Asian Journal of Applied Science and Technology (AJAST)
Volume 10, Issue 2, Pages 70-94, April-June 2026

Advanced Hydrogel-Based Strategies for Mitigating Salinity Stress in Salt-Affected Soils: Mechanisms, Classification, Agricultural Applications, Environmental Implications, and Future Perspectives

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DOI: https://doi.org/10.38177/ajast.2026.10207

Article Received: 08 April 2026 *Article Accepted: 15 June 2026* *Article Published: 19 June 2026*

ABSTRACT

Soil salinization represents one of the major threats to agriculture and food security worldwide due to its detrimental effects on crop productivity, water availability, and soil quality. Although conventional strategies for the remediation of saline soils, such as salt leaching, the application of chemical amendments, and irrigation management, have shown favorable results, these approaches still present significant limitations related to high water demand, secondary contamination, and heavy metal mobilization. In this context, hydrogels have emerged as promising materials for salinity stress mitigation because of their remarkable water absorption and retention capacity, as well as their potential to improve the physicochemical properties of soils.

This review analyzes the main advances associated with the use of hydrogels in salt-affected soils, addressing their structural characteristics, swelling mechanisms, relevant properties, and classification into natural, synthetic, and hybrid hydrogels. In addition, the mechanisms through which these materials contribute to reducing osmotic stress, enhancing water retention, and promoting the controlled release of nutrients and agrochemicals are described. Factors influencing hydrogel performance, including salinity, pH, crosslinking density, and environmental conditions, are also discussed.

Furthermore, the main agricultural applications reported in recent years, the environmental impact associated with these materials, and the current challenges related to production costs, stability, and industrial scalability are presented. Overall, hydrogels represent a highly promising alternative for the sustainable management of saline soils and the development of more resilient agricultural systems under conditions of climate change and water scarcity.

Keywords: Soil Salinization; Salt-affected Soils; Hydrogels; Natural Hydrogels; Synthetic Hydrogels; Hybrid Hydrogels; Superabsorbent Polymers; Salinity Stress; Water Retention; Controlled Nutrient Release; Sustainable Agriculture; Climate Change Adaptation.

1. Introduction

Soil constitutes one of the most important natural resources for life and the development of terrestrial ecosystems; however, it also represents a highly vulnerable system to physical, chemical, and biological degradation processes caused by both natural phenomena and anthropogenic activities (Instituto Geográfico Nacional (IGN), 2025). Among the major environmental issues currently affecting agricultural systems, soil salinization stands out as a phenomenon associated with the excessive accumulation of soluble salts in the root zone, which limits plant growth and significantly reduces agricultural productivity (Shrivastava and Kumar, 2015; Singh, 2022).

Soil salinization may occur naturally through processes such as rock weathering and evaporation in arid and semi-arid regions; nevertheless, human activities have considerably accelerated this problem over recent decades. The use of irrigation water with high salt concentrations, inadequate drainage systems, and the excessive application of chemical fertilizers promotes the progressive accumulation of salts in the soil and deteriorates its physicochemical properties (Bashir et al., 2020; Ojeda Barrios et al., 2020). As a consequence, the osmotic potential of the soil decreases, hindering water and nutrient uptake by plants and inducing physiological stress conditions that negatively affect crop yields (Shrivastava and Kumar, 2015).

In addition to salinity, agricultural soils may also be affected by contaminants such as heavy metals and hydrocarbons, which can enter the food chain and contaminate surface and groundwater bodies (Huang, 2024; Xu et al., 2025). Therefore, the search for sustainable strategies for the rehabilitation and management of degraded soils has become a priority within modern agriculture and environmental protection.

Traditionally, the management of saline soil has relied on conventional techniques such as salt leaching, the application of chemical amendments, and the implementation of salt-tolerant crops. Although these strategies have demonstrated a certain degree of effectiveness, they also present important limitations associated with high water requirements, secondary contamination, and the potential mobilization of heavy metals within the soil (Gashi et al., 2025; Trejo González et al., 2019). Consequently, there has been growing interest in the development of advanced materials capable of improving water-use efficiency and mitigating the adverse effects associated with salinity.

In this context, hydrogels have emerged as highly promising materials for agricultural applications because of their remarkable water absorption and retention capacity (Maksimova et al., 2023). These three-dimensional polymeric materials can function as water reservoirs, reduce evaporation losses, and promote the controlled release of nutrients and bioactive compounds, thereby supporting plant growth under saline stress conditions (Guo et al., 2022; R. Wang et al., 2024). Furthermore, certain hydrogels possess the ability to partially immobilize toxic ions present in the soil, helping to reduce the osmotic stress associated with salt accumulation.

Currently, a wide variety of natural, synthetic, and hybrid hydrogels have been developed for agricultural applications. Natural systems stand out because of their biodegradability and environmental compatibility, whereas synthetic materials exhibit greater mechanical stability and chemical resistance. Hybrid hydrogels, however, have attracted particular attention due to their ability to combine the advantages of both systems while simultaneously optimizing properties such as absorption capacity, stability, and resistance to saline environments (Agbna and Zaidi, 2025)

This review aims to analyze the main advances related to the use of advanced hydrogels for salinity mitigation in agricultural soils, addressing their structural characteristics, mechanisms of action, reported applications, environmental impact, current limitations, and future perspectives for the development of more sustainable and resilient agricultural systems under climate change conditions.

1.1. Study Objective

The main objectives of this review are:

1) Describe the global impact of soil salinization and its implications for agricultural productivity, soil quality, and food security.

2) Examine the limitations and environmental concerns associated with conventional strategies used for the management of salt-affected soils.

3) Analyze the structural characteristics, classification, and swelling behavior of natural, synthetic, and hybrid hydrogels intended for agricultural applications.

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4) Explain the physicochemical mechanisms through which hydrogels contribute to alleviating salinity stress and improving soil properties.
5) Identify the principal factors that influence hydrogel performance and efficiency under saline conditions.
6) Summarize recent agricultural applications, environmental considerations, current challenges, and future perspectives regarding the sustainable use of hydrogels for the management of salt-affected soils.

2. Literature Review

2.1. Salt-Affected Soils: A Global Problem

Soil salinity constitutes one of the major environmental and agricultural problems worldwide due to its negative impact on crop productivity, soil quality, and food security (Singh, 2022). This phenomenon refers to the excessive accumulation of soluble salts in the root zone, mainly sodium, calcium, magnesium, and potassium salts associated with anions such as chlorides, sulfates, and carbonates, which alter water and nutrient availability for plants.

Soil is considered saline when it exhibits an electrical conductivity of the saturation extract greater than 4 dS/m, a pH lower than 8.5, and an exchangeable sodium percentage below 15% (Singh, 2022). These characteristics differentiate saline soils from sodic and saline-sodic soils, which exhibit distinct physicochemical properties. In saline soils, calcium and other soluble salts generally predominate, contributing to a relatively more stable structure compared to sodic soils (Trejo González et al., 2019).

Soil salinization may originate from natural or anthropogenic causes. Among natural processes, the weathering of rocks and minerals plays a major role, as it gradually releases and accumulates salts in the soil (Zhang et al., 2022). Likewise, in arid and semi-arid regions, high evaporation rates and low precipitation favor the capillary rise of saline groundwater, resulting in salt accumulation in the upper soil layers (Singh, 2022).

On the other hand, human activities represent one of the main factors accelerating this problem. The use of irrigation water with high salt concentrations, inadequate drainage systems, and improper leaching practices promotes the progressive accumulation of salts in agricultural areas (Gashi et al., 2025; Trejo González et al., 2019). Furthermore, the excessive use of chemical fertilizers significantly increases soil salinity and contributes to the contamination of surface and groundwater bodies (Huang, 2024; Xiong et al., 2022).

The excessive presence of salts in soil severely affects plant development. One of the main consequences is the reduction of soil osmotic potential, which hinders water uptake by plant roots and generates a phenomenon known as physiological drought (Ojeda Barrios et al., 2020). In response, plants perform osmotic adjustments to maintain metabolic activity; however, this mechanism requires considerable energy expenditure, ultimately reducing plant growth and agricultural productivity. Additionally, salinity limits the uptake of essential nutrients such as potassium, phosphorus, calcium, iron, and zinc, decreases seed germination, and negatively affects crop quality (Ehtaiwesh, 2022; Najmaldin Ezaldin Hassan, 2024).

Climate change has intensified this problem due to increasing temperatures and decreasing precipitation in several regions worldwide, conditions that promote evaporation and salt accumulation in soils (Gashi et al., 2025).

Consequently, arid and semi-arid regions are becoming increasingly vulnerable to salinization processes. Currently, soil salinity represents a major issue in several countries. In China, approximately one-third of irrigated lands are affected by salinity (Seeda Abou et al., 2022). Particularly in the Shiyang River Basin, located in northwestern China, intensive groundwater exploitation for maintaining agricultural oases has caused severe salt accumulation in soils (Zhang et al., 2022). Similarly, Spain faces significant salinization problems, especially in agricultural regions such as Murcia, where water scarcity and intensive land use have contributed to the deterioration of soil properties (Trejo González et al., 2019).

In Mexico, approximately 600,000 hectares are estimated to be affected by salinity, mainly in northern and central states such as Sonora, Sinaloa, Chihuahua, Zacatecas, and Coahuila (Ojeda Barrios et al., 2020). In the latter, the Comarca Lagunera region represents one of the most severely affected areas due to the intensive use of saline groundwater and the cultivation of forage crops with high water demand, conditions that have progressively deteriorated soil quality (Luis González-Barrios et al., 2024).

Due to the environmental, economic, and social impacts associated with soil salinization, the development of efficient and sustainable technologies capable of mitigating this problem is essential to preserve agricultural ecosystems, food security, and human health (X. Wang and Nakane, 2020).

Soil salinization negatively affects plant growth and agricultural productivity through several physicochemical processes associated with the accumulation of soluble salts in the root zone. High evaporation rates and capillary rise promote salt accumulation in the upper soil layers, increasing osmotic stress and limiting water uptake by plants. As a consequence, root development, nutrient absorption, and overall plant growth are severely affected. Figure 1 illustrates the main mechanisms involved in soil salinization, including salt accumulation, evaporation, capillary transport of salts, root damage, and the differences between normal and saline soils.

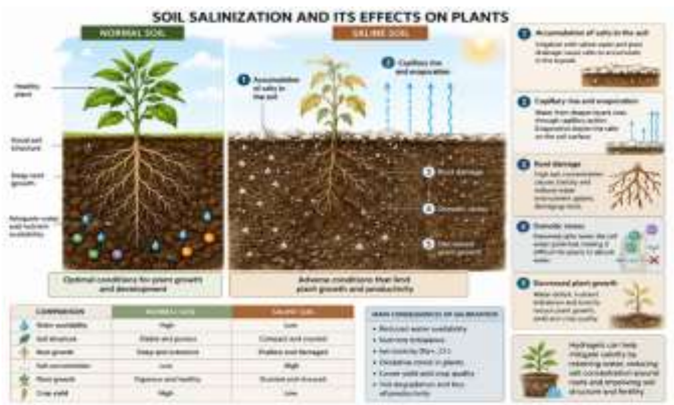

Figure 1. Schematic representation of soil salinization processes and their effects on plant development, comparing normal and saline soils and highlighting the main mechanisms of salt accumulation and their consequences on plant growth and productivity. (Authors' own elaboration).

2.2. Conventional Strategies for the Management of Soil Salinity

Over recent decades, several conventional strategies have been developed to reduce the excess of salts present in agricultural soils and minimize their adverse effects on plant productivity. Among the most widely used techniques is salt leaching, which consists of the abundant and frequent application of irrigation water to dissolve and displace soluble salts beyond the root zone, thereby restoring more favorable conditions for plant growth (Ojeda Barrios et al., 2020). This method is extensively applied in arid and semi-arid regions because of its relative simplicity and rapid effectiveness in reducing soil electrical conductivity.

Another commonly employed strategy involves the use of chemical amendments, mainly gypsum and sulfur, which modify the chemical and physical properties of soils to promote the recovery of salt-affected areas. Agricultural gypsum primarily acts through the replacement of sodium and magnesium ions adsorbed onto the soil cation exchange complex with calcium ions, thereby improving soil structure and enhancing water infiltration (Ojeda Barrios et al., 2020; Trejo González et al., 2019). Elemental sulfur, in turn, contributes to lowering soil pH through biological oxidation processes, promoting the solubilization of certain mineral compounds and partially improving soil conditions.

Proper irrigation management also represents a fundamental tool for preventing and controlling secondary salinization. This strategy involves efficiently planning and regulating both the quantity and frequency of water applied in agricultural systems to satisfy crop water requirements while simultaneously minimizing salt accumulation within the soil profile (Luis González-Barrios et al., 2024). The implementation of more efficient irrigation systems, such as drip irrigation, has partially reduced the negative effects associated with excessive water use and superficial salt accumulation. Likewise, the use of salt-tolerant crops has been considered a viable biological strategy for the utilization of salt-affected lands. These species possess physiological and biochemical mechanisms that allow them to germinate, develop, and maintain acceptable productivity under saline stress conditions (Singh, 2022). Among the most representative examples is Suaeda salsa, a halophytic plant with a remarkable capacity to accumulate salts within its tissues without significantly affecting its growth, making it a promising species for phytoremediation processes (Xu et al., 2025). Similarly, certain poplar species exhibit physiological mechanisms that enable them to survive and grow under high salinity conditions where other plant species fail to thrive (Costa et al., 2022).

Despite the favorable results achieved by these conventional strategies in the recovery of saline soils, they still present several limitations that restrict their long-term efficiency and sustainability. One of the main disadvantages of salt leaching is the potential generation of secondary contamination, since the water used during the process may transport high concentrations of salts and sulfates into deeper soil layers or groundwater bodies, thereby deteriorating environmental quality (Gashi et al., 2025). Similarly, although chemical amendments improve certain soil properties, their application may promote the mobilization of heavy metals such as cadmium and lead (Gashi et al., 2025). In the case of sulfur-based compounds, oxidation in the presence of water and oxygen releases hydrogen ions, leading to acidification of the medium and promoting the leaching of heavy metals previously immobilized within the soil matrix (Martínez Carrillo et al., 2025). Likewise, gypsum application increases sulfate concentrations and promotes ion exchange processes capable of displacing certain metals into more mobile and potentially bioavailable forms (Batista Cruz et al., 2024).

Due to the limitations associated with conventional methods, there has been a growing interest in recent years in the development of more sustainable and environmentally friendly alternatives. In this context, hydrogels have emerged as promising materials for the remediation of saline soils because of their high-water retention capacity, their potential to improve the physicochemical properties of soils, and their ability to reduce salt accumulation without generating significant secondary residues. These characteristics position hydrogels as an innovative alternative for the sustainable management of salinity in agricultural systems.

3. Methodology

3.1. Literature Search Strategy

This review was conducted through a structured search of the scientific literature to identify studies addressing the use of hydrogels for the mitigation of salinity stress in salt-affected soils. Relevant publications were retrieved from internationally recognized academic databases, including Scopus, Web of Science, ScienceDirect, Google Scholar, and PubMed.

The literature search was performed using combinations of keywords related to the main topics of this review, including "hydrogels", "salt-affected soils", "soil salinization", "salinity stress", "water retention", "controlled nutrient release", "superabsorbent polymers", "agricultural applications", and "saline soils". Boolean operators (AND, OR) were employed to refine the searches and improve the relevance of the retrieved records.

Priority was given to peer-reviewed journal articles published from 2020 onward to provide an updated overview of the field. Particular emphasis was placed on incorporating the most recent advances reported in 2025 and 2026, while seminal studies published prior to this period were included when considered essential for understanding the evolution of hydrogel technologies and salinity management strategies.

3.2. Study Selection and Data Analysis

The identified publications were screened based on their relevance to the objectives of this review. Studies focusing on structural characteristics, classification, swelling mechanisms, physicochemical properties, agricultural applications, environmental implications, and limitations of hydrogels used under saline conditions were selected for detailed analysis.

The collected information was critically evaluated and organized into thematic sections to provide a comprehensive overview of the current state of knowledge. The findings were synthesized to identify emerging trends, current challenges, and future research opportunities associated with the sustainable application of hydrogels for the management of salt-affected soils.

4. Results and Discussion

4.1 Hydrogels: Characteristics and Fundamentals

Hydrogels are three-dimensional polymeric materials with a remarkable capacity for water absorption and retention, characteristics that have made them highly attractive for biomedical, environmental, and agricultural applications. These materials are composed of macromolecules formed through the repetitive linkage of monomers by chemical bonds, generating crosslinked structures capable of interacting with large amounts of water without completely losing their structural integrity (Bashir et al., 2020). Owing to these properties, hydrogels have been extensively investigated as promising alternatives for improving water retention and mitigating the effects associated with saline stress in agricultural soils.

4.1.1. Definition and Structure of Hydrogels

Hydrogels are composed of three-dimensional polymeric networks capable of absorbing and retaining significant amounts of water due to the presence of hydrophilic functional groups within their structure. These networks can be synthesized from either natural or synthetic polymers, depending on the intended application and the required physicochemical properties (López Saucedo et al., 2024). Natural hydrogels are synthesized from biopolymers naturally occurring in the environment, such as cellulose, starch, alginate, and chitosan, among others. These materials exhibit important advantages related to their biocompatibility, biodegradability, and low toxicity, which favor their application in agricultural and environmental systems (Huang, 2024). In contrast, synthetic hydrogels are produced using petroleum-derived polymers, including polyacrylates, polyvinyl alcohol (PVA), and polyethylene glycol (PEG), which generally exhibit greater mechanical strength, chemical stability, and water absorption capacity (X. Wang et al., 2025).

One of the most remarkable properties of hydrogels is their extraordinary water absorption capacity, which in some cases can exceed one thousand times their dry weight while simultaneously maintaining the stability of the polymeric network (Yang et al., 2024). Water retention capacity is commonly expressed as the amount of water absorbed per unit mass of dry polymer (g/g) and depends not only on the chemical composition of the hydrogel but also on external factors, including temperature, pH, and medium salinity (Costa et al., 2022).

In agricultural applications, hydrogels function as water reservoirs capable of storing moisture during periods of water availability and gradually releasing it as soil water content decreases (Frioni et al., 2025). This behavior helps reduce plant water stress and improve water-use efficiency under drought or saline conditions. Due to this capability, hydrogels are frequently described as sponge-like materials capable of absorbing large quantities of water and slowly releasing it into the surrounding environment (Agbna and Zaidi, 2025).

4.1.2. Swelling Mechanisms

The swelling capacity of hydrogels is directly related to the presence of hydrophilic functional groups within the polymeric chains, which promote interactions between the polymer and water molecules through the formation of hydrogen bonds (Wang et al., 2025). When the hydrogel comes into contact with water, the liquid begins to diffuse into the polymeric network, causing hydration and partial separation of the polymer chains. Subsequently, certain functional groups present within the structure may become ionized, generating differences in ion concentration between the interior of the hydrogel and the external medium. This osmotic gradient promotes the continuous diffusion of water into the polymeric network, resulting in an increase in material volume and the process known as swelling (Kim et al., 2026; R. Wang et al., 2024).

The swelling behavior of hydrogels is one of the most important properties associated with their agricultural applications. Due to the presence of hydrophilic functional groups within their polymeric structure, hydrogels can absorb large amounts of water, expanding their three-dimensional network. This process is governed by water diffusion, hydrogen bond formation, osmotic pressure gradients, and the degree of crosslinking within the polymeric matrix. Figure 2 illustrates the main stages involved in the swelling process, including water diffusion into the hydrogel structure, network expansion, and the interactions responsible for water retention within the material.

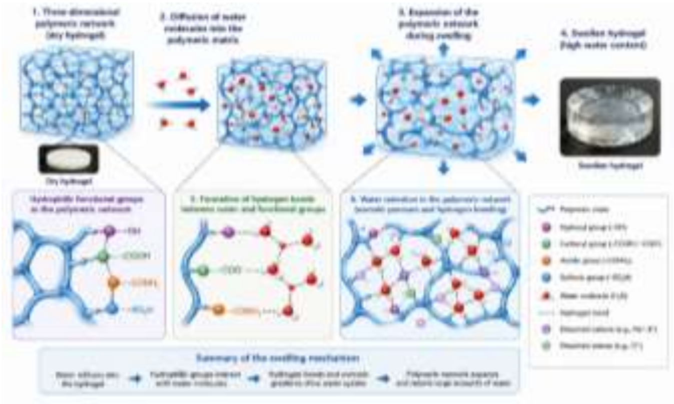

Figure 2. Schematic illustration of the water absorption and swelling mechanism of polymeric hydrogels, highlighting water diffusion, interactions with hydrophilic functional groups, and expansion of the polymeric network. (Authors' own elaboration).

The degree of swelling strongly depends on the type and density of the crosslinks present within the polymeric structure. Crosslinks or reticulations correspond to short bonding sequences that connect one polymeric chain to another, enabling the formation of stable three-dimensional networks (Ruiz Fresneda et al., 2024). Polymeric networks may be generated through either chemical or physical crosslinking mechanisms. In chemical crosslinking, polymer chains are connected through covalent bonds using crosslinking agents such as N,N-methylenebisacrylamide (MBA) or glutaraldehyde. This type of crosslinking produces permanent structures with high mechanical and chemical stability (Godiya et al., 2020; Huang, 2024). The synthesis of these hydrogels can be carried out through different methods, including bulk polymerization, ultraviolet radiation-induced reactions, and volume phase transition (VPT) processes (Kaur et al., 2023; Suzuki and Matsumoto, 2026).

Bulk polymerization represents one of the simplest techniques because it involves only monomers and initiators without requiring the use of solvents. On the other hand, volume phase transition occurs when certain polymeric chains spontaneously modify their three-dimensional conformation, shifting from a disordered structure to a more organized and compact configuration, thereby promoting chain entanglement and polymeric network formation (Kaur et al., 2023). In contrast, physical crosslinking is generated through non-covalent interactions, including hydrogen bonding, Van der Waals forces, and hydrophobic interactions. Because these interactions are relatively weak, physically crosslinked hydrogels generally exhibit lower structural stability compared to chemically crosslinked systems; however, they possess reversible properties and high sensitivity to external stimuli such as temperature, pH, or ionic strength variations (Huang, 2024).

4.1.3. Relevant Properties for Agricultural Applications

The physicochemical properties of hydrogels have promoted their increasing utilization in agricultural applications, particularly in regions affected by drought and salinity. Among the most relevant properties is their high-water retention capacity, which allows the reduction of soil water losses and improves water availability for plants during prolonged periods of water stress (Frioni et al., 2025). Another important property is their ability to provide the controlled release of active compounds, including fertilizers, nutrients, and soil-conditioning agents. Owing to their crosslinked structure, hydrogels are capable of absorbing these substances and gradually releasing them in response to variations in moisture and environmental conditions, thereby improving nutrient-use efficiency and reducing losses caused by leaching (Kaur et al., 2023; Maksimova et al., 2023).

Biodegradability represents another relevant characteristic, particularly in hydrogels synthesized from natural polymers. These materials can progressively degrade through biological processes, reducing the accumulation of persistent residues in the environment and promoting more sustainable agricultural practices (Huang, 2024). Likewise, the chemical and mechanical stability exhibited by certain hydrogels allows them to maintain their functionality throughout repeated cycles of water absorption and release, even under adverse environmental conditions. This property is particularly important in agricultural applications, where materials are continuously exposed to fluctuations in temperature, pH, and soil salinity (X. Wang et al., 2025). Due to the combination of these properties, hydrogels represent a promising alternative for the sustainable management of water resources and the mitigation of salinity-related effects in agricultural systems.

4.2. Classification of Hydrogels for Agricultural Applications

Hydrogels employed in agricultural applications can be classified according to the nature of the polymers composing their structure into natural, synthetic, and hybrid or nanocomposite hydrogels. Each of these systems exhibits specific advantages and limitations associated with properties such as biodegradability, mechanical stability, absorption capacity, and resistance to adverse environmental conditions. In recent years, hybrid hydrogels have gained particular attention due to their ability to combine the advantages of natural and synthetic materials, enabling the development of systems with enhanced structural and functional properties.

4.2.1. Natural or Biopolymeric Hydrogels

Natural hydrogels are polymeric networks obtained from renewable sources and naturally occurring biopolymers, making them an environmentally friendly and sustainable alternative to synthetic materials. Nevertheless, these materials also exhibit certain limitations, mainly associated with their mechanical stability and relatively short service life under environmental conditions (Garcia Garcia et al., 2024). Among the most widely used biopolymers is chitosan, which is obtained through the deacetylation of chitin, a polysaccharide naturally present in the shells of crustaceans such as shrimp, crabs, and lobsters. This material is a linear biopolymer characterized by its high biocompatibility, biodegradability, and strong interaction with water (X. Wang and Nakane, 2020). In agricultural applications, chitosan has demonstrated the ability to improve soil porosity and reduce bulk density, thereby enhancing water retention. However, its performance strongly depends on the degree of deacetylation, since inadequate values may result in materials with low stability or excessively rapid degradation (Garcia Garcia et al., 2024).

Another extensively studied biopolymer is cellulose, considered the most abundant polymeric material in nature and commonly found in sources such as wood, cotton, recycled paper, and agricultural residues. Cellulose stands out because of its low cost, high hydrophilicity, and biodegradability, properties mainly attributed to the presence of multiple hydroxyl groups capable of forming hydrogen bonds and stable three-dimensional networks (Godiya et al., 2020). Nevertheless, its high susceptibility to biological degradation may limit its permanence and functionality within the soil (Guo et al., 2022). In the case of alginate, this marine-derived biopolymer is primarily obtained from brown algae and certain soil bacteria. Its structure contains carboxyl groups capable of forming relatively stable crosslinked networks through ionic interactions (Garcia Garcia et al., 2024; Godiya et al., 2020). Despite these advantages, the presence of calcium ions may partially reduce its water absorption capacity by limiting the availability of hydrophilic groups required for hydrogen bond formation (Dardeer et al., 2024).

On the other hand, starch is a widely available polysaccharide obtained from plant sources such as corn, rice, and potatoes. Its utilization in agricultural hydrogels is mainly associated with its low cost and the presence of hydroxyl groups and ether linkages that favor interactions with water molecules (Adjuik et al., 2023; Xiong et al., 2022). However, this material exhibits high susceptibility to enzymatic degradation and considerable sensitivity to changes in temperature and pH, which may affect its stability during prolonged applications (Garcia Garcia et al., 2024).

4.2.2 Synthetic Hydrogels

Synthetic hydrogels are mainly produced from polymers derived from the petrochemical industry and are characterized by their high chemical stability, mechanical resistance, and water absorption capacity. Among the most widely used materials are polyacrylamide, polyacrylates, and acrylic copolymers because of their versatility and performance in agricultural applications. Polyacrylamide is one of the most commonly employed synthetic polymers in agriculture due to its high swelling capacity and its ability to form networks with relatively uniform pores (Gutiérrez Pérez Nestor et al., 2022). These properties favor water retention in soils and contribute to improving water-use efficiency in crops and horticultural systems (Nascimento et al., 2021).

On the other hand, polyacrylate, particularly in the form of potassium polyacrylate, exhibits a remarkable absorption capacity and ion-exchange properties that are especially useful for the treatment of saline soils (Huang, 2024). However, its excessive swelling capacity may produce negative effects, including the formation of compact layers that hinder water infiltration and restrict proper root development in plants (Abdelghafar et al., 2024). Finally, acrylic copolymers, formed through the combination of two or more different monomers, allow the adjustment of specific properties such as elasticity, stability, and absorption capacity depending on the chemical composition and crosslinking degree of the system (Guo et al., 2022). This versatility has promoted the design of hydrogels with optimized properties for different agricultural conditions.

4.2.3 Hybrid or Nanocomposite Hydrogels

Hybrid hydrogels represent one of the fastest-growing areas within polymeric materials applied to agriculture. These systems combine natural and synthetic polymers, as well as inorganic or nanoscale materials, to overcome the individual limitations of each component and improve the overall performance of the hydrogel (Ruiz Fresneda et al., 2024). Within this category, nanomaterial-reinforced hydrogels are particularly noteworthy, in which inorganic nanoparticles are incorporated into the polymeric matrix. The presence of these particles increases the rigidity, mechanical resistance, and thermal stability of the hydrogel while also improving its porosity and liquid absorption capacity (Xu et al., 2025). In addition, certain nanomaterials can provide intelligent properties to the system, enabling the hydrogel to respond to external stimuli such as changes in temperature, pH, or magnetic fields (Ruiz Fresneda et al., 2024).

Among the most used nanoparticles are magnetic particles, particularly magnetite, which enable the development of magnetically responsive hydrogels and facilitate material recovery after use (Ruiz Fresneda et al., 2024). Similarly, carbon-based nanomaterials, such as carbon nanotubes and graphene oxide, increase the surface area and the number of available active sites, properties that are especially useful in applications related to contaminant adsorption and the improvement of structural properties (Godiya et al., 2020).

Another important strategy involves the incorporation of clays into the polymeric network. Materials such as bentonite, montmorillonite, and halloysite function as reinforcing and crosslinking agents, increasing mechanical stability and reducing the environmental sensitivity of hydrogels (Ruiz Fresneda et al., 2024). In particular, sodium bentonite has demonstrated the ability to maintain high absorption capacity even under highly saline conditions, which is especially relevant for agricultural applications in arid and semi-arid regions (Costa et al., 2022).

The biodegradability of hydrogels strongly depends on the chemical nature of the polymers employed during their fabrication. Hydrogels produced from compostable materials can be degraded by microorganisms present in the soil, ultimately being transformed into carbon dioxide, water, and biomass (Lera et al., 2024). Traditionally, synthetic polymers were considered non-biodegradable because of the presence of long carbon chains and high molecular weight structures (Jendrossek, 2024). However, recent studies have demonstrated that certain synthetic materials may degrade under specific conditions and in the presence of suitable microorganisms, although this process is generally considerably slower (Ru et al., 2020).

Because natural hydrogels exhibit relatively rapid degradation while synthetic systems possess limited biodegradability, hybrid systems have emerged as a promising alternative by combining the stability of synthetic polymers with the ecological and biodegradable properties of natural biopolymers (Guo et al., 2022).

4.3. Mechanisms of Salinity Mitigation by Hydrogels

Hydrogels have emerged as promising materials for soil salinity mitigation because they can act through physicochemical, structural, and biological mechanisms that enhance water availability, reduce osmotic stress, and improve soil properties. Owing to their highly crosslinked three-dimensional structure, these materials function as reservoirs capable of absorbing and storing large volumes of water within their polymeric matrix and subsequently releasing it gradually into the plant root zone (Guo et al., 2022).

One of the main mechanisms associated with salinity mitigation involves the enhancement of soil water retention. Hydrogels absorb water during irrigation or precipitation events and reduce water losses caused by leaching and evaporation, thereby maintaining more stable moisture conditions around plant roots (Aslan and Canbolat, 2025). This behavior is particularly important in arid and semi-arid regions, where high evaporation rates favor the surface accumulation of salts. By conserving moisture for prolonged periods, hydrogels indirectly contribute to reducing salt concentration and alleviating plant water stress.

Additionally, the expansion of hydrogels within the soil matrix favorably modifies the physical properties of soils. During the swelling process, these materials increase the spaces between soil particles, reducing bulk density and promoting greater aeration and oxygen flow (Kaur et al., 2023). Therefore, root growth, root respiration, and overall

Asian Journal of Applied Science and Technology (AJAST)
Volume 10, Issue 2, Pages 70-94, April-June 2026

plant development are improved. Furthermore, the presence of hydrogels contributes to stabilizing soil structure and reducing compaction processes, thereby enhancing water infiltration and homogeneous water distribution.

Hydrogels mitigate soil salinity through multiple physicochemical and structural mechanisms that improve soil quality and plant development under saline conditions. These materials function as water reservoirs capable of retaining moisture, reducing evaporation losses, immobilizing toxic ions, and promoting the gradual release of nutrients in the rhizosphere. In addition, the swelling behavior of hydrogels improves soil porosity, aeration, and water distribution, contributing to enhanced root growth and reduced osmotic stress. Figure 3 summarizes the principal mechanisms through which hydrogels contribute to salinity mitigation and improved agricultural performance in salt-affected soils.

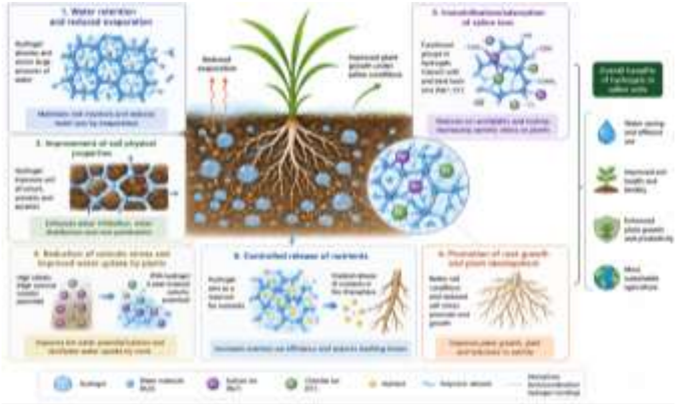

Figure 3. Main mechanisms by which hydrogels mitigate soil salinity in agricultural soils, including water retention, improvement of soil physical properties, ion immobilization, reduction of osmotic stress, controlled nutrient release, and promotion of root development (Authors' own elaboration).

Another relevant mechanism involves the interaction between the functional groups present in hydrogels and the saline ions dissolved in the soil. The excessive accumulation of ions such as sodium and chloride interferes with several metabolic and physiological processes in plants; however, certain hydrogels are capable of partially or temporarily retaining these ions within their polymeric structure through adsorption and ion-exchange mechanisms (Nascimento et al., 2021; Ojeda Barrios et al., 2020). As a result, the concentration of toxic ionic species available in the soil solution decreases, thereby reducing the osmotic stress associated with salinity.

In addition to their capacity to retain water and salts, hydrogels can also function as controlled-release systems for nutrients and bioactive compounds. During material synthesis, fertilizers, micronutrients, or soil-conditioning substances may be incorporated into the polymeric network (Sarhan et al., 2024). Subsequently, when the hydrogel becomes hydrated, these compounds can dissolve and gradually diffuse into the surrounding environment through diffusion processes controlled by concentration gradients, commonly described according to Fick's diffusion laws (X. Wang et al., 2025).

The gradual release of nutrients promotes higher fertilizer-use efficiency and reduces nutrient losses caused by leaching. Moreover, as partial degradation of the hydrogel and associated organic matter occurs, additional nutrients may be released into the soil, favoring microbial activity and progressively improving the fertility of the agricultural system (Maksimova et al., 2023). Due to the combination of these mechanisms, hydrogels represent a multifunctional strategy for the management of salt-affected soils, since they not only contribute to improving water availability but also promote structural stabilization, reduce ionic toxicity, and enhance the efficient release of essential nutrients required for plant growth.

4.4. Factors Affecting Hydrogel Performance under Saline Conditions

The efficiency of hydrogels in agricultural applications, particularly in salt-affected soils, depends on several physicochemical and environmental factors that directly influence their absorption capacity, structural stability, and swelling behavior. These factors determine the functionality of the material and its ability to retain water, release nutrients, and mitigate saline stress in plants.

One of the most important factors is the concentration of salts present in the medium. Increasing salinity significantly reduces the water absorption and retention capacity of hydrogels because of the increase in external osmotic pressure, which limits the diffusion of water molecules into the polymeric network (Guo et al., 2022). In addition, dissolved ions present in the soil solution interact with water molecules and compete for the hydrophilic sites within the hydrogel, decreasing hydrogen bond formation and reducing the material's ability to retain moisture (Nascimento et al., 2021).

The osmotic effect associated with salinity can be described through the osmotic pressure relationship (Eq. 1):

$$\Pi = iCRT \qquad \text{(Eq. 1)}$$

where Π represents osmotic pressure, i is the Van't Hoff factor, C is the molar concentration of solutes, R is the universal gas constant, and T is the absolute temperature. As the salt concentration in the surrounding environment increases, the external osmotic pressure also increases, making water diffusion into the hydrogel structure more difficult (Guo et al., 2022).

Another relevant parameter is soil pH, since numerous hydrogels exhibit sensitivity to variations in acidity or alkalinity, modifying their swelling degree and structural stability (Gutiérrez Pérez Nestor et al., 2022). In hydrogels containing anionic functional groups, such as carboxyl groups present in cellulose- or alginate-based materials, acidic conditions promote protonation of these groups, decreasing the ionization of the polymeric network. Consequently, internal osmotic pressure decreases and partial contraction or collapse of the three-dimensional structure may occur, limiting water absorption (X. Wang et al., 2025).

Conversely, under alkaline conditions, carboxyl groups become deprotonated and acquire negative charges, promoting electrostatic repulsion between polymeric chains and initially increasing the swelling of the material. However, in the presence of high concentrations of cations such as sodium, a phenomenon known as charge shielding may occur, reducing electrostatic repulsion between chains and consequently decreasing the expansion capacity of the hydrogel once again (Li et al., 2025).

Crosslinking density constitutes another fundamental factor affecting the performance of these materials. The degree of crosslinking determines pore size and polymeric network flexibility, directly influencing the absorption capacity and mechanical resistance of the hydrogel. A high degree of crosslinking generates more rigid and compact structures, reducing swelling while simultaneously increasing mechanical stability and resistance to pressures exerted by the soil (Xiong et al., 2022). In contrast, low crosslinking density favors greater water absorption due to increased mobility of the polymeric chains; however, this may also result in reduced structural stability and mechanical resistance of the material (Costa et al., 2022; Nascimento et al., 2021).

Likewise, environmental conditions represent a critical factor affecting the stability and functionality of hydrogels in agricultural applications. Temperature directly influences both water absorption capacity and the degradation rate of the polymeric network. In general, elevated temperatures may reduce water absorption efficiency and accelerate chemical and biological degradation processes of the material (Nascimento et al., 2021). Certain synthetic hydrogels have been reported to exhibit greater structural stability at moderate temperatures around 20 °C, whereas thermal increases accelerate bond rupture and reduce the service life of the system (Telin et al., 2024).

Furthermore, under field conditions, repeated freeze–thaw cycles may induce mechanical stress within the polymeric network, generating fractures and structural deterioration that negatively affect water absorption and release capacity (Adjuik et al., 2023). These environmental conditions must therefore be carefully considered during the design and selection of hydrogels intended for agricultural applications in regions with extreme climates.

Due to the influence of all these factors, the design of hydrogels for applications in saline soils requires an appropriate balance between absorption capacity, structural stability, environmental sensitivity, and biodegradability to obtain functional and efficient materials under real cultivation conditions.

4.5. Agricultural Applications of Hydrogels in Salt-Affected Soils

In recent years, several studies have demonstrated the potential of hydrogels as functional materials for agricultural applications, particularly under drought and salinity stress conditions. The incorporation of these materials into agricultural systems has significantly improved water retention, reduced evaporation losses, optimized nutrient release, and promoted plant growth under adverse environmental conditions (Agbna and Zaidi, 2025; Nascimento et al., 2021).

Reported results indicate that the chemical and structural composition of hydrogels directly influences their agronomic performance. Hydrogels produced from natural biopolymers, such as chitosan, cellulose, and xanthan gum, have demonstrated high biocompatibility and the ability to improve soil physical properties, whereas hybrid and nanocomposite systems provide additional advantages related to mechanical stability, controlled release, and resistance to saline environments (Tariq et al., 2023).

Moreover, several recent studies have demonstrated that hydrogels not only act as water reservoirs but can also favorably modify soil microbiota, reduce contaminant mobility, and promote environmental rehabilitation processes in degraded soils. In some cases, the incorporation of nanoparticles or minerals has enabled the development of smart materials capable of responding to environmental stimuli and improving the efficiency of agrochemicals and micronutrients (Maksimova et al., 2023; Xu et al., 2025). Table 1 summarizes some of the most relevant agricultural applications recently reported for hydrogels used in saline soils and drought-stress conditions, as well as their main effects on plant growth and soil properties.

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Volume 10, Issue 2, Pages 70-94, April-June 2026

Table 1. Representative agricultural applications of hydrogels used under saline and drought-stress conditions and their reported effects on plant growth, soil properties, and stress mitigation.

Material	**Application**	**Main Effects**	**Reference**
Chitosan, carboxymethyl cellulose, and silk fibroin	Conditioning against saline–alkaline stress	Delayed water loss by evaporation, increased fresh weight of wheat plants, and promoted root growth under saline conditions	(X. Wang et al., 2025).
Potassium acrylate, acrylamide, and minerals (clay)	Saline irrigation management in sandy soils	Reduced soil water losses by 58%; however, salinity decreased hydrogel absorption by 84% and reduced maize biomass because of sodium toxicity	(Costa et al., 2022).
P(AA-co-AM)/XLG (acrylic acid, acrylamide, and xanthan gum)	Combined phytoremediation	Exhibited a synergistic effect by reducing Cd content and soil salinity while positively modifying the microbial community	(Xu et al., 2025).
(CS + SL)@SA/AL (lignin, sodium alginate, chitosan, sodium lignosulfonate)	Alleviate the hydric stress of saline soils	Hydrogels with improved mechanical properties, resistant to degradation, with good water retention, and an increase in germination rate by 19.04%	(Li et al., 2025)
Chitosan with polyvinyl alcohol (PVA) and copper nanoparticles	Smart micronutrient release	Promoted plant growth, increased crop yield, and improved tomato quality and flavor	(Costa et al., 2022).
Alkaline lignin and polyethylene glycol	Waste valorization under extreme drought	Reduced water stress and promoted greater plant height, biomass production, and phosphorus assimilation in maize plants	(Kaur et al., 2023).
Chitosan and montmorillonite clay	Smart agrochemical release	Exhibited high biodegradability and slow, controlled nutrient release toward plant roots	(Ruiz Fresneda et al., 2024).
Chitosan crosslinked with glutaraldehyde	Soil conditioning for reforestation of marginal lands	Reduced soil bulk density, increased porosity, and improved moisture retention and available phosphorus content	(Gutiérrez Pérez Nestor et al., 2022)

The application of chitosan, carboxymethyl cellulose, and silk fibroin (CS-CMC-SF hydrogel) hydrogels as an amendment for saline-alkaline soil has been studied, examining their impact on water retention properties. These hydrogels significantly increase water retention by 130%, also reducing the evaporation rate compared to soil without these types of amendments. Additionally, it significantly promoted the early growth of wheat seedlings, increasing root length (~38%), leaf length (+20–43%, depending on the variety), biomass accumulation (+24–71%), and the plant's water status under stress conditions. (X. Wang et al., 2025).

The use of biochar and hydrogels of poly (2-ethyl-2-oxazoline), 2-hydroxyethyl methacrylate (HEMA as crosslinker), and chitosan (CS) (PEtOx-HEMA-CS5) has been used for carrot cultivation in saline soils. The use of this combination of materials reduces the harmful effect of salinity and provides favorable conditions such as the amount of available water (9.4%), bulk density (1.50 Mg m-3), soil pH (8.11), electrical conductivity (between 4.0 and 5.43 m-1), the percentage of exchangeable sodium, organic matter (0.57%), and cation exchange capacity (4.90 mmolc.kg-1), also increasing productivity by up to 49% (Abdeen et al., 2023).

Commercial hydrogels of acrylamide, potassium acrylate, and minerals have been evaluated for their water absorption behavior in saline solutions with electrical conductivity (EC) levels of 0.5, 1.5, 3.0, and 4.5 dS m^{-1} by adding NaCl to distilled water. Although the use of these materials increases water retention, salinity reduces the absorption of hydrogels by 58% for sandy soils. Additionally, the use of excessive doses (0.07% w/w) increases the availability of Na^+ in the soil by 0.1 mg kg^{-1} compared to the absence of polymer, while the K^+ content was 10 to 16 mg kg^{-1} lower than that observed without polymer. Therefore, initially, the development of the crop is not favored under irrigation with saline water (Costa et al., 2022).

To evaluate the reduction of salinity in soils, the synthesis of struvite in sodium alginate-poly(acrylic acid) hydrogel microspheres in the absence (Sa@S) and presence (Sa@SHa) of humic acid (HA) has been studied. The results indicated that the use of these materials reduces electrical conductivity starting from day 5 of incubation, and after 20 days, this conductivity decreases from 6.61 mS/cm to 3.83 and 3.52 mS/cm for the Sa@S and Sa@SHa samples, respectively. These microspheres act as a barrier, effectively inhibiting excessive nutrient leaching, promoting water retention, and maintaining electrical conductivity values associated with normal soils. Moreover, the use of Sa@Sha and Sa@S resulted in a more significant reduction in the percentage of exchangeable sodium, as well as in the levels of sodium adsorption ratio (60.58% and 54.09% respectively) (Hidayat et al., 2024).

Chitosan hydrogels with polyvinyl alcohol (PVA) and copper nanoparticles (chitosan–PVA, and Chitosan-PVA+Cu NPs) have been studied to evaluate their effect on growth, antioxidant capacity, mineral content, and salt stress in tomato plants. It was found that under salt stress conditions, chitosan-PVA increased the content of chlorophyll a and b (15% and 22%, respectively), total chlorophyll (16%), and carotenoids (15%) compared to the NaCl treatment. On the other hand, combining chitosan-PVA with Cu nanoparticles increased the activity of all enzymes, the mineral content in leaves and fruits, and decreased the antioxidant capacity in tomatoes (Hernández-Hernández et al., 2018).

Hydrogels made from liquefied sugarcane bagasse biomass, polyvinyl alcohol (PVA), and sodium tetraborate decahydrate (borax) have been used to mitigate soil salinity. A significant effect on the reduction of salinity in the interstitial water and soil has been observed. In this study, four concentrations of hydrogel were tested at two salinity levels (5 and 10 dS m^{-1}). In general, with the increase in the hydrogel application rate, the sodium adsorption ratio (SAR) value showed a consistent reduction compared to the control, with a maximum reduction of 27% in SAR with the 3% hydrogel treatment. On the other hand, the concentration of Na+ in soil samples incubated in a saline solution of 10 dS m^{-1} was 807, 684, and 541 mg kg^{-1} for hydrogel application rates of 1, 2, and 3%, respectively (Tefera et al., 2022).

Overall, these studies demonstrate that hydrogels possess considerable potential for improving water-use efficiency and agricultural productivity in soils affected by salinity and drought. However, they also reveal that the performance of these materials strongly depends on factors such as chemical composition, salinity concentration, environmental conditions, and interactions with the soil matrix. Therefore, the development of hydrogels with enhanced stability, biodegradability, and resistance to highly saline environments continues to represent one of the major research areas within advanced agricultural materials.

4.6. Environmental Implications and Sustainability Considerations

The environmental impact and sustainability of hydrogels mainly depend on the chemical nature of the polymers used in their synthesis, as well as their degradation capacity under environmental conditions. These characteristics are particularly relevant in agricultural applications, where materials remain in direct contact with soil, water, and microorganisms present in the ecosystem (Garcia Garcia et al., 2024).

Hydrogels produced from natural biopolymers, such as cellulose, starch, and chitosan, exhibit high biodegradability because of the presence of chemical bonds susceptible to biological degradation, including glycosidic and peptide linkages. These bonds can be easily fragmented by bacteria and fungi present in the soil, allowing the products generated during decomposition to be naturally incorporated into the biogeochemical carbon cycle without generating persistent toxic residues (Adjuik et al., 2023). In addition to their biodegradability, these materials provide important benefits for water conservation and the recovery of degraded soils. The three-dimensional networks of hydrogels promote water retention and reduce losses caused by surface evaporation, contributing to more stable soil moisture conditions. Certain hydrogels have been reported to increase the time required for soil drying by up to 16 days, significantly improving water availability for plants in arid and saline environments (Aslan and Canbolat, 2025).

Furthermore, as biodegradable hydrogels gradually degrade within the soil, they may contribute to increasing organic matter content, favoring soil structure and improving properties associated with fertility and microbial activity (Gutiérrez Pérez Nestor et al., 2022). In addition, several studies have demonstrated that certain hydrogels may contribute to reducing the pH of alkaline soils, thereby enhancing the availability and solubility of essential nutrients such as phosphorus and potassium (Xu et al., 2025).

Despite the environmental advantages associated with biopolymers, completely natural hydrogels present certain limitations related to their service life and structural stability. Because of their high hydrophilicity, these materials contain bonds that are more susceptible to hydrolysis and biological degradation, which may significantly accelerate their deterioration under agricultural conditions (Adjuik et al., 2023). Consequently, hydrogel functionality may decrease rapidly after soil application.

To overcome these limitations, the development of hybrid hydrogels composed of mixtures of biopolymers and synthetic polymers has increased considerably in recent years. These systems make it possible to combine the biodegradability and biocompatibility of natural materials with the greater mechanical stability and chemical resistance of synthetic polymers (Li et al., 2025). In this way, materials with prolonged service life and improved mechanical properties can be obtained while simultaneously maintaining sustainable and functional characteristics for agricultural applications, as observed in the materials summarized in Table 1.

Overall, hydrogels represent a promising alternative for promoting more sustainable agricultural practices, particularly in regions affected by water stress and salinity. However, the design of these materials must carefully consider the balance between biodegradability, structural stability, and functional performance to minimize potential environmental impacts and guarantee long-term efficiency under real application conditions.

4.7. Current Challenges and Limitations

Despite the significant advances achieved in the development of hydrogels for agricultural and environmental applications, several challenges still limit their large-scale implementation, particularly in agricultural systems affected by salinity and water stress. These challenges involve aspects related to production costs, structural stability, biodegradability, industrial scalability, and performance under real field conditions (Kaur et al., 2023; X. Wang et al., 2025).

One of the major obstacles is the high production cost of certain hydrogels, especially those synthesized from biopolymers or functionalized with nanoparticles and smart components. Although these materials exhibit important advantages associated with biodegradability and sustainability, synthesis, purification, and chemical modification processes continue to represent a significant economic limitation for their extensive application in agriculture (Tariq et al., 2023). Consequently, one of the current priorities is the development of simpler, more economical, and scalable production methods capable of reducing costs without compromising the functional properties of the materials.

Another important challenge is associated with the design of smart hydrogels capable of responding to external stimuli such as temperature, pH, salinity, or magnetic fields. To confer these properties, it is generally necessary to incorporate functional particles, nanomaterials, or stimuli-responsive compounds into the polymeric network. However, when the concentration of these components becomes excessively high, the hydrogel structure may become more rigid, brittle, and susceptible to mechanical fracture (Ruiz Fresneda et al., 2024). Therefore, achieving an appropriate balance between functionality, responsiveness, and mechanical resistance remains one of the major challenges in the design of advanced materials.

Likewise, real environmental conditions represent an important challenge for the stability and durability of agricultural hydrogels. Factors such as extreme temperature fluctuations, solar radiation, humidity changes, microbial activity, and high salinity may accelerate the degradation of polymeric networks and progressively reduce their functionality. As a result, there is a growing need to develop materials capable of maintaining their physicochemical properties for prolonged periods without generating persistent residues or secondary contaminants.

Within the context of sustainable agriculture, one of the most important trends involves the development of bio-based hydrogels produced from renewable resources and agro-industrial residues. The use of materials derived from cellulose, starch, lignin, chitosan, and other biopolymers reduces dependence on petroleum-derived polymers while simultaneously promoting the valorization of agricultural and industrial wastes that would otherwise represent an environmental problem (Guo et al., 2022; Gutiérrez Pérez Nestor et al., 2022). This strategy is closely aligned with the principles of the circular economy and environmental sustainability.

In parallel, there is increasing interest in replacing potentially toxic chemical crosslinking agents with physical self-assembly methods or crosslinking processes induced by physical stimuli. Among these strategies, systems based on silk fibroin and other biopolymers capable of forming stable three-dimensional networks without the need for aggressive chemical compounds have attracted particular attention, enabling the development of safer, biodegradable, and environmentally compatible materials for agricultural and environmental applications (R. Wang et al., 2024). Future perspectives in this field are directed toward the development of multifunctional hydrogels capable of simultaneously combining water retention properties, controlled nutrient release, contaminant adsorption, and intelligent responses to environmental changes. Furthermore, the integration of nanotechnology and hybrid materials will enable the design of systems with improved structural stability and enhanced performance under highly saline conditions.

Although the experimental results reported thus far are highly promising, additional pilot-scale and field-scale studies are still required to evaluate the real behavior of these materials under different climatic conditions and soil types. The optimization of material properties, production costs, and synthesis processes will be essential to establish hydrogels as a viable and sustainable alternative for salinity mitigation and efficient water management in modern agriculture.

5. Conclusion and Future Recommendations

Soil salinization continues to represent one of the major challenges affecting agricultural productivity and environmental sustainability worldwide. Although conventional strategies, such as salt leaching and the application of chemical amendments, have demonstrated favorable results, these approaches still present important limitations associated with secondary contamination, soil degradation, and high-water requirements. In this context, hydrogels have emerged as a promising alternative for the management of saline soils because of their ability to retain water, reduce evaporation losses, and improve the physicochemical properties of soils.

Natural, synthetic, and hybrid hydrogels exhibit particular advantages and limitations; however, hybrid systems have demonstrated greater potential by combining biodegradability, mechanical stability, and high absorption capacity. In addition, these materials can contribute to reducing osmotic stress, promoting the controlled release of nutrients, and improving plant growth under saline conditions.

Despite recent advances, important challenges remain regarding production costs, stability under real environmental conditions, and industrial scalability. Furthermore, factors such as salinity, pH, and environmental conditions directly influence hydrogel performance. Therefore, future research should focus on the development of more efficient, biodegradable, and sustainable materials through the use of renewable resources and environmentally friendly synthesis strategies. Overall, hydrogels represent a highly promising tool for contributing to the sustainable management of saline soils and the development of more resilient agricultural systems under conditions of climate change and water scarcity.

5.1. Future Perspectives

1. Develop hydrogel formulations with enhanced performance under highly saline conditions while maintaining their water absorption and retention capacities.
2. Promote long-term field studies to validate the effectiveness of hydrogels under real agricultural conditions and different climatic scenarios.
3. Design environmentally friendly and biodegradable hydrogel systems using renewable resources to minimize the accumulation of persistent residues in soils.
4. Explore multifunctional hydrogels capable of simultaneously improving water retention, regulating nutrient release, and immobilizing toxic ions present in saline soils.
5. Evaluate the economic feasibility, large-scale production, and industrial scalability of hydrogel-based technologies to facilitate their practical implementation in agriculture.
6. Investigate the interactions between hydrogels, soil microbial communities, and plant physiology to better understand their long-term effects on soil health and crop productivity.

Declarations

Source of Funding

Gabriela Sánchez acknowledges the scholarship granted through the Universidad Autónoma de Coahuila project. Daniel de la Peña Aguirre and Edgar Zamorano acknowledge the postgraduate scholarships provided by SECIHTI, with scholarship numbers 2061527 and 972571, respectively. This research was financially supported by SECIHTI through projects CBF-2025-I-4203 and MADTEC-2025-M-499, as well as by the Universidad Autónoma de Coahuila through the internal research project DIP-UADEC-C01-2025-40.

Competing Interests Statement

The authors have not declared any conflict of interest.

Consent for Publication

The authors declare that they consented to the publication of this study.

Authors' Contributions

All authors contributed equally to the conception, literature review, drafting, revision, and approval of the final manuscript.

Informed Consent

Not applicable for this study.

Availability of Data and Material

Supplementary information is available from the authors upon reasonable request.

Institutional Review Board Statement

Not applicable for this study.

Ethical Approval

Not applicable for this study.

Acknowledgements

The authors acknowledge the financial support provided by SECIHTI and Universidad Autónoma de Coahuila, as well as the institutional support from the participating institutions involved in this work.

Declaration of Artificial Intelligence

Artificial intelligence tools, including NotebookLM, were used to support language editing and the preparation of illustrative figures based on the authors' original content.

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