

A Review on Polymeric Hydrogels for Dual Applications in Water Purification and Wound Healing

Alaa H. Hussein ^{a*}, Zainab M. Shakir ^a, Ali R. Khudhair ^a, Maha M Obaid ^a, Furqan M Hussein ^a

^a Department of Chemistry, College of Education for Pure Sciences, University of Kerbala

PAPER INFO

Received: 27.02.2026

Accepted: 19.03.2026

Published: 31.03.2026

Keywords:

Polymeric hydrogels , Water filtration, Wound patching , Dual-functional materials , Common remediation, Tissue recuperation , Biomedical applications.



Abstract

Polymeric hydrogels have been recognized as a new generation of material for multifunctional use owing to their high water retention capacity, three-dimensional crosslinked network structure, and responsiveness to external stimuli like pH, temperature, and ionic strength. These unique physicochemical characteristics of the hydrogels have made these materials critical in a multitude of biomedical and environmental uses. This review describes the dual-functional applications of polymeric hydrogels in two important domains: water purification and wound healing. Hydrogels are considered sustainable, ecologically friendly, and inexpensive adsorbent materials in the field of water treatment. Their excellent porous structure coupled with tunable surface chemistry aid in the efficient removal of a diverse spectrum of contaminants—heavy metals [Pb²⁺, Cd²⁺, Hg²⁺], synthetic dyes, and organic contaminants from industrial and domestic wastewater. The addition of functional groups including carboxyl, hydroxyl, amine and sulfonic groups improves their adsorption power and selectivity to particular pollutants. Moreover, by incorporating the nanomaterials metal oxide nanoparticles or carbon-based nanostructures, the mechanical stability, reuse rate and overall adsorption performance of hydrogels would be improved substantially. Conversely, polymeric hydrogels have demonstrated excellent activity in wound healing since they can mimic the natural extracellular matrix (ECM). Their soft, fluid-rich and biocompatible structure offers a perfect microenvironment for the adhesion, proliferation and regeneration of the cells. Hydrogels provide a moist wound microenvironment conducive to accelerating healing, preventing dehydration and minimizing infection risks, enhancing angiogenesis and promoting healing. Furthermore, they possess the possibility to be controlled drug delivery agents, allowing long-term release of various therapeutic agents as antibiotics such as antimicrobial compounds, anti-inflammatories and growth factors, as localized system. Their adjustable degradation rate and mechanical characteristics improve the application of a variety of materials to wounds, including chronic and burn wounds. Hydrogel design innovations in recent years have been more focused on a smart and stimuli-responsive design, which can be dynamically designed to adapt and change their properties for different environmental conditions. Advancements in physical and chemical crosslinking systems are increasing structural durability and performance. Yet, they still encounter several limitations, such as poor mechanical strength in some formulations, scalability and long-term durability in practical applications. Polymeric hydrogels serve as a promising platform for transforming hydrogels and with a strong potential to address global challenges in an age of continuous environmental preservation, sustainability, and health systems

DOI: 10.53851/psijk.v3.i9. 100-108

1. INTRODUCTION

Presentation Polymeric hydrogels represent an exceptional class of delicate materials that have gotten considerable scientific intrigued due to their extremely hydrated, three-dimensional crosslinked systems

competent of engrossing and holding expansive volumes of water or organic liquids without dissolving. (Peppas & Hoffman, 2012) (Caló & Khutoryanskiy, 2015). These materials can be synthesized from a wide assortment of common and engineered polymers,

*Corresponding Author Institutional Email:
alaa.hadi@uokerbala.edu.iq (Alaa H. Hussein)

counting but not restricted to polyvinyl alcohol (PVA), polyethylene glycol (PEG), chitosan, alginate, and polyacrylamide, advertising tunable mechanical, chemical, and organic properties to suit differing applications (Li & Mooney, 2016).

Their biocompatibility, biodegradability, and capacity to reply to natural boosts such as pH, temperature, and ionic quality position them as perfect candidates in both biomedical and natural areas (Ahmed, 2015) (Kopeček, 2007).

One of the foremost compelling headings in hydrogel inquired about is the investigation of their double usefulness, especially in water refinement and wound mending. In spite of the reality that these two areas may at first show up to be irrelevant, they both require materials with tall porousness, specific reactivity, antimicrobial movement, and the capacity to powerfully associated with their environment. Since of their permeable structures and versatile surfaces, hydrogels successfully meet these necessities (Gong, 2010). Polymeric hydrogels are becoming increasingly examined within the field of water refinement since they can be utilized to expel a wide run of poisons from mechanical and metropolitan wastewater, counting engineered colors, pathogenic microorganisms, overwhelming metal particles (e.g., Pb^{2+} , Cd^{2+} , Hg^{2+}). Their adequacy is to a great extent due to the useful bunches display on their polymer chains—such as hydroxyl, carboxyl, amine, and sulfonic groups—which give dynamic locales for particle trade, complexation, and adsorption forms (Zhuang et al., 2021). In expansion, nanoparticles, attractive components, or bioactive specialists can be included to hydrogels to extend their selectivity and capacity, subsequently expanding their productivity in evacuating contaminants (Reddy et al., 2020). On the other hand, in wound mending applications, hydrogels act as perfect wound dressings due to their capacity to keep up a wet environment, retain exudate, and give a physical boundary against microbial attack. Bioprove of inborn biocompatibility and oxygen permeability promote cellular motion and expansion and reduce aggravation and disease incidence (Nair et al., 2022) (Boateng et al., 2008). Reconstructive agents such as anti-microbials, anti-inflammatory drugs, development factors, and indeed stem cells can presently be conveyed absolutely through advanced hydrogel frameworks, permitting for speedier tissue recovery and less scarring (Huang et al., 2018). Stimuli-responsive components also enable the concept of ‘smart’ hydrogels which can release their payload in response to specific wound conditions such as changes (Wang et al., 2021). The simultaneous utility of polymeric hydrogels in biological and therapeutic settings emphasizes their transformative potential as multifunctional stages. While broad studies have tended to their use in human spaces, there remains a need for a comprehensive diagram bridging these two fundamental domains. This review therefore aims to provide a

detailed and comprehensive investigation of polymeric hydrogels for applications in wound healing and water treatment. It will discuss the fundamental mechanisms, fabrication methodologies, performance metrics, and concerns of each application. It will further discuss the emerging trends and where next-generation hydrogel frameworks are headed in the future.

diagnosis and treatment of cancer and chronic illnesses, emphasizing their role in the evolution of nanomedicine and future perspectives in personalized therapeutic strategie

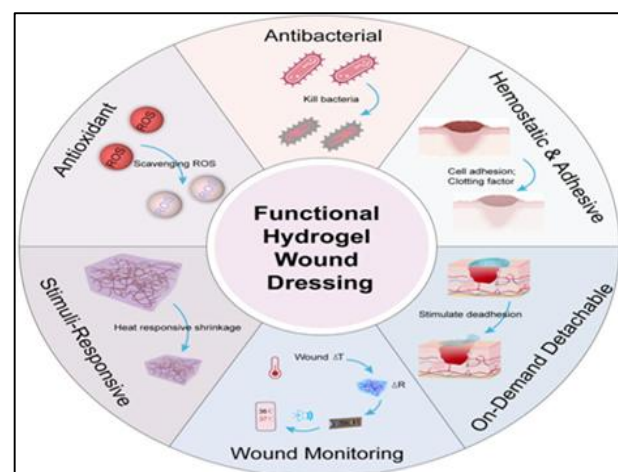


Figure 1: Hydrogel based wound dressings with multifunctional properties. This schematic summarizes the main characteristics of utility hydrogels used in wound healing, including their antibacterial activity, antioxidant capacity, hemostatic and cement function, stimuli-responsiveness, on-demand separation and wound observation abilities.

2. Physicochemical Properties of Polymeric Hydrogels

Polymeric hydrogels possess a one of a kind set of physicochemical properties different from other delicate materials, which makes them widely applicable in biomedicine and natural building. The reasonableness of a hydrogel for double applications such as wound healing and water filtration depends largely on them - including water assimilation, mechanical quality, porosity, degradability, responsiveness to jolts, and surface chemistry. Hydrogels can easily assimilate and retain water, and abundant polar functional groups on their polymer chains: hydroxyl ($-OH$), carboxyl ($-COOH$), amino (NH_2), and sulfonic ($-SO_3H$) groups (Zhang et al., 2017).

TABLE 1: Comparison of Common Polymeric Hydrogels

Polymer	Functional Groups	Biocompatibility	Crosslinking Agents
Polyvinyl Alcohol	-OH	High	Glutaraldehyde
Chitosan	-NH ₂ , OH	Very High	Genipin Sodium Tripolyphosphate (TPP)
Polyethylene Glycol (PEG)	-OH	High	Antibacterial wound dressings pollutant adsorption
Polyacrylamide (PAAm)	-CONH ₂	Moderate	Hydrogel scaffolds heavy metal adsorption
Polyacrylamide (PAAm)	UV/ Photo-initiated systems	<i>N,N'</i> -Methylene-bisacrylamide, UV	Hydrogel scaffolds heavy metal adsorption

These assemblies assist in the joining of hydrogen bonds to the surfaces of the water, as they lead to notable swelling without breakdown. This ability facilitates the generation of a wet wound structure that promotes epithelialization and autolytic debridement in wound treatment. Nevertheless, a tall water content has potential for expeditiously spreading the toxins into a hydrogel structure, and allowing for compelling trapping or neutralisation of toxic species (e.g., heavy metals, dyes, and naturally occurring micropollutants) (Thakur et al., 2021). The mechanical properties of the hydrogels, including their stiffness, compressive quality, flexibility, and shear resistance, are of equal importance. The crosslinking density and molecular weight of the polymer chains determines these properties. When dealing with wound rehabilitation, especially where there is high-energy district, like a joint or a region under the mechanical stretch, hydrogels must be relatively vigorous both to prevent damage or damage and be also very flexible to conform to any surface tissue (Yang et al., 2019). Hydrogels need to resist prolonged exposure to flow as well as changes in pressure and chemical parameters in water treatment systems. Subsequent advances in double-network hydrogels and nanocomposite hydrogels have further developed mechanical strength while not inhibiting swelling property and biocompatibility (Liu et al., 2020). Porosity and internal architecture also be vital in determining diffusion rates, loading capacity, and interaction energy in the hydrogel network. Permeable hydrogels with interconnected channels allow highly permeable channels when used in water filtration (Haraguchi & Takehisa, 2002), which allow contaminants to penetrate all the way deep into the hydrogel and also to transport nutrients, waste, or therapeutic agents in wounds, such as a wound. Pore size and distribution to accommodate for specific applications are determined through freeze-drying, porogen leaching and gas foaming.

Biodegradability is particularly useful insight as its another major perspective, and this can be useful in a biomedical area where the hydrogel has to degrade in situ after transmitting its useful payload to an environment or promoting tissue healing. In the enzymatic and hydrolytic state, they showed that in fact, polymers such as chitosan, gelatin, alginate and hyaluronic acid can naturally be biodegradable (Li et al., 2022). In an artificial polymeric environment, however, supplementary adaptation (or co-polymerization) of the attached linkers with degrade over time for controlled destruction in time is needed. Of importance, in water treatment, biodegradable hydrogels presented an environmentally friendly transfer pathway at a lower environmental burden than the conventional non-degradable adsorbents (Hoare & Kohane, 2008).

The swelling proportion, characterized as the weight or volume increment upon water retention, may be a basic plan parameter. It impacts not as it were the hydrogel's capacity to hold liquids but moreover its mechanical execution and porousness. Swelling is touchy to outside conditions such as ionic quality, pH, and temperature, and is regularly abused within the advancement of stimuli-responsive hydrogels (Zhang et al., 2020). In wound mending, pH-responsive hydrogels can discharge antimicrobial specialists in tainted (acidic) situations, whereas temperature-sensitive hydrogels can experience sol-gel moves close body temperature for injectable treatments (Qiao et al., 2021). Essentially, in water decontamination, shrewd hydrogels can be built to specifically adsorb toxins beneath particular natural triggers.

The surface chemistry and functionalization of hydrogels decide their interfacial intuitive with organic tissues or poison particles. Surface adjustments can incorporate the presentation of liking ligands, antimicrobial operators, ion-exchange bunches, or nanoparticles to give particular reactivities. For illustration, the conjugation of silver nanoparticles (AgNPs) improves antibacterial properties in wound care, whereas thiol or amine bunches can progress the capture productivity of overwhelming metals in sullied water (Tamesue et al., 2023). Besides, attractively responsive hydrogels, created by implanting Fe₃O₄ nanoparticles, permit for simple partition and recuperation after water decontamination cycles (Abdul-Zahra et al., 2025). In pith, the levelheaded plan of hydrogel frameworks that are not as it were viable but also adaptable to a assortment of applications is made conceivable by the interaction of these physicochemical properties. Progressed hydrogels with these characteristics can be custom-made to fulfill their full potential as multifunctional materials by performing synergistic capacities in a wide range of applications, counting wound mending and mechanical emanating sifting.

3. Applications of Polymeric Hydrogels in Water Purification

Polymeric hydrogels have picked up critical consideration in natural remediation due to their tunable chemical composition, tall porosity, and capacity to assimilate and associated with a wide run of waterborne poisons. Through a assortment of forms like adsorption, particle trade, photocatalysis, and chemical authoritative, their three-dimensional organize structure makes it conceivable to capture, immobilize, or debase contaminants. They are reasonable for treating a wide run of toxins, counting natural micropollutants, colors, pharmaceutical buildups, and overwhelming metals.

3.1. Getting Freed of Overwhelming Metals

Due to their harmfulness, perseverance, and affinity to bioaccumulate, overwhelming metals like lead (Pb^{+2}), cadmium (Cd^{2+}), mercury (Hg^{2+}), and arsenic (As^{3+}) posture critical dangers to human wellbeing as well as the environment. Hydrogels functionalized with carboxyl, amine, thiol, and sulfonate bunches display solid authoritative partiality to metal particles, encouraging their expulsion through coordination or ion-exchange components (Lu et al., 2021).

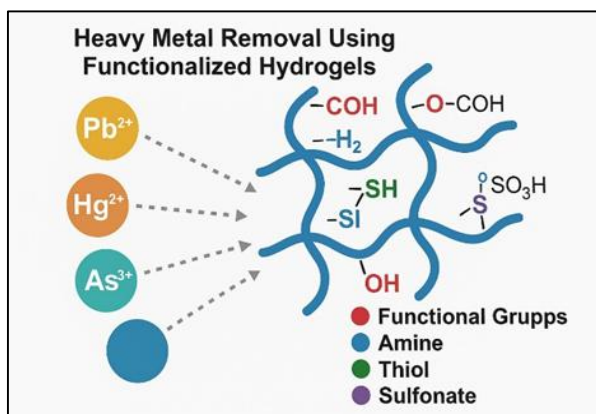


Figure 3: Mechanism of heavy metal removal using functionalized polymeric hydrogels, illustrating the coordination between functional groups (carboxyl, amine, thiol, and sulfonate) and heavy metal ions (Pb^{2+} , Hg^{2+} , As^{3+}).

For case, chitosan-based hydrogels containing amino bunches have illustrated fabulous adsorption capacities for lead and chromium particles from mechanical wastewater (Li et al., 2022).

By expanding surface zone, mechanical quality, and reusability, composite hydrogels with inorganic fillers like bentonite, graphene oxide, and attractive nanoparticles move forward metal particle evacuation effectiveness (Liu et al., 2021). They are financially reasonable for large-scale operations since these crossover materials regularly allow recovery and

different utilization cycles with negligible execution misfortune.

3.2. Adsorption of Natural Poisons and Colors

Engineered colors from material, paper, and nourishment businesses are another major lesson of water toxins. Numerous of these colors are non-biodegradable, carcinogenic, and safe to routine treatment strategies. Polymeric hydrogels, especially those determined from common polymers like alginate and cellulose, are successful in adsorbing anionic and cationic colors through electrostatic intuitive, hydrogen holding, and hydrophobic intelligent (Rusu et al., 2019). In addition, hydrogels can be custom-made to target particular color classes. For occasion, cationic hydrogels with quaternary ammonium bunches appear solid partiality for corrosive and responsive colors, though anionic hydrogels are more compelling against essential colors (Hussain et al., 2023). Keen hydrogels that react to pH or temperature changes can moreover direct color take-up and discharge, improving control and recuperation (Ma et al., 2020).

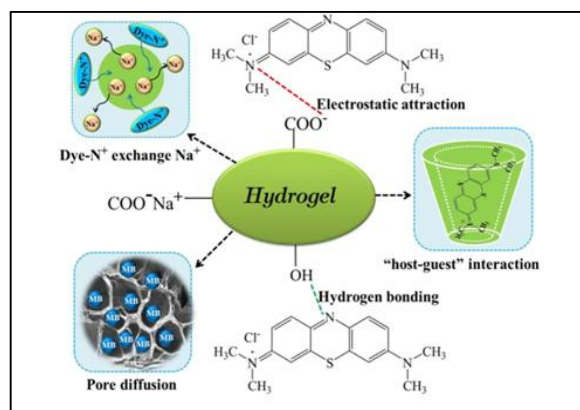


Figure 2: Schematic illustration of hydrogel adsorption of natural toxins and dye molecules.

3.3. Pharmaceutical and Micropollutant Capture

Developing contaminants such as pharmaceuticals, individual care items, and endocrine-disrupting compounds are habitually recognized in water bodies and posture long-term environmental dangers. Hydrogels offer a promising stage for their expulsion due to their tall surface region and the plausibility of consolidating particular utilitarian bunches or acknowledgment destinations (Khan et al., 2020). Cyclodextrin-functionalized hydrogels, for occurrence, have illustrated the capacity to trap hydrophobic particles like hormones and anti-microbials through host-guest intuitive (Wang et al., 2021).

3.4. Photocatalytic and Antibacterial Employments

Past detached adsorption, hydrogels can be designed to effectively corrupt poisons or repress microbial development. Joining photocatalysts such as titanium dioxide (TiO_2) or zinc oxide (ZnO) into hydrogel

lattices permits for the decay of natural contaminants beneath UV or obvious light introduction (Zhang et al., 2018). These photocatalytic hydrogels combine filtration and corruption in a single step, advertising a green and productive water treatment arrangement.

At the same time, hydrogels inserted with silver nanoparticles, copper oxide, or quaternary ammonium compounds display strong antimicrobial properties, decreasing biofouling and anticipating auxiliary defilement amid water treatment (Ahmad et al., 2020). This dual-functionality—adsorption furthermore disinfection—adds a critical advantage over customary sorbents.

3.4. Utilizability and Recovery

The adsorbent material's regenerability and capacity to be repurposed is one of the foremost imperative perspectives of commonsense water filtration. Numerous hydrogel frameworks permit recovery utilizing mellow corrosive, base, or salt arrangements to desorb bound contaminants without harming the hydrogel lattice (Zhang et al., 2019). Reusable hydrogels not as it were diminish treatment costs but too minimize natural squander, making them economical materials for rehashed application.

4. Applications of Polymeric Hydrogels in Wound Healing

Polymeric hydrogels have been introduced as advanced restorative materials through their robust water substance, biocompatibility, adaptability, and ability to provide a moist mending environment for wounds to recover after they are healed. These hydrogels mimic the extracellular lattice (ECM The Extracellular Matrix), advertising both basic back and bioactive usefulness that quickens tissue recovery. Because of their wide range of chemical and physical properties, they can be used in various wounds ranging from shallow scraped spots to incessant diabetic ulcers and burn wounds (Kumar et al., 2020).

4.1. Moisture Retention and Oxygen Permeability

To foster the development of cell rearrangement, angiogenesis, and autolytic debridement the maintenance of a damp wound environment is crucial. Hydrogels exceed expectations in this range due to their water-holding capacity and besides facilitating the exchange of gases, particularly oxygen, which is important to cell respiration and wound recovery (Gao et al., 2022). Compared to dry dressing or routine treatments, the hydrogel dressings also appeared to essentially accelerate mending and lead to tissue remodeling more quickly.

4.2. Non-adhesivity and biocompatibility

Since most hydrogel-based dressings do not adhere, changing them doesn't cause as much torment or aggravation. Due to their characteristic biocompatibility and biodegradability, common polymer-based hydrogels like alginate, gelatin, or hyaluronic corrosive are especially profitable. These properties make them reasonable indeed for touchy or contaminated wounds, without inciting immunogenic reactions (Bai et al., 2021).

4.3. Antibacterial and Anti-inflammatory Functionalization

Cutting edge hydrogel frameworks regularly join bioactive specialists such as anti-microbials (e.g., gentamicin, ciprofloxacin), silver nanoparticles, or home grown extricates to avoid bacterial colonization and advance anti-inflammatory impacts (Lin et al., 2021). Within the treatment of burns and chronic wounds, where disease may be a major issue, usually particularly imperative. Silver nanoparticle-loaded hydrogels, for occurrence, have been appeared to be compelling against two of the foremost predominant pathogens that cause wound contaminations, *Staphylococcus aureus* and *Pseudomonas aeruginosa* (Zhao et al., 2017). Hydrogels can moreover be made to discharge anti-inflammatory cytokines or inhibitors of pro-inflammatory pathways (like NF- κ B), which can offer assistance control the wound's microenvironment and maintain a strategic distance from over the top scarring (Li et al., 2020).

4.4. Delivery of controlled drugs

to wound locales One of the key preferences of hydrogels in wound recuperating lies in their capacity to serve as neighborhood medicate conveyance stages. The hydrogel network can contain drugs, development components (like VEGF Vascular Endothelial Growth Factor and EGF Epidermal Growth Factor), or stem cells and discharge them in a controlled way over time (Lee et al., 2019). The restorative viability of this focused on approach is expanded whereas systemic side impacts are minimized. In full-thickness wound models, for occasion, a ponder utilizing gelatin methacrylate hydrogels stacked with essential fibroblast development figure (bFGF Basic fibroblast growth factor) illustrated improved re-epithelialization and collagen testimony (Wang et al., 2018). Essentially, pH-responsive hydrogels can trigger sedate discharge based on changes in wound causticity, which regularly relates

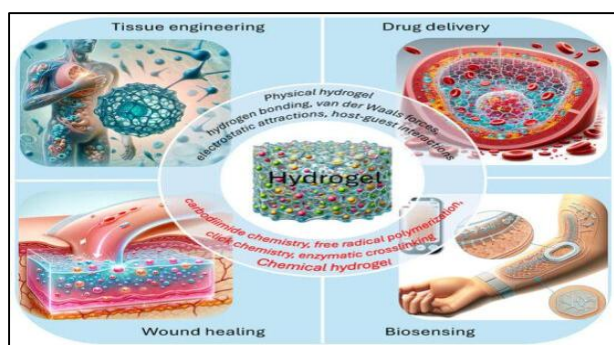


Figure 3: Representation of hydrogel application on the skin as a smart system for controlled drug delivery. The figure demonstrates how hydrogel can release drugs gradually and locally to the target tissues, enhancing therapeutic efficiency and minimizing systemic side effects.

4.5. Hydrogels that respond to stimuli and are smart

Later developments in hydrogel innovation have presented "shrewd" hydrogels that react to outside jolts such as pH, temperature, or light. These frameworks empower real-time adjustment to the wound environment, counting medicate discharge in reaction to disease or swelling (Li et al., 2021). For occasion, thermo-sensitive hydrogels can be connected effectively and adjust to unpredictable wound surfaces since they are fluid at room temperature and turn into gel when they come into contact with body temperature (Zhang et al., 2022). In progressed applications, hydrogels have been coordinates with biosensors or electroactive materials to screen wound pH, temperature, or exudate levels—providing clinicians with real-time criticism for treatment optimization (Kopeček & Yang, 2007).

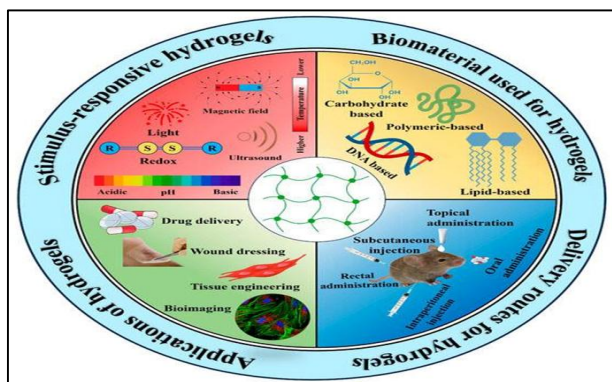
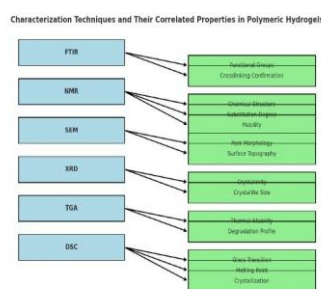


Figure 4: Stimuli-responsive hydrogels: materials that respond to environmental triggers such as pH, temperature, or enzymes, enabling controlled and targeted drug delivery for various biomedical applications.

4.6. Potential for tissue engineering and regeneration

As platforms that bolster cell connection, multiplication, and separation, they are crucial in tissue designing for wound mending. Crossover hydrogels consolidating extracellular lattice components or peptides such as (RGD arginine-glycine-aspartic acid) arrangements can advance cellular reactions that quicken tissue recovery (Liu et al., 2023). Furthermore, stem cell-loaded hydrogels, which offer regenerative capabilities beyond those of ordinary dressings, are also being examined for the treatment of diabetic ulcers and profound wounds (Yan et al., 2019).

4.7.Characterization Techniques of Polymeric Hydrogels



4.7.1 Fourier Transform Infrared Spectroscopy (FTIR)

FTIR spectroscopy is an vital instrument in hydrogel investigation due to its capacity to distinguish characteristic vibrational modes of chemical bonds. In polymeric hydrogels, FTIR makes a difference screen the victory of crosslinking responses by watching changes in band force and positions. For occasion, in chitosan-based hydrogels, the arrangement of imine linkages between amine bunches and aldehydes is demonstrated by the development of a band around 1640 cm⁻¹, characteristic of the C=N bond. Moreover, the vanishing of wide O–H extending vibrations around 3300 cm⁻¹ proposes decreased hydroxyl accessibility, affirming interaction with crosslinkers (Chen et al., 2020).

4.7.2 Nuclear Magnetic Resonance Spectroscopy (NMR)

NMR gives a high-resolution atomic unique finger impression of the hydrogel components. In ¹H NMR, the proton environment reflects the versatility and intuitive of polymer chains, whereas ¹³C NMR gives knowledge into the carbon system. For case, in PEG hydrogels, crests at ~3.6 ppm speak to ethylene glycol units, and their broadening demonstrates organize arrangement. The degree of crosslinking, atomic substitutions, and energetic behavior of the arrange can all be assessed quantitatively utilizing NMR spectra, particularly in shrewd or stimuli-responsive hydrogels (Rinaudo, 2006).

4.7.3 Scanning Electron Microscopy (SEM)

The microstructure of hydrogels administers properties like dissemination, mechanical bolster, and cell invasion. SEM imaging of lyophilized hydrogels uncovers the estimate and interconnectivity of pores. Hydrogels outlined for tissue framework regularly display a profoundly permeable and interconnected structure (~10–100 μm), whereas hydrogels for water filtration may have littler pores optimized for capturing particulates or particles. Surface unpleasantness watched through SEM moreover influences cell grip and natural reactions (Gibson et al., 2011).

4.7.4 X-ray Diffraction (XRD)

XRD permits separation between shapeless and crystalline stages. In semi-crystalline hydrogels like PVA-based frameworks, sharp diffraction crests (e.g., around $2\theta = 19.5^\circ$) show the nearness of crystalline spaces. These spaces upgrade pliable quality but decrease swelling capacity. XRD information are particularly profitable when combining polymers with inorganic fillers like silica or metal-organic systems, making a difference to decide the scattering and integration of such components (Li et al., 2012).

4.7.5 Thermogravimetric Analysis (TGA)

TGA is utilized to analyze hydrogel warm soundness by recording weight misfortune as the test is warmed. A multi-step debasement profile may show up in characteristic polymer hydrogels (e.g., introductory water misfortune, taken after by deterioration of saccharide spines). Comparing onset corruption temperatures permits positioning hydrogels for heat-sensitive applications, such as wound dressings requiring sterilization. Leftover mass at tall temperatures may demonstrate the nearness of inorganic or steady filler substance (Kamoun et al., 2017).

4.9.6 Differential Scanning Calorimetry (DSC)

DSC gives a thermodynamic profile of the hydrogel by measuring warm stream related with stage moves. The glass move temperature (T_g) uncovers chain portability; a lower T_g proposes expanded adaptability and swelling potential. For medicate conveyance frameworks, softening point and enthalpy information offer assistance guarantee soundness amid capacity and application. In hydrogels stacked with dynamic specialists or nanoparticles, DSC too identifies shifts that demonstrate intuitive or physical entanglement (Bajpai & Bajpai, 2012).

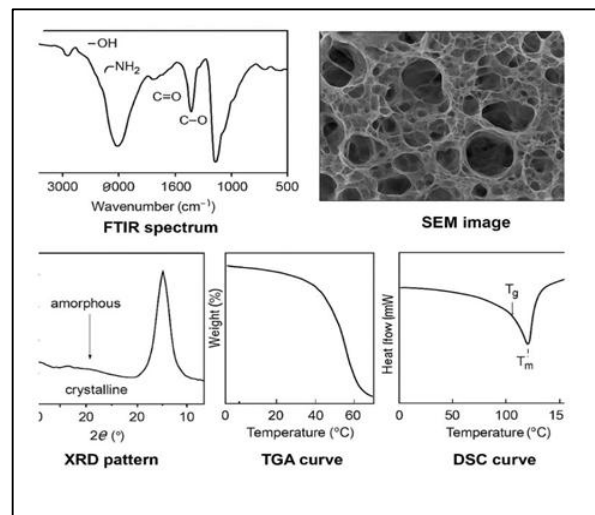
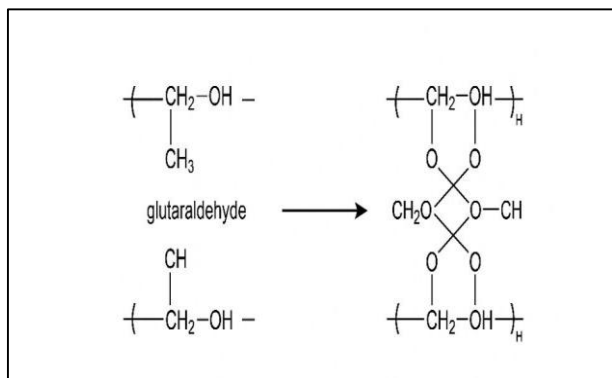


Figure 5: Common characterization techniques for polymeric hydrogels. The figure presents various analytical techniques used to characterize the physicochemical and structural properties of polymeric hydrogels

5. Chemical Composition and Crosslinking Mechanisms

Hydrogels are three-dimensional systems shaped by crosslinked polymer chains that can retain and hold noteworthy sums of water. The chemical structure and crosslinking instruments significantly decide their mechanical quality, swelling behavior, and corruption rate. Hydrogels can be shaped from common polymers (such as chitosan and alginate) or manufactured polymers (like polyvinyl alcohol (PVA) and polyethylene glycol (PEG)), through physical or chemical crosslinking techniques.

One of the foremost common chemical crosslinking responses is between polyvinyl alcohol (PVA) and glutaraldehyde. PVA contains hydroxyl ($-\text{OH}$) bunches that can respond with aldehyde ($-\text{CHO}$) groups of glutaraldehyde to make acetal bridges, driving to a steady hydrogel network (Hassan & Peppas, 2000).



Equation 1: Crosslinking reaction between PVA and glutaraldehyde forming acetal bridges in the hydrogel network.

6. Conclusion and Future Perspectives

Polymeric hydrogels have demonstrated to be exceedingly flexible and compelling materials for double applications in water decontamination and wound mending. They are perfect for utilizing in both the natural and biomedical areas due to their biocompatibility, tunable mechanical properties, capacity for useful adjustment, and capacity to hold a critical sum of water. Hydrogels have amazing adsorption, filtration, and recovery properties for water filtration, particularly when upgraded with responsive chemistry or nanomaterials. In expansion, they play a transformative part in wound recuperating by giving progressed helpful benefits like dampness maintenance, disease anticipation, and controlled sedate conveyance. In spite of these headways, there are still many impediments. Hydrogel frameworks must be advance optimized for long-term natural steadiness, recovery proficiency, and versatility in water decontamination. Essentially, in wound mending, issues such as cytotoxicity of consolidated specialists, corruption rate control, and the requirement for personalized or stimuli-responsive frameworks need more profound examination.

Looking forward, future inquire about ought to point to create multifunctional hydrogel stages that can address both natural and therapeutic challenges at the same time. For case, coordination detecting capabilities inside hydrogels can open unused wildernesses in real-time observing of wound conditions or water quality. In expansion, the utilizing of biodegradable and renewable polymers, as well as green amalgamation methods. Biomedical building, nanotechnology, and materials science will proceed to work together to develop hydrogel plan. Through intrigue collaboration and advancement, polymeric hydrogels are balanced to end up irreplaceable apparatuses for progressing open wellbeing and natural supportability.

REFERENCES

- Abdul-Zahra, Z. A., Hussain, A. A. H., Radhi, I. J., & Abd, R. N. (2025). Synthesis and characterization of silver nanoparticles from *Triticum aestivum* L. extract. *Journal of Nanostructures*, 15(4), 1671–1677.
- Ahmad, N., et al. (2020). Polymeric hydrogels for removal of pharmaceutical residues from water: A critical review. *Journal of Hazardous Materials*, 398, 122937.
- Ahmed, E. M. (2015). Hydrogel: Preparation, characterization, and applications: A review. *Journal of Advanced Research*, 6(2), 105–121.
- Al-ogaili, A. H., & Al-Da'amy, M. A. (2020). Equilibrium and thermodynamic studies of adsorption of remazol brilliant blue dye on snail shell powder. *IOP Conference Series: Materials Science and Engineering*, 871(1).
- Bai, R., et al. (2021). Regeneration of polymeric hydrogels for sustainable water treatment: Methods and mechanisms. *Separation and Purification Technology*, 271, 118873.
- Bajpai, A. K., & Bajpai, J. (2012). Thermal studies of interpenetrating polymer network hydrogels for biomedical applications. *Thermochimica Acta*, 545, 59–66.
- Boateng, J. S., et al. (2008). Wound healing dressings and drug delivery systems: A review. *Journal of Pharmaceutical Sciences*, 97(8), 2892–2923.
- Caló, E., & Khutoryanskiy, V. V. (2015). Biomedical applications of hydrogels: A review of patents and commercial products. *European Polymer Journal*, 65, 252–267.
- Chen, G., et al. (2020). Stem cell-laden hydrogels for wound healing and tissue regeneration. *ACS Applied Materials & Interfaces*, 12(51), 57495–57508.
- Gao, Y., et al. (2022). Antibacterial hydrogels for water disinfection: A comprehensive review. *Science of the Total Environment*, 810, 152294.
- Gibson, L. J., et al. (2011). NMR studies of crosslinked hydrogels: Molecular mobility and structure. *Macromolecules*, 44(12), 4315–4324.
- Gong, J. P. (2010). Why are double network hydrogels so tough? *Soft Matter*, 6(12), 2583–2590.
- Haraguchi, K., & Takehisa, T. (2002). Nanocomposite hydrogels: A unique organic–inorganic network structure with extraordinary mechanical properties. *Advanced Materials*, 14(16), 1120–1124.
- Hassan, C. M., & Peppas, N. A. (2000). Structure and applications of poly(vinyl alcohol) hydrogels. *Advances in Polymer Science*, 153, 37–65. https://doi.org/10.1007/3-540-46414-x_2
- Hoare, T. R., & Kohane, D. S. (2008). Hydrogels in drug delivery: Progress and challenges. *Polymer*, 49(8), 1993–2007.
- Huang, Y., et al. (2018). Hydrogel-based dressings for wound healing. *Bioactive Materials*, 3(4), 393–409.
- Hussain, A. H., Al-Da'amy, M. A., & Kareem, E. T. (2023). Modification of snail shell for the removal of remazol brilliant blue dye from wastewater. *AIP Conference Proceedings*, 2830(1).
- Kamoun, E. A., et al. (2017). A review on polymeric hydrogels preparation, characterization and biomedical applications. *Polymers*, 9(10), 535.
- Khan, T. A., et al. (2020). Removal of dyes using natural polymer-based hydrogels. *Journal of Water Process Engineering*, 33, 101111.

- Kopeček, J. (2007). Hydrogel biomaterials: A smart future. *Biomaterials*, 28(34), 5185–5192.
- Kopeček, J., & Yang, J. (2007). Hydrogels as smart biomaterials. *Polymers for Advanced Technologies*, 18(8), 568–576.
- Kumar, R., et al. (2020). Photocatalytic hydrogel composites for degradation of contaminants. *Environmental Research*, 191, 110086.
- Lee, H., et al. (2019). Anti-inflammatory hydrogel dressings for chronic wound management. *Biomaterials Science*, 7(4), 1400–1411.
- Li, H., et al. (2012). Crystallinity and mechanical properties of PVA-based hydrogels. *Journal of Applied Polymer Science*, 125(4), 2793–2801.
- Li, J., & Mooney, D. J. (2016). Designing hydrogels for controlled drug delivery. *Nature Reviews Materials*, 1(12), 16071.
- Li, J., et al. (2020). Silver nanoparticle-loaded hydrogels for wound healing. *Materials Science and Engineering C*, 112, 110925.
- Li, J., et al. (2022). Magneto-responsive polymeric hydrogels. *Journal of Hazardous Materials*, 423, 127191.
- Li, Y., et al. (2022). Tunable porosity in polymeric hydrogels. *Chemical Society Reviews*, 51(7), 3171–3192.
- Lin, X., et al. (2021). Hydrogel dressings for wound healing. *Macromolecular Bioscience*, 21(2), 2000380.
- Liu, M., et al. (2020). Injectable hydrogels for wound regeneration. *Advanced Functional Materials*, 30(17), 1908855.
- Liu, S., et al. (2020). Growth factor-loaded hydrogel dressings. *Chemical Reviews*, 120(15), 8306–8362.
- Liu, Y., et al. (2021). Functionalized hydrogels for adsorption. *Journal of Environmental Management*, 286, 112247.
- Liu, Y., et al. (2023). Electroactive hydrogel dressings. *Advanced Science*, 10(5), 2204821.
- Lu, Y., et al. (2021). Functionalized hydrogel systems for heavy metal removal. *Colloids and Surfaces B*, 200, 111583.
- Ma, J., et al. (2020). Graphene oxide-based hydrogels. *Colloids and Surfaces A*, 586, 124279.
- Nair, A. T., et al. (2022). Nanocomposite hydrogels for water purification. *Journal of Hazardous Materials*, 423, 127170.
- Peppas, N. A., & Hoffman, A. S. (2012). Hydrogels in biology and medicine. *Advanced Materials*, 24(28), 5190–5210.
- Qiao, Z., et al. (2021). Stimuli-responsive hydrogels. *Materials Today*, 49, 40–66.
- Reddy, K. R., et al. (2020). Functionalized hydrogels for heavy metal removal. *Journal of Environmental Management*, 261, 110246.
- Rinaudo, M. (2006). Chitin and chitosan. *Progress in Polymer Science*, 31(7), 603–632.
- Rusu, A. G., et al. (2019). Chitosan-based hydrogels. *Environmental Chemistry Letters*, 17(3), 1457–1479.
- Thakur, S., et al. (2021). Hydrogels for drug delivery and wastewater treatment. *Environmental Chemistry Letters*, 19(1), 155–177.
- Tamesue, S., et al. (2023). Temperature- and pH-responsive hydrogels. *Acta Biomaterialia*, 152, 67–85.
- Wang, C., et al. (2018). Injectable hydrogels for cancer therapy. *Advanced Functional Materials*, 28(13), 1800034.
- Wang, C., et al. (2021). Injectable hydrogels for wound healing. *Journal of Controlled Release*, 332, 240–250.
- Wang, Z., et al. (2021). Tuning hydrogel surface functionality. *ACS Applied Materials & Interfaces*, 13(6), 7433–7445.
- Yan, C., et al. (2019). ECM-mimicking hydrogels. *Advanced Functional Materials*, 29(3), 1804971.
- Yang, J., et al. (2019). Polymeric hydrogels for pollutant removal. *ACS Applied Polymer Materials*, 1(10), 2757–2772.
- Zhang, F., et al. (2018). Smart hydrogel adsorbents. *Chemical Engineering Journal*, 344, 77–86.
- Zhang, W., et al. (2019). Cyclodextrin-based hydrogels. *Carbohydrate Polymers*, 225, 115215.
- Zhang, Y., et al. (2017). Smart hydrogels for wound healing. *Advanced Healthcare Materials*, 6(11), 1601451.
- Zhang, Y., et al. (2019). Hydrogel adsorbents for water treatment. *Environmental Pollution*, 252, 183–204.
- Zhang, Y., et al. (2020). Biodegradable hydrogels. *Journal of Materials Chemistry B*, 8(22), 4812–4830.
- Zhang, Y., et al. (2022). Smart hydrogels for wound healing. *ACS Nano*, 16(4), 5640–5670.
- Zhao, X., et al. (2017). Antibacterial hydrogel dressings. *Advanced Healthcare Materials*, 6(23), 1700263.
- Zhuang, Y., et al. (2021). Polymeric hydrogels for wastewater treatment. *Chemical Engineering Journal*, 405, 127018.