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Hydrogels as a key solution for sustainable agriculture: Exploring water retention and soil improvement

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Abstract
Hydrogel technology offers promising solutions for sustainable agriculture by addressing critical challenges such as water scarcity, soil degradation, and inefficient nutrient management. Hydrogels, which can absorb and retain large amounts of water, help improve soil moisture retention, reduce irrigation needs, and enhance crop yields, particularly in regions facing drought or irregular rainfall. This review explores the mechanisms, types, applications, and potential benefits of hydrogels in agriculture, emphasizing their role in improving water-use efficiency, preventing soil erosion, and minimizing fertilizer runoff. However, the widespread adoption of hydrogel technology faces challenges, including high initial costs, concerns over the environmental impact of non-biodegradable synthetic hydrogels, and limited accessibility for smallholder farmers. To overcome these obstacles, future research is focused on developing biodegradable, cost-effective and customized hydrogels tailored to specific soil types and climates. Additionally, integrating hydrogels with precision agriculture tools, such as IoT sensors and automated systems, offers new opportunities for optimizing their performance. Despite these challenges, hydrogels hold the potential to revolutionize water management and nutrient delivery in agriculture, offering significant environmental and economic benefits. Continued innovation, alongside supportive policies and educational initiatives, will be essential for maximizing the potential of hydrogels in fostering sustainable agricultural practices worldwide.

Keywords: Hydrogel technology, sustainable agriculture, water retention, soil improvement, irrigation, crop productivity

1. Introduction

Agriculture is facing growing challenges due to climate change, water scarcity, and soil degradation. With the global population projected to reach 9.7 billion by 2050, the demand for food will increase significantly, putting pressure on agricultural systems. At the same time, agricultural practices are exacerbating environmental stress, particularly in terms of water usage and soil health. Around 70% of global freshwater use is dedicated to agriculture, but much of this water is wasted due to inefficient irrigation systems. Furthermore, soil degradation affects about 33% of the Earth's land area, undermining crop productivity and long-term agricultural sustainability [1, 2].

Hydrogel technology, characterized by its water-absorbing and retaining properties, offers a promising solution to these challenges. Hydrogels are polymers capable of absorbing and storing large amounts of water, releasing it gradually to maintain soil moisture and improve water efficiency. These materials not only conserve water but also enhance soil structure, reducing soil compaction and promoting better root growth, which can improve crop yields. As a result, hydrogel technology is increasingly being recognized as a key tool for sustainable agriculture, particularly in regions experiencing water scarcity and soil degradation [1, 2].

In India, which has a population exceeding 1.4 billion, agriculture plays a vital role, employing more than 50% of the workforce and contributing 17-18% to the national GDP. However, India faces severe water stress, with 54% of its agricultural land relying on irrigation and significant soil degradation in many regions. The adoption of hydrogel technology in India could help address these challenges.

For example, states like Rajasthan, Maharashtra, and Tamil Nadu, which experience frequent droughts, can benefit from hydrogels by improving water retention and reducing the need for frequent irrigation. This could lead to better yields, even in arid conditions [3]. Hydrogels are already being applied in several regions of India, showing promising results in water conservation and soil improvement. However, high initial costs, lack of awareness, and the need for region-specific solutions remain barriers to widespread adoption. Thus, hydrogel technology holds significant potential to improve water efficiency and soil health, making it a key tool for achieving sustainable agricultural practices globally and in India, where water scarcity and soil degradation are pressing issues [4, 5].

2. Hydrogel Technology: Mechanisms of Action

Hydrogels are three-dimensional, water-absorbing polymers that can retain large amounts of water within their structure. Their unique properties make them highly effective in improving water retention and enhancing soil health in agricultural systems. The mechanisms through which hydrogels function in agriculture primarily involve water absorption and release, soil conditioning, and nutrient retention, each of which plays a crucial role in supporting plant growth and improving agricultural productivity [6].

2.1 Water Absorption and Retention

The most prominent characteristic of hydrogels is their ability to absorb and hold large volumes of water. Hydrogels can retain several hundred times their weight in water, depending on the type of polymer and its formulation. This property is primarily due to the hydrophilic (water-attracting) nature of the polymer chains that make up the hydrogel structure. These polymers form a network of cross-linked chains that create a highly porous structure capable of trapping water molecules. Once water is absorbed, hydrogels swell and retain moisture in the soil for extended periods. During dry spells or drought conditions, the hydrogel gradually releases stored water to the surrounding soil, providing consistent moisture to plants. This action ensures that crops receive adequate hydration even when irrigation is sparse or during periods of low rainfall, reducing dependency on frequent irrigation [6, 7].

2.2 Water Release

Hydrogels function as **a** controlled-release system for water. The amount of water released by a hydrogel depends on the moisture content of the surrounding soil. In dry conditions, the hydrogel releases water into the soil, maintaining optimal moisture levels for plant roots. Conversely, when the soil is wet, the hydrogel absorbs excess water, preventing waterlogging and maintaining balanced soil moisture. This controlled release of water helps maintain a stable environment for plants, reducing the stress caused by alternating wet and dry conditions. It also minimizes water loss through evaporation, especially in arid regions, making hydrogels an excellent solution for water conservation in agriculture [6, 7].

2.3 Soil Conditioning and Structure Improvement

In addition to water retention, hydrogels help improve the physical structure of the soil. When incorporated into the soil, hydrogels help bind soil particles together, enhancing soil aggregation. This process reduces soil compaction and improves the porosity of the soil, allowing for better aeration, root penetration, and water infiltration. Hydrogels also aid in improving soil structure in sandy soils, where water retention is typically poor, and in clay soils, where drainage is often inadequate. By creating a more uniform distribution of moisture, hydrogels enable plant roots to access water and nutrients more effectively, supporting healthier and more resilient crops [6].

2.4 Nutrient retention and slow release

Some hydrogels are designed to not only retain water but also absorb and hold nutrients such as fertilizers and minerals. These hydrogels can then slowly release nutrients to the plants over time, providing a consistent supply of essential elements. This reduces the risk of nutrient leaching, which is common in conventional farming systems, particularly when excessive irrigation leads to the loss of valuable nutrients from the soil. By optimizing the release of both water and nutrients, hydrogels promote efficient plant growth while reducing the need for chemical fertilizers and preventing environmental pollution from nutrient runoff [7-9].

2.5 Protection against soil erosion

Hydrogels also play a role in protecting against soil erosion. By improving soil aggregation and water retention, they help maintain the stability of the soil, particularly in areas prone to wind or water erosion. In regions with heavy rainfall or high winds, the presence of hydrogels can reduce soil displacement, preserving topsoil and preventing degradation [7].

3. Types of hydrogels used in agriculture

Hydrogels used in agriculture can be broadly classified into synthetic hydrogels and natural hydrogels, based on their origin and chemical composition. Both types offer distinct advantages and challenges, and their suitability depends on factors such as environmental impact, soil conditions, and cost-effectiveness. This section discusses the various types of hydrogels employed in agriculture, their properties, and their potential applications [10].

3.1 Synthetic Hydrogels

Synthetic hydrogels are chemically engineered materials that are designed to have superior water absorption and retention capabilities. These hydrogels are typically made from synthetic polymers that are cross-linked to form a three-dimensional structure capable of holding large amounts of water [7, 8].

Examples of synthetic hydrogels include:

- **Polyacrylamide (PAM)**

Polyacrylamide is one of the most commonly used synthetic hydrogels in agriculture. It is effective at absorbing water and releasing it slowly to the soil, making it ideal for improving water retention in dry soils. PAM is particularly useful in irrigation systems**,** where it helps to reduce water usage by extending the intervals between irrigation cycles. However, concerns regarding its environmental impact, especially its non-biodegradability, have prompted research into more sustainable alternatives [7, 8].

- **Polyethylene Glycol (PEG)**

Polyethylene glycol is another synthetic polymer that is used to enhance water retention in soils. PEG is known for its ability to form hydrophilic interactions with water, allowing it to maintain soil moisture for extended periods. It is often used in arid regions or in areas where efficient water management is critical. While PEG has a high water-holding capacity, its cost can be a barrier for widespread adoption in low-income farming areas [7, 8].

- **Polyvinyl Alcohol (PVA)**

Polyvinyl alcohol is a synthetic polymer that is highly soluble in water. When used in hydrogels, it enhances water absorption and release. PVA-based hydrogels are typically more stable and resistant to degradation compared to other synthetic hydrogels, making them suitable for long-term agricultural applications. These hydrogels are commonly used in greenhouse farming or in areas requiring stable moisture levels [8].

3.2 Natural Hydrogels

Natural hydrogels are derived from natural polymers, such as polysaccharides, proteins, and other organic materials. These hydrogels are generally biodegradable and environmentally friendly, making them more sustainable options for agricultural applications.

Examples of natural hydrogels include

- **Starch-based Hydrogels**

Starch-based hydrogels are produced from natural starches derived from plants like corn, potato, and wheat. These hydrogels are biodegradable and can absorb significant amounts of water. They are considered an eco-friendly alternative to synthetic polymers and are used to improve water retention in soils, particularly in organic farming. Starch-based hydrogels also help improve soil structure and prevent soil erosion [8].

- **Cellulose-based Hydrogels**

Cellulose is the most abundant natural polymer, and cellulose-based hydrogels are increasingly being explored for agricultural use. These hydrogels are biodegradable and derived from plant fibers like cotton or wood. They offer good water retention properties and improve soil aeration by reducing compaction. Cellulose-based hydrogels are particularly useful in improving soil quality in sandy or loamy soils [8].

- **Alginate-based hydrogels**

Alginate hydrogels are made from alginic acid, which is extracted from seaweed. These hydrogels are biocompatible and biodegradable, making them an excellent choice for sustainable agriculture. Alginate-based hydrogels can enhance water retention and reduce the leaching of nutrients from the soil. They are often used in hydroponic systems and for plant root coatings to ensure consistent moisture supply [8].

- **Chitosan-based Hydrogels**

Chitosan is derived from chitin, a natural polymer found in the shells of crustaceans like shrimp and crabs. Chitosan-based hydrogels have been shown to have excellent water-holding capacity and are also effective at enhancing soil fertility by facilitating nutrient uptake. These hydrogels are biodegradable, making them environmentally friendly and suitable for use in organic farming practices [8].

3.3 Hybrid Hydrogels

Hybrid hydrogels are a combination of synthetic and natural polymers, designed to combine the advantages of both types. These hydrogels aim to provide superior water retention and enhanced biodegradability [8].

Example of Hybrid Hydrogels:

- **Starch and polyacrylamide-based hydrogels:** By combining starch, a natural polymer, with synthetic polyacrylamide, hybrid hydrogels can offer improved water retention capabilities while maintaining biodegradability. These hydrogels can be customized to have specific properties such as enhanced swelling capacity or faster water release, depending on the agricultural requirements [8].

Table 1: Summarizing common types of natural hydrogels

Type of Hydrogel	Source	Chemical Composition	Characteristics	Uses
Starch-Based Hydrogels	Plants (e.g., corn, potato)	$(C_6H_{10}O_5)n$ (Polysaccharide)	Biodegradable, hydrophilic, non-toxic, moderate water retention	Used for water retention in soil, controlled release of nutrients.
Cellulose-Based Hydrogels	Plants (e.g., cotton, wood)	$(C_6H_{10}O_5)n$ (Polysaccharide)	Renewable, biodegradable, good moisture retention, hydrophilic	Soil improvement, water retention, enhancing plant growth.
Chitosan-Based Hydrogels	Crustacean shells (e.g., shrimp)	$(C_6H_{11}NO_4)n$ (Polysaccharide)	Biodegradable, antimicrobial, good moisture retention	Used in agriculture for soil conditioning and seed coating.
Alginate Hydrogels	Brown seaweed (e.g., kelp)	$(C_6H_7NaO_6)n$ (Polysaccharide, Sodium Alginate)	Biodegradable, hydrophilic, gel-forming, good water retention	Used for soil conditioning, water retention, and fertilizer delivery.
Gelatin-Based Hydrogels	Animal collagen (e.g., pig, bovine)	$(C_{60}H_{106}N_{14}O_{19})n$ (Protein-based polymer)	Biodegradable, thermosensitive, good water holding capacity	Used in controlled-release fertilizers, water retention.
Pectin-Based Hydrogels	Fruits (e.g., citrus, apples)	$(C_6H_{10}O_6)n$ (Polysaccharide)	Biodegradable, water-absorbing, hydrophilic	Used for soil improvement and controlled release of nutrients.

Table 2: Summarizing common types of synthetic hydrogels

Type of Hydrogel	Chemical Composition	Characteristics	Uses
Polyacrylamide (PAM)	$(C_3H_5NO)n$	High water absorption, non-biodegradable, strong crosslinking	Soil conditioning, erosion control, and water retention.
Polyethylene Glycol (PEG)	$H_4C_6O_{24}$	Non-toxic, water-soluble, moderate retention capacity	Used in controlled irrigation and soil conditioning.
Polyvinyl Alcohol (PVA)	$(C_2H_4O)n$	High water absorption, non-biodegradable, thermoresistant	Water retention, fertilizer carrier, and soil conditioner.
Poly(N-isopropylacrylamide) (PNIPAM)	$(C_3H_5NO)n$ (with $-CH_3$ group)	Thermoresponsive, high water absorption capacity	Used in responsive irrigation and controlled water release systems.
Polyacrylic Acid (PAA)	$(C_3H_5CO_2H)n$	Super absorbent, high swelling index, non-biodegradable	Used in agriculture for soil moisture retention and erosion control.
Polysaccharide-based (Synthetic)	Derived from synthetic modification of natural polysaccharides	Biodegradable, customizable water retention properties	Used in precision agriculture for moisture control and nutrient release.

Table 3: Summarizing common types of hybrid hydrogels

Type of hydrogel	Chemical Composition	Characteristics	Uses
Starch-Polyacrylamide (Starch-PAM)	Starch and Polyacrylamide	Biodegradable, high moisture retention, improved mechanical strength	Soil moisture retention, erosion control, and water conservation.
Cellulose-Acrylic Acid Hydrogels	Cellulose and Polyacrylic Acid	High swelling capacity, biodegradable, tunable properties	Used for water retention and as a carrier for slow-release fertilizers.
Chitosan-Polyethylene Glycol (Chitosan-PEG)	Chitosan and Polyethylene Glycol	Biodegradable, water-soluble, enhanced moisture retention	Used for water retention, soil conditioning, and enhanced nutrient delivery.
Alginate-Polyacrylamide (Alginate-PAM)	Sodium Alginate and Polyacrylamide	Improved gel strength, biodegradable, high water retention	Soil improvement, erosion control, water retention.
Gelatin-Polyvinyl Alcohol (Gelatin-PVA)	Gelatin and Polyvinyl Alcohol	Biodegradable, thermoresponsive, good moisture holding capacity	Used for seed coating, water retention, and nutrient delivery.
Chitosan-Polyvinyl Alcohol (Chitosan-PVA)	Chitosan and Polyvinyl Alcohol	Enhanced moisture retention, biodegradable, good mechanical strength	Used for controlled water release, soil improvement, and seed protection.

4. Applications of hydrogels in sustainable agriculture

Hydrogels are emerging as a vital tool in sustainable agriculture, offering significant benefits in areas such as water conservation, soil improvement, and nutrient management. Their ability to absorb and retain large amounts of water, release it gradually, and enhance soil structure makes them an effective solution for improving agricultural productivity while minimizing environmental impacts. This section explores the various applications of hydrogels in sustainable agriculture [8].

4.1 Water conservation and irrigation efficiency

Water scarcity is one of the most pressing challenges in agriculture, particularly in regions with irregular rainfall or where irrigation is the primary source of water. Hydrogels can significantly improve water use efficiency by enhancing the soil's ability to retain water, thus reducing the frequency and amount of irrigation required [9].

- **Water Retention in Soil:** Hydrogels are mixed into the soil to absorb water during irrigation or rainfall. This absorbed water is then slowly released to the plants over time, ensuring a more consistent moisture supply. This is particularly beneficial in arid and semi-arid regions where water is a limited resource [9].
- **Reduction in Irrigation Frequency:** With hydrogels in the soil, crops need less frequent irrigation, as the hydrogel helps maintain moisture levels for extended periods. This reduces the overall water demand in farming systems [9].

4.2 Soil improvement and erosion control

Hydrogels are particularly effective in improving soil structure, making them valuable in combating soil degradation and erosion, which are common problems in many agricultural regions [17].

- **Improved Soil Aggregation:** By absorbing water and swelling, hydrogels help bind soil particles together, reducing soil compaction and improving soil aeration**.** This makes it easier for roots to penetrate the soil and access water and nutrients, promoting healthier plant growth [9].
- **Prevention of Soil Erosion:** In areas prone to erosion, hydrogels help retain moisture in the soil, preventing it from drying out and becoming loose. This results in better soil cohesion and stability, reducing the risk of erosion due to wind and water [17].

In regions with loose, sandy, or degraded soils, hydrogels improve the soil's physical properties, promoting better root growth and reducing the risk of erosion. They are also helpful in protecting against wind erosion in dryland [11].

4.3 Enhanced crop yield and growth

Hydrogels improve crop yield by ensuring that plants receive a consistent supply of water, even in periods of drought or limited irrigation. This is particularly crucial in areas with erratic rainfall patterns or during drought conditions when crops are at risk of water stress.

- **Consistent Moisture Supply:** Hydrogels help provide plants with continuous moisture, reducing water stress and allowing crops to grow more efficiently. For example, in crops like wheat**,** maize and sunflower**,** hydrogels have been shown to increase yield by ensuring a steady water supply to the roots [10].
- **Root Development and Plant Health:** By improving water retention and soil aeration, hydrogels support better root development and overall plant health. This leads to improved nutrient uptake, better growth, and higher yields [10].

4.4 Fertilizer and Nutrient Management

Hydrogels can also be used to improve the efficiency of fertilizers by preventing nutrient leaching and ensuring that nutrients are available to plants when they are needed most. Some hydrogels are designed to absorb and retain nutrients along with water, releasing them gradually to the plants.

- **Slow-Release Fertilizers:** Hydrogels can be used to encapsulate fertilizers, ensuring a slow and controlled release of nutrients to the plant. This reduces the risk of nutrient runoff, which is a major environmental concern in conventional farming systems. The slow release also helps in maintaining a steady supply of nutrients to the plants over time [10].
- **Reduced Fertilizer Waste:** By improving water and nutrient retention in the soil, hydrogels reduce the need for frequent fertilization, leading to cost savings for farmers and a reduction in the environmental impact of over-fertilization [11].

4.5 Hydroponic and Greenhouse Farming

Hydrogels are increasingly used in hydroponic systems and greenhouse farming as they provide an efficient means of maintaining consistent moisture and nutrient levels in controlled environments.

- **Hydroponics:** In soilless farming systems like hydroponics, hydrogels can be used to retain water and nutrients, ensuring that plants receive adequate hydration and nutrients for growth without the need for large volumes of water [12].
- **Greenhouse Farming:** Hydrogels are used in greenhouses to manage water more efficiently, reducing the need for

irrigation systems that can be costly and resource-intensive [12].

4.6 Seed coating and germination enhancement
Hydrogels are used as seed coatings to enhance germination rates and seedling establishment, particularly in dry or drought-prone areas.

- **Seed Coating:** Seeds coated with hydrogels are able to absorb water more effectively during germination. This ensures that seeds have a steady supply of moisture during the early stages of growth, improving germination rates and seedling survival [13, 14].
- **Enhanced Germination:** In regions where rainfall is erratic, hydrogel-coated seeds can germinate faster and develop stronger root systems, ensuring better crop establishment and early growth [14].

5. Environmental and Economic Considerations
The adoption of hydrogel technology in agriculture presents both environmental and economic opportunities and challenges. While hydrogels offer significant benefits for sustainable agriculture, their environmental impact, cost-effectiveness, and long-term viability must be carefully considered. This section explores the key environmental and economic aspects of hydrogel use in agriculture [15].

5.1 Environmental Considerations
Hydrogels, particularly synthetic variants, can have both positive and negative environmental impacts depending on their composition and disposal methods.

Positive Environmental Impacts

- **Water Conservation:** One of the most significant benefits of hydrogels is their ability to conserve water. By improving water retention in soils, hydrogels help reduce irrigation needs, especially in drought-prone or water-scarce regions. This leads to less water wastage and more efficient water usage in agriculture, which is crucial as freshwater resources become increasingly scarce [15, 16].
- **Reduction in Soil Erosion:** Hydrogels help improve soil structure and prevent soil erosion by enhancing soil aggregation. This is particularly beneficial in areas prone to wind or water erosion. By retaining moisture in the soil, hydrogels help maintain soil stability, protecting topsoil and reducing soil degradation [15, 16].
- **Decreased Fertilizer Runoff:** Hydrogels can absorb and release nutrients along with water, reducing the need for excessive fertilizer applications. This can help mitigate nutrient runoff, a major contributor to water pollution and eutrophication in nearby water bodies. By preventing nutrient leaching, hydrogels contribute to reducing environmental contamination [15].

Negative Environmental Impacts

- **Non-Biodegradability of Synthetic Hydrogels:** Many synthetic hydrogels, such as polyacrylamide (PAM), are not fully biodegradable, leading to potential long-term accumulation in the soil. Over time, these non-biodegradable materials could affect soil health and microbial communities, and their persistence in the environment could pose risks to ecosystems [16].
- **Microplastic Formation:** Some synthetic hydrogels, particularly those made from petroleum-based products, may break down into microplastics over time, leading to contamination of the soil and water. The gradual release of synthetic materials could negatively impact soil organisms and aquatic life. Therefore, ensuring the biodegradability of hydrogels is essential for minimizing their long-term environmental impact [17].
- **Resource Use in Production:** The production of synthetic hydrogels often involves energy-intensive processes and the use of chemicals, which could contribute to carbon emissions and pollution if not managed responsibly. However, some natural hydrogels (e.g., starch-based or cellulose-based) offer a more sustainable alternative with lower environmental footprints [27].

5.2 Economic Considerations
From an economic standpoint, hydrogels can provide significant benefits in terms of cost savings, productivity increases, and long-term sustainability. However, the initial cost of hydrogels and their economic viability for smallholder farmers must be considered.

Economic Benefits

- **Reduced Water and Irrigation Costs:** By significantly reducing water requirements and irrigation frequency, hydrogels can lower water bills for farmers. In regions where water is scarce or expensive, such as parts of India and Africa**,** hydrogels can be particularly beneficial in cutting costs associated with irrigation infrastructure and water sourcing [18, 19].
- **Improved Crop Yields:** Hydrogels enhance crop productivity by ensuring that plants have a steady supply of water and nutrients. This can result in higher yields, especially in areas with unreliable rainfall or limited water availability. Increased yields can improve farm profitability by maximizing the efficiency of water and nutrient inputs [18, 19].
- **Reduced Fertilizer Use:** Hydrogels can reduce the need for frequent fertilizer applications by providing slow-release nutrient delivery, leading to cost savings on fertilizers. This is particularly important for smallholder farmers who may struggle with the high cost of chemical fertilizers and the environmental impact of overuse [19].
- **Prevention of Crop Losses:** By improving water retention and reducing the risk of water stress, hydrogels help ensure a more consistent crop production cycle. This reduces the likelihood of crop failure due to drought, contributing to a more stable income for farmers, particularly in areas prone to erratic rainfall [19, 20].

Economic Challenges

- **High Initial Cost:** One of the primary barriers to the widespread adoption of hydrogels, especially in developing countries, is the high initial cost of hydrogel materials. While the long-term benefits of hydrogels (e.g., reduced irrigation and fertilizer costs) may outweigh the initial investment, smallholder farmers may struggle to afford the upfront costs, limiting access to this technology [20].
- **Limited Availability and Awareness:** In many regions, farmers may not be fully aware of the benefits or availability of hydrogels. Awareness campaigns and training programs are essential to ensure that farmers understand how to properly use hydrogels and optimize their benefits. Additionally, supply chains for hydrogels

may not be well-established in rural or remote areas, making them harder to access [20].

- **Maintenance and Application Costs:** While hydrogels can reduce irrigation and fertilization needs, there are still costs associated with their application and maintenance. For example, farmers may need to purchase additional equipment for hydrogel incorporation into the soil, or they may need to reapply hydrogels after a certain period, depending on their degradation rate [20].
- **Market Conditions:** The economic feasibility of hydrogels is also influenced by market conditions such as the cost of water, fertilizer, and labor, as well as government subsidies or support programs. In regions where the cost of water is low or subsidies are provided for conventional irrigation systems, the economic incentives to adopt hydrogel technology may be less compelling [20].

6. Challenges and Limitations

While hydrogel technology presents a promising solution for sustainable agriculture, its widespread adoption and effectiveness face several challenges and limitations. These obstacles range from economic and environmental concerns to practical issues regarding application, performance, and scalability [20, 21].

6.1 High Initial Costs

One significant barrier is the high initial cost of hydrogels, especially for smallholder farmers in developing countries. The expense of synthetic hydrogels, such as polyacrylamide, can be prohibitive. While long-term benefits may offset the initial costs, the financial barrier remains a challenge for many farmers [22].

6.2 Environmental concerns with synthetic hydrogels

Synthetic hydrogels, especially petroleum-based ones, pose environmental risks due to their non-biodegradability and potential to degrade into micro plastics. These materials can disrupt soil ecosystems and contaminate water systems. The development of biodegradable hydrogels from natural resources like starch and cellulose may offer a more sustainable solution [22].

6.3 Limited availability and accessibility

Hydrogel availability is limited in many rural areas due to underdeveloped supply chains and a lack of awareness among farmers. Expanding distribution networks and providing education on hydrogel benefits and applications are crucial for overcoming these barriers [22, 23].

6.4 Variable performance in different soil types and conditions

Hydrogel performance varies depending on soil type and climatic conditions. They may be less effective in clay soils or under extreme weather conditions, necessitating customized hydrogels tailored to specific environments [23].

6.5 Durability and Reapplication

Hydrogels may degrade over time, necessitating reapplication, which adds cost and labor. Research into more durable materials with longer-lasting effects is needed to improve cost-effectiveness [23].

6.6 Regulatory and Policy Barriers

Regulatory challenges, especially concerning synthetic hydrogels, could limit adoption. Ensuring compliance with safety and environmental standards and promoting supportive policies will be essential for broader implementation [23].

6.7 Public awareness and adoption barriers

Slow adoption is partly due to lack of awareness, cultural resistance, and limited exposure to new technologies. Training programs, demonstrations, and financial incentives could help increase adoption and awareness of hydrogel technology [23].

7. Future Directions

The application of hydrogel technology in sustainable agriculture has gained significant attention due to its potential to address critical challenges such as water scarcity, soil degradation, and nutrient management. While the technology has shown promise, further advancements are necessary to enhance its performance, scalability, and sustainability. This section explores key future directions for hydrogel technology in agriculture [23].

7.1 Development of biodegradable and eco-friendly hydrogels

One of the most pressing needs in hydrogel technology is the development of biodegradable and eco-friendly hydrogels. Many existing synthetic hydrogels, such as polyacrylamide-based formulations, are not fully biodegradable and can accumulate in the soil over time, posing environmental risks such as contamination and micro plastic formation [24].

Future Research Directions

- **Natural Polymers:** There is an increasing focus on the development of hydrogels made from renewable, natural polymers such as starch**,** cellulose**,** chitosan, and alginate**.** These materials offer the potential for biodegradability and sustainability**,** reducing the environmental impact of hydrogel use [24].
- **Hybrid Hydrogels:** Researchers are exploring hybrid hydrogels, which combine natural and synthetic materials, to enhance both performance and biodegradability. These hybrid formulations could offer a balance between the effectiveness of synthetic hydrogels and the environmental friendliness of natural polymers [24].
- **Green Chemistry Approaches:** Innovations in green chemistry are leading to the development of environmentally friendly hydrogel production processes that minimize the use of toxic chemicals and reduce the carbon footprint associated with hydrogel production [24].

7.2 Customization for local soil and climatic conditions

One of the limitations of current hydrogel technology is its variable performance across different soil types and environmental conditions. Hydrogels may perform well in certain regions but may not be as effective in others due to differences in soil structure, moisture retention needs, and climate conditions [23].

Future Research Directions

- **Tailored Hydrogels:** Researchers are working on developing customized hydrogels designed to perform optimally in specific soil types and climatic conditions. For example, hydrogels could be formulated to have a high moisture retention capacity for sandy soils or to break down more slowly in dry, arid conditions [23].
- **Smart Hydrogels:** The development of smart hydrogels materials that can respond to external stimuli (such as

changes in temperature, humidity, or soil moisture) offers a promising avenue. These hydrogels could adapt to fluctuating weather conditions, ensuring optimal performance in both wet and dry seasons [23].
- **Soil-Specific Formulations:** Hydrogels can be engineered to address soil-specific challenges such as salinity**,** alkalinity**, or** high compaction, ensuring their broad applicability in different agricultural regions [23].

7.3 Integration with precision agriculture and IoT
Hydrogel technology can be further enhanced through integration with precision agriculture tools, including the use of Internet of Things (IoT) devices and sensor technologies. These technologies can help optimize the use of hydrogels by monitoring soil moisture levels, weather conditions, and crop needs in real-time [24].

Future Research Directions
- **IoT-Enabled Hydrogels:** Future hydrogel applications could incorporate IoT devices that monitor soil moisture, temperature, and nutrient levels. These sensors could work in tandem with hydrogels to determine the optimal time for irrigation or reapplication of hydrogel, ensuring water and nutrient use is both efficient and cost-effective [24, 25].
- **Data-Driven Decision-Making:** Data from precision agriculture systems can be analyzed to provide farmers with actionable insights on how to best use hydrogels in their fields. This could include recommendations on where and when to apply hydrogels for maximum water conservation and yield improvement [25].
- **Automated Application Systems:** Integration with automated machinery (such as drones or robotic systems) could allow for the precise application of hydrogels across large areas, reducing labor costs and ensuring accurate distribution of the material [25].

7.4 Advancing smart fertilizer and nutrient delivery systems
One of the most promising applications of hydrogels in agriculture is their ability to act as slow-release carriers for fertilizers and nutrients. The development of smart fertilizers that release nutrients in response to soil conditions or plant needs could revolutionize nutrient management in agriculture [26].

Future Research Directions
- **Nutrient-Loaded Hydrogels:** Hydrogels could be developed to encapsulate macro- and micronutrients along with water, ensuring that nutrients are gradually released to plants over time. This would reduce nutrient leaching, improve fertilizer use efficiency, and reduce the environmental impact of fertilizer runoff [26].
- **Responsive Hydrogels:** Future hydrogels could be designed to release nutrients in response to specific environmental stimuli, such as changes in soil pH, temperature, or moisture levels. This would ensure that crops receive the right nutrients at the right time, promoting more efficient growth [26].
- **Integration with Organic Farming:** Smart hydrogels could also be adapted to organic farming systems, where they can help improve nutrient availability and reduce reliance on chemical fertilizers [26].

7.5 Enhancing scalability and affordability
For hydrogel technology to have a significant impact on global agriculture, particularly in developing countries, it must become more affordable and scalable. The cost of synthetic hydrogels and the infrastructure required for their application currently limits their widespread adoption, especially among smallholder farmers [27].

Future Research Directions:
- **Cost-Effective Production Methods:** There is a need for the development of low-cost production techniques that reduce the overall price of hydrogels. This could involve optimizing manufacturing processes or using locally available, renewable resources to produce hydrogels, making them more accessible to farmers in developing regions [27].
- **Local Production and Distribution Networks:** To improve accessibility, local production and distribution networks for hydrogels should be established, ensuring that farmers in remote or rural areas can easily access the technology at affordable prices. This could be facilitated through cooperatives or government partnerships [27].

7.6 Policy support and regulatory frameworks
The successful adoption of hydrogel technology in agriculture requires appropriate policy support and regulatory frameworks that promote innovation while ensuring environmental and health safety. Governments and international organizations must work together to foster an enabling environment for the development and deployment of hydrogel technology [28].

Future Research Directions:
- **Incentive Programs:** Governments could introduce subsidies, grants, or tax incentives for farmers and businesses that invest in hydrogel technology. These programs would help reduce the financial burden on farmers, making the technology more accessible [28].
- **Standardization and Certification:** The development of standards and certifications for hydrogel products will help ensure that they meet quality, safety, and environmental criteria. This will increase trust in the technology and facilitate its widespread adoption [28].

7.7 Long-term monitoring and impact assessment
To ensure that hydrogels are truly beneficial for sustainable agriculture, it is important to conduct long-term monitoring and impact assessments to evaluate their effectiveness and environmental impact. Studies should focus on the degradation rates, Eco toxicity, and long-term soil health to better understand how hydrogels interact with different agricultural systems over time [29]

Future Research Directions
- **Field Trials and Long-Term Studies:** Large-scale field trials and longitudinal studies will provide valuable data on the long-term performance of hydrogels in different crops, soil types, and climates. This data can help refine hydrogel formulations and guide future applications [30].
- **Ecosystem Impact Studies:** Research on the broader environmental impact of hydrogels, including effects on soil microbiota, carbon sequestration, and biodiversity, will be critical in assessing their role in sustainable agriculture [30].

8. Conclusion
Hydrogel technology presents a transformative solution for sustainable agriculture by addressing critical challenges such as water scarcity, soil degradation, and nutrient management. Its ability to enhance soil moisture retention, reduce irrigation needs, and improve nutrient delivery makes it a powerful tool for improving crop yields and minimizing environmental impacts. However, the widespread adoption of hydrogels faces several challenges, including high initial costs, environmental concerns with synthetic materials, and limited scalability for smallholder farmers. The future of hydrogel technology lies in the development of biodegradable and eco-friendly hydrogels, as well as tailored formulations for specific soil types and climatic conditions [31]. Additionally, integrating hydrogels with precision agriculture technologies, such as IoT devices and sensors, can optimize their use and ensure greater efficiency. Research into smart fertilizers and nutrient delivery systems holds the potential to enhance the benefits of hydrogels, reducing reliance on chemical fertilizers and improving crop nutrition. Affordability and accessibility remain key barriers, especially for farmers in developing regions, necessitating efforts to reduce production costs and establish local supply chains. Furthermore, long-term monitoring and impact assessments are essential to fully understand the environmental and economic effects of hydrogels on agriculture. In conclusion, while challenges remain, hydrogel technology has the potential to significantly contribute to water-efficient**,** resilient**,** and sustainable agricultural practices**.** Continued research, innovation, and policy support will be crucial in ensuring that hydrogels can play a key role in addressing the growing global demand for food while protecting natural resources [30, 32].

9. References

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