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Factor Influence on Characteristics of Polymer Hydrogels: Challenges, Modifications, and Future Perspectives for Improved Performance

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P A P E R I N F O

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Abstract

Polymer hydrogels (PHGs) are materials bearing functional loving water for their water absorption and retention, which makes them highly valuable in agriculture, drug delivery, Environmental pollution, and other related fields. Their performance depends on synthesis parameters such as monomer composition, cross-linking density, initiator type, ion concentration, and functional group diversity. This review evaluates strategies to improve salinity tolerance, swelling kinetics, reusability, and overall efficiency. It also highlights emerging directions including AI-assisted design, quantum-informed modeling, multi-responsive materials, and bio-interactive systems that enable next-generation PHGs with enhanced performance and sustainability. Nevertheless, challenges such as reduced efficiency under saline conditions, mechanical instability during repeated use, and elevated production costs hinder broader application. Integration of computational tools, sustainable manufacturing, and interdisciplinary collaboration offers a pathway toward environmentally friendly PHGs with transformative potential in clean water technologies, precision agriculture, energy .storage, and biomedical engineering.

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1. INTRODUCTION

Highly hydrophilic groups and a three-dimensional cross-linked network are characteristics of polymer hydrogels (PHGs)(Yang et al., 2023), which are sophisticated functional materials. Because of their special structure, they can absorb and hold huge amounts of aqueous liquids inside their polymeric matrix(Zia,2022). Because of their greater swelling capacity and water retention ability, PHGs have gradually supplanted traditional absorbent materials in feminine hygiene products and disposable diapers since their introduction in the late 1970s. These days, their uses go beyond sanitary products to include industrial wastewater treatment, biomedicine, concrete engineering, and agriculture(Zhuo et al., 2020). The connection between hydrogels and PHGs is significant. PHGs are mildly cross-linked hydrogels with a substantially higher-absorption capacitance, whereas hydrogels are cross linked polymeric networks with a typical water absorption of up to 10 g/g.)PHGs) indicate minimally cross-linked hydrogels with significantly higher absorption capacity(Wang et al., 2022). Several reviews have addressed different aspects of hydrogels and PHGs including their classification, chemical structures, synthesis techniques, and applications. Based on their ionic characteristics, (PHGs) can be categorized into nonionic, ionic (anionic or cationic), amphoteric ,(electrolytes (containing both acidic and basic groups and zwitterionic types (containing both anionic and .(2020 ,.cationic groups in each repeating unit)(Tong et al Their synthesis has been achieved using various approaches, such as Polymerization via inverse suspension and inverse emulsion techniques, solution polymerization, radiation-induced polymerization, and ultrasound-assisted synthesis. The water absorption behavior of (PHGs) is governed by the hydration of ,hydrophilic groups and osmotic pressure gradients which facilitate the diffusion of water molecules into the polymer network. This process involves both chemical adsorption, where water molecules form bonds with hydrophilic groups, and physical adsorption, which is driven by concentration gradients and capillary action(Tomlinson et al., 2021). Consequently character and frequency of hydrophilic functional groups, the internal morphology, pore distribution, and the nature of raw materials are decisive factors influencing (PHGs)

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Performance (Thamer et al., 2023). Ideally, (PHGs) should exhibit three essential characteristics: high swelling capacity, rapid absorption rate, and excellent reusability. While traditional absorbents require several hours to achieve maximum swelling, (PHGs) are designed to combine high water retention with rapid uptake, which is particularly critical in applications such .as hygiene products and ecological water management Despite significant research efforts, most reviews on PHGs) have focused on isolated aspects, such as) synthesis mechanisms, swelling kinetics, or raw material properties(Thamer et al., 2019). Comprehensive analyses addressing the combined effect of synthesis parameters .and performance improvement strategies remain limited -Critical factors, including the type of monomers, cross linking agents, initiators, and raw materials, play a . (central role in determining the efficiency of (PHGs For researchers entering this specialized field, systematic reviews provide critical value by identifying the key parameters that determine the operational efficiency of polymer hydrogels (PHGs) and by mapping emerging opportunities for technological advancement. This ,review, therefore examines in detail the raw materials specialized monomers (Thakur et al., 2022) advanced cross-linking agents, and catalytic initiators employed in PHG synthesis. It also discusses innovative monomeric systems, engineered pore-forming agents, and modern , strategies designed to enhance salinity tolerance Reusability, volumetric absorption, and swelling kinetics. Polymer hydrogels (PHGs) are advanced functional materials characterized by strong hydrophilic groups and three-dimensional cross-linked networks. This molecular distinction can absorb 100-1000 times their own weight in water, making them highly effective in applications that demand rapid and durable water uptake. Since their commercialization in the late 1970s, PHGs have largely replaced conventional absorbents in disposable diapers and feminine hygiene products due to their superior swelling and water retention capacities(Thakur et al., 2023). Their applications have expanded dramatically, into diverse fields including biomedical engineering, concrete reinforcement, agriculture, vaginal delivery, (rectal, ocular, transdermal) delivery, and wastewater treatment. (Thakur et al., 2021).

Various studies have examined the classification, chemical structures, synthesis methods, and applications of (PHGs) . Depending on the ionic nature of the polymer chains, (PHGs) are categorized as nonionic, ionic (anionic or cationic), amphoteric (containing both acidic and basic groups), or zwitterionic (with both anionic and cationic groups in each repeating unit)(Fahad, 2024). Common synthesis methods include inverse suspension polymerization, inverse emulsion polymerization, solution polymerization, radiation-induced polymerization, and ultrasound-assisted techniques. The water absorption mechanism of (PHGs) involves both chemical and physical processes. Hydrophilic groups in the polymer bind water molecules through chemical adsorption, while physical adsorption is driven by concentration gradients and capillary action. (Singh et al., 2024).The type and density of hydrophilic groups, internal morphology, pore structure, and the properties of raw materials critically influence (PHGs) performance. (Fabryanty et al., 2017). An effective superabsorbent polymer should have three key properties: high swelling capacity, rapid water uptake, and good reusability. Traditional absorbents often need hours to reach full swelling capacity, but poly(acrylic acid) hydrogels (PHGs) are specifically designed for both high water retention and fast absorption—essential characteristics for hygiene products and environmental applications. Most existing research has focused on individual aspects of PHGs, such as how they absorb water, their swelling behavior over time, or the properties of starting materials (Sharma et al., 2019). . However, comprehensive reviews that examine how synthesis conditions work together to improve performance are rare. Several key factors—initiators, raw materials, monomers, and cross-linking agents—determine how well PHGs perform. By systematically analyzing these factors, researchers can identify ways to improve these materials. This review examines these components in detail, covering raw materials, monomer selection, cross-linking methods, initiators, and new approaches for enhancing water absorption, reusability, and performance in saline conditions (Shariatinia, 2020).

2. Influencing Factors

2.1. Influence of Monomer Type

Monomers play a critical role in defining both the structural integrity and the water absorption performance of polymer hydrogels (PHGs). Their primary function lies in introducing loving water groups groups into the polymer network, thereby enhancing the material's affinity for water.(Zhang et al., 2021) These monomers displayed considerable diversity, differing in the type and Numerous of their functional groups as well as in the length of their grafted chains.

Based on their electrical properties, monomers are generally classified into ionic and nonionic groups.

- **Ionic Monomers:** These Bear an electrical charge and can be further classified as cationic or anionic. They characteristically exhibit superior water absorption compared to nonionic monomers.(Durga et al., 2021) This advantage arises from the dissociation of ionic groups in

aqueous environments, which generates electrostatic repulsion within the polymer network, increases chain flexibility, and creates an osmotic pressure gradient that drives water molecules into the matrix.(Devi & Dutta, 2017) **Nonionic Monomers:** Electrically neutral in nature, these rely on hydrogen bonding between water molecules and hydrophilic groups such as carboxylic acid functionalities to fulfill water uptake. Representative examples include acrylamide, 2-hydroxypropyl methacrylate, and 2-hydroxyethyl methacrylate.(Carter et al., 2022). In addition, zwitterionic monomers contain both acidic and basic groups within the same molecular chain, providing excellent adsorption properties for both cationic and anionic dyes. For example, poly(3-acrylamidopropyl)- trimethy lammonium chloride combined with 2-acrylamide-2-methylpropanesulfonic acid has been used to create zwitterionic (PHGs) hydrogels with high dye removal efficiency(Mansour et al., 2021). Monomers can also be categorized based on their physical properties and functionality into hard, soft, and functional types. Hard monomers, characterized by a high glass transition temperature, are used to enhance the mechanical strength and hardness of the copolymer resin. (Hayes et al., 2022). Examples of hard monomers include methyl methacrylate, styrene, acrylonitrile, and acrylamide. The careful selection of monomer type, considering ionic nature, functionality, and compatibility with other components, is essential for designing (PHGs) with optimal water absorption, mechanical stability, and application-specific arises from electrostatic interactions, whereas covalent cross-linking results from the formation of strong chemical bonds. High cross-linking density can reduce the free pore spaces within the three-dimensional network, limiting water penetration and consequently ,decreasing water absorption capacity.(Maitra & Shukla(2014 2. 2. Influence of Cross-Linking Agent

-The cross-linking agent primarily determines the cross linking density of Polymer Hydrogels (PHGs) and facilitates the formation of their three-dimensional network structure. Its addition affects several physical properties of (PHGs)(Yang et al., 2023) , including elasticity (ability to stretch and recover), viscosity restriction of polymer chain mobility), solubility (due to) strong covalent bonds between chains), glass transition temperature (Tg, influenced by reduced free volume and altered molecular packing), melting point, strength, and toughness (BALAMURUGAN et al., 2020). During of PHGs) synthesis, the cross-linking agent acts more) effectively under the influence of an initiator. For instance, in starch-based (PHGs) , the monomer grafts onto the main chain under the initiator's action to form branches, which are then connected by the cross-linking agent to create a three-dimensional network (illustrated in Figure 1. Relationship Between Cross-Linking Amount and Network Tightness in Hydrogels. Variations in the type and amount of cross-linking agent affect gel point times, thereby influencing the pore formation by pore-making agents . Cross-linking transforms a liquid .polymer into a solid or gel by restricting chain mobility This process can be ionic or covalent. Ionic cross-linking

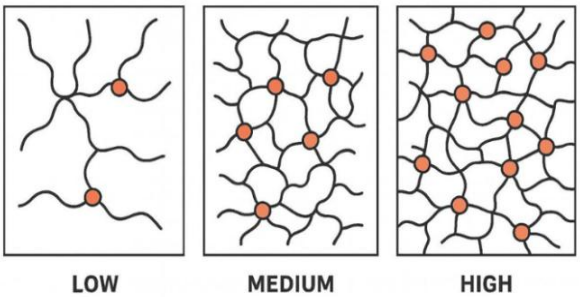

Figure 1. Relationship Between Cross-Linking Amount and Network Tightness in Hydrogels

2. 3. Influence of Initiator

The initiator plays a crucial role in determining the grafting rate and the length of the monomer branch chains, as well as influencing the effectiveness of the cross-linking agent. Its amount affects both the reaction rate and the distribution of the polymer's relative molecular weight(Fang et al., 2018). In free radical polymerization, the polymerization rate of the monomer is largely dependent on the decomposition rate of the initiator. The initiator first decomposes to generate primary free radicals, which react with hydroxyl groups on the main polymer chain to produce oxygen free radicals. These oxygen radicals then attack the double bonds of the monomer, forming highly reactive monomer radicals. The monomer radicals quickly react with other monomer molecules to form chain radicals, which in turn react with the cross-linking agent to form the three-dimensional network of (PHGs)(Lee et al., 2022) When the initiator content is low, there are insufficient active centers, resulting in fewer grafting sites and monomer radicals. Consequently, fewer branch chains react with the cross-linking agent, leading to an incomplete polymer network and reduced water absorbency. Conversely, excessive initiator generates a high number of free radicals, which shortens the average branch chain length, decreases the relative molecular weight of the polymer, and increases graft density. This can promote chain termination reactions and result in a denser but less absorbent polymer netwo

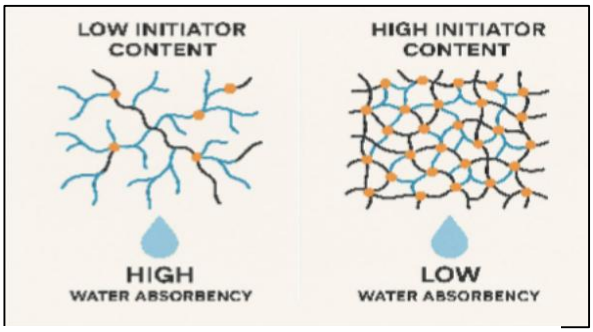

Figure 2. Effect of Initiator Center Concentration on Polymer Network Structure and Water Absorbency

2 . 4.Influence of Raw Material

Raw materials play a pivotal role in determining the structural integrity and functional performance of superabsorbent polymers (PHGs) . Acting as the primary backbone of the three-dimensional network, they define the polymer's absorption behavior, mechanical stability, and overall efficiency.(Pastrafidou et al., 2025)

The selection of raw materials can be guided by several key criteria: **Source of the material:** Raw materials may be derived from natural sources such as cellulose and starch, synthetic polymers like resins, or hybrid organic–inorganic composites, offering a balance between mechanical strength and chemical functionality.(Khoshraftar, 2025).

Hydrophilic characteristics: The water absorption efficiency often depends on physical mechanisms such as capillary action or swelling behavior. For example, cross- linked polyvinylpyrrolidone (PVPP) operates primarily through capillary action, while compounds like croscarmellose sodium (CCNa) and carboxymethyl starch sodium (CMS-Na) exhibit both swelling and capillary properties.These features make them particularly useful in solid dosage forms, such as tablets and capsules, where quick water absorption and a high swelling capacity are necessary for the release of drugs and disintegration. (Liu et al., 2025).

Application-specific functionality: A thorough comprehension of absorption mechanisms allows the strategic selection of raw materials beyond conventional resin systems, supporting the development of PHGs with enhanced mechanical stability and superior salt tolerance. Latest studies underscore the importance of this approach; for example(Zhu et al., 2022) synthesized a novel superabsorbent copolymer by grafting acrylic acid onto carboxymethyl tragacanth (CMT). The resulting material demonstrated strong salt resistance, though its water absorption capacity remained relatively low. Similarly developed a multifunctional superabsorbent resin by blending waste plastics with acrylic acid, yielding a material suitable for use as both a water-retaining agent and an effective desiccant in industrial and agricultural applications(Zhang & Zhang, 2018).

2.5. Influence of Monomer Type

Monomers play a **dual and critical role** in the synthesis and performance of (PHGs). First, monomers interact with cross-linking agents and initiators to establish the three-dimensional network that constitutes the fundamental polymer framework. Second, they introduce a variety of hydrophilic functional groups that significantly enhance the water absorption properties of (PHGs) . Different monomers vary in functional group composition, chain length, and charge properties(Bachra et al., 2021), which in turn determines the structural and functional behavior of the resulting polymer. Based on their electrical characteristics, monomers are commonly categorized into ionic, nonionic, and zwitterionic types: Ionic monomers: Ionic monomers carry either positive (cationic) or negative (anionic) charges. (PHGs) synthesized from ionic monomers typically exhibit higher water absorption capacity compared to nonionic (PHGs) . This enhanced performance is attributed to ion dissociation upon contact with water, generating electrostatic repulsion within the polymer chains. This repulsion increases the free volume within the network, while the osmotic pressure gradient between internal and external phases drives additional water penetration until equilibrium is reached(Bachra et al., 2021). Nonionic Monomers: Nonionic monomers lack an electrical charge. Their water absorption mechanism depends on hydrogen bonding interactions between water molecules and hydrophilic groups, such as including carboxyl (-COOH), hydroxyl (-OH), and amine ($-NH_2$) groups which create strong intermolecular attractions that trap water within the polymer network..

Common examples include 2-hydroxyethyl methacrylate, 2-hydroxypropyl methacrylate, and acrylamide (Alokour, 2019).
Zwitterionic Monomers: Zwitterionic monomers incorporate both acidic and basic groups within the same molecular chain, offering unique adsorption and interaction properties (Damiri et al., 2024). For example, Rehman et al developed a zwitterionic (PHGs) hydrogel by using poly (3 - acrylamidopropyl)- t r imethyl ammonium chloride and 2-acrylamide-2- methylpropanesulfonic acid. This hydrogel exhibited superior adsorption for both cationic (crystal violet) and anionic (Congo red) dyes, demonstrating its versatility in environmental and industrial applications (He et al., 2025).

In addition to electrical characteristics, monomers can also be classified based on their mechanical and functional contributions to the polymer: Hard Monomers: Monomers with a high glass transition temperature (Tg) improve the rigidity and tensile strength of the resulting copolymer resin. Examples include methyl methacrylate, styrene, acrylonitrile, and acrylamide(Ida et al., 2021). Soft Monomers: Monomers with a low Tg (−20 °C to −70 °C) enhance the flexibility and elongation properties of copolymers. Typical soft monomers include ethyl acrylate, butyl acrylate, and 2-ethylhexyl acrylate.(Di Lorenzo et al., 2024)

2.6. Enhancing Hydrophilicity by Increasing the Type and Number of Functional Groups The water absorption rate of superabsorbent polymers (PHGs) is directly proportional to the affinity of their hydrophilic groups for water. The hydrophilic capacity of common functional groups generally follows the order: $–SO_3^-$ > $–COO^-$ > –OH > $–NH_2$ > –O– .
Groups with stronger polarity exhibit higher hydrophilicity compared to weakly polar groups, while polar groups are more hydrophilic than nonpolar ones. However, relying on a single type of hydrophilic group can make SAPs highly sensitive to external factors. To overcome this limitation, ionic hydrophilic groups can be introduced to complement the low hydrophilicity of nonionic groups, while nonionic hydrophilic groups can be added to mitigate the performance fluctuations of ionic groups under varying ion concentrations.(Sun et al., 2019) Therefore, incorporating multiple types and higher quantities of hydrophilic groups significantly enhances the overall water absorption performance of PHGs. The water absorption capacity of (PHGs) increases significantly when multiple types and quantities of hydrophilic functional groups are incorporated into their structure.

2.7. Increasing Ion Concentration within the Network
In (PHGs), the majority of the water present within the network exists as free water. Water movement into PHGs is driven primarily by the osmotic pressure gradient between the polymer network and the external solution. Absorption continues until osmotic equilibrium is reached between these phases. Higher ion concentrations within the PHG network create a larger osmotic pressure differential, which accelerates water influx. This increased driving force results in greater water uptake at equilibrium. Consequently, elevating the internal ion concentration enhances both the rate of water diffusion and the maximum swelling capacity of PHGs (Lavrenko et al., 2018).

3. Challenges and Future Directions

Despite remarkable progress, several challenges persist. First, environmental stability remains problematic, as PHGs often exhibit reduced performance in saline or harsh environments, limiting their application in agriculture and wastewater treatment. Second, mechanical durability is compromised by repeated swelling and deswelling cycles, which degrade structural integrity over time. Finally, balancing biodegradability with cost-effectiveness continues to present a significant hurdle in sustainable PHG design (Fan & Gong, 2020).

4. Detailed Research Recommendations

4.1. AI-Driven Design and Advanced Modeling

- Artificial Intelligence (AI) and Machine Learning**:** Apply machine learning and computational modeling to predict structure-property relationships, enabling rational design of hydrogel compositions and cross-linking architectures with minimized empirical testing (Zhang et al., 2025) .
- Molecular Dynamics (MD) and Finite Element Modeling**:** Leverage computational simulations to model coupled processes—swelling dynamics, electrolyte transport, and mechanical deformation—under realistic operating conditions such as variable pH, salinity, and temperature (Ma et al., 2025).

4.2. Quantum-Informed Materials and Multi-Responsive Hydrogels

- Quantum-Inspired Computation**:** Apply quantum chemical simulations to identify monomer interactions and optimize functional group selection for high- performance PHGs(Mohsenzadeh et al., 2024).
- Multi-Stimuli Responsive Systems**:** Design polymer hydrogels capable of responding simultaneously to diverse external stimuli such as light, pH, temperature, and electromagnetic fields thereby

broadening their applicability in advanced biomedical devices and precision agriculture(Mohite & Adhav, 2017).

4.3. Adaptive and Bio-Interactive Hydrogels

- Self-Healing Hydrogels**:** Design dynamic polymer networks with reversible covalent bonds or supramolecular interactions for improved durability and reusability(Zhang et al., 2024) .
- Bio-Interactive Platforms**:** Integrate bioactive ligands or peptides for targeted cell signaling, controlled drug release, or tissue engineering scaffolds(Schmidbauer, 2024) .

4.4. Emerging Applications

- Smart Desalination and Water Remediation**:** Create hydrogels with selective ion-binding capacities for efficient desalination and removal of heavy metals (Weerasundara et al., 2021).
- Energy Storage and Conversion**:** Explore PHGs as electrolytes or separators in hybrid batteries and supercapacitors, leveraging their tunable ionic conductivity (Wang & Zhao, 2023; Zanbili et al., 2025).
- Microbe-Integrated Hydrogels: Incorporate functional microorganisms within hydrogel scaffolds to enable diverse applications including: (i) accelerated biodegradation of polyethylene and other persistent plastics, (ii) enhanced removal of dyes, pesticides, and organic pollutants from wastewater, and (iii) in-situ biosynthesis of pharmaceuticals, biofuels, or specialty chemicals.(Bishnoi et al., 2024).

4.5. Innovative Manufacturing Strategies

- **3D and 4D Printing**: Utilize additive manufacturing to fabricate complex hydrogel constructs with patient-specific geometries and programmable shape-changing capabilities. Enable precise spatial patterning of functional groups, cells, and bioactive molecules(Malekmohammadi et al., 2021; Mehmood et al., 2021).
- **Green Chemistry Pathways:** Design sustainable synthesis routes employing enzymatic catalysis, renewable bio-based monomers, and aqueous reaction Circumstances to minimize environmental Influence while achieving cost-effective, scalable production.(Koh et al., 2025) .

5. Conclusion

Polymer hydrogels (PHGs) represent a remarkably versatile class of advanced materials with diverse applications spanning agriculture, medicine, environmental remediation, and emerging technologies. Their exceptional water absorption capacity, tunable network architecture, and compatibility with functional modifications position them as cornerstone materials for next-generation systems. However, persistent challenges—including diminished performance in saline or chemically harsh environments, mechanical degradation under cyclic loading, and elevated production costs—continue to constrain broader implementation. Overcoming these limitations demands integration of transformative strategies: AI-driven materials design, quantum-informed computational modeling, stimuli-responsive architectures, and sustainable manufacturing paradigms. Through interdisciplinary collaboration and adoption of these cutting-edge approaches, PHGs can advance into intelligent, high-performance materials that simultaneously achieve technical excellence and environmental sustainability, enabling breakthrough applications in water purification, energy storage, precision agriculture, and regenerative medicine.

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