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TRANSFORMING AGRICULTURE: THE ROLE OF HYDROGEL IN CULTIVATING A GREENER AND MORE SUSTAINABLE FUTURE

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ABSTRACT

Hydrogels have become a revolutionary innovation in farming, tackling major issues like lack of water, declining soil health, and wasteful use of fertilizers. These incredibly absorbent materials can hold up to 400 to 1500 times their weight in water, greatly increasing soil water levels and cutting down on the need for watering, particularly in arid regions. They enhance the soil structure, enabling it to retain water and support plant growth more effectively. Hydrogels not only aid in water retention but also improve nutrient delivery to plants, making them highly efficient tools for modern agriculture. This review explores the latest advancements in hydrogel applications for sustainable agriculture and their role in reducing environmental impact, enhancing productivity, and addressing climate-resilient farming.

INTRODUCTION

Sustainable farming addresses the increasing demands associated with population growth while safeguarding the environment. Its goal is to use limited resources effectively and produce sufficient food in a manner that is socially and economically fair to farmers. Adopting ecological principles boosts biodiversity, enhances soil and water quality, and minimizes reliance on non-renewable resources. This comprehensive strategy not only satisfies today's food needs but also ensures environmental protection for future generations, thus enabling the long-term viability of agriculture (Gliessman 2016; Pretty 2018; Reganold & Wachter 2016). However, the availability of our food supply and the advancement of sustainable agricultural practices are threatened by soil salinization and desertification, resulting from droughts and water shortages. Therefore, improving water use efficiency in agriculture is essential. In the quest for sustainable agriculture, the use of hydrogels has emerged as a significant innovation. Superabsorbent polymers greatly enhance the water retention ability of soil, facilitate improved nutrient distribution, and promote soil health, supporting more sustainable and resilient farming methods (Ahmed 2015).

Three-dimensional hydrogels are versatile polymers that can absorb water and retain significant quantities of water or biological fluids. They are particularly suitable for various applications in sectors such as agriculture, healthcare, and environmental conservation. Hydrogels can be produced from natural polymers like chitosan and alginate, which are appreciated for their biodegradability and suitability for biological systems, or from synthetic polymers like polyvinyl alcohol and polyacrylamide, which are engineered for specific mechanical and stability characteristics (Peppas et al., 2000).

There are two categories of hydrogels: chemical hydrogels, which rely on covalent bonds for enhanced stability, and physical hydrogels, whose structure is formed through noncovalent interactions such as hydrogen bonding and hydrophobic forces (Drury and Mooney 2003; Hoffman 2012). Attributes such as mechanical strength, porosity, and the ability of hydrogels to respond to external factors like pH and temperature make them exceptionally beneficial for sustainable agricultural practices (Caló and Khutoryanskiy 2015).

Agriculture is in urgent need of innovative water management approaches due to the escalating impacts of climate change, including unpredictable rainfall and extended dry periods (Masson-Delmotte et al. 2021). In particular, conventional irrigation methods in arid and semi-arid regions can lead to significant water losses through evaporation and runoff, worsening the water scarcity (Fereres and Soriano 2007). As water-retaining materials, hydrogels present a promising solution for mitigating drought conditions and enhancing water use efficiency by slowly supplying moisture to plant roots as required (Nair and Hajare 2024). Moreover, the ability of hydrogels to improve soil structure and aeration, alongside promoting root growth and nutrient absorption, will elevate agricultural productivity (Abdelghafar et al. 2024; Ji et al. 2022).

In addition to managing water resources, hydrogels can significantly contribute to the targeted and controlled delivery of crucial nutrients and agrochemicals, which helps to reduce environmental pollution and lessens the need for excessive use of fertilizers (Park et al. 2025). This precise release mechanism can increase the availability of nutrients to plants, enhance the efficiency of fertilizer usage, and minimize the leaching of nutrients into groundwater, thus supporting sustainable practices in nutrient management (Agbna and Zaidi 2025). Furthermore, the creation of biodegradable hydrogels made from natural polymers presents an eco-friendly alternative to synthetic hydrogels, alleviating concerns regarding the accumulation of polymers in the soil (Ali et al. 2024).

This review aims to thoroughly investigate the role that hydrogels play in ensuring that agriculture is pursued sustainably. Hydrogels, known for their high water retention properties and for delivering nutrients efficiently, have emerged as some new directions in solving problems within agriculture, such as a scarcity of water and worsening of soil, while conserving synthetic fertilizers from becoming excessive. This review focuses on the current advancements and uses of hydrogels, aimed at explaining their potential to bolster crop resilience, improve water-use efficiency, and minimize environmental effects. Additionally, it seeks to highlight current challenges and propose future research directions to enhance the integration of hydrogels in sustainable agricultural practices (Fereres and Soriano 2007; Nair and Hajare 2024). Figure 1 illustrates the versatile benefits provided by hydrogels in sustainable agriculture.

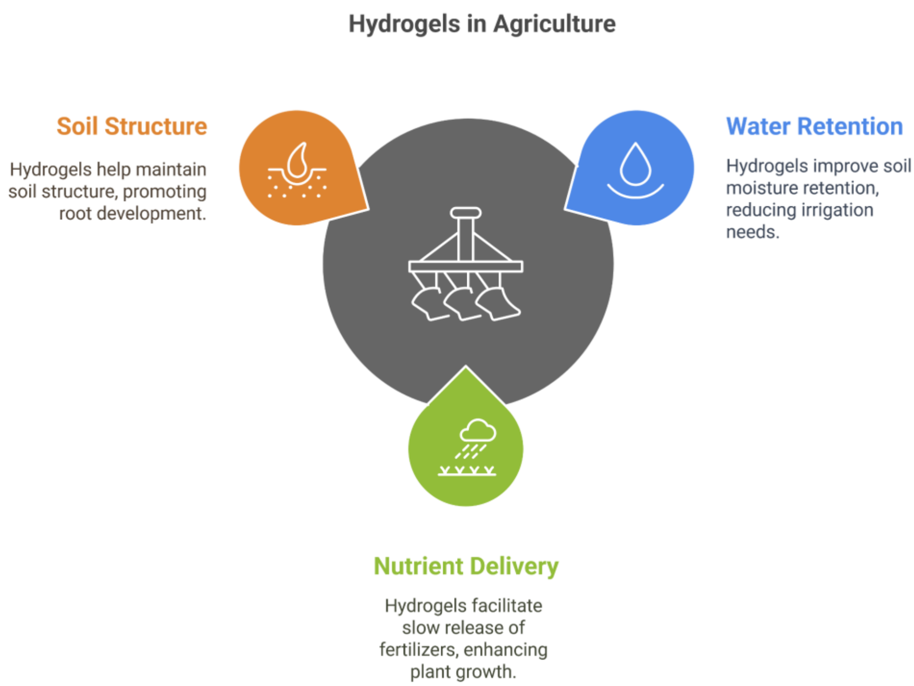

Fig 1: Multifunctional Benefits of Hydrogels in Sustainable Agriculture

2. The Science Behind Hydrogels

Hydrogels are complex three-dimensional structures composed of chains of hydrophilic polymers that can absorb and hold onto large volumes of water or biological fluids. Along its chain are hydrophilic functional groups (-OH, -COOH, and -NH2) that interact favorably with water molecules, increasing the polymer's capacity to swell (Ahmed 2015). These polymers can come from both natural and synthetic sources. Natural polymers such as hyaluronic acid, gelatin, alginate, and chitosan are prized for their biocompatibility and biodegradability, which qualifies them for use in eco-friendly applications (Lee and Mooney 2012). On the other hand, synthetic polymers with targeted mechanical and chemical characteristics, such as polyvinyl alcohol (PVA), polyethylene glycol (PEG), and polyacrylamide (PAM), offer improved stability and regulated rates of degradation (Peppas et al., 2000). Three-dimensional networks can be produced by crosslinking, which can be done chemically or physically. Since physical crosslinking depends on non- covalent reversible interactions like hydrophobic effects, hydrogen bonds, and van der Waals forces, it may compromise the stability over time although it offers flexibility (Yu et al. 2021). In contrast, chemical crosslinking establishes strong covalent bonds, leading to tougher and more resilient networks, even though they might demonstrate decreased flexibility (Hoffman 2012). The selection of the crosslinking method significantly influences the hydrogel's swelling properties, mechanical strength, and responsiveness to external factors like pH, temperature, and ionic strength (Caló and Khutoryanskiy 2015).

Hydrogels are very much known for their exceptional mechanism of water absorption, retention, and release. Such water absorbency and release have created various applications, especially in the agricultural sector. Hydrogel absorption capabilities depend on the chemical structure and density of crosslinking and other environmental conditions such as pH and ionic strength. For instance, hydrogels can absorb water mainly based on the osmotic pressure difference due to the presence of hydrophilic functional groups such as -COOH and $-SO_3H$ (Wang and Wang 2010; Rashid and Hashim 2021). Hydrated, these materials can swell tremendously to have a gel-like consistency that maintains moisture for a long time to reduce irrigation requirements (Vashuk et al. 2001). The amount of moisture released by hydrogels depends on temperature and humidity which provides plants with a sustainable supply of moisture, thus optimizing growth conditions and hence avoiding water stress (Díaz-Marín et al. 2024; Chin et al. 2023). Some factors influencing absorption and desorption processes include formulation as well as the structure of the hydrogels, which significantly enhances their performance in agricultural fields, hence making hydrogels an integral part of sustainable agricultural practices that efficiently use water (Díaz-Marín et al. 2024).

The three classification groups in agricultural hydrogels are natural, synthetic, and hybrid hydrogels. Natural hydrogels are derived from biopolymers such as cellulose, chitosan, or alginate; these materials possess properties that include biodegradability, non-toxicity, and the ability to improve soil structure with simultaneous water conservation. These compounds are very helpful in sustainable practices since they improve water retention and encourage the growth of plants in arid environments (Buragohain 2024; Palanivelu et al. 2022). However, synthetic hydrogels are typically made from petroleum and include polymers like polyvinyl alcohol and polyacrylamide. Although these materials are designed to have certain qualities, such as greater mechanical strength and water absorption, their slow rates of disintegration do pose environmental problems. In the end, hybrid hydrogels combine natural and synthetic elements to take advantage of the benefits of each. They are often subjected to dual crosslinking techniques to endow them with desirable properties such as enhanced elasticity and recovery after deformation, thus finding applications in various agricultural sectors (Palanivelu et al. 2022). This classification also highlights the diversity of hydrogels in tackling water scarcity and enhancing agricultural productivity in diverse environments.

3. Hydrogels in Agriculture

3.1 Water Management

Hydrogels are absorbent materials that can hold 400 to 1500 times their dry weight in water. They promise to be an excellent tool for improving irrigation management in agriculture, especially in arid and semi-arid regions that experience water scarcity (Abdallah 2019). Hydrogels release water slowly to the plant roots, which reduces the rate of evaporation, deep seepage, and runoff; therefore, increasing irrigation efficiency and providing uniform soil moisture even during drought. Drought reduces soil water levels, causing water stress in plants and leading to excessive production of reactive oxygen species (ROS). These oxygen radicals trigger lipid peroxidation, damaging cell membranes and disrupting essential functions. If not controlled by the plant's system of antioxidant defense, oxidative stress can cause cell damage and low plant health. This can negatively affect plant anatomy, leading to shorter plant height, smaller leaf areas, and damage to the leaves. Hydrogel application has been shown to enhance the available water content in the soil by up to 49% and improve WUE by 41% in sandy soils and 67% in silty clay loam soils, which means that there is a substantial reduction in wastage of water (Bai et al. 2010). Hydrogels are most effective in coarse-textured sandy soils, where they improve soil physical properties such as aggregate stability, infiltration rate, and hydraulic conductivity. These enhancements further augment efficient water use and losses due to evaporation. Besides enhancing soil conditions, hydrogels have enhanced crop yields by 11–55% in diverse crops such as sunflower, wheat, onion, rice, and banana (Kumar Naik et al. 2020). Therefore, hydrogels exhibit strong potential as a sustainable means of improving water management, with their performance depending on soil type, hydrogel concentration, and crop needs.

In recent studies researchers have designed a biodegradable water-storing hydrogel to assist farmers in fighting droughts in a sustainable manner. Composed of plant-derived materials such as carboxymethylcellulose and hydroxyethyl cellulose , cross-linked with citric acid, the hydrogel is like a reservoir for water they soak up moisture, store it, and release it slowly to the plants according to their requirement.

When incorporated into soil, it enhanced soil structure by enhancing porosity by 4% and decreasing density by 8.6%, creating improved conditions for root growth. In cucumber, tomato, and mung bean plant trials, this hydrogel-treated soil enhanced water use efficiency by 25–45%, increased seed germination, and increased chlorophyll content by 17%, supporting healthier growth and improved yields. This helps to prevent environmental pollution but also cuts down on fertilizer expenses for farmers. Unlike conventional plastic-based alternatives, this hydrogel naturally decomposes over time, making it a more sustainable option particularly for farmers in arid regions (Bai et al. 2025).

3.2 Soil Health and Fertility

Hydrogels can be seen as playing a key role in improving soil quality by enhancing structure and aeration. Increases in soil porosity, as well as reductions in bulk density, enhance permeability, leading to better aggregation and improved airflow. This develops an optimal environment for plant roots to thrive. Hydrogel improves the structure and aeration of soil because it increases the stability of aggregate soil, with up to 35% increases in water-stable aggregates at higher hydrogel concentrations. It also increases the soil's resistance to erosion and compaction - hydrogel increases infiltration rates and reduces hydraulic conductivity, which can limit surface runoff and soil loss (Chirino et al. 2011). In addition, hydrogels also prevent soil erosion by binding soil particles together, thus reducing surface runoff and minimizing damage from water or wind erosion. They resist compaction at deeper layers of the soil while maintaining their ability to absorb water, further supporting a healthier soil structure. Potassium and nitrogen ions can also be used for making fertilizer components as hydrogels. Specifically, chemicals held in the polymer matrix are not washed away at once but are released to the soil gradually, hence available for uptake by the plant (Konzen et al. 2017). The combined application of hydrogels with some of the fertilizers, namely, traditional herbaceous NPK, superphosphate, and potassium chloride was studied. Observations made on seedlings of Mimosa Scabrella showed that it grew better due to an increase in water retention capacity and nutrient uptake. Incorporation of hydrogels within the soil can improve its physical, chemical as well as biological characteristics positively and thus makes the soil more amiable in supporting plant growth, especially within drought-prone areas.

Hydrogels are critical for improving soil fertility and crop health due to their ability to enhance soil structure, nutrient use efficiency , and water retention. In soybean-wheat cropping systems, research in the Journal of the Indian Society of Soil Science indicated that the use of Pusa hydrogel at a level of 2.5 kg ha^{-1} promoted crop yields under water deficit conditions and enhanced soil health parameters (SHI: 0.77–0.93) (Biswas et al. 2023). Same observations were recorded in research on deficit irrigation superabsorbent hydrogels, where an application of 0.3% hydrogel at 85% levels of irrigation maintained lettuce production while improving the water use efficiency (WUE) by 15% to 20%, particularly in clay soils (Abdelghafar et al. 2024).

Since hydrogels act as reservoirs for water, they are highly beneficial in arid regions since they effectively reduce evaporation and deep percolation losses (Abdelghafar et al. 2024; Adjuik et al. 2022). They also enhance hydro-physical properties of soils such as hydraulic conductivity and water availability by stable formation of aggregates favoring root growth (Adjuik et al. 2022). Besides, hydrogels also improve nutrient uptake through the reduction of fertilizer leaching, as reported in controlled-release systems where they maximize nitrogen and phosphorus levels for crops (Biswas et al. 2023; Abdelghafar et al. 2024). Application favors healthy microbial life through ensuring stable soil water content that maximizes decomposition of organic matter and nutrient cycling. While synthetic hydrogels are more long-lasting, bio-based hydrogels provide environmental options, even if hybrid formulations can marry longevity with sustainability (Adjuik et al. 2022). Irrespective of texture in the soil, hydrogels show consistent benefits, with the greatest improvements in crop attributes such as greater fresh weight and chlorophyll content being shown by clay soils (Abdelghafar et al. 2024). The technology offers a scalable and cost-effective means of sustainable agriculture, commercially reducing water stress while enhancing agricultural yield in water-restricted ecosystems (Biswas et al. 2023; Abdelghafar et al. 2024; Adjuik et al. 2022).

3.3. Plant Growth and Productivity

Promising results for seed germination and plant growth, especially when subjected to stress conditions from water, are hydrogel treatments. A superabsorbent hydrogel was derived from acrylamide-acrylic acid-starch, mixed with polyethylene glycol, enhancing maize seed germination rates as well as that of the young plants (Camele et al. 2020). Regarding the fresh and dry weights of the leaves and roots, the hydrogel used exhibited better hydration and development (Cheng et al. 2004). Hydrogels are gel-like substances referred to as "root watering crystals," "water retention granules," or "raindrops" because they are designed to absorb and then slowly release water. The application increases soil water storage, enhances water availability, and improves leaf water content, leading to faster plant growth rates. Therefore, in water-stressed environments, hydrogels contribute to reducing water loss, ensuring steady hydration, and supporting a healthy plan (Kramer 1988) because the effects of hydrogel treatment can vary depending on the type of seed and the surrounding conditions, it is not consistent throughout the germination phase. They are therefore a crucial instrument for sustainable agriculture. Development found that a superabsorbent hydrogel made from acrylamide, acrylic acid, and starch, combined with polyethylene glycol (PEG), positively influenced maize seed germination and the growth of young plants compared to seeds that were not treated with the hydrogel (Ismail et al. 2013). In this review, we have highlighted various natural polymer-based strategies for controlled release systems in agriculture, as depicted in Figure 2.

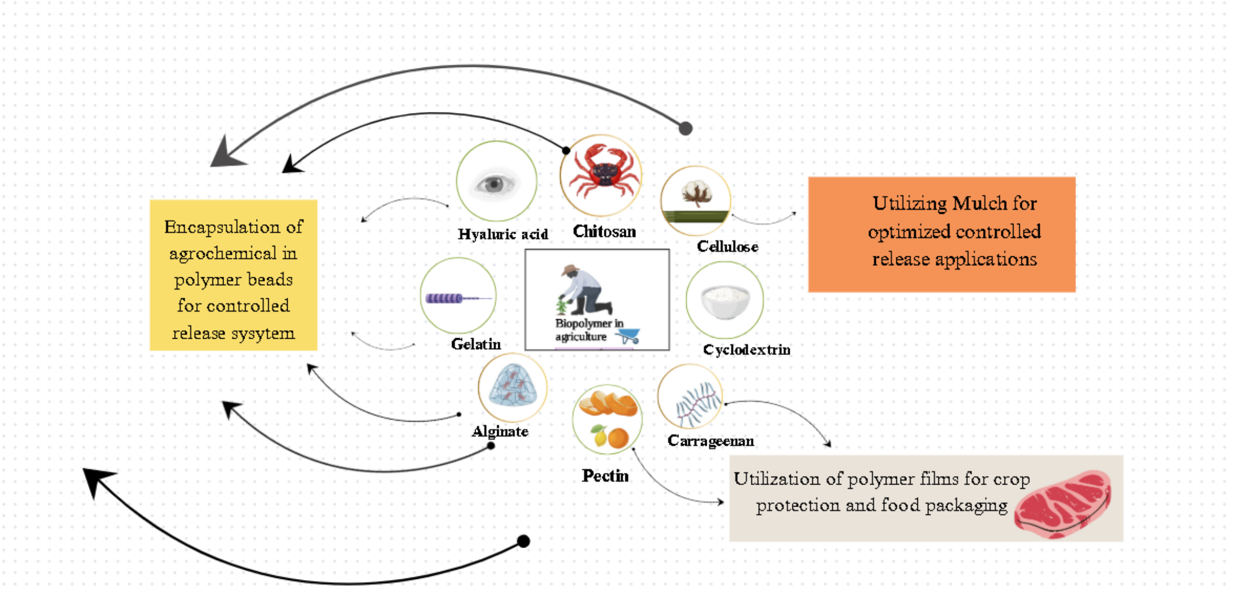

Figure 2: Natural polymer-based controlled release systems offer an eco-friendly solution for effective pest management, ensuring long-lasting protection for crops while safeguarding the environment.

3.4 Controlled Release of Nutrients and Agrochemicals

Pesticides and fertilizers are two of the most important agrochemicals, widely used in modern agriculture and horticulture for enhancing crop productivity. Nevertheless, pesticides, when introduced deliberately into the environment, significantly contribute to environmental pollution through several pathways. Among the most problematic pesticide classes are organochlorines, organophosphates, and carbamates (Van Dyk and Pletschke 2011). Due to their high potential for leaching and volatilization, these chemicals often contaminate both groundwater and surface water. Hydrogels may provide carriers and act as a physical barrier to the soil surface for pesticides and fertilizers. These act, therefore, as slow-release substances and prevent leaching as well as volatilization as a result of the tiny pore network size in the structure of hydrogels. Pesticides play a very complex and essential role in modern agriculture by helping to safeguard food production and ensure food security. However, their use also brings great challenges associated with environmental sustainability and human health in reducing environmental pollution, pesticides play a vital role in protecting crops from pests and diseases, which helps keep agricultural productivity stable and safeguards food supplies (Ramachandran et al. 2024). Many of the active ingredients (AIs) in pesticides are lipid-soluble, enabling them to dissolve cell membranes and target specific biological processes within pests. This characteristic of pesticides ensures their potency in controlling harmful organisms but has also been characterized as causing them to persist in the environment, potentially harming human health and non-target species (Kaur et al. 2019). Figure 3 illustrates the synthesis of a low-cost hydrogel using starch and citric acid, designed to encapsulate nutrients such as nitrogen and potassium.

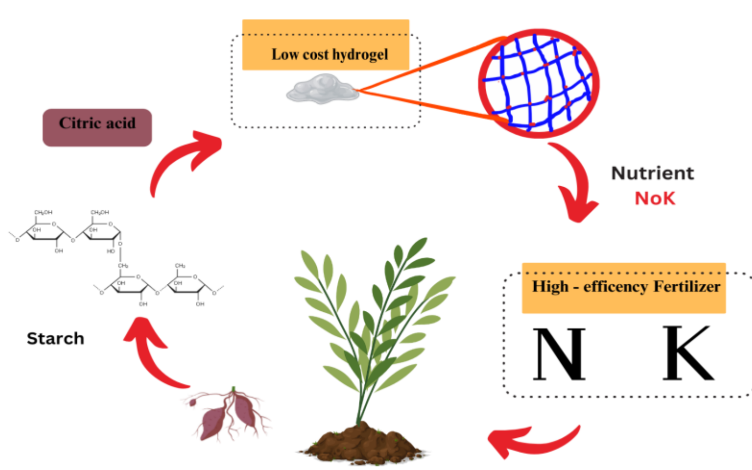

Figure 3: The cyclic process of developing a low-cost hydrogel derived from starch and citric acid for use as a high-efficiency fertilizer.

4. Challenges and Limitations

Hydrogels might benefit agriculture through better moisture retention in soil and even nutrient delivery; they need to be more economically and at-scale feasible. Conventional hydrogels prepared from polymers such as polyacrylamide can potentially be more economical. Conventional synthetic hydrogels do have an environmental and an economic concern since most durable hydrogels may degenerate into harmful microplastic. However, given the fact that biodegradable hydrogels derived from natural polymers such as cellulose and chitosan are more environmentally friendly, their widespread application is limited by their expensive production costs and complex manufacturing processes. These monetary factors, the uncertainty of the long-term advantages, and the ignorance of the advantages of hydrogel technology can discourage farmers from using them. Advances in material science to create affordable biodegradable hydrogels would also be necessary, as would extensive education and training programs for farmers about its potential benefits and safe usage practices (Wu et al. 2023).

5. Recent Advances and Innovations

A recent and significant advancement in sustainable agriculture is the use of biodegradable and eco-friendly hydrogel, which can enhance soil water and nutrient retention while reducing negative environmental effects. Hydrogels based on biopolymers, such as those composed of starch, chitosan, and alginate, exhibit tremendous potential due to their non-toxicity and biodegradability. These hydrogels absorb huge volumes of water and then gradually release the water to the soil; hence, the moisture available to vegetation is increased with minimal requirements for frequent irrigation. Biopolymer-based hydrogels play a significant role in agriculture, where they are utilized as soil conditioners (Tariq et al. 2023). Furthermore, using biodegradable hydrogels complies with environmental conservation goals since they will reduce reliance on synthetic materials that cause soil pollution. Research shows that "application of biodegradable biopolymer hydrogels reduces the frequency of land irrigation and increases its ability to infiltrate and retain water" (Skrzypczak et al. 2020). But though these ideas are quite promising, more needs to be done in terms of improving their formulation for different agriculture practices and completely understanding the long-term impact on soil health as well as the ecosystem.

Integration of hydrogels with precision agriculture and IoT provides novel solutions for improving resource efficiency and crop management. Hydrogels can absorb large quantities of water and can be incorporated with IoT sensors for real-time soil moisture monitoring to allow the precise scheduling of irrigation to prevent water waste. In arid regions where water is limited, hydrogels, which are known for their ability to collect and gradually release water into the soil like "mini-reservoirs," allowing farmers to manage irrigation based on real-time soil conditions rather than fixed schedules (Qingdao SOCO New Material Co., Ltd. 2024; Khan 2024). IoT technologies complement this by introducing advanced tools to monitor, save, and utilize water effectively throughout the growing season (Bouni et al. 2024). Precision agriculture is supported by smart hydrogels that respond to environmental changes by enabling adaptable crop management strategies (Atalla et al. 2023). The combination of hydrogels with the Internet of Things makes agriculture a far more robust, effective, and sustainable industry (Qingdao SOCO New Material Co., Ltd. 2024).

6. Future Trends

The opportunities for highly scalable application of hydrogels in agriculture are huge and are determined by their capacity to improve the retention of water and nutrient supply in different soil types. The global hydrogel market is expected to grow from approximately USD 29.18 billion in 2023 to nearly USD 47.47 billion by 2030 with a compound annual growth rate of 7.2% over the forecast period. The demand for hydrogels is growing rapidly, fueled by their use in agriculture and environmental cleanup. By incorporating natural and biodegradable polymers, these materials help tackle environmental challenges while improving how water is managed in farming (MAXIMIZE MARKET RESEARCH PVT. LTD. 2024). Scalable methods like polymerizing hydrophilic monomers and cross-linking macromers make it possible to produce hydrogels on an industrial scale (Bashir et al. 2020). Hydrogels are very versatile, which makes them ideal for a range of agricultural applications, from mitigating pollution to improving soil quality (SPHERICAL INSIGHTS LLP 2024). To help farmers grow more crops while making better and more efficient use of resources, these materials will become indispensable as farming technologies develop (Mordor Intelligence 2024).

To encourage hydrogels in sustainable agriculture, some policies could be introduced that would improve water management, soil health, and farmer education. Subsidies or financial support would make it easier for farmers to incorporate hydrogel technology into their traditional practices. Research has indicated that hydrogels can increase crop growth significantly, enhancing both shoot and root biomass (Agaba et al. 2011). Support for the development of biodegradable hydrogels can further reduce environmental impact while making agriculture sustainable (Dar et al. 2017).

Hydrogels also help soil to absorb water thus reducing the fertilizer running off and increasing crop yields (Agbna and Zaidi 2025). The education of farmers through hydrogel application training can loosen every barrier to the successful adaptation process. Innovation can be promoted through these learning opportunities, and policymakers will assist farmers in constructing strong and more climate-resilient agricultural systems.

CONCLUSION

Hydrogels represent an innovative breakthrough for sustainable agriculture, addressing one of the most pressing needs, and solving water scarcity and soil degradation issues while maximizing nutrient availability. It maintains and regulates water content so that there is an ideal supply and release for efficient crop development and healthy soils. It is therefore very beneficial in arid and semi-arid areas. Although synthetic hydrogels are durable and effective, biodegradable alternatives derived from natural polymers are needed due to their adverse environmental consequences. Technical and financial barriers to adoption are present but advances in material science and increased awareness could make hydrogel technology more accessible to farmers. By using eco-friendly practices and precision agriculture, hydrogels can greatly aid in the creation of sustainable farming systems that balance productivity and environmental preservation. Further study and supportive legislation are needed to fully realize hydrogels' potential to transform agriculture into a more environmentally friendly and sustainable industry.

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Conflict of Interest

The authors declare no conflict of interest.

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