International
Journal of Agriculture Innovations
and Cutting-Edge Research

Polysaccharide-Based Hydrogels for Sustainable Agriculture: Recent Advances and Applications

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Abstract

Hydrogels are three-dimensional networks of polymer chains that have the property to absorb and retain a significant amount of water. Polymers like cellulose, chitosan, alginate, starch, and pectin are usually used to prepare hydrogels. Cross-linking is a fundamental process in hydrogel formation, transforming soluble polymers into three-dimensional networks capable of absorbing and retaining large amounts of water. Over the past few years, polysaccharide-based hydrogels have emerged as a sustainable material for agricultural practices to address the issues of limited water supply and increase the protective properties of the soils. This review discusses the types of hydrogels and the principles of swelling and cross-linking of hydrogels, especially in biopolymers (guar gum, pectin, and sodium alginate). These biopolymers are biodegradable, eco-friendly, and increase the capability of arid and semi-arid soils to retain water, enhance the utilization of nutrients, and promote plant growth. A thorough search of scientific databases was conducted to identify the relevant studies that were used to compile the most relevant and reliable results. This review also highlights the recent developments and limitations in the hydrogel technology for sustainable agricultural practices.

Keywords: Polysaccharide hydrogels, Arid soil, Agriculture, Biopolymers, Cross-linking, Water retention,

DOI:	https://zenodo.org/records/17309484
Journal Link:	https://jai.bwo-researches.com/index.php/jwr/index
Paper Link:	https://jai.bwo-researches.com/index.php/jwr/article/view/163
Publication Process	Received: 25 Jul 2025/ Revised: 29 Sep 2025/ Accepted: 02 Oct 2025/ Published: 10 Oct 2025
ISSN:	Online [3007-0929], Print [3007-0910]
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Indexing:	Academia.edu, DRJI, doi, zenodo, Google Scholar, INDEX COPERNICUS INTERNATIONAL

Publisher: BWO Research International (15162394 Canada Inc.) https://www.bwo-researches.com

Introduction:

Modern agricultural production is under increasing pressure, with water scarcity, soil erosion, and the necessity to address the issue of sustainable farming practices being more complicated due to climate change (Ahmad et al., 2019). The rising occurrence of droughts and extreme weather conditions poses a threat to food security and makes it hard to achieve sustainable agricultural development. One of the priorities is thus the effective and ecologically sustainable utilization of resources, especially water (Bashir et al., 2020). Hydrogels based on polysaccharides have become a promising solution to these problems. These hydrogels have significant benefits in agricultural systems due to their high water-retention levels, structural benefits, and their capacity to transfer nutrients to the plants. Hydrogels produced using natural polysaccharides, especially, can lead to a decrease in irrigation requirements, the reduction of fertilizer usage, and enhanced harvests (Guilherme et al., 2015). Their integration within soil has been demonstrated to increase productivity and, at the same time, improve the soil structure and quality (Albalasmeh et al., 2022). Hydrogels are hydrophilic polymers with a three-dimensional structure, cross-linked chemically and/or physically, and they can retain a significant amount of water without dissolution (Ahmed, 2015). Hydrogel properties can be customized to meet swelling behaviour, biodegradability, release kinetics, and other aspects through different preparation strategies, such as graft polymerization, chemical and radiation cross-linking, free radical and enzymatic, and self-assembly (Ahmad et al., 2019). They are also environmentally sensitive, e.g., sensitive to pH, temperature, and material concentration, which increases their applications in agriculture (Ata et al., 2020). The purpose of this review is to assess the nature, characteristics, and agricultural uses of polysaccharide-based hydrogels in sustainable agriculture in terms of enhanced water retention and nutrient release. It also shows their role in retaining soil water and crop production, and also looks at the innovations that have been made to increase their agricultural importance. Also, the review contains a discussion of existing constraints to their extensive application and the future of hydrogel technologies. Systematic searches were used to identify the relevant studies that would offer reliable and current coverage and provide a comprehensive view of the potential role of these in modern agriculture.

Types of Polysaccharide-based Hydrogels:

Types of polysaccharide-based hydrogels depend on the kind of polymer. Polymers like cellulose, chitosan, alginate, starch, and pectin are usually used to prepare hydrogels (Figure 1). The details of different types of hydrogels are discussed below:

Cellulose-Based Hydrogels:

Cellulose is the most abundant polysaccharide found on Earth. It is one of the major components of plant cell walls and has been widely considered as an electrolyte to create hydrogels. Cellulosic hydrogel can be formed by using physical cross-linking, via chemical modification, or grafting. They are non-toxic, have a high gelation capacity and are widely applicable in the drug delivery, tissue engineering and purification of wastewater. They are also applicable in soil conditioning of agricultural soils because they retain water (Chang & Zhang, 2011).

Chitosan-Based Hydrogels:

Chitosan is prepared by deacetylation of chitin obtained from the exoskeletons of crustaceans. Chitosan hydrogel is antimicrobial, meaning that it can be employed in wound healing, delivering drugs, and agriculture. They promote water retention in the soil and prevent excessive development of pathogenic microorganisms, thus promoting plant growth and soil conditioning (Nordin et al., 2024).

Alginate-Based Hydrogels:

Alginate is a natural polysaccharide which is extracted from brown seaweed as soluble sodium alginate. It is a highly biocompatible polymer and acts as a fine gelling agent. The applications of alginate hydrogels include medicine, pharmaceuticals and agriculture. In agriculture, it increases the water-holding capacity of soil and helps in the controlled release of fertilizers, thus promoting sustainable agriculture practices (Zowada & Foudazi, 2023).

Starch-Based Hydrogels:

Starch is a cross-linked polymer of glucose that forms a network structure. Due to their non-toxic, biodegradable, biocompatible, and water retention properties, starch-based hydrogels are mostly used in agricultural practices. These hydrogels not only increase water water-holding capacity of soils but also release nutrients and fertilizers in a controlled manner (Kong et al., 2019).

Pectin-Based Hydrogels:

Pectin is a complex carbohydrate found in the peels of fruits and vegetables. It is abundantly found in the peels of apples and citrus fruits. Due to its sticky nature, it is involved in the binding of plant cells together. The pectin hydrogels have a good water retention capacity and biodegradability, which is an advantage to maintain the soil conditioning process and water savings in the farmlands (Li et al., 2024).

Protein and Gum-Based Hydrogels:

The family of gelatin-based hydrogels is protein-derived hydrogels and highly biocompatible systems whose application in biomedical research spans wound healing and tissue engineering. Gelatin can absorb a large amount of water and control the release of agrochemicals (Calo & Khutoryanskiy, 2015). Natural gum is also significant in farming. Guar gum is one of them, having the ability to form a hydrogel with high water-absorbing capabilities and serving in soil conditioning, nutrient delivery, and plant promotion (Wade et al., 2021).

Lignin-Based Hydrogels:

Complex aromatic polymer (lignin) found in plant cell walls has also been investigated as a hydrogel. Hydrogels derived from lignin improve soil water retention and nutrient delivery, providing green technologies to sustainable food production (Berek, 2014).

Composite Hydrogels:

Grafted or blended composite hydrogels are more stable in terms of mechanical aspects and water retention ability than single-component systems. For example, pectin-starch composite hydrogels are hybrids of pectin and starch that combine the pectin polymerization capacity with starch to enhance efficacy in soils (Li et al., 2024). Likewise, graft copolymers made from starch increase water retention and remain biodegradable, promoting sustainable agriculture (Kong et al., 2019).

Stimuli-Responsive Hydrogels:

Stimuli-responsive hydrogels are the most innovative and smart among all the types of hydrogels discussed so far. These hydrogels experience reversible change in their properties in response to external stimuli like temperature, pH, ionic strength, light, enzymes, magnetic fields, or redox conditions (Bashir et al., 2020). Hydrogel containing Poly (Nisopropylacrylamide (PNIPAM) polymer has the ability to absorb water when the surrounding temperature is lower and release it when the temperature is higher (Tenório-Neto et al., 2015). Hydrogels that are sensitive to ionic strength also regulate swelling behaviour with salinity changes, thus beneficial to arid or salty soils (Tefera et al., 2022). Enzyme-sensitive hydrogels are degraded by extracellular enzymes like hydrolases and oxidases, which are produced by microbes residing in the soil. This degradation helps in nutrient release, increases soil porosity, and enhances microbial activity for soil remediation. Hydrogels that are light- and magnetic-responsive are being explored for the creation of accurate irrigation systems and greenhouse agriculture systems (Stuart et al., 2010). Hydrogel-based systems can undergo structural modification in response to lower levels of oxygen in waterlogged soils. In waterlogged soils, these types of hydrogels can be used to increase soil porosity and help in water drainage. Even in their early stages of development, these intelligent systems have demonstrated considerable potential in the field of controlled irrigation and soil moisture management (Manimaran & As with 2024).

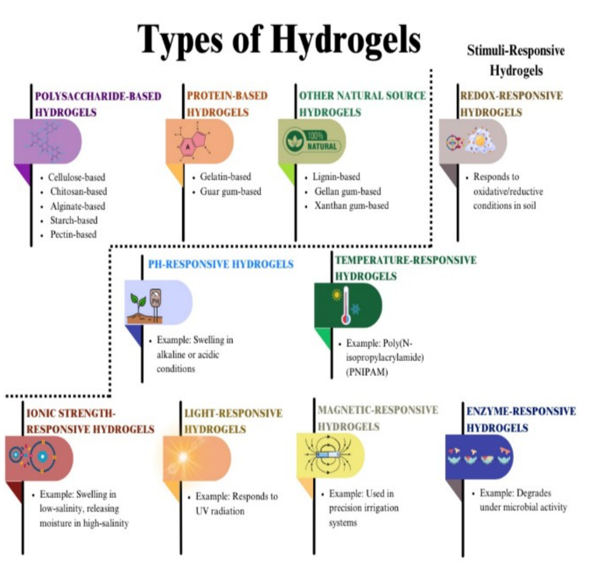

Figure 1: Classification of Hydrogels Based on Natural Sources and Stimuli-Responsive Properties

Hydrogel Synthesis and Cross-Linking:

Cross-linking is a fundamental process in hydrogel formation, transforming soluble polymers into three-dimensional networks capable of absorbing and retaining large amounts of water (Bashir et al., 2020). The nature and degree of cross-linking strongly influence hydrogel properties, including swelling behaviour, mechanical strength, stability, and biodegradability (Ahmad et al., 2019). Figure 2 demonstrates the phenomenon of cross-linking in hydrogel formation.

Chemical Cross-Linking:

Chemical cross-linking involves the formation of covalent bonds between polymer chains to make a stable three-dimensional structure. The reagents like Glutaraldehyde or N, N′-Methylenebisacrylamide have been extensively used as chemical linkers to synthesize different hydrogels (Ahmed, 2015). Glutaraldehyde can be cross-linked to chitosan hydrogels by covalent linking of amino groups to aldehyde groups (Ata et al., 2020). Photo-crosslinking is another chemical method whereby a cross-linking reaction is triggered by light energy, which generates free radicals that help in the formation of a covalent bond between polymer chains. (Kloxin et al., 2009).

Physical Cross-Linking:

Physical cross-linking involves non-covalent interactions between polymer chains in a hydrogel to create a three-dimensional matrix. These interactions include hydrogen bonds, ionic interactions, and hydrophobic forces (Bashir et al., 2020). The oppositely charged polymer chains of chitosan and alginate can bind to form a stable hydrogel (Ata et al., 2020). The polymer chains in alginate hydrogels are usually cross-linked with calcium ions, which form interactions with alginate carboxylate groups, for stabilization (Zowada & Foudazi, 2023). Physical cross-linked gels are also obtained by entangling long polymer chains, such as polyvinyl alcohol systems (Cao et al., 2024). This type of reversible network may be particularly useful in agriculture due to soil conditioning and nutrient carrier abilities.

Factors affecting cross-linking:

The factors affecting cross-linking include cross-linking agent, type of interaction, concentration of cross-linking agent, pH, temperature, initiation methods, and mechanical strength (Tenório-Neto et al., 2015). At higher temperatures, the reaction rate increases and there would be a denser hydrogel matrix. However, at a temperature higher than the optimal temperature, the structure of the hydrogel would be damaged. Similarly, the change in pH also affects the cross-linking reactions. Cross-linking also depends on the molecular weights of the polymers, as high-molecular-weight polymers will result in stronger and more interconnected gels, and vice versa (Zowada & Foudazi, 2023).

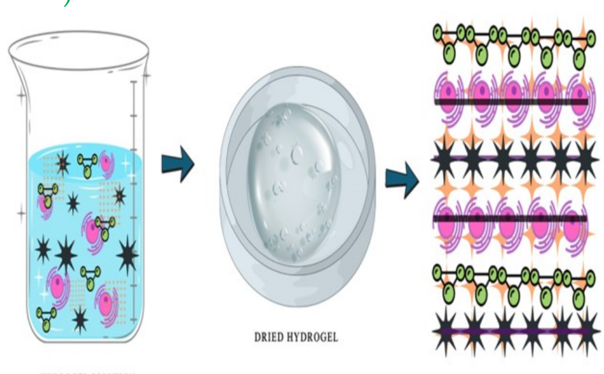

Figure 2: Hydrogel Formation Process: From Polymer Dispersion to Stable 3D Network

Synthesis According to Initiation Methods:

Hydrogels are three-dimensional networks of polymer chains that have the property to absorb and retain a significant amount of water (Bashir et al., 2020). These polymer chains are often cross-linked to synthesize a hydrogel matrix. This cross-linking can be initiated chemically or enzymatically (Table 1).

Initiation Method	Parameter	Common linker	Citations
Chemical	Temperature Dose	Glutaraldehyde	(Ata et al., 2020)
Enzymatic	Enzyme load pH Temperature	Tyramine agents	(Ahmed, 2015)

Table 1: Illustrating key control parameters and typical cross-linking agents associated with different hydrogel initiation methods.

Chemical Initiation:

It is one of the common methods deployed in the synthesis of hydrogels. In the chemical initiation approach, free radicals are generated by chemical reagents to initiate the process of polymerization. For example, Azobisisobutyronitrile (AIBN), an Azo compound, is used as a reagent to generate free radicals upon dissociation (Ahmed, 2015).

Enzymatic Initiation:

Enzymatic initiation is an environmentally friendly and biocompatible process which relies on the use of enzymes to catalyze the cross-linking between polymer chains. It is widely used to synthesize hydrogels that are used in agriculture and biomedicine (Ahmed, 2015).

Applications of Polysaccharide-Based Hydrogels in Sustainable Agriculture:

Water Retention and Irrigation Efficiency:

Hydrogels have perfect water retention and swelling capacity, and they can be applied as water reservoirs in soil (Saha et al., 202). They are found to be valuable, especially in semi-arid and water-dry regions that have lower crop production due to a lack of water. Such hydrogels maintain a uniform supply of water to the soil, as stored water reaches the plant roots with time, thus decreasing the use of water resources (Koupai et al., 2008). Approximately, water up to 60 percent can be saved by the use of hydrogels in arid/semi-arid regions (Akhter et al., 2004). Hydrogel-treated plants exhibit an initial physiological advantage, such as water stability (Cao et al., 2024), therefore results in superior growth properties, including biomass enhancement, fruit yield and root development (Hou et al., 2018). In water-scarce regions, hydrogels are also being engineered to harvest water directly from the air. Hydrogels made from lignin, chitosan, and calcium chloride can absorb humidity at night and gradually release it into the soil during the day. This simple but effective mechanism improved soil moisture and plant growth, making it a promising climate-smart irrigation strategy for arid agriculture (Bai et al., 2025).

Figure 3: Schematic Illustration of Comparison of Plant Growth with and without Hydrogel

Soil Health and Structural Improvement:

Hydrogels play a crucial role in enhancing soil health and structure. Hydrogels form a three-dimensional structure that helps in increasing the porosity of the soil, thereby facilitating root penetration and better aeration for gaseous exchange (Bai et al., 2010). The increase in the number of pores in the soil promotes more infiltration of water and reduces soil erosion (Elshaikh & Mabrouki, 2024). In sandy soils, hydrogels inhibit massive drainage of water at the root zone level (Banedjschafie & Durner, 2015), whereas in clayey soils they overcome soil compaction and enhance oxygen diffusion (Khanfous et al., 2023). These physical changes in the structure of the soil enhance crop growth and productivity (Helalia & Letey, 1989). Figure 3 shows the effect of the application of hydrogels on growth. The bonding of hydrogels with soil particles increases the soil matrix, which is beneficial in long-term soil conservation, especially in vulnerable ecosystems (Berek, 2014). Polysaccharide hydrogels also support the growth of bacterial colonies residing in the soil (Peppas et al., 2006). These carbon-rich hydrophilic matrices provide a beneficial growth environment for soil microbes, especially for nitrogen-fixing *Rhizobia*, phosphate-solubilizing *Azospirillum*, and plant growth-promoting rhizobacteria (PGPR), such as Bacillus species and *Trichoderma* fungus. The functional groups in these natural polymers, such as hydroxyl (-OH) and carboxyl (-COOH) groups, amplify the enzymatic activities that promote nutrient cycling and organic matter decomposition (Ali et al., 2024).

Seed Coating and Germination Enhancement:

Polysaccharide-based hydrogels can be applied as seed coatings. They have played an efficient role in enhancing seed germination and seedling development, especially in drought conditions. Natural polymers, including sodium alginate, chitosan, and guar gum, are used for this purpose to create a moisture microenvironment around the seeds (Palma, 2024). As seeds are sown, they absorb moisture from the surrounding hydrogel, thereby seeds undergo uniform germination even in soils with low moisture content (Chirino et al., 2011). Accordingly, the hydrogel coating around seeds results in high germination and growth rates, which include the promoted growth of the radicle and plumule, later facilitating the growth of roots and shoots (Xu et al., 2018). In addition to controlling soil moisture, polysaccharide hydrogels also transport micronutrients such as zinc and iron to seedlings in a sustainable manner. Once the hydrogel structure splits, the release time of these essential minerals is aligned with the growth physiology of the maturing seedlings (Tenório-Neto et al., 2015). The synergy between water retention and slow nutrient release by hydrogels helps plant survival when the moisture and nutrients are scarce. Seed priming and coating technologies are increasingly being integrated with biopolymer hydrogels that help crops deal with environmental stress. For example, melatonin-loaded hydrogels have been shown to boost germination and seedling vigour in tomato under salinity stress by slowly releasing melatonin during early growth. This highlights how hydrogels can act not only as protective seed coatings but also as delivery systems for bioactive compounds, offering a sustainable way to strengthen crop resilience in saline soils (Athanasiou et al., 2025). The capacity of Hydrogels to absorb ions also helps in germination of the seeds in salty soils, as it provides a controlled local ionic environment. This approach prevents ionic toxicity and lowers oxidative damage (Liao et al., 2016). Recently, the utilization of hydrogel-based medium for seed germination and growth has been opening new opportunities for soil-less farming, which is particularly valuable in cities or regions with limited supply of water (Kanagalakshmi et al., 2025).

Controlled Release of Nutrients and Agrochemicals:

Hydrogels offer an efficient and smart system to release nutrients and agrochemicals in a controlled manner. Hydrogels of natural polymers, for example, guar gum and sodium alginate, retain agrochemicals by encapsulation and protect them from degradation. Once the hydrogel matrix is introduced into the soil, it swells by absorbing water and releases the trapped nutrients and agrochemicals slowly and continuously (Skrzypczak et al., 2020). The use of such hydrogel-based delivery systems has shown a number of benefits. For example, the application of such hydrogels reduced the use of pesticides and herbicides up to 40%, thereby proving cost-effective and reducing environmental pollution as well (Hoogendoorn et al., 2023). Polysaccharide hydrogels also enable the time-release of bio-stimulants such as Humic acids and Sea-Weed extracts that promote the plant growth and stress tolerance (Hüttermann et al., 2009). The continuous supply of bio-stimulant-loaded hydrogels for about 30 days promotes continuous root growth, promotes biological processes in the soil, and guarantees improved assimilation of nutrients (Xu et al., 2018). The hydrogel-encapsulated bio-stimulants produced more than 25–30 % increases in plant height and root biomass, compared to conventional methods that were often limited by rapid nutrient washout. Further modulation in the concentrations of these agrochemicals enables these hydrogels to enhance effectiveness in pest and weed control, and also reduces the chances of runoff and groundwater contamination (Kim et al., 2022). Moreover, they are biodegradable and after the release of agrochemicals, they decompose into harmless substances, reducing the environmental hazards related to the systematics effects of synthetic polymers. Due to their biodegradable nature, these hydrogels, after release of agrochemicals, decompose into harmless by-products, therefore act as an attractive green alternative for crop protection and promote environmental sustainability (Adjuik et al., 2022).

Limitations of Natural Polymer-Based Hydrogels:

Sustainable agriculture remains threatened by the long-term issues of ineffective irrigation and water shortage. Hydrogels are capable of storing large amounts of water; therefore, it is considered a solution to improve the process of water retention in soil (Saha et al., 2020). Another additional benefit of using polysaccharide-based hydrogels is that they are eco-friendly, as they are biodegradable and decompose into non-toxic products (Montesano et al., 2022). In spite of many advantages of natural hydrogels, they also possess some disadvantages that should be addressed to improve their performance. They showed low mechanical strength in the soil environment. Natural hydrogels also undergo premature degradation due to soil pressure, alternate wetting and drying cycles, and microbial attack. All these physical and biological factors disrupt the hydrogel network (Ahmed, 2015). To address this issue, nanocomposite reinforcements (e.g., clay, graphene oxide or silica nanoparticles) and smarter cross-linkers have been incorporated into hydrogels that can enhance structural stability and reduce premature biodegradation. However, it increases the cost and can alter the intrinsic characteristics of polysaccharide polymers. These hydrogels are sensitive to changes in their environment, like pH, temperature, and salinity (Stuart et al., 2010). Natural polymers, especially starch or chitosan, are affected by a change in pH and undergo inconsistent swelling, which leads to deterioration (Dehkordi & Shamsnia, 2020). To deal with pH sensitivity, pH-sensitive hydrogels are prepared that maintain the stability of the gel matrix by modification of functional groups. The biodegradation of hydrogels is another problem, though a natural process, which reduces the hydrogel mass and decreases the water retention capacity. The microbial degradation decreases the life of a hydrogel, therefore increasing the use of material and labour costs to recycle the substrate (Siddique, 2024). In order to reduce biodegradation, chemical modification or encapsulation of hydrogels can be done to protect them from a damaging environment. Another concern is that natural hydrogels have poor solubility and do not distribute water and nutrients evenly in the root zone (Albalasmeh et al., 2022). Recent reports showed that natural hydrogels can be surface functionalized and coated with dispersing agents to increase their implantation within the soil matrix, and therefore, greater consistency in water distribution. Economics is another obstacle, as chemical modification is costly and dependent on solvents, which restricts their application in agriculture on a large scale (Patra et al., 2022). Enzyme-assisted modification and green synthesis approaches are low-cost substitutes to address this issue. Lastly, saline and dry soils, where hydrogels are highly demanded, are affecting their swelling capacity and efficiency (Abedi-Koupai et al., 2008). Recent advances in the field incorporate ionic-tolerant hydrogel models and multi-network hydrogel systems to retain water even at high salinity (Saha et al., 2020). Table 2 summarizes the limitations and strategies to deal with these limitations.

Table 2: Limitations of hydrogels in agricultural practices

Limitation	Observed Effects	Strategies to Overcome	Citations
Low mechanical strength	Prone to collapse under soil pressure and microbial attack	Use of Nano-composite reinforcements (clay, GO, silica nanoparticles); smart cross-linkers to improve stability without losing biodegradability	(Bashir et al., 2020)
Sensitivity to pH, temperature, and salinity	Unpredictable swelling; reduced stability in variable soils	Development of pH-sensitive cross-linking systems; functional group modifications to stabilize hydrogels	(Tenorio et al., 2015)
Rapid biodegradation	Short lifespan; frequent re-application needed	Partial chemical modification; encapsulation techniques; enzyme-assisted modifications to slow degradation without harming the environment	(Montesano et al., 2022)
Solubility and dispersion issues	Uneven soil distribution; Irregular root hydration	Functionalization and coating with dispersing agents to improve soil matrix implantation and water distribution	(Mahgoub, 2020)
High cost of chemical modification	Increases production cost; reduces eco-friendliness	Use of low-cost enzyme-assisted modifications; green synthesis methods to balance performance and cost	(Siddique, 2024)
Poor performance in saline and arid soils	Reduced swelling capacity and water retention	Development of ionic-tolerant hydrogel models; multi-network hydrogels to retain water under salinity and drought stress	(Tefera et al, 2022)

Conclusion:

Polysaccharide-based hydrogels offer a promising solution to modern agriculture because they are biocompatible, biodegradable and capable of retaining water. These properties make them ideal components for sustainable farming, increase crop productivity, and minimize the adverse effects on the environment. These biodegradable materials can be utilized by researchers and farmers to improve soil structure, increase plant growth, and develop more resilient and productive agricultural systems, particularly in the context of climate change. Some advantages of hydrogels are still not fully understood and require further research on what are their limitations and how to use them effectively in agricultural settings. Future studies should explore the innovation in the development of new hydrogel formulations, performance under differential environmental conditions, and data generation for economic evaluation.

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