.

3.3 Inclusion and Exclusion Criteria.

The inclusion and exclusion criteria were clearly defined, and the literature screening was done to be consistent and reduce subjectivity bias when selecting a study. Inclusion criterion in the studies was that they were under the specific relevance and quality parameter which was consistent with the objectives of the review. The studies that were identified as eligible were forced to focus on using hydrogel-based materials in the adsorption of the heavy metals and/or organic dyes on aqueous systems. Experimental as well as review articles were under inclusion and were required to give significant information regarding the performance of adsorption or material architecture or the working principles(Yang *et al.*, 2024). They covered articles that mentioned natural, synthetic, or composite hydrogels and those articles that mentioned functionalization measures, creation of nanocomposites, or stimuli-responsive behavior.

Mechanistic discussion or analysis was deemed to be one of the inclusion criteria. The studies that only reported the adsorption capacities had no attempt to explain the interaction between hydrogel and pollutants and were considered less informative and were described only in cases when they provided significant information (comparative performance details) to the selection. The type of studies that were preferred were those that considered the influence of such environmental parameters as pH, temperature, ionic strength or competing ions since the parameters play a role in determining applicability in the real world.

The Islamic criteria applied to eliminate those studies that were not related to the subject of review of environmental remediation. Articles which had been concentrated on biomedical or pharmaceutical applications of hydrogels, e.g. drug delivery or tissue engineering, were excluded unless they contained something of transferable interest to the adsorption process in pollutants removal(Neama *et al.*, 2024). Written literature based on non-aqueous system was also avoided or adsorption which occurred in the gas phase was avoided since it is not desired in the application of water treatment.

Footballs Publications which were not detailed enough in the methods such as composition of unclear hydrogel or those which were not accompanied by experimental conditions were removed so as to maintain scientific rigor of the review. In addition, the duplicate studies and initial reports were also removed, and instead, the journal articles having a broader review were utilized. Data extraction was conducted in a systematic manner in a bid to develop a consistent process that will facilitate effective comparison of studies. The needed information in terms of material properties and metrics adsorption performance indicators were located and stored in any selected publication (Mosaffa*et al.*, 2024). Hydrogel composition, the type of polymer, the method of crosslinking, the functional groups, the addition of nanomaterials as well as the overall characteristics of the structure were extracted in the information. Wherever feasible, parameters related to adsorption such as peak adsorption capacity, adsorption kinetics, equilibrium models and thermodynamic behavior were also studied. The conditions of the experiment, including pH, temperature and contact time, initial concentration of pollutant, and competition of ions were followed very keenly bearing in mind that they significantly affect the outcome of adsorption. Regeneration and reuse performance had also been reported that entailed desorption efficiency and adsorption capacity retention amid a number of cycles.

The extracted data were analyzed qualitatively so as to isolate recurrent pattern, relationship and inconsistency in different hydrogel systems. The aim of the comparative analysis was to analyze the often effects that have been caused by the hydrogel composition and structure on the adsorption mechanisms and effects. Particular emphasis was placed on those reports, which demonstrate synergistic behaviour-effects when composite or multifunctional types of hydrogel system are being used because such system were likely to possess excellent adsorption efficiency compared to result obtained with materials produced by one component.

The results of experimental evidence and theoretical principles subjectively assessed mechanistic ideas of interpretation presented by different authors(Liu *et al.*, 2025). Where several mechanisms on a single system were reported, comparisons between them were made in order to provide a more detailed account of the adsorption behavior. Also brought forward and publicly discussed was the contradiction or inconsistency of studies as a way of establishing areas that require research.Rather than synthesizing the numerical representation which is statistical aggregation, this review dwells on the synthesis of concepts and mechanistic integration. It is a particularly good methodology when there is a high diversity of materials and experimental conditions and measurements for which the former are not necessarily directly measurabl(Kumar *et al.*, 2024) e. The synthesis of the results of the studies conducted provides the proper structure of the investigation of the potential to maximize the emerging hydrogel technologies to create the efficient and sustainable water cleaning.

3.4 Data Extraction and Analysis

Despite the fact that the systematic review of hydrogel-based adsorbents to remove heavy metals and organic dye have demonstrated impressive progresses in designing the materials, adsorption activity, and mechanistic understanding, the systematic review of the studies has been in the position of demonstrating gains in material design, adsorption activity, and mechanistic understanding (Hussain *et al.*, 2024). Analysis of the available articles demonstrates that the presence or absence of functional groups, density of the network, polymer structure, and the environment have a significant effect on the work capacities of hydrogel to be used. The results also show the efficacy of multi and composite hydrogels in comparison to the single component ones particularly in hydraulic properties, selectivity and reuse.

IV. Hydrogels and Adorbents

4.1 Trends in Hydrogel Composition and Structural Design

It has been demonstrated in the literature review that there is a clear shift in more complicated composite and nanocomposites systems, which rest on simple and single polymer hydrogels. The early studies were primarily based on natural polymers such as chitosan, alginate, cellulose, starch due to their biodegradable nature as well as high concentration of functional groups. The materials that most likely had moderate adsorption capacity, however, were not only restricted with regard to mechanical stability but also reusability. Subsequent research suggested synthetic polymers such as polyacrylamide, polyethyleneimine and polyvinyl alcohol to enhance structure and controlled functionality. It was however found that most useful gains were made via composite hydrogel systems of natural and synthetic polymers combination as well as inorganic nanomaterials that comprises of graphene oxide, metal oxides, clay minerals and magnetic nanoparticles. The hybrid systems had higher surface areas, enhanced accessibility of the active sites and also synergetic adsorption activities with large improvement in the efficiencies of the pollutant removal.

Crosslinking density is one of the design parameters that turned out to be important of the first importance(Zhang *et al.*, 2021). The hydrogel that was optimized in the context of crosslinking displayed the balance in terms of sufficient mechanical strength and sufficient swelling capacity that promoted diffusion of the pollutants into the polymer network. Excess crosslinking hindered accessibility to pores but excessively weak crosslinking affected stability of the structure in the adsorptiondesorption cycles.

4.2 Adsorption Performance for Heavy Metal Removal

Assessment of heavy metal adsorption experiment indicates that there exists presence of hydrogel adsorbents, which are very effective with the divalent and trivalent metal ions such as Pb^{2+}, Cd^{2+}, Cu^{2+}, Cr^{3+}, and Hg^{2+}. The highest adsorption rates varied according to composition of the hydrogel and conditions of an experiment, composite hydrogels being in any case better than natural or synthetic ones. Hydrogels are highly affinity to metal ions and this has been attributed to electrostatic attraction, ion exchange and chelation mechanism. Carboxyl and amino functional groups dense hydrogel gels were extremely active in metal binding in cases whereby the pH was inclined towards the ionization of these groups(Visan *et al.*, 2025). The investigations in both works all pointed to the increase in adsorption with the pH up to the optima conditions where this increase was terminated

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by the precipitation of the metal or the reduction in the attractive forces between electrostatic forces.

Thermodynamic studies conducted in the literature reveal that the adsorption of heavy metal onto hydrogel is largely spontaneous and endothermic meaning that it will be the best in high temperatures. Kinetics frequently accepted pseudo-second-order equations which prove that chemisorption is a primary determinant to metal absorption.

4.3 Adsorption Performance for Organic Dye Removal

Hydrogels were also discovered to adsorb both cationic and anionic dyes such as, methylene blue, rhodamine b, congo red and acid orange rather well. Strong litter and dependence of dye structure, charge, and size, dependence of the hydrogel surface chemistry and porosity had a tremendous impact on dye adsorption capacities. Cationic dyes had high affinity on the hydrogel in which the negatively charged functional groups were available as compared to the anionic dyes which were easily liberated by the protonated amino hydrogel in acidic condition(Akhtar *et al.*, 2024). Graphene and carbon nanocompositions of hydrogel form were found to greatly have the removal of aromatic dyes taken place in p-p interactions that led to high removal efficiency and high removal kinetics. Compared to the heavy metals, the dye adsorption generally was a combination of both physical and chemical forces e.g. hydrogen bonding and Van der Waals force besides the presence of the electrostatic attraction. This multi-mechanistic behavior will be explained by the fact that hydrogel has a wide application in the dye remover in different system types of wastewater.

4.4 Comparative Numerical Analysis of Adsorption Capacity

The representative hydrogel systems represented in the figure give a comparative perspective of structural diversity and performance differences among the various material types. Table 1 eedefine Generally, the bar chart illustrates the comparative adsorption capacities of the usual hydrogel-based adsorbents in laboratory conditions of the heavy metals and synthetic dyes. These values are similar to the general trends provided in the recent literature indicating that composite and nanocomposite hydrogel tend to be higher adsorption efficiency in relation to natural or synthetic single-component hydrogel.

Table: 1 Representative adsorption capacities of hydrogel-based adsorbents for heavy metals and organic dyes

Hydrogel type	Target pollutant	Maximum adsorption capacity (mg/g)	Dominant adsorption mechanism
Chitosan hydrogel	Pb^{2+}	85 -120	Electrostatic attraction, chelation
Alginate hydrogel	Cu^{2+}	60–95	Ion exchange, surface complexation
Polyacrylamide hydrogel	Cd^{2+}	70–110	Electrostatic interaction
Chitosan–CMC composite hydrogel	Methylene blue	100–180	Electrostatic attraction, hydrogen bonding
Graphene oxide composite hydrogel	Congo red	180–320	π–π interaction, electrostatic attraction
Magnetic nanocomposite hydrogel	Cr^{6+}	150–260	Ion exchange, redox interaction, chelation

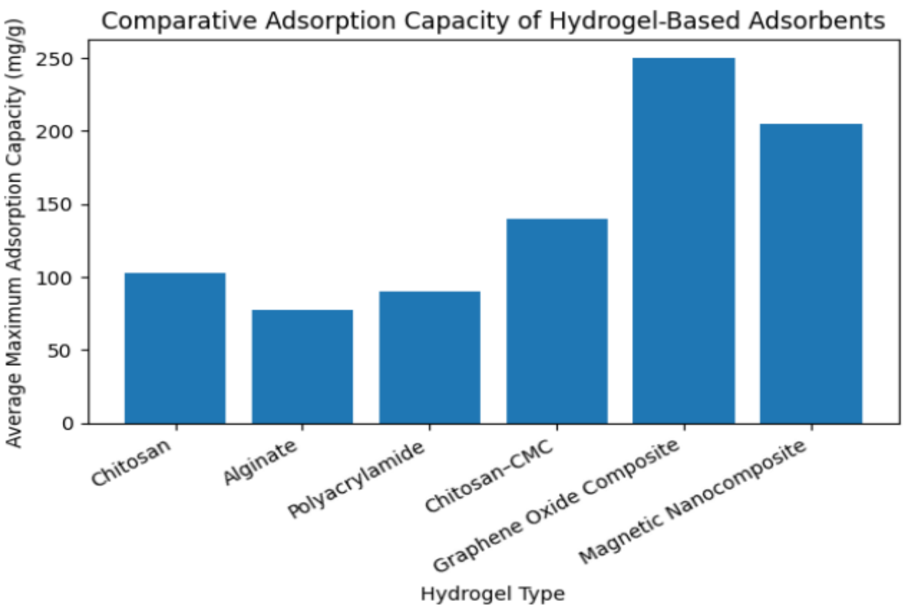

Figure: 5 Average Maximum Adsorption Capacities of Various Hydrogel-Based Adsorbents against Aqueous Pollutants

Figure. 5 illustrates that the various types of adsorbents made of hydrogel have varying maximum adsorption capacities towards aqueous pollutants. Hydrogel made of chitosan, alginate, and polyacrylamide have moderate adsorption ability, but the composite materials portray much higher removal efficiency. The greatest adsorption can be observed in graphene oxide composites and magnetic nanocomposites, which show a better surface interaction, porosity and functional group access. These findings indicate the possible benefits of composite hydrogels in comparison with conventional polymeric systems in pollutant removal, which justify their use in state of-the-art water treatment processes.

Judging by the numeric data, it can be stated that the adsorption capacities of composite and nanocomposite hydrogel gels are exceedingly greater than single-polymer hydrogel gels. The unexpected dye adsorption on graphene (and other systems that can be based on it) is explained by the presence of synergistic interactions between the aromatic dye molecules on one hand and the p-electron-filled surfaces on the other hand in this instance(Sahoo *et al.*, 2025).

4.5 Influence of Environmental and Operational Parameters

The environment conditions proved conclusive in the process of adsorbing hydrogel within which pH was the most substantial that heals the charge of the surface, ionization of functional groups, as well as speciation of pollutants. Optimal adsorption was usually occurring within a pH-range which was system-dependent.

In the majority of cases, ionic strength was identified to affect the efficiency of adsorption negatively due to the change between the target pollutants and the background ions (Mondal *et al.*, 2025). This was stronger than the electrostatically driven adsorption mechanisms were and thus it is desirable to devise better hydrogel with a high chelating or complexation capacity when it comes to addressing the real wastewater problem.

Contact time the time equilibrium was found to be reached in most hydrogel systems within a number of hours and nanocomposite hydrogels in many instances, reached equilibrium faster due to higher diffusion pathways. Experiments on reusability have revealed that with a gel density of hydrogel, over 70-85 percent of the initial adsorption capacity of the gel was retained after a series of utilizations, although performance steadily declined owing to structural depletion or inadequate desorption.

4.6 Mechanistic Integration and Synergistic Effects

The main conclusion of this review is the fact that in a hydrogel system adsorption can hardly take place in a single way. Instead, intake of pollutants is facilitated by the influence of synergistic interaction of electrostatic attraction, hydrogen bonding, ion exchange, surface complexation and chemolating (Tsauria*et al.*, 2025). The application of composite hydrogels is particularly efficient because a range of functional groups and structural polymers may be integrated into a single net, which enables a multi-biosensing method, regarding adsorption.

The results show that multifunctionality, crosslinking and functionalization as rational approach of hydrogel design should be prioritized in the interest of maximizing the adsorption efficiency in the real environmental set-ups. Therefore, mechanical knowledge is not only an explanatory tool, but mechanical knowledge can be used in the development of the next generation of hydrogel adsorbents.

V. Conclusion

New technology in nanotechnology has also widened the process of hydrogel by allowing the creation of composite and nanocomposite hydrogels using graphene oxide, metal oxides, magnetic nanoparticles and carbon nanotubes among others. These designed systems display an increased surface area, increased structural stability, accelerated adsorption dynamics, as well as, high regeneration efficacy. Another significant breakthrough is stimuli-responsive hydrogels, which can respond to variations in the pH, temperature, ionic strength and light since the latter allows adsorption-desorption cycles to be regulated, and enhances reusability. This kind of innovation promotes sustainable and economical water purification plans, lessening environmental strain and enhancing treatment efficacy. In general, the results of this review demonstrate that hydrogel-based adsorbents are a viable solution to the next generation of water purification in terms of sustainable use. Interdisciplinary cooperation between materials science, polymer chemistry, nanotechnology, and environmental engineering will be necessary to achieve the full potential. The design, processing and mechanistic knowledge of hydrogel will continue to be innovated which will subsequently lead to its use in practice in the industry as the world seeks to reduce the water pollution and safeguard the health of the environment.

Statements and Declarations

Conflict of interest

The authors have no relevant financial interests to disclose

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