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REVIEW ARTICLE

Evaluation of hydrogels for plant preservation, conservation and growth

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Abstract

Climate change, water scarcity, salinity, extreme temperatures, urbanization and the degradation of soils used for cultivating plants and crops pose multiple challenges to agricultural lands, the most significant being water scarcity and soil degradation. Faced with this situation, alternatives are being sought to enable the rational use of water. Among the sustainable alternatives to solve this problem is the use of hydrogels, which improve water retention, act as gradual nutrient releasers that enhance nutrient absorption and availability and promote crop growth and yield. They help alleviate water stress and provide a viable solution to water scarcity in plants and crops. This review provides a comprehensive, critical and objective overview of the use of hydrogels in sustainable agriculture as an innovative solution to climate change, soil degradation and water scarcity. It also highlights the benefits of hydrogels in water retention, nutrient release, plant and crop performance and hydraulic stress mitigation, adopting an ecological perspective. Furthermore, it summarizes the most recent advances research reported in the Elsevier and Google Scholar databases, emphasizing the most relevant findings related to the application of hydrogels in sustainable agriculture.

Keywords: agronomy; biostimulants; hydrogel applications; sustainable agriculture; water retention

Introduction

Plants play a fundamental role in human life and development, providing humans with basic and essential needs (1). In this context, agriculture is a key component of global food sustainability. However, the increasing demand for food, combined with the impacts of climate change, has resulted in insufficient irrigation, negatively affecting plant and crop ecosystems. Extreme environmental conditions, such as drought, temperature, salinity and excess or deficit of water, cause abiotic stress in plants, significantly reducing their productivity (2).

Currently, agriculture consumes approximately 70 % of global freshwater and uses nearly 30 % of fertilizers, making it the largest water-consuming sector worldwide (3, 4). It is estimated that more than 60 % of agricultural areas experience water-stress, resulting in inefficient water use. Projections indicate that by 2025, water demand in agricultural fields will increase by approximately 60 %, leading to water shortages, reduced crop yields and agricultural losses (5). This challenge is characterized by declining soil moisture and limited water retention capacity is considered a major obstacle for modern agriculture. To mitigate these constraints, farmers have increasingly relied on fertilizers to boost crop productivity; however, excessive fertilizer use has generated serious environmental impacts (6).

A biostimulant is defined as a substance that improves nutrient absorption, assimilation and use efficiency, while also enhancing plant tolerance to abiotic stress and promoting higher crop yields from germination through fruiting (7, 8). The use of these biostimulants enhances plant performance and quality, including sugars, color and firmness, while reducing environmental impacts (9). Among these, hydrogels stand out as a promising alternative biostimulant technology, offering self-irrigation capability, high efficiency and slow release of water and nutrients, particularly in arid and semi-arid regions.

Hydrogels are biodegradable, crosslinked polymers networks capable of retaining large amounts of water and nutrients, gradually releasing them into the root zone based on plant uptake (10-12). This capacity helps reduce water stress and can significantly decrease irrigation requirements, making hydrogels a valuable tool for agriculture, forestry and horticulture (13, 14). Previous studies have shown that hydrogels prolong plant survival and improve morphological and physiological traits under drought conditions (13, 15).

The global use of hydrogels in agriculture has shown sustained growth. According to Global Growth Insights, approximately 15 % of the hydrogel market is devoted to agricultural applications, with reported increase of up to 50 % in irrigation efficiency and more than 40 % in soil moisture retention (16). The hydrogel market is projected to reach USD 4641.5 million in 2024, with an annual growth rate of approximately 6.9 % for the period 2025-2030 (17). Although the benefits are promising, the implementation of hydrogels faces challenges related to performance variability, initial costs and environmental concerns, prompting the development of biodegradable hydrogels formulations to optimize their use in sustainable agriculture (18).

Objectives and methodology

This work focused on an exhaustive literature search and analysis, highlighting the use of hydrogels and the advantages of their application in agriculture, with the goal of improving soil quality and promoting crop growth. The most recent advances in hydrogel research reported in the Elsevier and Google Scholar databases were summarized, highlighting the most relevant findings related to sustainable agricultural applications.

Characteristics of hydrogels

Hydrogels are three-dimensional polymeric networks capable of absorbing large quantities of water or biological fluids without losing their original structure, allowing them to swell until they reach equilibrium (19). The three-dimensional network of hydrogels is composed of homopolymers or copolymers, cross-linked physicochemically, which makes them insoluble in water yet highly hydrophilic (Fig. 1). Owing to this composition, hydrogels have remarkable properties: they can easily adapt to different shapes and sizes depending on the environmental conditions; they are biocompatible, biodegradable, flexible, easy to modify and respond to pH changes (20). In addition, they are capable of releasing active ingredients in a controlled and timely manner. Hydrogels may be of natural or synthetic origin (21, 22).

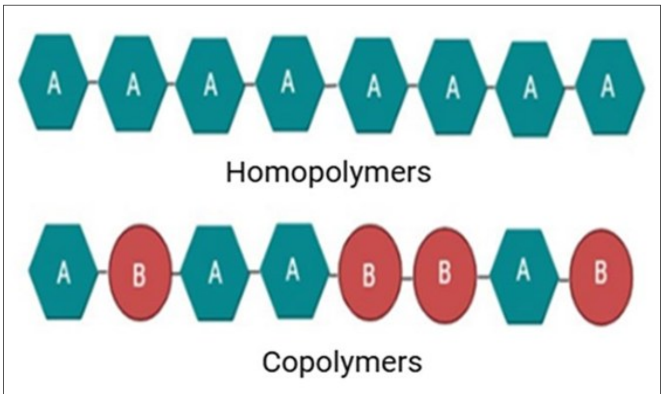

Fig. 1. Components of hydrogels.

Depending on their origin, hydrogels can be classified into two main groups, natural hydrogels, derived from polysaccharides such as alginates, agarose and chitin and synthetic hydrogels, produced from polymers such as polyacrylate or polyacrylamide, which offer greater stability and durability under demanding conditions (22). This versatility in origin and functionality greatly expands their potential uses in agriculture and other sectors (23).

Hydrogels designed for controlled release, function based on the rate of water migration rate into the hydrogel (hydration and relaxation) (Fig. 2). This mechanism allows the hydrogel to swell progressively, facilitating the dissolution of the active ingredient contained within its matrix and its subsequent diffusion to the outside (24). This property is especially useful in agricultural and biomedical applications where a prolonged or localized delivery of active compounds is required.

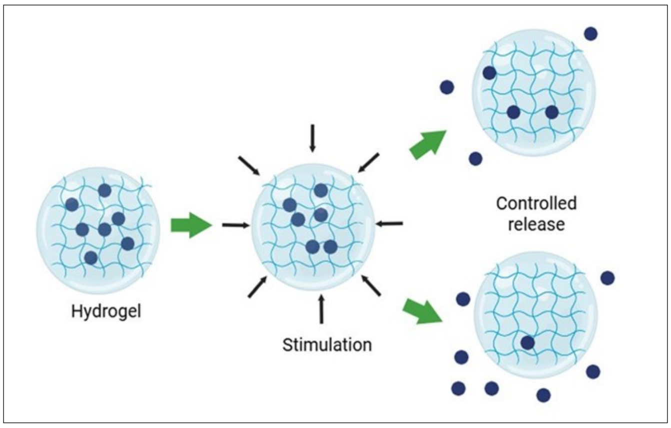

Fig. 2. Release of the active ingredient from the hydrogel.

The versatility of hydrogels is essential in the agricultural sector, positioning them as an innovative solution for optimizing resources and improving crop yield. In this context, hydrogels have been used as an effective strategy to act as a water supply for plants and growing media, especially in regions with water scarcity, constituting one of the most important advances in modern agriculture (14). Agricultural hydrogels have proven effective in seed germination, root development, increased crop yield and reduced nutrient leaching, with high potential as a valuable tool in sustainable agricultural management. For these reasons, their use has increased not only as soil amendments but also as components of efficient irrigation systems (25).

In addition to soil application, hydrogels can be used directly on seeds to promote germination, either as seed coatings, root dips or immobilization matrices for delivering growth regulators or crop protection agents (Fig. 3) (26). The use of hydrogels has also been improve various soil properties, such as permeability, density, structure, texture, evaporation rates and water infiltration through the soil, while reducing erosion and water runoff by enhancing soil aeration and microbial activity (14).

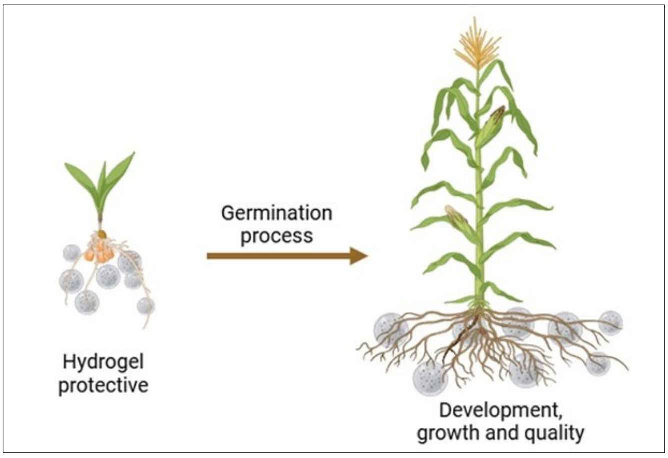

Fig. 3. Use of hydrogels in the germination process.

Water efficiency of hydrogels

Hydrogels used in agriculture represent are an innovative tool with high potential for improving soil quality, promoting root development, conserving water and increasing plant resistance to water stress. These polymeric matrices maintain optimal moisture conditions in the rhizosphere, significantly reducing nutrient loss through leaching.

The use of hydrogels in agricultural fields represents a high initial investment (approximately $160 USD), which varies depending on the application rate (2–5 kg/ha). However, this investments to prove economically beneficial in the medium and long term by, improving water and nutrient retention in the soil and significantly reducing irrigation requirements, thus significantly contributing to crop growth and yield (27, 28).

This ability not only favors plant growth but also promotes the proliferation of beneficial microorganisms in the soil, which are essential for plant health and productivity (Fig. 4). Proper use of hydrogels can significantly reduce irrigation requirements, improving water use efficiency even under conditions of severe water stress. Furthermore, their properties make them a sustainable and environmentally friendly alternative, positioning hydrogels as an ecological solution to the challenges of climate change and water resource scarcity (29). Among the main properties and benefits of hydrogels applied in the agricultural sector are:

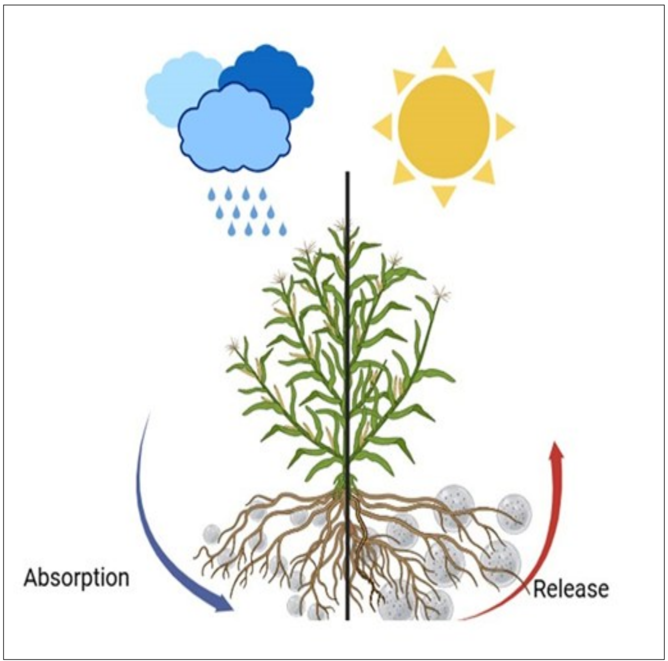

Fig. 4. Mechanism of action of hydrogels.

Water absorption and retention: Maintains optimal water levels, promoting soil moisture and mitigating water scarcity (30).

Nutrient absorption and release: Improves nutrient absorption and promotes crop growth and yield (30, 31).

Irrigation reduction: By retaining water, hydrogels make irrigation more efficient and reduce water use (31).

Drought resistance: Hydrogels help plants to tolerate prolonged drought conditions (30).

Improves soil structure: Enhances aeration, reduces compaction and supports better root development (30).

Extends the crop cycle: Maintains favorable growing conditions for longer periods, allowing for multiple harvests (31).

Environmentally friendly: Retains water and nutrients, contributing to environmental conservation (32, 33).

Compatibility with fertilizers and agrochemicals: Some types, such as potassium polyacrylate, integrate well into various management schemes (34).

Reduction in soil erosion: Decreases surface runoff and improves water infiltration (32).

Biocompatible and biodegradable: Many hydrogels are made with biodegradable materials, reducing environmental impact (33).

Cost-effectiveness: By improving crop yields and reducing water use, hydrogels offer an economically viable option for farmers (32, 30).

The absorbent properties of hydrogels not only maintain soil moisture but also enable them to serve as carriers for minerals, biostimulants, fertilizers and other active ingredients (35, 36). Their application in planting media improves the integrity of the cell membrane and the water content of leaf tissues, reducing xylem and phloem obstruction during translocation, prolonging water availability in plants and increasing and increasing resilience to adverse environmental conditions.

Mechanism of action of hydrogels

Currently, the agronomic approach has incorporated the use of biostimulants, biofertilizers and bioactive products, whose purpose is to reduce the incidence of diseases and improve crop yield (37). A biostimulant is a substance or group of microorganisms that is applied to plants and enhances the efficiency of nutrient absorption and assimilation, improving and optimizing plant tolerance to biotic and abiotic stress and enhancing the agronomic properties of the soil. The positive impact of biostimulants extends from germination to fruiting (38, 39).

Within the category of biostimulants, hydrogels stand out as a promising alternative, as they help mitigate negative environmental effects by significantly reducing fertilizer and pesticide leaching, while simultaneously optimizing water use. Their application has been shown to improve key indicators of crop quality, including sugar content, firmness, coloration and nutrient bioavailability (6). Hydrogels also play a crucial role in reducing surface runoff and preventing soil erosion (40).

The mechanism of action of hydrogels is based on their ability to absorb large quantities of water through swelling, during which they increase volume and retain water within their three-dimensional structure. This stored water is gradually released according to the plant needs. By improving soil porosity and oxygenation, hydrogels stimulate root growth and reduce irrigation frequency. In this way, water is conserved and losses through evaporation or runoff is minimized (25).

The ability of hydrogels to retain and slowly release water promotes the development of more vigorous plants with greater leaf and root density, ultimately increasing yield and productivity. Hydrogels enable plants to tolerate prolonged drought and high salinity, while improving the soil's water absorption capacity (41, 42). This capacity helps delay wilting in arid environments, reducing the costs associated with crop losses. Hydrogels are widely used in agriculture due to their durability and contribution to soil stability without causing environmental harm, consolidating them as an innovative solution for reducing agrochemical use and promoting more sustainable agricultural production (43).

Furthermore, hydrogels protect and enhance the development of plants and seeds without compromising soil fertility. For these reasons, hydrogels are highly promising for the controlled release of fertilizers, as they optimize nutrient availability and reduce leaching losses. Their use in controlled-release fertilizer systems is especially valuable because it allows progressive nutrient dosing, minimizes leaching losses and improves plant uptake (44-46).

Results and Discussion

The most important and crucial phases of plant growth are seed germination and development, which are directly related to soil water availability. Hydrogels can be very useful, as they allow water storage and create reservoirs close to the plant root, which reduces water stress and improves soil osmotic moisture. This leads to a significant improvement in seed germination, root development, viability, ventilation and water uptake in plants, thus promoting their growth (43). In recent years, interest in developing hydrogels capable of improving plant and crop properties in the agricultural field. Below, various research projects addressing the use of hydrogels and their applications in agriculture are presented. The information presented is documentary and based on an exhaustive literature review, supported by publications in indexed journals, articles and reliable top-level sources related to the study.

The behavior of gelatin hydrogels crosslinked with poly acrylic acid, which were subsequently modified with carbon nanotubes, was reported in earlier studies (47). The resulting hydrogels were capable of absorbing water equivalent to 100 % of their weight, surpassing those without carbon nanotubes. The results demonstrated that hydrogels incorporating carbon nanotubes improve the efficiency of water absorption and gradual release, depending on exposure time to heat, making them ideal for agricultural applications (47).

A hydrogel based on poly (acrylamide-co-acrylic acid (AAm/AAc)) crosslinked with silver-coated nanoclay was synthesized for sustainable agriculture (48). The AAm/AAc hydrogels showed greater swelling: 59.6 and 82.6 % of their weight at 15 and 30 days, respectively. These properties allowed for water saving and management by prolonging irrigation cycles, as well as reducing non -biodegradable waste in the soil. These hydrogels can be used as water and nutrient regulators in agricultural systems (48).

Different doses of hydrogel and compost were evaluated for use as soil moisture retainers, along with their photosynthetic effects and impact on forage corn production (49). The concentrations used were 12.5 and 25 kg ha^{-1} applied to larger plots, followed by small plots where the compost dose was 0 and 20 t ha^{-1}. The results showed that the photosynthetic activity of the forage corn plant increased 20.2 % and 28.0 % at concentrations of 12.5 and 25 kg ha^{-1}, respectively. Likewise, fresh forage production increased from 19.5 t ha^{-1} in the control to 77.6 and 81.6 t ha^{-1} with the aforementioned doses of hydrogel, evidencing its effectiveness in improving the soil in corn crops (49).

Hydrogels of polyvinylpyrrolidone (PVP) and carboxymethylcellulose (CMC) were prepared and subsequently loaded with fertilizers for application to corn plants (50). The results showed that varying the CMC content (PVP/CMC: 60/40) in the hydrogel increased swelling and improved water retention capacity for up to 9 days. PVP/CMC hydrogels present potential application as conditioners and controlled release systems for fertilizers in agricultural applications (50).

Likewise, a hydrogel was prepared by gamma irradiation of carboxymethylcellulose (CMC) and polyacrylamide (PAM) with the addition of olioalginate and nutrients, and subsequently analyzed as an immobilizer and nutrient reservoir for the growth of Chinese mustard (Brassica juncea) and lettuce (Lactuca sativa) in agriculture (51). This study showed that the synthesized hydrogel improved the seed germination of the plants (presented greater height when compared to the control) and controlled the humidity in the medium. This research shows PAM/CMC hydrogels as a hydroponic medium for the cultivation and germination of seeds, showing that their growth was improved in terms of root length, shoot height and total fresh biomass, being promising as a new technique for the production of safe vegetables with high yield and quality (51).

A hydrogel based on chitosan, gelatin, and polyvinyl alcohol was synthesized through cryogenic and chemical treatment, with subsequent incorporation of inulin to protect chili plants from microorganisms (52). The results of this work showed that the synthesized hydrogel presented biodegradability, with high porosity and crosslinking and also presented resistance against *Phytophthora capsica*, which is a pathogenic fungus that affects crops of the Solanaceae family such as peppers, chilies, tomatoes, eggplants and also cucurbits, causing economic losses. These hydrogels have great potential in agricultural applications such as agrochemical carriers and inducers in plant resistance treatments (52).

The growth of banana plantations was evaluated and their characteristics were determined using Aloe vera hydrogels and compound fertilizer (53). This work showed that incorporating *A. vera* into the hydrogel can improve the plant's ability to absorb fertilizer and increase its growth (53).

A hydrogel composed of calcium montmorillonite (NCMMt), PAAm (polyacrylamide compression), and CMC (carboxymethylcellulose) was developed and applied to tomato plants to evaluate its impact on growth and development (55). These hydrogels showed greater growth and development of tomato plants, by increasing height, stem diameter, leaf area and height/weight ratio, without presenting any toxic effect on this plant when compared to a control. Demonstrating that these hydrogels can be successfully applied in the agricultural area (54).

A biodegradable hydrogel composed of polyvinyl alcohol (PVA) and *Premna oblongifolia* Merr. (POM) extract was fabricated using glutaraldehyde as a crosslinker, and a zinc nitrate fertilizer solution was subsequently used to evaluate its absorption and release behavior (55). The absorption and release capacity of zinc nitrate shows 550 % in the water absorption capacity for approximately 3 weeks. PVA/POM hydrogels are a promising alternative as a material to absorb and subsequently release water in the field (55).

A potassium acrylate (PA)–based hydrogel was synthesized for use as a water reservoir to reduce fertilizer loss while maintaining tomato and cucumber production (4). The results indicated that these hydrogels represent an effective alternative for saving water and fertilizers, managing to conserve 747 ppm of nitrogen and 139 ppm of phosphorus. These hydrogels are promising for increasing the yield of cucumber (2.3 kg m^{-2}) and tomato (4.7 kg) crops, reducing water consumption (tomato 86 % and cucumber 47 %) and environmental impact, while maintaining plant quality (4).

Carrageenan/psyllium hydrogels incorporating montmorillonite were synthesized, resulting in an increase in soil water retention capacity from 0.533 to 0.836 g/g and an increase in soil water content by more than 60 % (56). The obtained results show carrageenan/psyllium hydrogels as an ecological and biodegradable alternative applied as an absorbent in agriculture (56).

A hydrogel in the form of Fe(III) alginate beads was developed to recover nutrients from agricultural waste and use them as fertilizers (57). Subsequently, they evaluated its efficiency in the nutrient release process and also assessed the growth of tomato plants (*Solanum lycopersicum*). The developed hydrogels absorbed 0.05 mg g^{-1} of NH_4 and NO_3 from 100 ppm solutions at pH 7, with a phosphate absorption greater than 80 % and an ammonium and nitrate absorption of approximately 30 %. The hydrogel beads promoted the growth of fruits and roots in the plant when compared to a conventional fertilizer solution, showing a controlled supply of nutrients for plants. These hydrogels are capable of being used in the agricultural field to improve the growth and formation of fruits in plants, as well as a slow-release natural fertilizer system and contribute to the mitigation of environmental problems (57).

Soybean product manufacturing waste (okara) was investigated as a soil supplement through the synthesis of okara hydrogels by grafting poly acrylic acid (PAA) crosslinked with N,N′-methylenebisacrylamide (58). The Ok- PAA hydrogels showed an increase in the yield of the cultivated plants with an increase of 113 % when compared to the control. These hydrogels proved to be innovative with potential in agricultural and environmental applications (58).

A hydrogel composed of 96 % potassium polyacrylate was evaluated on purple corn crops at three application rates (50, 70, and 90 kg ha^{-1}) compared with a control to assess corn plant development and yield (59). The 90 kg concentration showed better yield and water retention with 6.50 ha^{-1} and less irrigation (8 irrigations). These hydrogels can be efficiently used in agronomy as a soil additive to alleviate drought stress in purple corn crops (59).

A hydrogel containing Aloe vera extract was synthesized to evaluate its biostimulant effect during the initial growth phase of tomato (*Solanum lycopersicum*), as well as its influence on phenological development when applied foliarly to tomato plants. The hydrogels synthesized in this work showed an increase in height, number of leaves (17.8 cm), as well as the number of roots, length and radial volume (4.1 mm) in tomato, demonstrating that *A. vera* hydrogels are beneficial in the growth and development of tomato.

The effect of alginate hydrogels, nopal polysaccharides, *Aloe vera*, and chitosan was evaluated against a commercial potassium polyacrylate hydrogel in terms of water retention capacity, biodegradability, and morphometry and germination of alfalfa plants under controlled conditions (3). The results showed that the nopal, *A. vera* and chitosan hydrogels presented higher water retention (714 ± 40.84 %) and biodegradability (30.36 ± 0.58 %), as well as higher germination potential 30 % higher than the commercial one, greater height and foliage development in the *Alfalfa* plant compared to the potassium acrylate hydrogel. These natural polymer hydrogels are a potential alternative for the rational use of irrigation water in *Alfalfa* cultivation (3).

An *Aloe vera*–based hydrogel was synthesized to improve water retention in arid soils (60).The results showed a 25 % increase in biomass and 30 % growth in crops treated with this hydrogel when compared to untreated hydrogels. They were also able to retain up to 50 % more water in dry soil. This work showed that *A. vera* hydrogels are capable of absorbing large amounts of water and gradually releasing it during prolonged periods of drought. These hydrogels are promising for improving agricultural sustainability in regions with water scarcity, offering better crop yields, as well as reducing water (60).

A hydrogel based on N-isopropylacrylamide (NIPAM) incorporating calcium chloride ($CaCl_2$) was developed to improve plant growth through a controlled, self-sustained supply of water and nutrients, focusing on self-irrigation and slow release (SISRH) (61). The developed hydrogel showed hygroscopic properties, as well as controlled nutrient release, achieving improved water savings (40 %), reducing irrigation frequency and improving plant growth in the crop. These hydrogels are promising to meet the needs of water scarcity and efficient nutrient absorption in sustainable agriculture (61).

It is of utmost importance to mention that the agroindustrial engineer Eduardo Luligo Montealegre, from the National University of Colombia (UNAL) was granted a patent for the creation of "Water absorbent composition comprising dry particles of the cuticle of *Aloe barbadensis* Miller", used as a biodegradable technology to retain water in soils and improve water efficiency in agronomy and thus give greater vigor to plants. This hydrogel was synthesized with agroindustrial waste from the cuticle of *A. vera* leaves. Field trials showed that the synthesized hydrogel is safe and beneficial for crop growth, through vigorous development, with optimal root growth, height and diameter. One of the most important aspects to mention is the resistance they present to changes in pH, temperatures and the presence of salts in the soil (62).

Table 1 summarizes the research conducted in recent years on synthesized hydrogels, as well as their applications in the agricultural field. Research demonstrates that hydrogels are an effective tool for mitigating agricultural problems, such as soil water retention, improving seed germination and aiding plant growth. The existence of a wide variety of hydrogels used in the agricultural field for their multiple applications. Research focuses primarily on water retention capacity, irrigation reduction and plant growth and development without compromising quality. It is important to emphasize that the research documented in this work is highly relevant as a scientific contribution to the development of new sustainable agricultural methodologies. This work explores and demonstrates that hydrogels are capable of retaining water and enabling the development of multiple external stimuli (temperature and pH) that aid plant growth and development. This research also serves as an innovative way of improving the efficiency of water and nutrient uptake and release, optimizing their use in various agricultural areas, especially in arid areas or places where irrigation water is scarce.

Throughout the literature review, it is observed that research has presented positive results on various plants, highlighting hydrogels as an ideal material with high potential for use in agriculture, improving soil moisture, increasing crop yields and promoting sustainable agricultural practices. Hydrogels play a very important role in ensuring safety and environmental sustainability and although there are relevant studies on hydrogels in the agricultural field, there are still areas of opportunity for future research in the agronomic field.

Limitations of hydrogels

Synthetic hydrogels have multiple limitations and disadvantages, as they are not biodegradable and their partial degradation can release toxic compounds that accumulate in the soil for several years, causing damage to the soil and aquifers (63). The accumulation of these hydrogels for long periods alters the structure and fertility of the soil since their degradation is extremely slow and depends on

Table 1. Summary of hydrogel research in agronomy

Years	Hydrogel	Water absorption/ retention	Results	Reference
2010	PAA[a], G[b]-NTC[c]	100 % absorption	Increased efficiency in water absorption and release	(44)
2015	Aam/Aac[d]-Ag[e]	190 g/g absorption	Excellent water retention capacity	(48)
2017	Compost	95 % absorption	Increased photosynthetic activity and forage production	(49)
2017	PVP/CMC[f]-Fertilizer	36 % retention	Increased swelling, water retention, fertilizer release and soil conditioner	(35)
2017	PAM/ CMC[g]- olioalginate	351 % absorption	Increased plant growth, improved seed quality and germination and controlled soil moisture	(51)
2018	CS/G/PVA[h] dahlia inulin	-	carrier and inducer of agrochemicals, it presented biodegradability and resistance against *Phytophthora capsica* and was biodegradable	(52)
2018	AV[i]	-	Improved soil capacity and plant growth	(53)
2019	NC-MMt/PAAm/CMC[j]	-	Increased plant growth and development	(54)
2019	PVA/POM [k]	550 % absorption	Improved water absorption and release	(55)
2020	AP[l]	-	Ecological and biodegradable applied as an absorbent	(4)
2020	Carrageenan/psyllium-MMt[m]	83 % retention	Growth promoter and nutrient releasers	(56)
2020	ALG/Fe[n]	-	Increased plant yield	(57)
2020	Ok– PAA[ñ]	-	Increased plant growth and flowering	(58)
2023	Potassium polyacrylate	-	Increased plant growth and development	(59)
2023	AV	-	Greater water retention, germination, biodegradability and growth	(9)
2023	ALG/N/AV/CS[o]	95 % absorción	Greater water absorption	(3)
2024	AV	50 % retention	Greater water absorption	(60)
2024	NIPAM[p] - $CaCl_2$[q]	-	It improved its hygroscopic properties and increased plant growth	(61)

PAA: poli (ácido acrílico)[a]; G: gretetina[b]: NTC: nanotubos de carbono[c]; AAm/AAc: poli(acrilamida-co-ácido acrílico[d]; Ag: plata[e]; PVP/ CMC: polivinilpirrolidona/carboximetilcelulosa[f]; PAM/CMC: poliacrilamida y carboximetilcelulosa[g]; CS/G/PVA; quitosano, gelatina y alcohol polivinílico[h]; AV: *Aloe vera*[i]; NC-MMt/PAAm/CMC: montmorillonita de calcio/poliacrilamida/carboximetilcelulosa[j]; PVA/POM: alcohol polivinílico/extracto de *Premna oblongifolia merr*[k], AP: acrilato de potasio[l]; MMt: montmorillonita[m] ALG/Fe: alginato de Fierro[n]; Ok– PAA:okara/ poli(ácido acrílico[ñ]; ALG/N/AV/CS: alginato, nopal,alo vera y quitosano[o]; NIPAM: N-isopropilacrilamida[p]; $CaCl_2$: cloruro de calcio[q]

environmental factors, impacting their useful life (64). In addition, the costs of synthetic hydrogels are relatively high, sometimes being inaccessible to farmers (65). On the other hand, natural hydrogels also have limitations that affect their effectiveness because they degrade more quickly. This degradation depends on the soil's environmental conditions. Furthermore, they require improved optimization during synthesis to increase their stability and functionality (63, 65).

Synthetic hydrogels, therefore have a negative environmental impact, slow degradation, generate toxic waste and their high costs make them less sustainable compared to natural hydrogels since these, despite their limitations, are preferable to synthetic hydrogels, due to their biodegradability and non-toxicity. The water retention capacity improves irrigation efficiency, decreases the use of fertilizers, the availability of nutrients and seed germination especially in periods of drought. It is of utmost importance to mention that despite the challenges presented by natural hydrogels, they are respectful with the environment, contributing in a resilient and sustainable way, being an ecological and sustainable alternative in agriculture (66, 67).

Recommendations

The effectiveness of hydrogels in reducing the effects of water stress on plants remains limited, making further research essential to optimize plant growth and yield and to determine the optimal application rate of hydrogels for different types of crops and soil conditions. Furthermore, it is crucial to raise awareness among farmers about the economic benefits of using hydrogels, as they not only improve productivity and increase crop and biomass production, but also maintain efficient water retention and plant yield, promoting sustainable plant development. To encourage wider adoption, it is recommended to implement outreach programs through demonstration plots, accessible educational materials, technical training and field trips, beginning in agricultural areas affected by drought. Such initiatives would help farmers better understand the advantages of hydrogels and integrate them effectively into their agricultural practices.

Conclusion

The development and application of hydrogels in agriculture have emerged as a highly effective, sustainable and innovative strategy, with a positive impact on water efficiency and crop resilience. Their capacity to absorb and release water in a controlled manner makes them an innovative tool in the face of extreme climate change (drought), which is increasingly affecting the world's agricultural regions. In water-scarce areas, hydrogels improve soil moisture retention, increasing water availability and, in turn, reducing the frequency of irrigation during prolonged periods of drought.

Furthermore, hydrogels strengthen root system, improve nutrient absorption efficiency and promote uniform germination, leading to greater increases in agricultural yields without compromising plant quality. Their adaptability to different soil types and climates, as well as their biodegradable nature, reinforce their application as an ecological and economically accessible solution.

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Authors' contributions

AJMH was responsible for research and the writing of the original draft. RINC provided supervision and contributing to the writing, review and editing of the manuscript. YKRA contributed to the writing, review and editing, while MCIA, CACG and MGNV assisted with writing and reviewing the manuscript. As this is a review paper, no new data were generated. All authors made substantial contributions to the development of the work and actively participated in the drafting and revising the manuscript. Each author has read and approved the final version and assumes full responsibility for the content and integrity of the manuscript.

Compliance with ethical standards

Conflict of interest: The authors have no conflicts of interest to declare.

Ethical issues: None

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