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Review

An Overview of Polymeric Hydrogel Applications for Sustainable Agriculture

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Abstract: Agriculture, a vital element of human survival, confronts challenges of meeting rising demand due to population growth and product availability in developing nations. Reliance on pesticides and fertilizers strains natural resources, leading to soil degradation and water scarcity. Addressing these issues necessitates enhancing water efficiency in agriculture. Polymeric hydrogels, with their unique water retention and nutrient-release capabilities, offer promising solutions. These superabsorbent materials form three-dimensional networks retaining substantial amounts of water. Their physicochemical properties suit various applications, including agriculture. Production involves methods like bulk, solution, and suspension polymerization, with cross-linking, essential for hydrogels, achieved through physical or chemical means, each with different advantages. Grafting techniques incorporate functional groups into matrices, while radiation synthesis offers purity and reduced toxicity. Hydrogels provide versatile solutions to tackle water scarcity and soil degradation in agriculture. Recent research explores hydrogel formulations for optimal agricultural performance, enhancing soil water retention and plant growth. This review aims to offer a comprehensive overview of hydrogel technologies as adaptable solutions addressing water scarcity and soil degradation challenges in agriculture, with ongoing research refining hydrogel formulations for optimal agricultural use.

Keywords: hydrogels; cross-linking; grafting techniques; soil water retention; nutrient release; agricultural technology

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Citation: Vedovello, P.; Sanches, L.V.; da Silva Teodoro, G.; Majaron, V.F.; Bortoletto-Santos, R.; Ribeiro, C.; Putti, F.F. An Overview of Polymeric Hydrogel Applications for Sustainable Agriculture. *Agriculture* **2024**, *14*, 840. https://doi.org/10.3390/agriculture14060840

Academic Editors: Claudia Di Bene, Valentina Baratella and Silvia Vanino

Received: 10 April 2024
Revised: 15 May 2024
Accepted: 21 May 2024
Published: 27 May 2024

1. Introduction

An essential aspect of human existence is agriculture [1,2]. It is under constant pressure to increase production due to population increase and the growing availability of products in developing nations [1,3]. Agricultural growth internationally was first propelled by the need to increase productivity per unit amount of land employed for crop production. Over time, this has been accomplished by heavily utilizing pesticides and fertilizers as well as by exploiting natural resources like soil and water [4]. However, food security and sustainable agricultural expansion are threatened due to soil salinization and desertification brought on by droughts and shortages of water. Thus, it is imperative to improve agricultural water use efficiency [5].

Several technologies, including low-pressure micro spreaders and drip irrigation systems, are employed to boost this efficiency. However, these technologies are highly costly, demanding specific farmers' skills. Hydrogels with high water retention capacities can offer a technological alternative to continuous irrigation, attracting attention from the research community in recent years [6,7]. The use of hydrogels in agriculture as soil conditioners originates in the 80s and 90s, highlighting their use in the controlled release of pesticides and nutrients, improving soil structure, texture, infiltration, density, and water reserves in the microenvironment. Hydrogels are promising tools for agriculture due to their unique water retention properties and controlled nutrient release capabilities. These highly hydrophilic and superabsorbent materials can be applied as a potential solution to help manage soil water during water scarcity conditions [6].

The swelling capacity defines the classification of a material as a hydrogel, and in this sense, many natural materials (e.g., collagen [8], gelatin [9], alginate [10], etc.) can have hydrogel properties [7]. However, synthetic hydrogels are more versatile, being synthesized by reactions of monomers or multifunctional polymers leading to a three-dimensional network. The polymeric backbone of hydrogels contains hydrophilic functional groups that enable them to absorb and hold water. Moreover, the hydrophilic polymer and the embedded tiny particles that are insoluble—like nanofibrils or microscopic particles—interact to generate hydrogels. Initial monomers dissolve in water, but the degree of cross-linking increases with the addition of cross-linking compounds. Eventually, the physical or chemical interactions that form between the polymer chains cause this macroscopic substance to become insoluble in water [11,12].

In the case of ionic hydrogels, the gel and solvent phases combine to generate this variation in swelling owing to osmotic pressure. Cross-links across network chains are the source of the resistance to dissolution [11]. Furthermore, hydrogels can have their physicochemical properties, such as mechanical and rheological properties, modified through changes in their content, organization, and chemical structure, as well as their biological roles in biodegradability and other characteristics [12].

The polymers used in the synthesis can be synthetic, like poly(N-isopropylacrylamide), poly(2-hydroxyethylmethacrylate), or biohybrid, or they can be of natural origins, like proteins and DNA, and they can absorb and retain vast volumes of liquid, like water c.a. 10–20% (a subjective lower limit), without disintegrating [12,13]. Hydrogel can be added to soil to help maintain adequate moisture for plant growth, reducing the need for frequent watering, especially in areas where water availability is limited [7]. It can also be impregnated with specific nutrients for controlled release into the soil as the gel breaks down. It helps prevent nutrient loss through leaching and provides plants with a steady supply over time [14,15]. This review summarizes and discusses various hydrogel applications to comprehensively evaluate agronomic benefits and provides references and guidance for agricultural research.

2. Hydrogel Classification

Classification can be made based on several factors, including the material source, the synthesis technique, and the polymer network nature. The classification choice often relies on the unique characteristics of the hydrogel that are pertinent to a given application. In accordance with the type of material, it is possible to distinguish between three different kinds of hydrogels: natural hydrogels, which come from biological sources, such as proteins, polysaccharides, or nucleic acids; synthetic hydrogels, which are made from synthetic monomers; and hybrid hydrogels, which are made of both natural and synthetic materials [16,17]. Natural polymer-based hydrogels are made of polymers derived from alginate [18], pectin [19], carrageenan [20], chitosan [21], polylysine [22], collagen [18], carboxymethyl chitin [23], carboxymethylcellulose [24], dextran [25], agarose [26], and pullulan [27], among other matrices [28–30]. Synthetic polymer-based hydrogels include polyvinyl alcohol [31], polyethylene glycol [32], and polyacrylic acid [33], among others.

Synthetic polymers are often more widely used, as they can provide the desired mechanical and degradation properties. They can be divided into anionic, cationic, amphipathic, and neutral groups according to the charge on the hydrogel's surface. For example, a hydrogel is classified as anionic when it is made with a polymer that has anionic properties, such as hyaluronic acid [34] or alginic acid [35]. In contrast, cationic hydrogels are made with polymers that capture positive charges [36], such as chitosan [37] and polylysine [38]. In addition, neutral polymers, such as pullulan, agarose, and dextran, can be combined with polysaccharides to develop hydrogels based on synthetic polymers [12,39].

Hydrogels can be categorized according to preparation techniques, such as mass polymerization, solution polymerization, and suspension polymerization. They fall into one of four categories: interpenetrating networks (IPNs), copolymers, homopolymers, and semi-interpenetrating networks (semi-IPNs) [39]. Homopolymers, such as poly(2-hydroxyethyl methacrylate) [40] and polyethylene glycol [41], have only single kind of monomer in their structure and can have a cross-linked structure depending on the monomer's nature and the polymerization process. On the other hand, in co-polymeric hydrogels, two distinct kinds of monomers are combined, such as carboxymethyl cellulose [42] and methyl acrylate [43], at least one of which is hydrophilic. In this context, a semi-IPN is created when a polymer with a linear structure permeates a cross-linked network without forming any chemical bonds between the monomers. Because semi-IPNs lack a constricting interpenetrating elastic network, they are better able to maintain fast kinetic reaction rates to pH or temperature [39]. Examples of semi-IPN hydrogel monomers include acrylamide/acrylic acid copolymer and linear cationic polyallylammonium chloride [44]. If one polymer is already in solution and the other is synthesized or cross-linked in situ, then the two polymer combinations can result in the NPIs creation, such as poly(*N*-isopropylacrylamide) and chitosan [45].

One way to categorize hydrogels is by type of polymeric network: this classification considers whether hydrogels have a physical or chemical polymeric network. Physical hydrogels are formed by physical bonds, such as van der Waals bonds or electrostatic interactions [6,46]. However, chemical network hydrogels offer durability and resistance because covalent bonds preserve the structure. Certain hydrogels are based on molecular structure; these include three-dimensional network hydrogels, which possess a cross-linked three-dimensional structure, and linear chain hydrogels, which are made of polymer chains [46]. Figure 1 provides a summary of the hydrogel classification details.

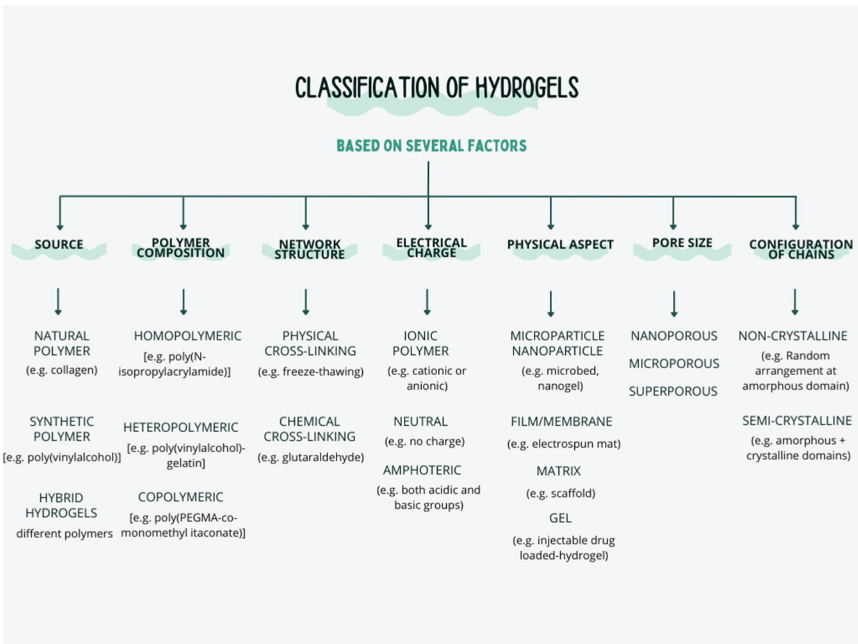

Figure 1. Classification of hydrogels. Adapted from Tariq et al. [6] and Vasile et al. [47], (created with canva.com).

Hydrogels can be based on biomedical hydrogels, which are utilized in medical applications, including controlled medication release, tissue engineering, and wound dressings [47–49]. Sensors, packaging, and other industrial applications are among the uses of hydrogels [50,51]. Finally, the focus of this review is agricultural hydrogels that are used to retain water in the soil in addition to controlling the release of nutrients [52].

3. Hydrogel Preparation

The hydrogel synthesis can be carried out using different techniques and materials, based on the hydrogel's intended characteristics, Figure 2 presents a summary of the preparation methods for hydrogels. The hydrogel synthesis basis is the polymerization technique [53]. Several approaches are used in this polymerization process, including bulk, solution, suspension, and emulsion polymerization [46]. Additionally, there are non-conventional techniques for radical polymerization, like reversible addition-fragmentation chain transfer polymerization (RAFT) [54] and atom transfer radical polymerization (ATRP) [55].

Cross-linking in polymer chain hydrogels can happen either after the polymer chains are synthesized or concurrently with their growth [46]. Additionally, this may have an impact on the polymer's resistance, toughness, elasticity, viscosity, solubility, glass transition temperature (T_g), and melting point [56]. Because links prevent rotational movement between polymer chains, cross-linked polymers have a greater T_g, and the molecular mobility nature is often assessed using the T_g [46,56–58]. Moreover, cross-linking makes the polymer chains heavier molecularly and less mobile, reducing the polymer's solubility. The cross-link density, or the cross-link quantity per unit volume, determines how much solvent a network polymer can absorb [56]. Cross-linking is often produced by graft polymerization, radiation, and physical or chemical cross-linking methods [12].

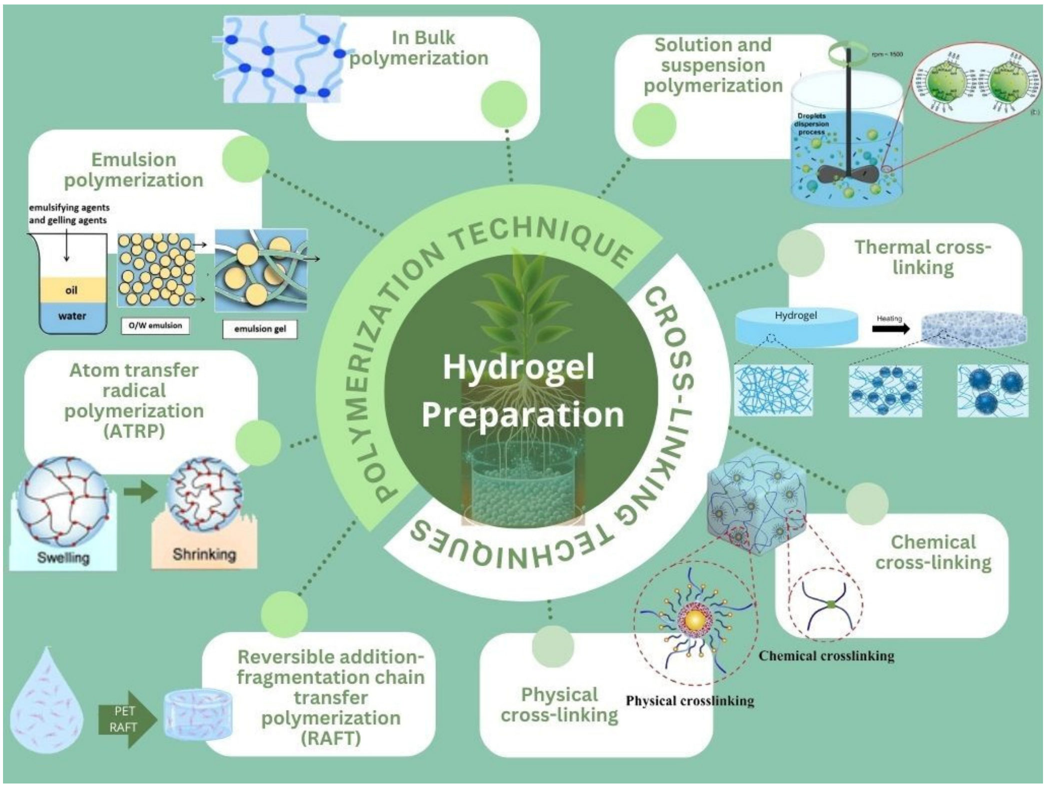

Figure 2. Scheme of the preparation methods for hydrogels. Figures used were adapted from refs. [58–64], (created with canva.com).

3.1. Techniques for Cross-Linking

3.1.1. Cross-Linking via Chemistry or Physics Methods

The convenience of using a physical cross-linking strategy lies in the fact that no cross-linker is needed. Consequently, the toxicity level is reduced. Polymers can be cross-linked by altering external factors like pH and temperature, as well as using physical agents, such as nanoparticles that act as anchoring points for the polymers through physical interactions, including hydrogen bonding and Van der Waals interactions [12,65,66]. However, this method results in hydrogels with limited mechanical resistance because of their weak connections [12,65].

One way to obtain hydrogels is by physical cross-linking via hydrogen bonds. In the context of hydrogels, hydrogen bonds can occur between the polymer chains themselves or between the chains of polymers and water molecules [65]. When hydrogel precursors containing functional groups capable of hydrogen bonding are mixed with water or an aqueous solution, hydrogen bonds can form between the polymer chains and water molecules. These hydrogen bonds help hold the polymer chains together, creating a cross-linked network structure that provides hydrogel with its distinctive characteristics, including its high-water content and swelling capacity [12,65,67].

It is possible to cross-link some hydrogels thermally, i.e., the hydrogel precursors are heated and cooled in cycles to temperatures below and above the polymer's melting point [12,67]. T. Inoue filed a patent application for "Gelled vinyl alcohol polymers and articles therefrom" in 1973 [68]. The patent suggests creating physically cross-linked PVA hydrogels. A series of freeze/thaw cycles can be used to create PVA hydrogels with induced crystallites by H-bonds as cross-linking points, as Peppas related in 1975 [69]. Because of their sensitivity to stimuli and non-toxicity, physically cross-linked hydrogels are widely employed in the pharmaceutical [70], medical [71], and drug delivery [72] industries [67]. Nevertheless, because of their reversible nature and low mechanical strength, physically cross-linked hydrogels are not designed for use in agricultural settings. However, the covalent bonds of the chemical hydrogel give it the ability to form a permanent, strong, thermally stable, and controlled gel that is perfect for use in agricultural settings [73–75]. As a result, scientists have been improving cross-linking techniques to create the necessary hydrogels [75,76].

Chemical cross-linking creates cross-linked chains by use of a covalent bond-based direct reaction between homopolymers or branched polymers [74]. Citric acid, glutaraldehyde, and epichlorohydrin are examples of frequently used cross-linking agents. These molecules result in cross-linked structures [12]. For instance, carboxymethylcellulose-poly (ethylene glycol) hydrogel is created employing citric acid as a cross-linker [49,77]. Using carboxymethyl cellulose and citric acid as cross-linking agents, the study of St. Mesias et al. (2020) was based on synthesizing cellulose-based particles. The authors created an encapsulating method based on carboxymethyl cellulose to release nitrogen, phosphorus, and potassium (NPK) fertilizer under controlled conditions. The cross-linking of this system, which used citric acid as a cross-linking agent and alginate as a stabilizer, was successful, and the encapsulated NPK formulation displayed controlled release behavior at different pH levels [78].

Comparable to this, a gelatin/alginate hydrogel is made by cross-linking glutaraldehyde [79,80]. Glutaraldehyde (GA) was employed as a cross-linking agent and sodium alginate (Na-Alg) as a controlled-release polymer by Kulkarni et al. (2000). Encapsulation experiments utilizing 'neem (*Azadirachta indica A. Juss.*) seed oil', a natural liquid pesticide, produced positive results [81].

3.1.2. Chemical Grafting with In Situ Polymerization

With the chemical method, an initiator is used to stimulate grafting using the free radical technique. The initiator then reacts with the macromolecular structures to generate the grafted polymer. Another method for grafting is atom-transfer radical polymerization [82]. Through in situ free radical copolymerization in an aqueous media between acrylamide, acrylic acid, and sodium alginate, El Idrissi et al. (2022) synthesized a novel hydrogel nanocomposite for the slow release of fertilizer (nitrogen). The authors did this by using cellulose nanocrystals functionalized with citric acid as nanofiller and N, N′-methylene bis-acrylamide as a crosslinking agent. Nitrogen was supplied using urea. According to El Idrissi et al. (2022), the hydrogel benefited from adding functionalized cellulose nanocrystals, which improved water absorption. Under ideal circumstances, the composite material exhibited a high swelling degree and a total nitrogen content of around 14%, making it an appropriate choice for water-saving agricultural applications [83].

Another method is the use of radiation; in particular, X-rays, gamma rays, and electron beams are used most frequently. Radiation synthesis of hydrogels has the advantage of producing less toxicity and highly pure products when compared to conventional techniques since it is devoid of the application of chemical initiators. In addition, this method allows you to reduce costs and production time by combining synthesis and sterilization in a single technological step [12]. For example, Chen et al. (2023) presented a new approach to produce slow-release fertilizers by preloading urea into the starch suspension, followed by in situ radiation synthesis of starch-based monolithic hydrogels embedded in urea via polyacrylamide grafting, which was initiated by gamma irradiation. Figure 3 illustrates this process. According to Chen, starch-based monolithic hydrogels embedded in urea and synthesized by radiation have demonstrated possibilities for producing new slow-release fertilizers using an environmentally friendly, straightforward, and effective process [84].

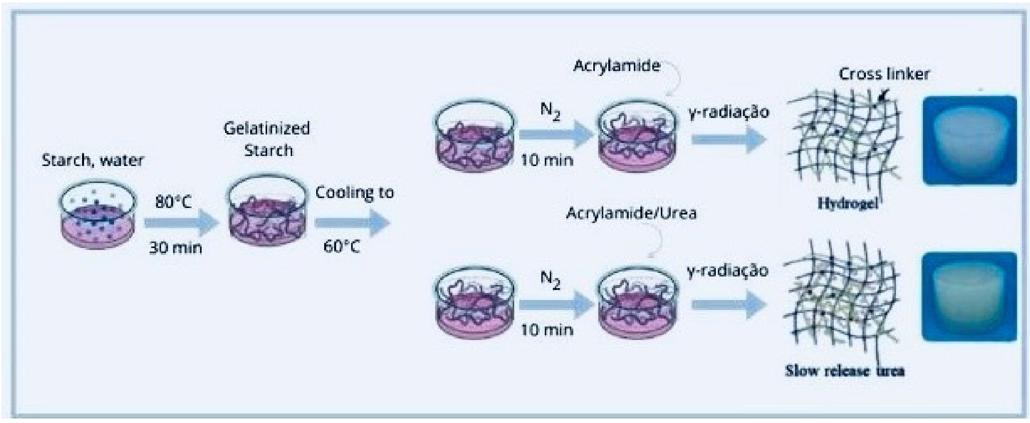

Figure 3. Illustration of the process and principle of polyacrylamide-grafted starch using γ-rays. Adapted from Chen et al. (2023) [84].

In summary, the literature provides a thorough overview of the physical and chemical cross-linking involved in the hydrogel synthesis process, highlighting advancements across several sectors such as the pharmaceutical industry, medicine, and agriculture. On the plus side, physical cross-linking eliminates the need for extra chemicals and reduces toxicity; however, hydrogels may become less mechanically stable as a result. By creating strong covalent links between the polymers, chemical cross-linking creates a resilient network. Techniques that combine the tasks of synthesis and sterilizing, such as radiation synthesis and in situ free radical polymerization, provide minimal toxicity to the final product.

4. Applying Hydrogels in Agriculture

4.1. Hydrogels' Advantages in Agriculture

The main advantages of using hydrogels, which vary depending on soil conditions, encompass many benefits that enhance agricultural productivity and sustainability. These advantages include an increase in soil germination alongside the growth of seedlings and their roots, leading to a denser plant population and higher yields. Hydrogels also facilitate better absorption of excess water, allowing for its gradual release during periods of water stress, thereby alleviating the impact of such conditions on plants and enabling them to tolerate prolonged droughts. Furthermore, these materials can resist salt concentrations within the soil, improving its physical, chemical, and biological attributes. This improvement extends to delaying the onset of the permanent wilting point in arid environments characterized by intense evaporation, ensuring more efficient water utilization. Hydrogels significantly increase water use efficiency by reducing water loss through evaporation and leaching, diminishing the frequency of watering, the necessity for crop fertilizers, and the costs associated with irrigation. Lastly, hydrogels are utilized for their maximum durability and contribution to soil stability without posing risks to the environment.

4.2. Agriculture-Related Uses for Hydrogels

Hydrogels have recently found numerous uses, particularly in arid and semi-arid regions where water is scarce, to increase the effectiveness of water and fertilizer utilization in agriculture. The hydrogels allow the plant to absorb water and nutrients when the soil surrounding its roots dries. Recently, researchers have described numerous hydrogels for use in efficient irrigation and fertilizer release systems. Table 1 shows an overview of some reported hydrogel applications for agriculture.

Rationalizing water is one of the main concerns in any crop, and it is a factor at all stages of the production process. Hydrogels have been used since the 1960s to manage this natural resource because they have been proven to improve the physical and chemical properties of soils [85,86]. As a result, the hydrogel reduces the necessary crop irrigation rate, maintaining the soil's water concentration for longer. It also means that the nutrients required for plant development remain available in the soil for longer, which means that the application of synthetic polymers directly and positively affects profits in crop development [85,86].

According to Klar (1991), it is essential to know the soil's water variables, such as the characteristic curve of water in the soil and the field capacity, as well as the effective depth of the roots followed by their characterization, and finally the atmospheric factors [87,88]. The correlative behavior of these components interferes with the quality of plant development since all the processes that occur within the plant are affected by water presence [89]. However, only a fraction of the water in the soil remains available for plant consumption. This is the water retained between field capacity and the permanent wilting point [90].

Studies with *Eucalyptus urograndis* show that the hydrogel application makes a significant difference to the maintenance and survival time of the plant during water deficit periods [89]. The polymer use allowed the seedlings to remain without showing symptoms of water deficit for approximately seven days longer than those without it. The water management configuration used on the seedlings during the production phase was minimally influential in the evolution of water stress symptoms. The study also showed that the seedlings most adapted to a lack of water, when they presented a moderate state of water stress, allowed a flexible window of 10 days for the forester to plan in relation to the seedlings that did not have the polymer [89].

Conversely, studies by Ferreira et al. [84] and Silva et al. [85] concluded that acclimatizing seedlings to water stress supports the highest survival rate due to the planting system [91,92]. Within the scope of the subject in the literature, the difference in water availability for plants due to soil and substrate fertility is also pointed out, considering that these parameters can deteriorate the hydrogel or reduce its water storage capacity in the presence of Mg and Ca [93,94].

Table 1. Summary of applications of some hydrogels.

Hydrogels	Crosslinker	Characteristics	Applications	pH or/and Ionic Force Tests	Swelling	Ref.
[1] CMC/Nano-calcium carbonate	Citric Acid	Physically Cross-linked	Biocompatible hydrogels for retention in maize cultivation in clayey and sandy soil	pH 4, 5 to 6, and 7 to 9 in 0.500 mol_{ion} L^{-1}	32 g g^{-1}	[95]

Table 1. *Cont.*

Hydrogels	Crosslinker	Characteristics	Applications	pH or/and Ionic Force Tests	Swelling	Ref.
CMC/Nanocellulose CMC/Montmorillonite	Citric Acid	Chemical Cross-linked	Fertilizer (NPK) release in water and soil	-	36 g g^{-1}	[96]
CMC/Bentonite	Citric Acid	Chemical Polymerization	Insecticide thiamethoxam (3-(2-chloro-1,3-thiazol-5-ylmethyl)-5-methyl-1,3,5-oxadiazinan4-ylidene(nitro)amine)	pH 4, 7, and 9	8 g g^{-1}	[87]
Modified Starch/Acrylic Acid	N,N′-methylene bisacrylamide	Chemical Polymerization	Fertilizer release (N and K) in water and soil	pH 3 to 10, and 0.0017 to 0.017 mol_{ion} L^{-1}	1020 g g^{-1}	[88]
Lignin/Methacrylate	Onto Lignin	Chemical Esterification/ Polymerization	Reserve of water in soil	-	10 g g^{-1}	[97]
Gum tragacanth/ Glutaraldehyde/ Acrylic acid	Glutaraldehyde	Chemical Cross-link	Fertilizer (K) release in water and soil	-	2.8 g g^{-1}	[98]
Guar Gum/Acrilic Acid/[2] EGDMA	[2] EGDMA	Chemical Cross-link	Reserve of water in soil	pH 4, 7, and 9 in 0.015 mol_{ion} L^{-1}	806 g g^{-1}	[99]
Amino-Ethyl-Chitosan/acrylic acid	N,N′-methylene bisacrylamide	Chemical Polymerization	Reserve of water in soil	pH 1 to 14	741 g g^{-1}	[100]

[1] Carboxymethyl cellulose; [2] Ethylene glycol dimethacrylate.

4.2.1. Effective Irrigation

It is possible to hyperaccumulate excess water in the soil to a volume hundreds of times larger than its weight by implementing hydrogels as soil conditioners. It minimizes water loss and enhances the detrimental effects of water stress and de-hydration on crops [95,96,99–102]. Indeed, the first reported use of polyacrylamide for plant growth stabilization of road embankments was in France, where arid, barren soil was converted into established vegetation [103,104]. According to Barakat et al. [105], some polymers can be used to overcome problems with traditional irrigation techniques, where hydrogel polymers can serve as a reservoir in the central part of the root zone and prevent water loss through percolation [106,107].

Growing water constraints in semi-arid areas need extra care to stop soil erosion and reduce the negative consequences of water stress scenarios. At Sri Karan Narendra University of Agriculture's research farm, Jobner, Rajasthan, Kumawat et al. (2024) conducted a field experiment during the winter to boost production of Indian mustard—*Brassica juncea* (L.) Czern., which is facing water scarcity in the arid and semi-arid regions of Rajasthan. The authors evaluated the hydrogel impact based on the growth, yield, profit, and water use efficiency of Indian mustard. The results of the study demonstrated a notable and successful effect of applying hydrogel at a rate of 5.0 kg/ha in conjunction with foliar spraying with 200 ppm of salicylic acid. Numerous indicators, such as growth characteristics, yield qualities of the seed and straw, protein content, and water use efficiency of 8.53 kg/ha-mm, were all superior to previous treatments [104].

Saha et al. (2021) recycled natural coconut fiber using the polyacrylic acid graft polymerization process to create a superabsorbent hydrogel composite. In distilled water, the synthetic hydrogel exhibited a water absorption of 342 g g^{-1}, suggesting that it could find agricultural use with superior re-swelling properties throughout more than eight alternating cycles of wetting and drying (Figure 4). Water availability in clay loam soil rose from 56% to 125% with the addition of the hydrogel. At an ideal application rate of 0.2%, the hydrogel decreased the requirement for irrigation water by 29% as compared to bare soil [108,109].

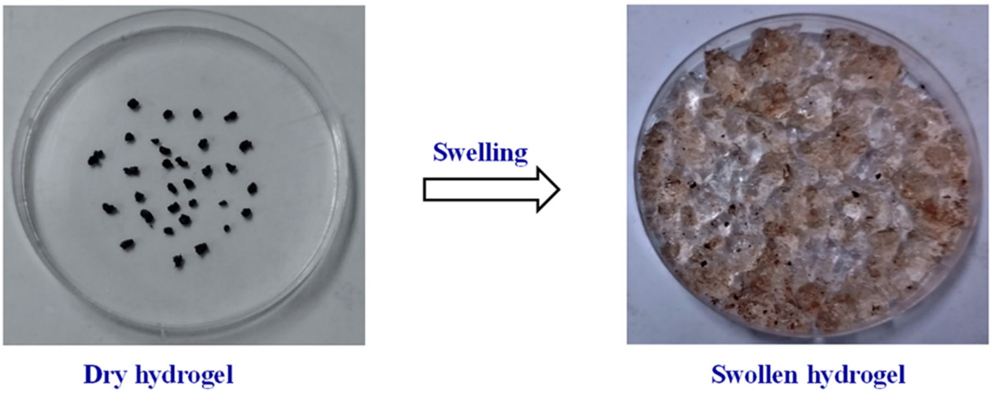

Figure 4. The superabsorbent hydrogel composite's swelling mechanism in aqueous media. Adapted from Saha et al. [108,109].

Kaur et al. (2024) created several hydrogels using PVA as a model matrix and lignin and xylan, removed from rice straw (*Oryza sativa*), as raw ingredients, looking forward to ways to reduce the quantity of water needed for rice crop growth while addressing the disposal of rice straw. Two types of crosslinkers were utilized: citric acid and succinic acid. Hydrogels cross-linked with citric acid exhibited wide pores and loose polymer bonds, whereas hydrogels cross-linked with succinic acid displayed decreased porosity and a tight bond network. With a swelling rate ranging from 0.21 to 0.40 and a resurgent capacity, the lignin hydrogels performed better than any other hydrogel [98,107].

Recently, Zhan et al. (2024) created conductive hydrogel as a solenoid valve controller for smart irrigation to accomplish on-demand irrigation and more intuitive soil moisture monitoring. Na_2SO_3-APS (ammonium persulfate) was utilized as an initiator to create the smart poly(acrylic acid-co–N-methylolacrylamide)/poly(3,4-ethylenedioxythiophene): polystyrene sulfonate hydrogel with double network under mild conditions. The resulting hydrogel demonstrated sensitive sensing capabilities and outstanding mechanical qualities [110].

In general, the utilization of hydrogels can assist in water management and can be integrated with irrigation techniques. To the best of our knowledge, there is scarce literature about integrative methods of irrigation machines and methods and hydrogels' design, which are an open challenge.

4.2.2. Applying Fertilizer

Research into improving food nutrition through fertilization, choosing raw materials from waste, by-products, and biomass, and adopting more environmentally friendly chemical processes and cleaner processes for field applications are some of the challenges in research on new materials in agriculture. Biopolymer-based slow-release or controlled-release fertilizers are environmentally friendly due to their ability to boost fertilization efficiency and reduce the surplus fertilizer that low-performing fertilizers discharge into the surrounding area [109,111]. Therefore, research has demonstrated superabsorbent polymers are highly effective in regulating fertilizer release into the soil, thus increasing their application in horticultural and agricultural fields [52,112].

For example, the new hydrogel made of biopolymers based on acidic whey and cellulose derivatives and polyvinyl alcohol (PVA) was processed by Fabian et al. [107] to create an environmentally friendly soil additive that increases the capacity of the soil for retaining water. According to the PVA content and cross-linking density, the significant swelling characteristics of the hydrogels were revealed by the results. With an associated ratio of up to 1400%, the new hydrogel demonstrated swelling behavior that depended on temperature and pH in addition to its ability to resurface. The soil's ability to hold onto water was raised by 19% with the application of 2% PVA hydrogel [113].

Mikula et al. [104] researched creating a method for hydrogel preparation using starch, carboxymethylcellulose, and alginate as micronutrient (Cu, Mn, and Zn) carriers. To achieve this, Mikula et al. [104] conducted tests to determine the hydrogel matrix's constituent parts. These included comparing viscosity and density as well as examining the impact of additions of carboxymethylcellulose and starch on the structures' capacity to expand and maintain their strength. The desired characteristics of the hydrogel, such as water absorption and enhanced mechanical resistance, were guaranteed by additives, including CMC and starch. Mikula's work demonstrated that utilizing calcium chloride to create hydrogels and then enriching them with micronutrient ions through sorption is preferable to directly introducing the biopolymer solution into Cu(II), Mn(II), and Zn(II) solutions, as shown in Figure 5. Germination tests have verified the utility of micronutrient transporters in wheat cultivation [111].

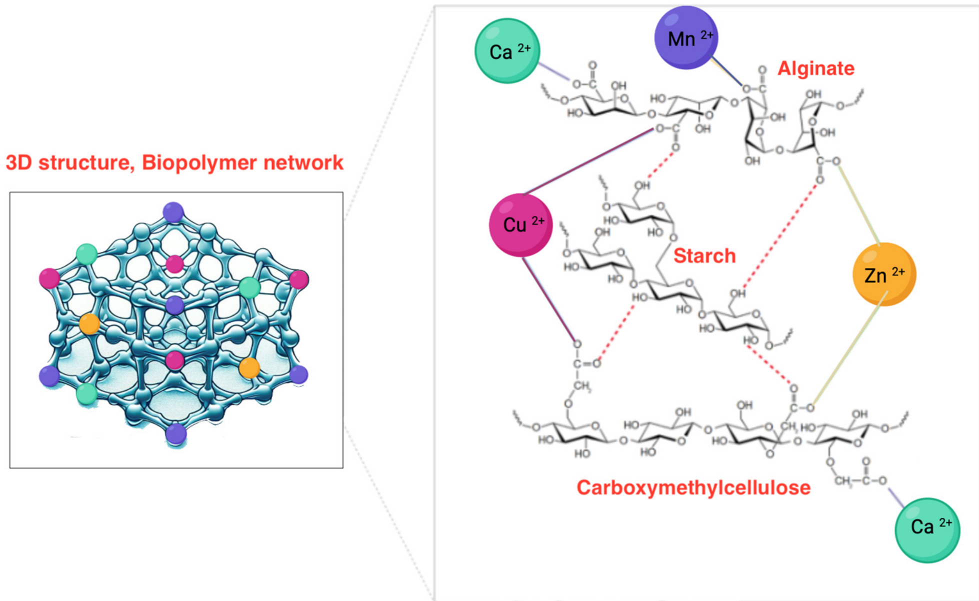

Figure 5. Cu(II), Mn(II), and Zn(II) micronutrient-enriched hydrogel matrix structure. Adapted from Mikula et al. [111].

4.2.3. Hydrogels in Soil

Brazil is always represented among the largest grain producers in the world, and it is at the top of cattle production, but little is discussed about the formation of Brazilian soil. The soil in the country is considered of poor quality for production since it has an acidic pH and low nutrient availability. It is necessary to correct this soil so that production can be fully developed [112,113]. Thus, it was possible to observe that in the case of soil with these conditions, rooting happens in an abbreviated way since the soil has a significant presence of aluminum and iron oxide, among others [114]. In Brazilian soil, the leaching tends to be higher since the soil does not have a high nutrient content and, therefore, tends to be sandy, as is the case of soils in desert places.

Some studies showing hydrogel interaction with soil have been reported, but there is an evident lack of knowledge about its interactions in specific biomes. Among the few examples found, a study carried out in Cerrado conditions investigated the use of three different hydrogel weights (4, 8, and 12 g) and their water availability, and the authors analyzed the electrical conductivity of the soil as well [114]. The results showed that the water absorption between the different dosages was very close. However, they highlighted the 12 g dosage, in which the soil presented cracks, suggesting that it absorbed more water throughout the experiment. Moreover, the electrical conductivity analysis showed an inverse relationship with water absorption since the more significant the water absorption, the lower the conductivity present in the soil [115].

Impact on Soil Properties

Studies indicate that hydrogels help in water retention, in a positive way, in soils considered arid and semi-arid, which makes it interesting to the view of agriculture since this characteristic of the hydrogel will increase the amount available in-depth for the plants, making their root zones get more time between successive irrigations throughout the plant's life. Hydrogels have satisfactory characteristics in relation to their texture and porosity, which will provide an ideal flow of air and water directed to the soil, in addition to releasing the water that the material stores when the soil has low humidity, facilitating the maximum potential for plant growth [29,116]. In part, this is because the leaching of the water present in the soil is partially suspended by the swollen hydrogel particles in the dry soil, so that in relation to the porosity of the soil there will be no modification unless the size of the particles or agglomerates of swollen hydrogel is fixed in centimeters [117]. Adequate porosity for soils should not be less than 10% of the critical value in relation to plant growth [118]. However, when dealing with soil whose moisture retention is of a high standard, the use of hydrogel should be minimal so that it does not hinder the aerobic interactions of plant roots [119]. With the presence of the hydrogel, the porosity of the soil increases, which will lead to better oxygenation for the roots of the plants [116].

Impacts of Hydrogels on Microbial and Fungal Growth

The nutrient pathways for uptake by plants are only possible through the microorganisms of the soil matrix that are involved in this role. Bacteria and other unique, multicellular species break down the complex nutrients present in the soil and release them into plant roots. Thus, a healthy population of nitrogen- and other nutrient-fixing bacteria equates to optimizing overall plant yield [120]. This entire ecosystem is important to the environment for plant growth since these combinations carried out within it will generate a natural balance between the transfer of nutrients and the survival of each species. Considering that the organisms naturally propagate in an aqueous medium and with the availability of moisture generated by the water retention promoted by the hydrogel, it ends up building an incubation center for these organisms. In general, the interaction of microbes such as in the hydrogel can be classified as a complex relationship, and with enzyme exchanges, the microbes end up being exposed to the release of nutrients and the degradation of the hydrogel's residues. Thus, since the hydrogel is applied for agricultural purposes, as in the case of productivity, it must not show toxicity to the organisms that help in making the symbiosis, since this process is essential for plant growth. In any case, hydrogels need to undergo tests to analyze the effects that this element can have on microbes, whether these effects are positive or negative. Performing a cytotoxicity test and genomic sequencing of microbes found in the soil are methods adopted to evaluate hydrogels' effects on the microbial community in the soil [121,122].

Hydrogels based on polyacrylamide (PAAm) do not present satisfactory results when it comes to interaction with the soil and thus their use is discouraged in agriculture. On the other hand, polyacrylate-based hydrogels (PUSA) were tested as bioinoculants under study, resulting in an increase from 3 months to 2 years under controlled conditions, and with the treatment of the selected cultures of microbes, the hydrogel was shown to be positive for plant growth [123,124]. However, even with the studies showing positive effects, it is still necessary to carry out long-term studies to understand the results of this application in agriculture.

Impact of Hydrogels on Plant Growth

When discussing the use of hydrogels in agriculture, attention should be paid to the interactions that occur with the water in the soil resulting from its application and the development that the plant exposed to this treatment will have. The application of the hydrogel polymer can be carried out in some ways, such as coating seedlings or seeds or directly applying it to the soil where it is mixed with the soil adjacent to the sown plants [125]. The hydrogel will bind to the roots of the plants in a variety of cases and thus improve the surrounding nutrient environment. On the other hand, there may be cases, depending on the hydrogel, that the polymer will swell in such a way that it may tend to block the pores of the soil that are intended for aeration, which results in seedling mortality [29]. In general, the hydrogel introduced to aid the cultivation is very favorable, and there are no studies that present phytotoxicity results. An experiment carried out by Montesano (2015) [125] showed that in the cultivation of cucumber, there was an increase of about 30 cm in the height of the plant, in addition to an increase in the biomass of the plant and the fruit in terms of weight [125]. Considering that chlorophyll production is linked to water availability, plants that are grown without the hydrogel technique have shown a decrease in their chlorophyll content compared to those with the use of polymer in soil. The plant's defensive system has also been shown to be different from that of the hydrogel, where there is a decrease in phytopathogenic actions, in addition to blocking the growth of nutrient-intensive fungal species [29].

5. Future Challenges and Prospects

Hydrogels bring many benefits, including the incorporation of hydrogels into agricultural soil, where they can effectively improve water retention, helping crops to resist water stress. They can also be used to control the release of nutrients to plant roots, improving crop growth and ensuring efficient use of fertilizers. In addition to its use as a seed coating, it improves germination rates as it creates a favorable microenvironment around the roots, promoting healthy growth.

By evaluating the complexities of these hydrogel agricultural technology challenges and their prospects, we will have a more complete picture of their potential impacts. Large-scale hydrogel implementation may also be hampered by issues such as the cost-benefit ratio, the security of the logistics system in distribution, and the stability of many traditional agricultural practices [126]. The recycling of hydrogels is challenging since recovery after application is hard to achieve, i.e., the mixture in soils and other substrates makes recovery for recycling impracticable. Thus, the development of biodegradable hydrogels is necessary, intending to incorporate them to soil organic matter after application. However, most hydrogels' utilization is still based on synthetic polymers, which leads to a concern about their role in long-term applications. Another point of attention is to understand how these hydrogels can influence the soil microbiota in long-term applications. The current low application in specialized sectors leads to it becoming a concern for utilization in large-scale cultures. The consideration of these environmental issues (i.e., the biodegradability of polymeric waste and the long-term impact of the hydrogel on the soil ecosystem) is a critical point for the widespread use of hydrogel films. To this end, researchers are exploring hydrogels based on natural biopolymers, which are advantageous due to their biodegradability, minimizing negative environmental impacts [126,127].

Therefore, it is necessary to integrate hydrogel production in an "eco-friendly" production chain, not only addressing the material itself but the association with other technologies that provide sustainable use of water (e.g., precision agriculture and irrigation), natural resources, and environmental concerns, especially including materials' circularity indexes to analyze their whole impact, which also reduces costs and positively impacts agricultural productivity [128,129].

The review can more effectively advise relevant parties on the availability and limitations of hydrogel technology, identify issues, and attract opportunities for sustainable agricultural practices in the future. By optimizing its properties and applications, we can create a promising agricultural scenario and guarantee environmental compatibility.

6. Conclusions

To summarize, hydrogels hold some of the answers for the future of agri-innovations and technologies promising to address the challenges and limitations associated with conventional agricultural practices and technologies, but it is necessary to analyze the technology with reservations. Recent research clearly shows that farmers can use them to solve some agricultural issues, like maintaining the water-holding ability of the soil, improving seed germination, and helping in the growth of plants. Therefore, the option for customization of the fabrication method confirms the process's feasibility in all kinds of agricultural environments.

Nevertheless, as we go through the literature, we can assume that the results were positive in most studies; the areas that still need to be improved are also something we need to consider. First, there are a few challenges to further perfecting such a hydrogel-based system, like enhancing the nutrient release mechanism and, most probably, exploring new applications. In addition, hydrogel technologies offer a variety of solutions to prevailing issues such as food security and the environment; however, they need to undergo extensive research and development before large-scale uptake can be ensured.

Overall, although hydrogels are expected to play a significant role in contributing to the sustainability of agriculture and helping address food security and environmental threats posed by climate change and population growth, the aim is to keep developing and making innovations in order to deliver their expected results.

Author Contributions: Writing—original draft preparation, P.V., L.V.S., G.d.S.T. and V.F.M.; writing—review and editing, P.V.; review and visualization, R.B.-S.; supervision C.R. and F.F.P.; project administration, EMBRAPA (Brazilian Agricultural Research Corporation); funding acquisition, FAPESP (São Paulo Research Foundation) and CAPES (Coordination for the Improvement of Higher Education Personne). All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by FAPESP (Sao Paulo Research Foundation, grant number #2020/12210-3 and 2022/03005-2); CAPES (Coordination for the Improvement of Higher Education Personne—Finance Code 001; CNPq (proj # 402713/2023-0) and Embrapa.

Acknowledgments: The authors also acknowledge the support of Brazilian S&T&I Ministry through SISNANO (CNPq proj #442575/2019-0) and INCT Programs (CNPq proj # 406925/2022-4; CNPq 405924/2022-4) and CNPq (proj # 402713/2023-0).

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

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