

Review

Recent Advances in Sustainable Hydrogel-Based Functional Materials: Design Strategies, Functional Applications, and Future Perspectives

Canjie Xu ¹, Junfeng Cheng ¹, Xin Wang ¹, Shasha Li ², Zihong Pan ¹ and Enze Li ^{1,*}

¹ Institute of Resources and Environmental Engineering, State Environmental Protection Key Laboratory of Efficient Utilization Technology of Coal Waste Resources, Shanxi Laboratory of Yellow River, Shanxi University, No. 92 Wucheng Road, Taiyuan 030006, China

² College of Chemical Engineering and Technology, Taiyuan University of Science and Technology, No. 66 Waliu Road, Taiyuan 030024, China

* Correspondence: lienze@sxu.edu.cn

Abstract

Hydrogel-based functional materials have garnered widespread attention across various fields due to their unique three-dimensional network microstructure and versatile, tunable properties. However, owing to the absence of a systematic analysis of the application mechanisms of hydrogels in diverse fields, accurately choosing the suitable type of hydrogel, its preparation method for specific application scenarios, and critical sustainability concerns still present challenges. A systematic framework connecting hydrogel design, functional performance, and sustainability is therefore needed. This review summarizes recent advances in chemical and physical cross-linking strategies and discusses their implications for material performance and environmental sustainability. Representative applications in separation engineering, sustainable agriculture, smart devices, and biomedical materials are evaluated from both functional and sustainability perspectives. Finally, key trade-offs between performance, functionality, scalability, and environmental impact are identified, and future directions toward sustainable-by-design hydrogel systems are proposed. This review aims to provide comprehensive theoretical references and technical insights for the development of sustainable hydrogel materials with more potential applications.

Keywords: sustainable hydrogel-based materials; cross-linking technology; separation engineering; smart device; cell and drug delivery



Academic Editors: Irene Bavasso and Claudio Tosto

Received: 13 August 2026

Revised: 9 September 2026

Accepted: 28 September 2026

Published: 30 September 2026

Copyright: © 2026 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the [Creative Commons Attribution \(CC BY\)](https://creativecommons.org/licenses/by/4.0/) license.

1. Introduction

The term “hydrogel” was first proposed by Van Bemmelen in 1894 [1]. In the 1960s, Wichterle and Lim successfully applied it to contact lenses for the first time [2]. It is a gel with water as the dispersing medium, formed by hydrophilic polymer chains cross-linked either chemically or physically, typically possessing a three-dimensional network structure [3]. By introducing certain hydrophobic groups and hydrophilic residues (such as hydroxyl and carboxyl groups) into water-soluble, high-molecular-weight polymers with a network-cross-linked structure, the hydrophilic residues bind with water molecules and interconnect within the network, while the hydrophobic groups expand when in contact with water, thus forming a unique cross-linked polymer structure. Initially, hydrogel research focused mainly on the synthesis of relatively simple chemical cross-linked polymer networks. In the early 1970s, inspired by the work of Katchalsky [4], the focus of hydrogel

research shifted from relatively simple water-swollen macromolecular networks to hydrogels that can respond to changes in environmental conditions such as temperature or pH [5]. Subsequently, with the growth of organic chemistry knowledge, research on chemically cross-linked hydrogels with various functionalities gained momentum [6]. Monomers, initiators, and cross-linkers are three important components in hydrogel synthesis. The properties of hydrogels can be adjusted by altering the synthesis factors, such as reaction containers, reaction time, reaction temperature, monomer types, and cross-linker types [7]. This allows the synthesis of hydrogels to be tailored by selecting different preparation methods depending on the specific application field.

With the development and diversification of preparation methods, hydrogels suitable for different application fields have been researched and developed. Hydrogels exhibit distinct characteristics due to variations in preparation methods, such as the following: (i) Water absorption and retention [8,9]: This ability allows hydrogels to expand rapidly in water, absorbing hundreds of times their weight in water while maintaining their original shape and three-dimensional network structure, without dissolving in water. The water absorbed by hydrogels can be stably stored and released to maintain the surrounding humidity. (ii) Biocompatibility and biodegradability [10–12]: The water content of hydrogels ranges from a few percent to as high as 99%. Since the water content of hydrogels is similar to that of biological tissues (about 70% or up to 99% water), they exhibit strong biocompatibility, which promotes cell growth and proliferation. Additionally, many hydrogel materials naturally degrade *in vivo*, avoiding secondary pollution. (iii) Unique stimulus-responsive characteristics [13–15]: Many hydrogels can respond to changes in the surrounding environment (such as pH, temperature, or light) by physically or chemically altering their volume, shape, or properties. (iv) Excellent mechanical properties [16,17]: Hydrogels have good stability and formability, and their mechanical properties can be controlled through different preparation methods. For instance, when using a small amount of cross-linking agent, a very soft gel can be obtained. In contrast, the rigidity of the polymer increases with the degree of cross-linking.

In this review, sustainability is treated not as an isolated material property, but as a life-cycle-oriented design criterion that connects hydrogel synthesis, functional performance, practical use, and end-of-life management. Specifically, hydrogel sustainability is evaluated from six interrelated dimensions: (i) renewable and low-impact feedstocks; (ii) low-toxicity cross-linkers, initiators, and solvents; (iii) energy and resource-efficient fabrication; (iv) durability, regeneration, and reusability during service; (v) biodegradability, recyclability, and ecological safety at end of life; and (vi) scalability and manufacturing feasibility. These criteria are used throughout this review to critically examine whether improvements in hydrogel functionality translate into genuine sustainability benefits or merely shift environmental burdens between different stages of the material life cycle [18].

Accordingly, this review does not simply catalogue hydrogel preparation methods and applications. Instead, it establishes a structure–function–sustainability framework to examine how network construction and material composition simultaneously determine functional performance and environmental impact. Chemical and physical cross-linking strategies are first compared from both performance and sustainability perspectives, followed by application-specific analyses in separation engineering, agriculture, smart devices, and biomedical materials. Finally, sustainable design principles, unresolved trade-offs, and future opportunities for sustainable-by-design hydrogels are discussed.

2. Hydrogel Preparation Strategies: Performance and Sustainability Considerations

There are various methods for preparing hydrogels. Based on the types of interactions involved in the matrix formation process, they can be classified into chemical cross-linking and physical cross-linking.

2.1. Chemical Cross-Linking Method

The chemical cross-linking method refers to the process in which macromolecular chains are connected through chemical bonds to form a network or three-dimensional structured polymer under the influence of cross-linking agents or other media. The cross-linking agents serve as bridges between linear molecules, facilitating the formation of covalent bonds between polymer chains. Hydrogels synthesized by this method typically exhibit enhanced mechanical properties, as well as higher stability and durability. The chemical cross-linking method can be further divided into monomer cross-linking polymerization and carrier graft copolymerization.

2.1.1. Monomer Cross-Linking Polymerization

Monomer cross-linking polymerization is the preparation of macromolecular hydrogel material by free radical homopolymerization or copolymerization in the presence of cross-linkers. Haraguchi et al. [19] first polymerized N-isopropylacrylamide (NIPAM) monomer through in situ free radical polymerization in a dispersion of lithium montmorillonite (Laponite) nanoparticles without adding a chemical cross-linker, resulting in a nanocomposite hydrogel with excellent tensile strength and toughness. N, N'-methylenebisacrylamide (MBA) is commonly used as a cross-linking agent for the preparation of hydrogels. Researchers prepared poly (acrylic acid-acrylamide) (PAA) hydrogels with good swelling and adsorption properties from acrylic acid (AA), acrylamide (AM) and other materials in the presence of MBA [20–22]. Guo et al. [23] also used MBA as a chemical cross-linker and acrylamide as raw materials to polymerize composite hydrogels with unusual and reversible thermo-responses via aqueous solution polymerization. Wang et al. [24] likewise synthesized a novel hydrogel using MBA as a cross-linking agent, which exhibited excellent transparency, flame retardancy, and anti-aging properties. From a sustainability perspective, monomer cross-linking polymerization benefits from mature processing and scalability but may involve petroleum-derived monomers, toxic residual initiators or cross-linkers, and considerable purification requirements. Future development should therefore prioritize bio-derived monomers, low-toxicity cross-linkers, aqueous polymerization, and high monomer conversion to minimize chemical waste and post-treatment demand [25].

2.1.2. Photo-Cross-Linking

Photo-cross-linking is a method that uses light (usually UV or visible light) as a “switch”. It mainly relies on light-sensitive groups or photoinitiators to produce free radicals under light, which then trigger covalent bonds between molecular chains to form a 3D hydrogel network [26]. Trucco et al. [27] developed an injectable, visible-light-cross-linkable hydrogel made from the methacrylated gellan gum (GGMA) using a ruthenium–sodium persulfate photoinitiator system, allowing in situ cross-linking under visible light and the encapsulation of human chondrocytes. The study systematically looked at how gel concentration, photoinitiator ratio, light exposure time, and steam sterilization affect the material's properties. The research shows that visible-light-cross-linked GGMA has promising potential for cartilage defect repair. Photo-cross-linking offers spatial and temporal control and can reduce thermal energy input compared with conventional thermally initiated polymerization. Nevertheless, its sustainability depends strongly on the photoinitiator

toxicity, light source, exposure time, and penetration depth. Visible-light-responsive and initiator-efficient systems are therefore preferable to UV-intensive processes when comparable functionality can be achieved [28].

2.1.3. Carrier Graft Copolymerization

Hydrogels can be grafted onto carriers with a certain strength to improve the poor mechanical strength. The most typical example is the work by Fanta et al. [29] in 1983. They utilized ammonium cerium nitrate as an initiator and found that Ce^{4+} coordinated with the glucose rings of starch, causing breaks of rings and forming free radicals, which then led to the grafting of acrylonitrile and other monomers onto starch. Athawale et al. [30] and Cao et al. [31] also used ammonium cerium nitrate as an initiator to graft acrylamide onto starch, to prepare hydrogels with thermal stability and high water absorption. Li et al. [32] used liginosulfonate (LS), a natural high molecular material, acrylamide (AM) and hydroxyethyl methacrylate (HEMA) as monomers, and MBA as a cross-linker, to successfully prepare a novel polymer hydrogel with pH responsiveness and excellent mechanical properties by grafting copolymerization.

The carrier graft copolymerization method can introduce various functions into hydrogels by grafting different monomers or functional groups. Compared to the other two methods, hydrogels prepared using this approach typically possess high functionality and customization potential, but the process is relatively complex. The use of renewable carriers such as cellulose, starch, chitosan, and lignin can reduce dependence on fully synthetic polymer matrices. However, multistep functionalization, solvent consumption, low grafting efficiency, and purification requirements may offset these benefits. Sustainability assessment should therefore consider the entire modification route rather than the renewable origin of the carrier alone [33].

2.1.4. Radiation Cross-Linking

The radiation cross-linking method is the process of using the primary active free radicals produced by various kinds of radiation to trigger the cross-linking of polymer chains to form hydrogels. El-Rehim et al. [34] prepared cross-linked CMC-N/PAAm hydrogels using electron beam irradiation. Ammonium carbonate was added as a gas-blowing agent in the irradiation process to make hydrogels with an ultra-porous structure. Nizam et al. [35] prepared the hydrogels using an acrylamide monomer (AM) and carboxymethyl cellulose (CMC) as the base materials by gamma irradiation. Radiation cross-linking can eliminate chemical initiators and simultaneously enable cross-linking and sterilization, thereby reducing chemical residues. However, the high-energy radiation source, specialized equipment, and associated energy demand must be considered when evaluating its overall environmental advantage [36].

2.2. Physical Cross-Linking Method

Physical cross-linking is a method for creating a gel through physical forces such as electrostatic attraction, ionic interactions, hydrogen bonding, and chain entanglement. The hydrogel prepared by this method is non-permanent and can undergo reversible changes when conditions are altered. Therefore, it exhibits good adjustability and dynamic responsiveness, making it suitable for applications in short-term functional fields such as drug carriers or adjustable material fields like smart devices. Physical cross-linking can be categorized into ionic interactions, hydrogen bonding, and hydrophobic bonding. Physical cross-linking provides potential sustainability advantages because reversible non-covalent interactions can reduce the use of permanent chemical cross-linkers and facilitate reprocessing, self-healing, or controlled degradation. However, lower long-term

stability may shorten the service life and increase the replacement frequency, illustrating that “greener synthesis” does not necessarily guarantee a lower life-cycle impact [37].

2.2.1. Ion Interactions

The preparation of hydrogels through ion interactions can be categorized into two groups: (i) the electrostatic interaction between the polyelectrolyte and oppositely charged polyvalent ions forms physical hydrogels; (ii) the electrostatic interaction between two oppositely charged polyelectrolytes forms polyelectrolyte complex hydrogels. Xu et al. [38] developed a dual ionically cross-linked hydrogel by in situ polymerization of acrylic acid in the mixed solution of 2-hydroxypropyltrimethyl ammonium chloride chitosan (HACC) and iron ions (Fe^{3+}), in which the ionic bond between positively charged HACC and negatively charged PAAc is the first set of cross-linking points and the ionic interaction between the trivalent iron ion (Fe^{3+}) and the carboxyl group serves as the second set of ion cross-linking points. The synthesis of hydrogels through ion interactions has been widely researched and applied in the biomedical field. Using this method, Cheng et al. [39] developed a zinc-cross-linked hydrogel containing zinc–insulin hexamers for oral insulin delivery, while Wei et al. [40] prepared a three-dimensional porous hydrogel scaffold.

2.2.2. Hydrogen Bond Cross-Linking

In the polymer aqueous solution system, the intramolecular and intermolecular hydrogen bonds can also play the role of physical cross-linking points. For example, Li et al. [41] used acrylamide as a hydrogen bond donor and choline chloride as a hydrogen bond acceptor, dispersing ZnO into the system they constructed, resulting in a nanocomposite hydrogel with excellent antibacterial properties. Chen et al. [42] also combined hydrogen bonding and electrostatic attraction to construct a mechanically stable hydrogel bead with a core–shell structure for the removal of Cu^{2+} from wastewater.

2.2.3. Hydrophobic Association

The hydrophilic monomer is used as the main reaction monomer to copolymerize with a small number of monomers with hydrophobic groups. During the reaction process, the hydrophobic groups of the hydrophobic monomer will gather together with the hydrophobic groups of the added surfactants in aqueous solution through hydrophobic association to form a mixed micelle. Hydrogels with a dense three-dimensional network structure were synthesized by connecting these mixed micelles with the main hydrophilic chains. Zhao et al. [43] used the cationic surfactant (dodecyl trimethyl ammonium bromide) to form micelles with the hydrophobic agent as the physical cross-linking point of the three-dimensional network. The hydrophobic association hydrogels can be prepared successfully using micelles copolymerizing acrylamide and lauryl methacrylate, with excellent mechanical, rheological, and recovery properties.

Furthermore, in addition to the chemical cross-linking or physical cross-linking alone, there are also hydrogels with chemical and physical synergistic cross-linking. For example, Wan et al. [44] successfully prepared a multifunctional conductive hydrogel via an interpenetrating network (IPN) and multiple hydrogen bond interaction with strong self-healing shape memory and good thermal stability. The chemical cross-linking in the hydrogel system was obtained by in situ polymerization of acrylic acid (AA) and aniline (ANI). Physical cross-linking is achieved through the formation of an IPN skeleton by polyvinyl alcohol (PVA), PAA-PANI polymer and PVA, in which multiple hydrogen bonds interact between polyvinyl alcohol and polydopamine (PDA) and PF127 diamino oxygen derivatives (AOP).

Hydrogels prepared by chemical cross-linking typically exhibit more stable properties, making them suitable for long-term use. However, their complex reaction conditions and potential environmental hazards require special attention. The physical cross-linking

method is easy to operate and highly adjustable, but the stability of the hydrogel needs further enhancement.

3. Applications of Hydrogels

The outstanding adsorption performance, good biocompatibility and degradability, unique stimuli-responsive characteristics, and excellent mechanical properties mean hydrogels are widely applied in fields such as separation engineering, sustainable agriculture, smart devices, and biomedical materials. In addition, the properties of hydrogels can also be used to encapsulate substances in hydrogels, thereby expanding their applicability in diverse fields. In the field of separation engineering, hydrogels can serve as effective adsorbents for oil–water separation and extraction of metal ions. Additionally, they can also be used as soil conditioners in agriculture. Within the realm of smart devices, the multifaceted attributes of hydrogels position them as crucial materials for flexible sensors that enable precise monitoring of stress and strain. In biomedical engineering, hydrogels are employed as delivery systems for cell transport and controlled drug release.

3.1. Separation Engineering

In recent years, hydrogels have been widely applied in the field of separation engineering. Their unique three-dimensional network structure and excellent interfacial regulation properties can effectively enhance mass transfer efficiency in substance separation processes, showing great potential in applications such as oil–water separation and metal ion separation.

3.1.1. Separation of Metal Ions

The efficient separation or extraction of metal ions has always been a significant challenge. Numerous studies have shown that hydrogels have great potential in adsorbing metal ions [45–50]. Emulsion hydrogels are prepared by encapsulating oil phase extractants into hydrogels. Functional groups in emulsion hydrogels can chelate or exchange ions with metal ions, which is a new method for the extraction or separation of metal ions. Yuan et al. [51] prepared a three-dimensional network structure of Pickering emulsion hydrogels (PEHGs) using acrylamide as the raw material and SiO₂ as the emulsifier. The PEHGs were used to encapsulate the copper ion extractant 5-dodecylsalicylaldoxime (N902), providing a channel for the diffusion of Cu²⁺ from the aqueous phase to the extractant droplet oil–water interface, thereby achieving the effective extraction of Cu²⁺ from the solution. Yuan et al. [52] prepared size-controllable O/W/O Pickering emulsion hydrogel microspheres using two types of SiO₂ particles with opposite wettability. Both types of hydrogel beads were used for the adsorption of Cu²⁺ from water, with extraction efficiencies reaching 97%. Gao et al. [53] encapsulated the synergistic phosphoric acid 2-ethylhexyl hydrogen-2-ethylhexyl ester/phosphoric acid tributyl ester (P507/TBP) hydrogel in a semi-permeable polymer network (SIPN) structure of polyacrylamide/sodium alginate (PAM/SA). They prepared Pickering emulsion hydrogels (PEHGs) with dual-component absorption and studied their adsorption performance for Zn²⁺ in water. The results showed that the adsorption capacity for Zn²⁺ could reach 76.51 mg/g. Then, Gao et al. [54,55] prepared water-in-oil Pickering emulsion hydrogels using 2-ethylhexyl hydrogen-2-ethylhexyl phosphate (P507)/kerosene and di (2-ethylhexyl) phosphoric acid (D2EHPA)/kerosene as dispersed phases, polyacrylamide-co-diacetone acrylamide (P (AM-co-DAAM)) pre-gel solution as the continuous phase, and nano-SiO₂ particles as the stabilizer. At 298 K, the adsorption capacities for Zn²⁺ and In³⁺ reached 138.2 mg/g and 28.232 mg/g, respectively.

3.1.2. Oil–Water Separation

With the continuous increase in industrial oily wastewater and the frequent occurrence of various oil spills, oil–water separation has been a global challenge. Hydrogels have excellent water absorption and retention, and they are considered promising candidates for designing new oil–water separators. A variety of superwetttable hydrogel materials have been developed for oil–water separation [56]. The utilization of hydrogels for oil–water separation primarily hinges on their exceptional superhydrophilicity and superhydrophobicity. Upon contact with an oil–water mixture, the hydrogel’s pronounced affinity for water enables it to rapidly absorb aqueous phases while effectively repelling oily components, thus facilitating efficient oil–water separation. Hydrogels are usually combined with a micron-sized porous substrate (stainless steel mesh) to form a hydrogel-coated mesh; when the oil–water mixture is injected into the mesh, the oil remains on the mesh, while the water is separated, and there are no oil stains in the permeated water. For instance, Liu et al. [57,58] successively prepared two hydrogels with superhydrophilic and superoleophobic properties and combined the hydrogels with stainless-steel mesh for oil–water separation. The efficiency of oil–water separation of the two hydrogels can reach more than 98%. Likewise, Wu et al. [59] utilized a similar approach to prepare PVA/CS/PAM IPN hydrogels (HAPC-Gel) by two-step free radical polymerization. The interpenetrating network gives the hydrogel material high mechanical properties due to the presence of physical and chemical cross-linking. The first network was formed by cross-linking CS and PVA with glutaraldehyde (GA). Based on CS/PVA, acrylamide (AM) is designed to form PAM through free radical polymerization as the second network, and the formed PAM network interpenetrates a PVA/CS network. HAPC-Gel coating filter cloth has super-oleophobic properties underwater, and it can stably separate the oil–water mixture under different oil phases and complex environments (acid, alkali and salt). The HAPC gel has good chemical stability and recyclability, which provides the possibility to recover oil and water in complex environments, and the removal rate remains above 99% after 20 instances of oil–water separation. Chen et al. [60] prepared multifunctional Ag NPs/guar gum hybrid hydrogels by in situ reduction and self-cross-linking methods. The hydrogels achieved a separation efficiency of over 98% for various oil–water mixtures.

The substances to be separated are often not present in isolation within the separation system. The complexity of multi-component coexistence, along with the synergistic effects of environmental factors, presents significant challenges for the application of hydrogels in the field of separation engineering. Enhancing the ability and efficiency of hydrogels to separate target components in complex systems is critical for their industrial applications. From a sustainability perspective, separation performance should not be evaluated solely by adsorption capacity or separation efficiency. The regeneration efficiency, number of reuse cycles, consumption of acids, bases and organic solvents during regeneration, recovery of the separated resources, hydrogel lifetime, and generation of secondary waste are equally important. A hydrogel exhibiting exceptionally high adsorption capacity but requiring chemically intensive regeneration may not provide a genuine environmental advantage over conventional separation technologies. Future studies should therefore report both separation performance and resource consumption over repeated operating cycles [61].

3.2. Sustainable Agriculture

In sustainable agriculture, bio-based hydrogels are developed to balance crop productivity with ecological safety [62]. They are widely applied for soil water retention, controlled delivery of agrochemicals, seed coating, and degraded soil remediation. These materials can mitigate water scarcity and agrochemical leaching, while reducing micro-plastic risks compared with conventional non-degradable synthetic superabsorbents. Cui et al. [63]

developed a physically and chemically cross-linked hydrogel made from quaternary ammonium guar gum (QAG) and humic acid (HA). HA contains a large number of carboxyl, hydroxyl, and carbonyl groups, which can physically cross-link with the hydroxyl and quaternary ammonium groups in QAG through electrostatic and hydrogen bonding interactions. The results showed that the presence of four hydrophilic groups (quaternary ammonium, hydroxyl, carboxyl, and carbonyl) in the hydrogel improved the soil's water retention by more than double, and the adhesion strength between soil particles increased by 650% compared to the original. Furthermore, compared to direct fertilization, the biodegradable hydrogel not only improved the germination rate and growth condition of mung beans but also reduced the negative impact of over-fertilization on plant roots. Ghobashy et al. [64] proposed a novel approach for preparing a highly porous super absorbent hydrogel (SAH). They used gamma radiation to polymerize and cross-link synthetic and natural hydrogel-based acrylamide (Am) and gelatin (G) to form hydrogels. The hydrogels were modified in concentrated alkali, and under the alkaline hydrolysis of concentrated NaOH, the CONH₂ group was converted to the COONa carboxyl group. The experimental results showed that the water absorption performance of the modified hydrogel material was significantly improved, and it had good sustained-release properties. Based on the purpose of the integration of "water and fertilizer", Niu et al. [65] put forward the strategy of synchronous chemical loading. A biodegradable and environmentally friendly multifunctional superabsorbent material SA/urea hydrogel was designed and synthesized. In this method, urea was used as a cross-linking agent to construct an SA network. High porosity and a large number of hydrophilic groups ensure that the hydrogel has excellent water absorption, water retention, and biodegradability. During the degradation process, the hydrogel can release nitrogen, phosphorus and potassium into the soil for a long time, promoting plant growth and increasing nutrients.

Hydrogels show great potential for application in soil improvement, but the environmental friendliness and biocompatibility of the materials used for their preparation are essential prerequisites for their practical use. Therefore, the development of green preparation materials will become a key of this field. However, agricultural hydrogels should not be considered sustainable solely because they improve water retention or fertilizer-use efficiency. Their long-term degradation behavior, accumulation of non-degradable polymer fragments, potential microplastic formation, effects of degradation products on soil microorganisms, and economic feasibility at the field scale must also be considered. Future evaluations should therefore integrate agronomic benefits with soil persistence, ecotoxicity, and end-of-life behavior [66].

3.3. Smart Device

The excellent tunability and dynamic responsiveness of hydrogel materials have garnered significant attention in the field of smart devices. As a three-dimensional network of hydrophilic polymers, hydrogels have Young's moduli similar to human skin and have special elasticity, stretching ability, biocompatibility and self-healing properties [67,68]; these properties also give hydrogels unique advantages in the field of smart devices.

In the field of flexible wearable sensors, hydrogels have shown promising application potential. Hydrogel sensors detect stress-strain by capturing the volume or shape change in the hydrogel material when it is subjected to external stresses and converting it into a quantifiable electrical signal. In addition, hydrogel sensors can utilize the ionic conductivity, piezoelectric effect, and other properties of hydrogels to respond to pressure, touch, and other stimuli. Using these principles, hydrogels have been widely studied and applied in electronic skin, human health monitoring, implantable devices, and human-computer interaction systems [69].

Researchers are continuously exploring new conductive fillers and polymer substrates to optimize the performance of wearable hydrogel sensors [70]. For example, Song et al. [71] developed a sweat sensor with anti-fouling and antibacterial properties by incorporating MXene and CeO₂ nanomaterials into amyloid albumin hydrogels (ABSAG), which enhanced the sensor's sensitivity and stability. Additionally, researchers have effectively improved the mechanical properties and sensitivity of hydrogel sensors by introducing materials such as cellulose, cellulose nanocrystals (CNCs), and ionic cellulose [72–78].

Human–machine interaction has been closely integrated into every aspect of people's lives, and traditional human–machine interaction devices are mostly made of strong materials, which poses a challenge to wearability. Compared with traditional human–computer interaction materials, hydrogels have good mechanical properties, excellent biocompatibility and ultra-high sensitivity. By combining hydrogels with flexible electronic components, smart devices with touch-sensitive functions can be developed. These devices can accurately identify the user's touch position for a more natural and intuitive human–computer interaction experience. To overcome the problems of one-dimensional nanomaterials being insensitive and expensive, and two-dimensional materials having scalability and dispersion. Li et al. [79,80] successfully developed double-network PAM/CMC/TA hydrogels by reinforcing polyacrylamide (PAM) and sodium carboxymethyl cellulose (CMC) polymer with tannic acid (TA). PAM/CMC/rGO hydrogels were also prepared with polyacrylamide (PAM), sodium carboxymethyl cellulose (CMC) and reduced graphene oxide (rGO). These two hydrogels have been applied to human–machine interface systems for motion recognition and wearable one-handed keyboards with gesture recognition functions respectively. Among them, the PAM chain provides the elasticity of the hydrogel through covalent cross-linking. CMC, a biodegradable polymer widely existing in nature and rich in carboxyl and hydroxyl functional groups, readily engages in robust hydrogen bonding with other materials. Its addition, it gives the hydrogels better biocompatibility and mechanical properties. Dong et al. [81,82] have also developed different hydrogels for smart wearable human–computer interaction. Inspired by the adaptation mechanism of organisms in cold environments, Fu et al. [83] doped with both antifreeze protein (AFP) and inorganic salt (NaCl) in Agar/PAAm dual-network hydrogel to prepare a multi-functional antifreeze hydrogel. The antifreeze effect is derived from the synergistic mixing of AFP and NaCl, which can maintain the core performance even at −20 °C and ensure accurate and stable monitoring of human movement. Using these excellent properties, they assembled the hydrogel into wearable electronic devices for HMI (intelligent control and telematics transmission). Despite rapid improvements in sensitivity, conductivity, stretchability, and self-healing ability, the sustainability of hydrogel-based smart devices remains insufficiently addressed. The incorporation of nanomaterials, conductive fillers, salts, and complex electronic components can complicate material recovery and end-of-life treatment. Moreover, high durability may conflict with biodegradability, while disposable wearable sensors may generate additional electronic waste. Sustainable hydrogel electronics therefore require not only a high sensing performance but also simplified compositions, low-energy fabrication, extended service life, repairability, and compatible recycling or degradation pathways [84].

3.4. Biomedical Materials

3.4.1. Cell Delivery

The viscoelastic properties of hydrogels and their similarity to extracellular matrices (ECMs) allow them to encapsulate cells as cell support scaffolds to form cell–hydrogel complexes. By encapsulating cells in hydrogels, cells can be protected from interference from the external environment while providing oxygen and nutrients required for cell growth. What's more, the cells encapsulated in the hydrogel remain resident at the implant

site for a long time. Kwokdinata et al. [85] investigated the use of an injectable hydrogel consisting of thiolated hyaluronic acid and thiolated gelatin. They encapsulated SCPCs in thiol-modified hyaluronan gelatin hydrogels and transplanted them into the rat spinal cord to treat spinal cord injuries. Pupkaite et al. [86] modified collagen with a sulfhydryl group, and hydrogels were prepared by cross-linking with 8-arm polyethylene glycol-maleimide. The results showed that the thiol-collagen hydrogel was also suitable for cell delivery. In addition, self-assembled peptide hydrogels have great potential in cell delivery due to their high biocompatibility, low immunogenicity, and reabsorption of degradation products by organisms [87].

Delivery of therapeutic cells to injured or diseased tissues through controlled degradation can reduce inflammation and increase the regenerative potential of several tissues. Ansari et al. [88] encapsulated the GMSCs in a hydrogel to develop an injectable 3D RGD-coupled alginate brine gel cell encapsulation structure with multiple growth factor delivery capabilities. According to their biomechanical analysis, GMSCs encapsulated in alginate gel have the highest muscle differentiation ability compared with other hydrogels, so the cell-encapsulated hydrogels have the potential to enable muscle tissue repair/regeneration. Torres-Ortega et al. [89] developed and characterized a drug delivery system for brain tissue repair, where mesenchymal stem cells (MSCs) and glial cell line-derived neurotrophic factor (GDNF) were included in a nanoparticle-modified supramolecular guest–host HA HG. The results showed that the incorporation of NPs into supramolecular guest–host HG enhanced the mechanical properties of the biomaterial as a physical cross-linking agent of the HG compared to conventional HA gels. It was also demonstrated that the developed HG enhanced the anti-inflammatory properties of MSCs, promoted their relationship with ECM, and promoted differentiation into neuron-like cells.

3.4.2. Drug Delivery

Hydrogels have a high water content, biocompatibility, and a structure similar to the macromolecular composition of the human body. As a drug carrier, hydrogel can be used for wound healing, which can not only maintain a moist wound environment and promote cell growth and tissue repair but also achieve the slow release and controlled release of drugs, to improve the therapeutic effect and action time of drugs. Yang et al. [90] prepared LL-37/CS hydrogel dressings by the physical blending method. Chitosan was used as the base material of hydrogel, and LL-37 was encapsulated in hydrogel. Their results showed that the LL-37/CS hydrogel could effectively deliver LL-37 peptide to the wound site and produce antimicrobial and pro-healing activity. Self-assembled peptide hydrogels are considered to be good choice materials for drug delivery carriers due to their structural similarity to natural extracellular matrix. Cui et al. [91] developed a dual drug delivery system. They used FGF-alginate fiber as the core material and antibiotic self-assembled peptide hydrogel as the shell material, and encapsulated micron-scale alginate fiber in the instant self-assembled peptide hydrogel to construct a dual-loaded drug delivery system. When the hydrogel was applied to rats, the wounds of the rats were gradually healed, demonstrating that the two-drug delivery system can rapidly control acute inflammation and promote wound healing. Compared to pure peptide hydrogels and pure alginate fiber gels, the fiber–peptide hydrogel exhibited a slow degradation rate.

Hydrogels can also be used as probiotic carriers to protect probiotics from harsh environmental influences (such as damage by stomach acid and digestive enzymes) to ensure that sufficient amounts of probiotics reach the target areas of the intestine. Xiao et al. [92] encapsulated a model probiotic (*Lactobacillus rhamnosus*) in a hydrogel to alleviate bacterial enteritis. When exposed to H₂S secreted by surrounding intesti-

nal pathogens, the hydrogel can be locally degraded and rapidly release the cargo to compete with the source pathogen in turn for binding to the host. More importantly, the presence of hydrogels enhances the survival of *Lactobacillus rhamnosus* in the face of gastrointestinal injury.

In biomedical applications, biocompatibility and biodegradability are often regarded as indicators of sustainability; however, they should not be considered equivalent to environmental sustainability. Complex chemical modification, sterile manufacturing, single-use products, and energy-intensive purification may substantially increase the environmental footprint of biomedical hydrogels. Sustainable design in this field therefore requires balancing clinical performance and patient safety with manufacturing efficiency, material utilization, controlled degradation, and waste management, without compromising regulatory requirements [93].

4. The Sustainability of Hydrogels

After discussing the methods for synthesizing hydrogels and their potential applications in different fields, we will move on to focus on the sustainability of hydrogels. Sustainable hydrogel design should start with reverse-engineering network architectures according to application demands [94]. For instance, separation applications prioritize selective mass transport and chemical stability; agricultural scenarios require water retention, sustained release and biodegradability; smart devices demand conductivity, toughness and cyclic stability; while biomedical materials focus on biocompatibility, tissue-matching mechanics and controllable degradation. Therefore, hydrogels should not be universally designed with high cross-linking density and high mechanical strength. Instead, cross-linking strategies, pore structures, water content and interfacial chemistry ought to be tailored to the targeted functions [95].

In network construction, low-toxicity, low-energy-consumption and reversible cross-linking strategies should be prioritized, including hydrogen bonding, ionic interactions, host–guest interactions, dynamic covalent bonds, and visible-light-mediated cross-linking, to reduce the utilization of conventional highly toxic cross-linkers and organic solvents. Meanwhile, double-network, interpenetrating network, gradient or phase-separated architectures can be adopted to spatially partition different functions. For example, one network bears the structural load and maintains mechanical stability, while the other network undertakes ion transport, self-healing or stimulus-responsive behaviors. This strategy helps alleviate the well-known trade-off where enhanced strength is accompanied by a deteriorated mass-transport performance [96].

Sustainability should also be reflected in raw material selection. Renewable or biobased polymers such as cellulose, chitosan, alginate, starch and gelatin are preferred, while the proportion of non-degradable petrochemical monomers should be reduced. Nevertheless, “natural origin” does not inherently guarantee true sustainability. Full assessments are required regarding raw material acquisition, chemical modification procedures, solvent usage, and final degradation products. Accordingly, a more rational principle is to minimize synthetic steps and the degree of functionalization, and prioritize material systems capable of direct gelation or mild modification.

For functional design, the concept of “more functions is better” should be avoided. Although excessive incorporation of nanofillers, conductive materials, complex cross-linkers or multi stimulus-responsive components may boost laboratory-scale performance, it will raise the production cost, manufacturing complexity, recycling barriers and potential environmental risks. A better approach is to “achieve maximum function with minimal components”, meaning we should leverage the network structure itself for mechanical, transport, and responsive functions, rather than constantly adding additives.

Scalability should also be considered at the early stage of material development. Hydrogels prepared in laboratories via sophisticated microfluidics, prolonged freeze–thaw cycles, multi-step grafting or precision lithography will face limited practical value if continuous manufacturing cannot be realized. Therefore, the raw material cost, reaction time, energy consumption, equipment requirements, batch consistency, and continuous manufacturability need to be evaluated in parallel.

When it comes to environmental impact, we should expand the focus from just “performance during use” to considering the “entire life cycle”. A truly sustainable hydrogel needs to account for things like where the raw materials come from, the energy used in production, the lifespan, the number of times it can be recycled, how it is disposed of, and the ecological safety of its degradation products. For example, with adsorption and ion-separating hydrogels, you should not just report the adsorption capacity; you should also look at how many times it can be reused and how much acid, base, and solvent are consumed during regeneration. For agricultural hydrogels, you need to pay attention to long-term residues and potential microplastic risks.

Table 1 systematically compares representative preparation methods, including chemical and physical cross-linking, core advantages, and main limitations, together with their suitable application scenarios and representative recent studies.

Table 1. Key conditions, advantages, limitations and application field of hydrogels with different cross-linking strategies.

Method	Key Condition	Core Advantage	Main Limitation	Sustainability Benefits	Sustainability Concerns	Applicable Field	Ref.
Chemical cross-linking	Monomer polymerization	The process is well-established, costs are low, you can easily tweak the cross-linking density and mechanical properties, and it is great for mass production	Residual monomers/initiators might be toxic; the network structure is uneven	Mature and scalable processing; aqueous synthesis possible	Residual monomers/cross-linkers; petrochemical feedstocks; purification waste	Adsorption separation, agricultural water retention, flexible sensors	[97,98]
	Carrier graft copolymerization	Retains the intrinsic properties of the carrier while introducing functional side chains; the covalent network has good stability in water; mechanical, charge, and responsive characteristics can be tuned; can enhance drug adsorption and cell adhesion	Prone to homopolymer side reactions; reaction parameters are sensitive, making scale-up consistency poor; leftover reagents pose a cytotoxicity risk; grafting rate involves a performance trade-off; covalent network degradation behavior is hard to control precisely			Biomedical materials, separation engineering	[30,99]
	Radiation cross-linking	No need for extra chemical initiators; cross-linking and sterilization can happen at the same time; strong penetration ability; low residues; the degree of cross-linking can be controlled by the radiation dose	High doses of radiation can cause polymer chains to break or degrade; equipment and safety protections are required; the radiation dose and cross-linking density need to be precisely controlled			Cell delivery, drug delivery	[100]
	Photo-cross-linking	High precision in space and time control; gels quickly; easy to build microstructures	Photoinitiator residues and UV might affect cells; light penetration is limited in thick samples			Flexible electronics	[101]
	Ion interactions	Charged polymers + multivalent ions; for example, the sodium alginate/Ca ²⁺ system	Mild conditions; gels quickly; no high temperature needed			Ion exchange may gradually destabilize the structure; long-term mechanical performance is limited	Agriculture slow release, adsorption separation, cell delivery, drug delivery
Physical cross-linking	Hydrogen bond cross-linking	No need for chemical cross-linkers; highly reversible; good self-healing properties; relatively high biocompatibility; easy to build dissipative networks	Hydrogen bonds are easily affected by water competition, temperature, and pH; long-term stability and wet mechanical performance might not be enough	Low chemical input; reversible; potentially reprocessable	Poor long-term stability; shortened service lifetime	Flexible sensors, drug delivery, separation engineering	[104,105]
	Hydrophobic association	High toughness; large deformation capability; reversible energy dissipation; fatigue resistance; some systems have self-healing properties	Hydrophobic monomers have poor water solubility; preparation and composition control are relatively complicated; excessive association may reduce swelling and mass transfer performance			High-strength tough hydrogel, smart devices	[106,107]

5. Conclusions and Perspectives

Hydrogels are emerging functional materials with versatile properties and flexible structures, and they have been widely studied and applied in fields such as separation engineering, sustainable agriculture, smart devices, and biomedical materials. The preparation methods of hydrogels can be classified into two categories: chemical cross-linking and physical cross-linking. Hydrogels prepared by different methods exhibit varying functions and properties, which in turn determine their application fields. Understanding the correlation between the preparation methods of hydrogels and their functions and properties is of great significance for improving the preparation level and application efficiency of hydrogel materials.

Hydrogel research has progressed from conventional water-swollen polymer networks toward highly functional materials for separation, agriculture, smart devices, and biomedical engineering. However, future advances should no longer be evaluated solely by improvements in adsorption capacity, mechanical strength, sensitivity, responsiveness, or therapeutic efficacy. A central challenge is to achieve these functions while simultaneously reducing material consumption, chemical hazards, energy demand, and end-of-life environmental burden.

A major unresolved issue is the trade-off between functional performance and sustainability. Increasing the cross-linking density may improve durability but reduce mass transport and degradability; incorporating nanofillers can enhance conductivity or mechanical strength but complicate recycling; biodegradable networks may reduce long-term persistence but exhibit insufficient service stability; and highly multifunctional architectures often require additional synthesis steps, reagents, and energy. Therefore, sustainable hydrogel design requires optimization across the entire material life cycle rather than maximization of a single performance metric.

Future studies should establish quantitative sustainability metrics alongside conventional performance indicators. Depending on the application, these may include renewable feedstock fraction, solvent and water consumption, synthesis energy demand, material utilization efficiency, functional lifetime, regeneration efficiency, number of reuse cycles, degradation rate, ecotoxicity of degradation products, recyclability, and manufacturing cost. Life-cycle assessment and techno-economic analysis should increasingly be incorporated to identify the environmental burden shifting between synthesis, use, and disposal stages. Programmable, self-healing, and adaptive hydrogels remain important future directions, but their value should increasingly be assessed in terms of whether they contribute to sustainability. For example, self-healing can extend the service lifetime, stimuli-responsive transport can reduce chemical and energy inputs, and data-driven or inverse design may reduce trial-and-error synthesis and material consumption. Thus, “smart” functionality and sustainability should not develop as independent objectives; instead, adaptive functions should be designed to reduce resource consumption and extend the material lifetime.

Overall, the next generation of hydrogel-based functional materials should move from a performance-centered paradigm toward a sustainability-by-design paradigm. The key question is no longer simply how to make hydrogels stronger, smarter, or more multifunctional, but how to deliver the required function with fewer materials, safer chemistry, lower energy input, a longer service life, and environmentally responsible end-of-life pathways. Establishing this balance among performance, sustainability, scalability, and cost will be essential for translating hydrogel technologies from laboratory demonstrations to practical applications.

Author Contributions: Conceptualization, C.X. and E.L.; methodology, C.X. and J.C.; formal analysis, C.X.; investigation, C.X., J.C. and X.W.; data curation, C.X. and X.W.; writing—original draft

preparation, C.X. and X.W.; writing—review and editing, E.L., Z.P. and S.L.; supervision, E.L. and Z.P.; project administration, E.L.; funding acquisition, E.L. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the National Natural Science Foundation of China, grant number 92575108, and the Natural Science Foundation of Shanxi Province of China, grant number 202303021221145.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: No new data were created or analyzed in this study. Data sharing is not applicable to this article.

Conflicts of Interest: The authors declare no conflicts of interest.

References

1. van Bemmelen, J.M. Der Hydrogel und das kristallinische hydratdes kupferoxydes. *Z. Anorg. Chem.* **1907**, *1*, 213–214. [CrossRef]
2. Wichterle, O.; Lím, D. Hydrophilic gels for biological use. *Nature* **1960**, *185*, 117–118. [CrossRef]
3. Akhtar, M.F.; Hanif, M.; Raniha, N.M. Methods of synthesis of hydrogels. . . A review. *Saudi Pharm. J.* **2015**, *24*, 554–559. [CrossRef]
4. Kuhn, W.; Hargitay, B.; Katchalsky, A.; Eisenberg, H. Reversible dilation and contraction by changing the state of ionization of high-polymer acid networks. *Nature* **1950**, *165*, 514–516. [CrossRef]
5. Kopeček, J. Hydrogels: From soft contact lenses and implants to self-assembled nanomaterials. *J. Polym. Sci. Part A Polym. Chem.* **2009**, *47*, 5929–5946. [CrossRef]
6. Hu, X.; Gao, C. Photoinitiating polymerization to prepare biocompatible chitosan hydrogels. *J. Appl. Polym. Sci.* **2008**, *110*, 1059–1067. [CrossRef]
7. de Siqueira, E.C.; de Franca, J.A.A.; de Souza, R.F.M.; da Silva Leoterio, D.M.; Cordeiro, J.N.; Doboszewski, D. Mechanisms of the chemical crosslinking to obtain the hydrogels: Synthesis, conditions of crosslinking and biopharmaceutical applications. *Res. Soc. Dev.* **2023**, *12*, e18312943072. [CrossRef]
8. Zhu, T.; Jiang, C.; Wang, M.; Zhu, C.; Zhao, N.; Xu, J. Skin-inspired double-hydrophobic-coating encapsulated hydrogels with enhanced water retention capacity. *Adv. Funct. Mater.* **2021**, *31*, 2102433. [CrossRef]
9. Huang, Y.; Zhu, T.; Yuan, H.; Tan, L.; Zhu, Z.; Yao, P.; Zhu, C.; Xu, J. An in situ encapsulation strategy for enhancing the stability of hydrogels in both air and water through surface-confined copolymerization. *Chem. Eng. J.* **2024**, *485*, 149847. [CrossRef]
10. Qu, X.; Wang, S.; Zhao, Y.; Huang, H.; Wang, Q.; Shao, J.; Wang, W.; Dong, X. Skin-inspired highly stretchable, tough and adhesive hydrogels for tissue-attached sensor. *Chem. Eng. J.* **2021**, *425*, 131523. [CrossRef]
11. He, M.; Han, B.; Jiang, Z.; Yang, Y.; Peng, Y.; Liu, W. Synthesis of a chitosan-based photo-sensitive hydrogel and its biocompatibility and biodegradability. *Carbohydr. Polym.* **2017**, *166*, 228–235. [CrossRef]
12. Wang, G.; Wang, S.; Hu, T.; Shi, F. Multifunctional hydrogel with 3D printability, fluorescence, biodegradability, and biocompatibility for biomedical microrobots. *Molecules* **2024**, *29*, 3351. [CrossRef]
13. Li, Y.; Qu, X.; Wang, Q.; Li, S.; Zhang, Q.; Zhang, X. Tannic acid and carboxymethyl chitosan-based multi-functional double-layered hydrogel with pH-stimulated response behavior for smart real-time infection monitoring and wound treatment. *Int. J. Biol. Macromol.* **2024**, *261*, 129042. [CrossRef]
14. Zhang, X.; Cheng, L.; Feng, L.; Peng, Y.; Zhou, Z.; Yin, G.; Li, W.; Zhang, A. Thermoresponsive dendronized chitosan-based hydrogels as injectable stem cell carriers. *Polym. Chem.* **2019**, *10*, 2305–2315. [CrossRef]
15. Di, R.; Song, Z.; Li, M.; Lian, M.; Wang, Y.; Guo, J.; Miao, H.; Yuan, T.; Liu, J.; Zhou, J. Temperature-switch-based light-responsive smart hydrogel for reversible message encryption and decryption. *Sci. China Mater.* **2024**, *67*, 2123–2134. [CrossRef]
16. Jung, S.A.; Malyaran, H.; Demco, D.E.; Manukanc, A.; Häser, L.S.; Kučikas, V.; van Zandvoort, M.; Neuss, S.; Pich, A. Fibrin-dextran hydrogels with tunable porosity and mechanical properties. *Biomacromolecules* **2023**, *24*, 3972–3984, Correction in *Biomacromolecules* **2024**, *25*, 2656–2657. <https://doi.org/10.1021/acs.biomac.4c00276>. [CrossRef]
17. Li, T.; Zhang, X.; Xia, B.; Ma, P.; Chen, M.; Du, M.; Wang, Y.; Dong, W. Hybrid double-network hydrogels with excellent mechanical properties. *New J. Chem.* **2020**, *44*, 16569–16576. [CrossRef]
18. Jha, M.K.; Das, P.P.; Gupta, S.; Chaudhary, V.; Gupta, P. Complementing the circular economy with a life cycle assessment of sustainable hydrogels and their future prospects. *Sus. Gel.* **2023**, *489*–503. [CrossRef]
19. Haraguchi, K.; Takehisa, T.; Fan, S. Effects of clay content on the properties of nanocomposite hydrogels composed of poly (N-isopropylacrylamide) and clay. *Macromolecules* **2002**, *35*, 10162–10171. [CrossRef]

20. Zhang, J.; Liu, R.; Li, A.; Wang, A. Preparation, swelling behaviors, and slow-release properties of a poly (acrylic acid-co-acrylamide)/sodium humate superabsorbent composite. *Ind. Eng. Chem. Res.* **2006**, *45*, 48–53. [\[CrossRef\]](#)
21. Li, S.; Zhang, H.; Feng, J.; Xu, R.; Liu, X. Facile preparation of poly (acrylic acid-acrylamide) hydrogels by frontal polymerization and their use in removal of cationic dyes from aqueous solution. *Desalination* **2011**, *280*, 95–102. [\[CrossRef\]](#)
22. He, G.; Ke, W.; Chen, X.; Kong, Y.; Zheng, H.; Yin, Y.; Cai, W. Preparation and properties of quaternary ammonium chitosan-g-poly (acrylic acid-co-acrylamide) superabsorbent hydrogels. *React. Funct. Polym.* **2017**, *111*, 14–21. [\[CrossRef\]](#)
23. Guo, P.; Li, H.; Ren, W.; Zhu, J.; Xiao, F.; Xu, S.; Wang, J. Unusual thermo-responsive behaviors of poly (NIPAM-co-AM)/PEG/PTA composite hydrogels. *Mater. Lett.* **2015**, *143*, 24–26. [\[CrossRef\]](#)
24. Wang, F.; Cai, M.; Yan, L.; Liao, J. Facile fabrication of multifunctional transparent flame-retarded hydrogel for fire-resistant glass with excellent transparency, fire resistance and anti-ageing property. *Polymers* **2022**, *14*, 2716. [\[CrossRef\]](#)
25. Chafran, L.; Carfagno, A.; Altalhi, A.; Bishop, B. Green hydrogel synthesis: Emphasis on proteomics and polymer particle-protein interaction. *Polymers* **2022**, *14*, 4755. [\[CrossRef\]](#)
26. Akhmetkarimova, Z.; Mukhlis, S.; Yildirim, E.; Zhumanazarova, G.; Ogay, V.; Altaeva, N.; Ashikbayeva, M.; Kudaibergen, G. Emerging trends in photo-crosslinkable polymeric biomaterials in regenerative medicine. *Mater. Today Chem.* **2025**, *50*, 103172. [\[CrossRef\]](#)
27. Trucco, D.; Vannozzi, L.; Gabusi, E.; Lenzi, E.; Manferdini, C.; Bacci, A.; Agresti, L.; Pascale, M.R.; Cristino, S.; Lisignoli, G.; et al. Visible light-mediated cross-linking of injectable gellan gum hydrogels embedding human chondrocytes. *Carbohydr. Polym. Technol. Appl.* **2023**, *6*, 100382. [\[CrossRef\]](#)
28. Soliman, B.G.; Longoni, A.; Major, G.S.; Lindberg, G.C.J.; Choi, Y.S.; Zhang, Y.S.; Woodfield, T.B.F.; Lim, K.S. Harnessing macromolecular chemistry to design hydrogel micro- and macro-environments. *Macromol. Biosci.* **2024**, *24*, 2300457. [\[CrossRef\]](#)
29. Fanta, G.F.; Burr, R.C.; Doane, W.M. Ceric-initiated polymerization onto polyacrylonitrile with carbohydrate end groups. Graft versus block copolymer formation. *J. Polym. Sci. Polym. Chem. Ed.* **1983**, *21*, 2095–2100. [\[CrossRef\]](#)
30. Athawale, V.D.; Vidyagauri, V.L. Graft copolymerization onto starch. 3: Grafting of acrylamide using ceric ion initiation and preparation of its hydrogels. *Starch-Stärke* **1998**, *50*, 426–431.
31. Cao, Y.; Qing, X.; Sun, J.; Zhou, F.; Lin, S. Graft copolymerization of acrylamide onto carboxymethyl starch. *Eur. Polym. J.* **2002**, *38*, 1921–1924. [\[CrossRef\]](#)
32. Li, B.; Wang, Y.; Wang, Z.; He, Y.; Song, P.; Wang, R. Preparation and properties of hydrogels based on lignosulfonate and its efficiency of drug delivery. *ChemistrySelect* **2021**, *6*, 8213–8218. [\[CrossRef\]](#)
33. Pandey, S.; Kumar, A.; Kumar, K.; Krishnamoorthi, S.; Tungala, K. Fabrication, characterization and flocculation properties of starch, chitosan or cellulose based graft copolymers: A review. *Bioresour. Technol. Rep.* **2025**, *29*, 102023. [\[CrossRef\]](#)
34. El-Rehim, H.A.A.; Hegazy, E.A.; Diaa, D.A. Characterization of super-absorbent material based on carboxymethylcellulose sodium salt prepared by electron beam irradiation. *J. Macromol. Sci. Part A* **2006**, *43*, 101–113. [\[CrossRef\]](#)
35. El-Din, H.M.N.; Alla, S.G.A.; El-Naggar, A.W.M. Swelling and drug release properties of acrylamide/carboxymethyl cellulose networks formed by gamma irradiation. *Radiat. Phys. Chem.* **2010**, *79*, 725–730. [\[CrossRef\]](#)
36. Ballarano, A.; Trotta, F.; Caldera, F.; Hoti, G.; López-Nicolás, J.M.; Matencio, A. Eco-hydrogels: The new frontier of sustainability: A review. *Sustain. Chem. Pharm.* **2025**, *48*, 102223. [\[CrossRef\]](#)
37. Li, Y.; Sun, J. Reversibly cross-linked polymers: A new method for high-performance and sustainable polymer materials. *Acc. Chem. Res.* **2026**, *59*, 298–310. [\[CrossRef\]](#)
38. Xu, B.; Zhang, X.; Gan, S.; Zhao, J.; Rong, J. Dual ionically cross-linked hydrogels with ultra-tough, stable, and self-healing properties. *J. Mater. Sci.* **2019**, *54*, 14218–14232. [\[CrossRef\]](#)
39. Cheng, H.; Wu, H.; Guo, T.; Park, H.J.; Li, J. Zinc insulin hexamer loaded alginate zinc hydrogel: Preparation, characterization and in vivo hypoglycemic ability. *Eur. J. Pharm. Biopharm.* **2022**, *179*, 173–181. [\[CrossRef\]](#)
40. Wei, L.; Wang, X.; Fu, J.; Yin, J.; Hu, J. A physically cross-linked double network polysaccharides/Ca²⁺ hydrogel scaffold for skeletal muscle tissue engineering. *Colloids Surf. A Physicochem. Eng. Asp.* **2023**, *668*, 131410. [\[CrossRef\]](#)
41. Li, B.; Zhou, M.; Cheng, M.; Liu, J.; Xu, X.; Xie, X. Rapid preparation of ZnO nanocomposite hydrogels by frontal polymerization of a ternary DES and performance study. *RSC Adv.* **2022**, *12*, 12871–12877. [\[CrossRef\]](#)
42. Chen, K.; Qin, F.; Fang, Z.; Li, G.; Zhou, J.; Qiu, X. Mechanically stable core-shell cellulose nanofibril/sodium alginate hydrogel beads with superior Cu (II) removal capacity. *Int. J. Biol. Macromol.* **2022**, *222*, 1353–1363. [\[CrossRef\]](#)
43. Zhao, Z.; Bai, Y.; Sun, J.; Lv, K.; Lei, S.; Qiu, J. Tough and self-healing hydrophobic association hydrogels with cationic surfactant. *J. Appl. Polym. Sci.* **2021**, *138*, 50645. [\[CrossRef\]](#)
44. Wan, L.; Li, P.; Yan, M.; Wang, J.; Li, X. Strong, self-healing, shape memory PAA-PANI/PVA/PDA/AOP conductive hydrogels with interpenetrating network and hydrogen bond interaction. *Eur. Polym. J.* **2023**, *191*, 112034. [\[CrossRef\]](#)
45. Yi, X.; Sun, F.; Han, Z.; Han, F.; He, J.; Ou, M.; Gu, J.; Xu, X. Graphene oxide encapsulated polyvinyl alcohol/sodium alginate hydrogel microspheres for Cu (II) and U (VI) removal. *Ecotoxicol. Environ. Saf.* **2018**, *158*, 309–318. [\[CrossRef\]](#)

46. Yi, X.; He, J.; Guo, Y.; Han, Z.; Yang, M.; Jin, J.; Gu, J.; Ou, M.; Xu, X. Encapsulating Fe₃O₄ into calcium alginate coated chitosan hydrochloride hydrogel beads for removal of Cu (II) and U (VI) from aqueous solutions. *Ecotoxicol. Environ. Saf.* **2018**, *147*, 699–707. [\[CrossRef\]](#)
47. Yuan, B.; Huang, X.; Yang, S.; Yang, Y.; Lin, Z.; Semiat, R.; Chen, J.P. Development of a magnetic calcium-alginate hydrogel-sphere encapsulated with Fe-Mn-Zr ternary metal composite for heavy metal adsorption. *Sep. Purif. Technol.* **2023**, *306*, 122531. [\[CrossRef\]](#)
48. Liu, Y.; Xin, Z.; Tian, L.; Villa-Gomez, D.; Wang, W.; Cao, Y. Fabrication of peptide-encapsulated sodium alginate hydrogel for selective gallium adsorption. *Int. J. Biol. Macromol.* **2024**, *263*, 130436. [\[CrossRef\]](#)
49. Deng, S.; Long, J.; Dai, X.; Wang, G.; Zhou, L. Simultaneous detection and adsorptive removal of Cr (VI) ions by fluorescent sulfur quantum dots embedded in chitosan hydrogels. *ACS Appl. Nano Mater.* **2023**, *6*, 1817–1827. [\[CrossRef\]](#)
50. Chu, W.; Yuan, Z.; Lin, P.; Jin, G. Recovery of rubidium using hydrogel beads encapsulating potassium copper hexacyanoferrate from saline lake brines. *Ind. Eng. Chem. Res.* **2024**, *63*, 1988–1999. [\[CrossRef\]](#)
51. Yuan, S.; Liu, Q.; Liang, Y.; Ning, K.; Yu, X.; He, Y. Dual 3-D networked Pickering emulsion hydrogels encapsulating copper extractants for the recovery of Cu²⁺ from water. *J. Environ. Chem. Eng.* **2021**, *9*, 105154. [\[CrossRef\]](#)
52. Yuan, S.; Liu, Q.; Zhu, L.; Ning, J.; Yang, H.; Ning, K.; He, Y. Emulsion hydrogel microbeads encapsulating extractants prepared by O/W/O double Pickering emulsions for the recovery of Cu (II) from water. *Colloids Surf. A Physicochem. Eng. Asp.* **2021**, *625*, 126932. [\[CrossRef\]](#)
53. Gao, J.; Dong, C.; Zhao, Y.; Ma, T.; He, Y. Preparation of two-component Pickering emulsion hydrogels for the removal of zinc ions from aqueous solutions. *Water Sci. Technol.* **2022**, *87*, 454–468. [\[CrossRef\]](#)
54. Gao, J.; Dong, C.; Zhao, Y.; Liang, Y.; Ning, K.; Yang, L.; He, Y. Removal of zinc ions from aqueous solution using zinc extractant-encapsulated hydrogels formed by Pickering emulsion technique. *Environ. Dev. Sustain.* **2023**, *26*, 8359–8375. [\[CrossRef\]](#)
55. Dong, C.; Gao, J.; Zhao, Y.; Zhao, W.; Ning, K.; Wu, P.; He, Y. Preparation of Pickering emulsion hydrogels containing indium (III) extractants and their indium (III) recycling properties. *Clean Technol. Environ. Policy* **2023**, *25*, 2987–2997. [\[CrossRef\]](#)
56. Matsubayashi, T.; Tenjimbayashi, M.; Komine, M.; Manabe, K.; Shiratori, S. Bioinspired hydrogel-coated mesh with superhydrophilicity and underwater superoleophobicity for efficient and ultrafast oil/water separation in harsh environments. *Ind. Eng. Chem. Res.* **2017**, *56*, 7080–7085. [\[CrossRef\]](#)
57. Liu, Y.; Su, M.; Fu, Y.; Zhao, P.; Xia, M.; Zhang, Y.; He, B.; He, P. Corrosive environments tolerant, ductile and self-healing hydrogel for highly efficient oil/water separation. *Chem. Eng. J.* **2018**, *354*, 1185–1196. [\[CrossRef\]](#)
58. Liu, Y.; Xia, M.; Wu, L.; Pan, S.; Zhang, Y.; He, B.; He, P. Physically cross-linked double-network hydrogel for high-performance oil-water separation mesh. *Ind. Eng. Chem. Res.* **2019**, *58*, 21649–21658. [\[CrossRef\]](#)
59. Wu, J.; Lv, Z.; Lei, Y.; Huang, Y.; Liu, X. Chitosan interpenetrating polymer network hydrogels for oil-water and emulsion separation. *J. Appl. Polym. Sci.* **2023**, *140*, 54058. [\[CrossRef\]](#)
60. Chen, T.; Li, X.; Wang, Q.; Li, Y.; Xu, L.; Yang, Y.; Qiao, Y.; Dai, Y.; Ke, J.; Wan, H.; et al. A multifunctional Ag NPs/guar gum hydrogel as versatile platform for catalysts, antibacterial agents, and construction of oil-water separation interfaces. *Int. J. Biol. Macromol.* **2024**, *270*, 132035. [\[CrossRef\]](#)
61. Meftah, S.; Meftah, K.; Addich, M.; Chahid, A. Comparative analysis of 13 types of adsorbent materials for water pollutant removal via a multi-criteria evaluation of performance cost circular economy green chemistry and durability. *Discov. Environ.* **2026**, *4*, 257. [\[CrossRef\]](#)
62. Ali, K.; Asad, Z.; Agbna, G.H.; Saud, A.; Khan, A.; Zaidi, S.J. Progress and innovations in hydrogels for sustainable agriculture. *Agronomy* **2024**, *14*, 2815. [\[CrossRef\]](#)
63. Cui, S.; Li, P.; Ji, L.; Wang, T.; Liu, Y.; Lan, Y.; Jiang, J. Superabsorbent quaternary ammonium guar gum hydrogel with controlled release of humic acid for soil improvement and plant growth. *Carbohydr. Polym.* **2024**, *337*, 122188. [\[CrossRef\]](#)
64. Ghobashy, M.M.; El-Damhougy, B.K.; Nady, N.; El-Wahab, H.A.; Naser, A.M.; Abdelhai, F. Radiation cross-linking of modifying super absorbent (polyacrylamide/gelatin) hydrogel as fertilizers carrier and soil conditioner. *J. Polym. Environ.* **2018**, *26*, 3981–3994. [\[CrossRef\]](#)
65. Niu, C.; Lin, Z.; Fu, Q.; Xu, Y.; Chen, Y.; Lu, L. An eco-friendly versatile superabsorbent hydrogel based on sodium alginate and urea for soil improvement with a synchronous chemical loading strategy. *Carbohydr. Polym.* **2024**, *327*, 121676. [\[CrossRef\]](#)
66. Piccoli, I.; Camarotto, C.; Squartini, A.; Longo, M.; Gross, S.; Maggini, M.; Cabrera, M.L.; Morari, F. Hydrogels for agronomical application: From soil characteristics to crop growth: A review. *Agron. Sustain. Dev.* **2024**, *44*, 22. [\[CrossRef\]](#)
67. Wang, R.; Yu, Q.; He, Y.; Bai, J.; Jiao, T.; Zhang, L.; Bai, Z.; Zhou, J.; Peng, Q. Self-assembled polyelectrolyte-based composite hydrogels with enhanced stretchable and adsorption performances. *J. Mol. Liq.* **2019**, *294*, 111576. [\[CrossRef\]](#)
68. Du, H.; Wang, J.; Xu, N.; Yu, Y.; Liu, S. Transparent, self-healable, shape memory poly (vinyl alcohol)/ionic liquid difunctional hydrogels assembled spontaneously from polymer solution. *J. Mol. Liq.* **2022**, *366*, 120226. [\[CrossRef\]](#)
69. Guo, W.; Ma, M. Conductive nanocomposite hydrogels for flexible wearable sensors. *J. Mater. Chem. A* **2024**, *12*, 9371–9399. [\[CrossRef\]](#)

70. Xu, P.; Shang, Z.; Yao, M.; Ke, Z.; Li, X.; Liu, P. Molecular insights on the mechanical properties of double-network hydrogels reinforced by covalently compositing with silica-nanoparticles. *J. Mol. Liq.* **2022**, *368*, 120611. [CrossRef]
71. Song, Z.; Li, R.; Li, Z.; Luo, X. Antifouling and antimicrobial wearable electrochemical sweat sensors for accurate dopamine monitoring based on amyloid albumin composite hydrogels. *Biosens. Bioelectron.* **2024**, *264*, 116640. [CrossRef]
72. Al-Qahtani, S.D.; Al-Senani, G.M. Preparation of cellulose nanocrystal-reinforced alginate hydrogel to optimize fluorescence and persistent emission of self-healable adhesive to combat counterfeiting. *J. Mol. Liq.* **2024**, *401*, 124590. [CrossRef]
73. Khan, M.; Shah, L.A.; Rahman, T.U.; Yoo, H.M.; Ye, D.; Vacharasin, J. Cellulose nanocrystals boosted hydrophobic association in dual network polymer hydrogels as advanced flexible strain sensor for human motion detection. *J. Mech. Behav. Biomed. Mater.* **2023**, *138*, 105610. [CrossRef]
74. Wei, D.; Lv, S.; Zuo, J.; Liu, J.; Wang, J.; Liu, L.; Zeng, Q. Engineering versatile bi-network ionic conductive hydrogels wearable sensors via on demand graft modification for real-time human movement monitoring. *Chem. Eng. J.* **2024**, *496*, 154176. [CrossRef]
75. Shen, J.; Lu, L.; He, R.; Ye, Q.; Yuan, C.; Guo, L.; Zhao, M.; Cui, B. Starch/ionic liquid/hydrophobic association hydrogel with high stretchability, fatigue resistance, self-recovery and conductivity for sensitive wireless wearable sensors. *Carbohydr. Polym.* **2024**, *346*, 122608. [CrossRef]
76. Dai, R.; Gao, Y.; Sun, Y.; Shi, K.; Gao, G.; Zhang, H. Ionic conductive amylopectin hydrogels for biocompatible and anti-freezing wearable sensors. *Eur. Polym. J.* **2023**, *200*, 112496. [CrossRef]
77. Lu, L.; Huang, Z.; Li, X.; Li, X.; Cui, B.; Yuan, C.; Guo, L.; Liu, P.; Dai, Q. A high-conductive, anti-freezing, antibacterial and anti-swelling starch-based physical hydrogel for multifunctional flexible wearable sensors. *Int. J. Biol. Macromol.* **2022**, *213*, 791–803. [CrossRef]
78. Li, X.; He, R.; Liu, X.; Blennow, A.; Ye, Q.; Hong, B.; Li, X.; Lu, L.; Cui, B. “Soaking-in-water” strategy stimulated starch/poly (vinyl alcohol)-based flexible hydrogel with heterogeneous network for highly sensitive underwater wearable sensor. *Sustain. Mater. Technol.* **2024**, *41*, e01049. [CrossRef]
79. Li, W.; Li, S.; Kang, M.; Xiong, X.; Wang, P.; Tao, L. Multi-characteristic tannic acid-reinforced polyacrylamide/sodium carboxymethyl cellulose ionic hydrogel strain sensor for human-machine interaction. *Int. J. Biol. Macromol.* **2024**, *254*, 127434. [CrossRef]
80. Li, W.; Wu, S.; Kang, M.; Zhang, X.; Zhong, X.; Qiao, H.; Chen, J.; Wang, P.; Tao, L. Wearable one-handed keyboard using hydrogel-based mechanical sensors for human-machine interaction. *J. Mater. Sci. Technol.* **2024**, *201*, 130–138. [CrossRef]
81. Hu, F.; Dong, B.; Zhao, R.; Li, Z.; Zhang, Y.; Zhang, F.; Liu, W.; Yu, D. Lignosulfonate sodium and ionic liquid synergistically promote tough hydrogels for intelligent wearable human-machine interaction. *Int. J. Biol. Macromol.* **2024**, *254*, 127958. [CrossRef]
82. Dong, B.; Yu, D.; Lu, P.; Song, Z.; Chen, W.; Zhang, F.; Li, B.; Wang, H.; Liu, W. TEMPO bacterial cellulose and MXene nanosheets synergistically promote tough hydrogels for intelligent wearable human-machine interaction. *Carbohydr. Polym.* **2024**, *326*, 121621. [CrossRef]
83. Fu, Z.; Li, D.; Liu, H.; Liu, R.; Lyu, Q.; Han, Y.; Wang, Y.; Zhang, K.; Chen, G.; Tian, Y. Antifreeze protein-based ultrastretchable and highly sensitive hydrogel for human-machine interaction. *Chem. Eng. J.* **2024**, *488*, 150775. [CrossRef]
84. Jia, L.; Li, Y.; Ren, A.; Xiang, T.; Zhou, S. Degradable and recyclable hydrogels for sustainable bioelectronics. *ACS Appl. Mater. Interfaces* **2024**, *16*, 32887–32905. [CrossRef]
85. Kwokdinata, C.; Ramanujam, V.; Chen, J.; de Oliveira, P.N.; Nai, M.H.; Chooi, W.H.; Lim, C.T.; Ng, S.Y.; David, L.; Chew, S.Y. Encapsulation of human spinal cord progenitor cells in hyaluronan-gelatin hydrogel for spinal cord injury treatment. *ACS Appl. Mater. Interfaces* **2023**, *15*, 50679–50692, Correction in *ACS Appl. Mater. Interfaces* **2024**, *16*, 24144. <https://doi.org/10.1021/acsami.4c06545>. [CrossRef]
86. Pupkaite, J.; Rosenquist, J.; Hilborn, J.; Samanta, A. Injectable shape-holding collagen hydrogel for cell encapsulation and delivery cross-linked using thiol-michael addition click reaction. *Biomacromolecules* **2019**, *20*, 3475–3484. [CrossRef]
87. Yamada, Y.; Patel, N.L.; Kalen, J.D.; Schneider, J.P. Design of a peptide-based electronegative hydrogel for the direct encapsulation, 3D culturing, in vivo syringe-based delivery, and long-term tissue engraftment of cells. *ACS Appl. Mater. Interfaces* **2019**, *11*, 34688–34697. [CrossRef]
88. Ansari, S.; Chen, C.; Xu, X.; Annabi, N.; Zadeh, H.H.; Wu, B.M.; Khademhosseini, A.; Shi, S.; Moshaverinia, A. Muscle tissue engineering using gingival mesenchymal stem cells encapsulated in alginate hydrogels containing multiple growth factors. *Ann. Biomed. Eng.* **2016**, *44*, 1908–1920. [CrossRef]
89. Torres-Ortega, P.V.; Campo-Montoya, R.D.; Plano, D.; Paredes, J.; Aldazabal, J.; Luquin, M.R.; Santamaría, E.; Sanmartín, C.; Blanco-Prieto, M.J.; Garbayo, E. Encapsulation of MSCs and GDNF in an injectable nanoreinforced supramolecular hydrogel for brain tissue engineering. *Biomacromolecules* **2022**, *23*, 4629–4644. [CrossRef]
90. Yang, X.; Guo, J.; Han, J.; Si, R.; Liu, P.; Zhang, Z.; Wang, A.; Zhang, J. Chitosan hydrogel encapsulated with LL-37 peptide promotes deep tissue injury healing in a mouse model. *Mil. Med. Res.* **2020**, *7*, 20. [CrossRef]
91. Cui, T.; Li, X.; He, S.; Xu, D.; Yin, L.; Huang, X.; Deng, S.; Yue, W.; Zhong, W. Instant self-assembly peptide hydrogel encapsulation with fibrous alginate by microfluidics for infected wound healing. *ACS Biomater. Sci. Eng.* **2020**, *6*, 5001–5011. [CrossRef]

92. Xiao, Y.; Lu, C.; Liu, Y.; Kong, L.; Bai, H.; Mu, H.; Li, Z.; Geng, H.; Duan, J. Encapsulation of *Lactobacillus rhamnosus* in hyaluronic acid-based hydrogel for pathogen-targeted delivery to ameliorate enteritis. *ACS Appl. Mater. Interfaces* **2020**, *12*, 36967–36977. [[CrossRef](#)]
93. Sutradhar, S.C.; Shin, H.; Kim, W.; Jang, H. Hydrogel films in biomedical applications: Fabrication, properties and therapeutic potential. *Gels* **2025**, *11*, 918. [[CrossRef](#)]
94. Zhang, C.W.; Si, M.; Chen, C.; He, P.; Fei, Z.; Xu, N.; He, X. Hierarchical engineering for biopolymer-based hydrogels with tailored property and functionality. *Adv. Mater.* **2025**, *37*, 2414897. [[CrossRef](#)]
95. Ciolacu, D.E. Hydrogels from renewable resources: Advances in 3D networks based on cellulose and hemicellulose. *Polymers* **2025**, *17*, 2760. [[CrossRef](#)]
96. Jia, R.; Cao, Y.; Yang, C.; Li, H.; Chen, W.; Li, X.; Ji, Q.; Tian, X.; Feng, J.; Tan, L. Dual dynamic networks enable a bio-Based hydrogel electrolyte with simultaneous robustness and fast Zn^{2+} transport for highly reversible zinc metal batteries. *Small* **2026**, *22*, e14065. [[CrossRef](#)]
97. Yuan, S.; Ning, K.; He, Y. Removal of copper ions using poly (acrylic acid-co-acrylamide) hydrogel microspheres with controllable size prepared by W/O Pickering emulsions. *Colloid Polym. Sci.* **2020**, *298*, 1465–1472. [[CrossRef](#)]
98. Cao, P.; Wei, J.; Zhang, T.; Deng, H.; Han, Y.; Chen, Z.; Chen, Y.; Guo, Y.; Ma, C. Multifunctional luffa sponge hydrogel with high mechanical strength, fatigue resistance, and ionic conductivity for monitoring human vital signs. *Adv. Funct. Mater.* **2025**, *35*, 2501131. [[CrossRef](#)]
99. Fadl, E.A.; Sadik, W.A.A.; El Demerdash, A.G.; Moukhtar, H.A.; Hamza, M.E.S. Microwave-assisted synthesis and characterization of Xanthan gum-grafted polyacrylamide hydrogel for the removal of acid red 8 dye from aqueous solutions. *Sci. Rep.* **2025**, *15*, 32425. [[CrossRef](#)]
100. Pérez-Garibay, M.S.; Bucio, E. Maleic acid-grafted poly (vinylpyrrolidone) hydrogels synthesized by gamma radiation for pH-responsive drug delivery. *Gels* **2026**, *12*, 739. [[CrossRef](#)]
101. Wei, H.; Lei, M.; Zhang, P.; Leng, J.; Zheng, Z.; Yu, Y. Orthogonal photochemistry-assisted printing of 3D tough and stretchable conductive hydrogels. *Nat. Commun.* **2021**, *12*, 2082. [[CrossRef](#)]
102. Jalomo, C.A.; Schroeder, A.G.; Hernandez, E.M.; Murphy, C.J. Copper-cross-linked alginate-based hydrogel nanoparticles for sustainable slow-release fertilizer applications. *Langmuir* **2025**, *41*, 18463–18470. [[CrossRef](#)]
103. Yanovska, G.; Goncharuk, O.; Honcharuk, D.; Guzenko, N.; Skwarek, E.; Szewczuk-Karpisz, K. Development of eco-friendly hydrogels loaded with stoichiometric and calcium-deficient hydroxyapatites for sustainable agriculture. *ACS Appl. Mater. Interfaces* **2026**, *18*, 26934–26951. [[CrossRef](#)]
104. Wang, Q.; Feng, S.; Long, Y.; Liu, J.; Zhu, Q. Hydrogen bonding-driven poly(vinyl alcohol)/cellulose nanofibril hydrogels with AgNPs for sensitive motion monitoring. *ACS Appl. Polym. Mater.* **2026**, *8*, 10019–10029. [[CrossRef](#)]
105. Zou, X.; Huang, J. Hydrogen bond-regulated rapid prototyping and performance optimization of polyvinyl alcohol-tannic acid hydrogels. *Gels* **2025**, *11*, 602. [[CrossRef](#)]
106. Bi, F.; Xu, Z.; Dong, L.; Li, Z.; Xue, B.; Gui, Y. Hydrophobic association hydrogels reinforced with carboxymethyl cellulose-grafted-acrylamide for flexible strain sensor. *ACS Appl. Polym. Mater.* **2025**, *7*, 16401–16415. [[CrossRef](#)]
107. Zhang, Z.; Yao, A.; Raffa, P. Transparent, highly stretchable, self-healing, adhesive, freezing-tolerant, and swelling-resistant multifunctional hydrogels for underwater motion detection and information transmission. *Adv. Funct. Mater.* **2024**, *34*, 2407529. [[CrossRef](#)]

Disclaimer/Publisher's Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.