RSC Advances

REVIEW

Cite this: *RSC Adv.*, 2025, **15**, 21212

Employing sustainable agriculture practices using eco-friendly and advanced hydrogels

Loshini Rodrigo and Imalka Munaweera *

Received 30th April 2025
Accepted 10th June 2025

DOI: 10.1039/d5ra03035h

rsc.li/rsc-advances

The increasing demand for sustainable agricultural practices has intensified the development of innovative materials that enhance productivity while alleviating the risks and negative impacts on the environment. This review discusses the role played by eco-friendly and advanced hydrogels in attaining sustainability in agriculture. An overview of modern agricultural practices is presented, highlighting the crucial role of hydrogels owing to their water-retaining ability and controlled release behavior. Furthermore, the types of hydrogels, their preparation methods, and various functions, such as swelling capacity, biodegradability, controlled release, and conductivity, that make them suitable for agriculture are discussed. Along with emphasizing on eco-friendly hydrogels, focusing on green synthesis approaches using bio-based raw materials and their environmental compatibility, advanced smart and responsive hydrogels are discussed. Subsequently, the practical applications of eco-friendly and advanced hydrogels in agriculture are examined, including soil moisture retention, controlled release for nutrient and agrochemical delivery, seed coating, soil remediation and soil-less cultivation. This review discusses the agronomic benefits together with the limitations of using hydrogels, concluding with future directions for the integration of sustainable hydrogel systems.

1 Introduction

1.1 Context of modern agriculture

Undeniably, agriculture holds the utmost importance in facilitating the existence of humans. Since the beginning of civilization, agriculture has played a major role, which has largely evolved over time, and currently, extreme caution is demanded, more than ever, owing to various adopted modern agricultural practices.[1,2] Continuous increase in global population has driven a higher demand for agricultural products, further worsening the food shortage issue.[3,4] It is predicted that by 2050, global population will surpass nine billion, with agricultural production anticipated to increase by 50%, eventually demanding a 15% rise in water requirement.[5] Agriculture consumes about 70% of world's freshwater, although it is becoming scarcer every day.[6] Furthermore, fertilizers and pesticides are used heavily, while natural sources such as soil and water have been misused in fulfilling the agricultural needs of the increasing population.[7] Introduction of nitrogen fertilizers has paved the way for improvements in agriculture over the past 50 years; however, according to present data, 2.50×10^6 tons of fertilizers are required yearly, which is an 800% increase in the use of nitrogen fertilizers.[8] Traditional chemical fertilizers exhibit a low utilization efficiency, as only 30–35% of the nutrients are absorbed by the crops.[9] Additionally, 50–70% of nitrogen fertilizers applied are lost through volatilization, denitrification and leaching, posing severe environmental risks of contaminating groundwater and depleting soil quality.[10,11] Furthermore, climate change has caused environmental degradation, where desertification has largely affected agricultural productivity.[6] Hence, producing adequate agricultural products while conserving the environment is a global challenge.

1.2 Sustainable agriculture in addressing global challenges

To meet the global demands, agricultural production must increase by 70% by 2050.[12] To accomplish the long-term goals in the agricultural sector, it is imperative to establish sustainable mechanism strategies to stand more resilient in the face of adverse climate changes.[13] Sustainable agriculture provides a holistic view with an integrated approach to global food production, ensuring they align with environmental conservation, economic resilience, and social well-being.[14] This includes reducing the labour burden on small-scale farmers, enhancing the suitability of farming operations, and increasing the efficiency of input utilization.[13] However, the downsides of chemical fertilizers pose a major challenge in attaining sustainability in agriculture, and thus innovations in fertilizers to enhance efficient nutrient use have attracted increasing interest.[15,16]

1.3 Hydrogels as a promising solution

Polymer chemistry has contributed largely to the development of innovative novel materials, such as hydrogels.[17,18] Hydrogels

Department of Chemistry, Faculty of Applied Sciences, University of Sri Jayewardenepura, Nugegoda, 10250, Sri Lanka. E-mail: imalka@sjp.ac.lk

present a promising solution to mitigate the prevailing obstacles and ensuring sustainability in agriculture, given that they enable the slow release of encapsulated active ingredients (AI) from their polymer matrix.[19] Additionally, hydrogels show the ability to improve soil quality, facilitate the growth of plants in arid and semi-arid areas and allow seed germination.[20] Hydrogels are 3D polymeric networks capable of absorbing large amounts of water without dissolving, which upon mechanical stress, desorb the water.[21,22] Hydrogels have been proven to act as water reservoirs and nutrient mobilisers when applied in soil.[23] They can absorb water by as much as 400-fold of their dry weight, and gradually releasing the absorbed water reduces the irrigation frequency, thus promising an effective solution for water scarcity.[24] Hydrogels are also referred to superabsorbent polymers or superabsorbent hydrogels, which when combined with fertilizers results in the formation of slow-release fertilizer hydrogels, having the potential to improve plant nutrition and reduce the negative impact of conventional fertilizers.[21–25]

Existing reviews highlight the potential of hydrogels in sustainable agriculture, focusing on water retention, controlled nutrient release, and crop protection. Prakash *et al.* emphasized the impact of hydrogels on water use efficiency and crop yield, while identifying research gaps in ideal properties and evaluation frameworks.[26] Michalik and Wandzik discussed the use of chitosan-based hydrogels as biodegradable alternatives to synthetic polyacrylates.[27] Malka and Margel explored PVA/PVP hydrogels for pest control and fertilization, demonstrating their effectiveness in stabilizing and releasing nutrients and biocides.[28] Piccoli *et al.* reported the consistent benefits of hydrogels in terms of soil properties and crop performance, particularly under water-deficit conditions.[29] Additionally, Piccoli *et al.* emphasized the need for research focusing on developing eco-friendly, smart hydrogels responsive to environmental stimuli and derived from biowaste, aligning with circular economy principles in agriculture.[29] This review focuses on eco-friendly and advanced hydrogel integrations in achieving sustainability in the agricultural sector, while challenges and limitations, as well as future directions are discussed.

1.4 Potential of eco-friendly advanced hydrogels

Polyacrylamide and acrylate are the most used sources to synthesize hydrogels.[30] However, although they are beneficial in agriculture, these synthetic materials pose environmental challenges given that they are not biodegradable. Specifically, upon exposure to certain environmental factors, they undergo degradation, generating microparticles and toxic by-products, which are neurotoxic and carcinogenic, in addition to causing possible contamination of soil and food.[31] Therefore, natural sources have been used as alternative materials to synthesize hydrogels, which are called biopolymeric hydrogels. They have the advantages of non-toxicity, biodegradability, biocompatibility and bio-mimicking traits, making them desirable in sustainable agriculture.[32–34] Natural polymers such as cellulose, chitosan, starch, alginate, xanthan, and others are used to synthesize these biopolymeric hydrogels.[25]

This review covers the role played by eco-friendly advanced hydrogels in establishing sustainability in the agriculture sector, their benefits and limitations and future directions of this type of soft material.

2 Hydrogels in agriculture

2.1 Types of hydrogels

Hydrogels can be classified based on various criteria including their material source, polymeric composition and configuration, crosslinking types, physical structures, polymer network charge and degradability.[6,24] The detailed classification of hydrogels is depicted in Fig. 1. Hydrogels can be classified based on their material source as natural, synthetic and hybrid. Natural hydrogels are synthesized using biological sources such as proteins, polysaccharides or nucleic acids, whereas synthetic hydrogels are made of polymers such as polycaprolactone, polyvinyl alcohol, pyrrolidone,[6] polyethylene glycol,[35] and polyacrylic acid.[36] Hybrid hydrogels are made of both natural and synthetic materials. Table 1 highlights the categorization of hydrogels into natural, synthetic and hybrid hydrogels based on their origin.

Natural polymer-based hydrogels have attracted increasing attention given that they are derived from renewable sources and possess the characteristics of biocompatibility and biodegradability. Among the commonly used natural polymers, lignin provides structural rigidity and antioxidant properties, while starch contributes to enhanced gel strength and biodegradability. Alginate, derived from seaweed, offers excellent gelation properties and ion responsiveness. Carrageenan, another seaweed-derived polymer, imparts thermoreversible gelation and mechanical stability. Chitosan, obtained from chitin, adds antimicrobial activity and pH sensitivity, making it ideal for biomedical and environmental applications.[54]

Crosslinking occurs during the synthesis of hydrogels, formulating a 3D polymeric network and preventing their dissolution in solvents, while enhancing their strength, elasticity and tensile strength.[44–48] Based on the crosslinking type, hydrogels can be classified as physical hydrogels, formed through hydrophobic interactions, chemical hydrogels, formed *via* cross-linking agents, and hybrid crosslinked hydrogels, referring to hydrogels prepared using both physical and chemical crosslinking methods.[24,49,50] The swelling capacity of hydrogels is mainly dependent on their degree of crosslinking, where higher crosslinking results in lower swelling capacity and *vice versa*.[51–53]

However, in this review, to delve deeper into the methods for the preparation of natural polymer-based hydrogels, the physical, chemical and radiation-crosslinked types are identified. Table 2 depicts a summary of these preparation methods. Physical hydrogels can be formed through self-assembly, a process in which polymer molecules spontaneously organize into stable structures *via* non-covalent interactions such as hydrogen bonding, van der Waals forces, hydrophobic interactions, and electrostatic forces.[55] Chemical crosslinking methods involve the formation of covalent bonds between polymer chains using crosslinking agents or chemical reactions.[56]

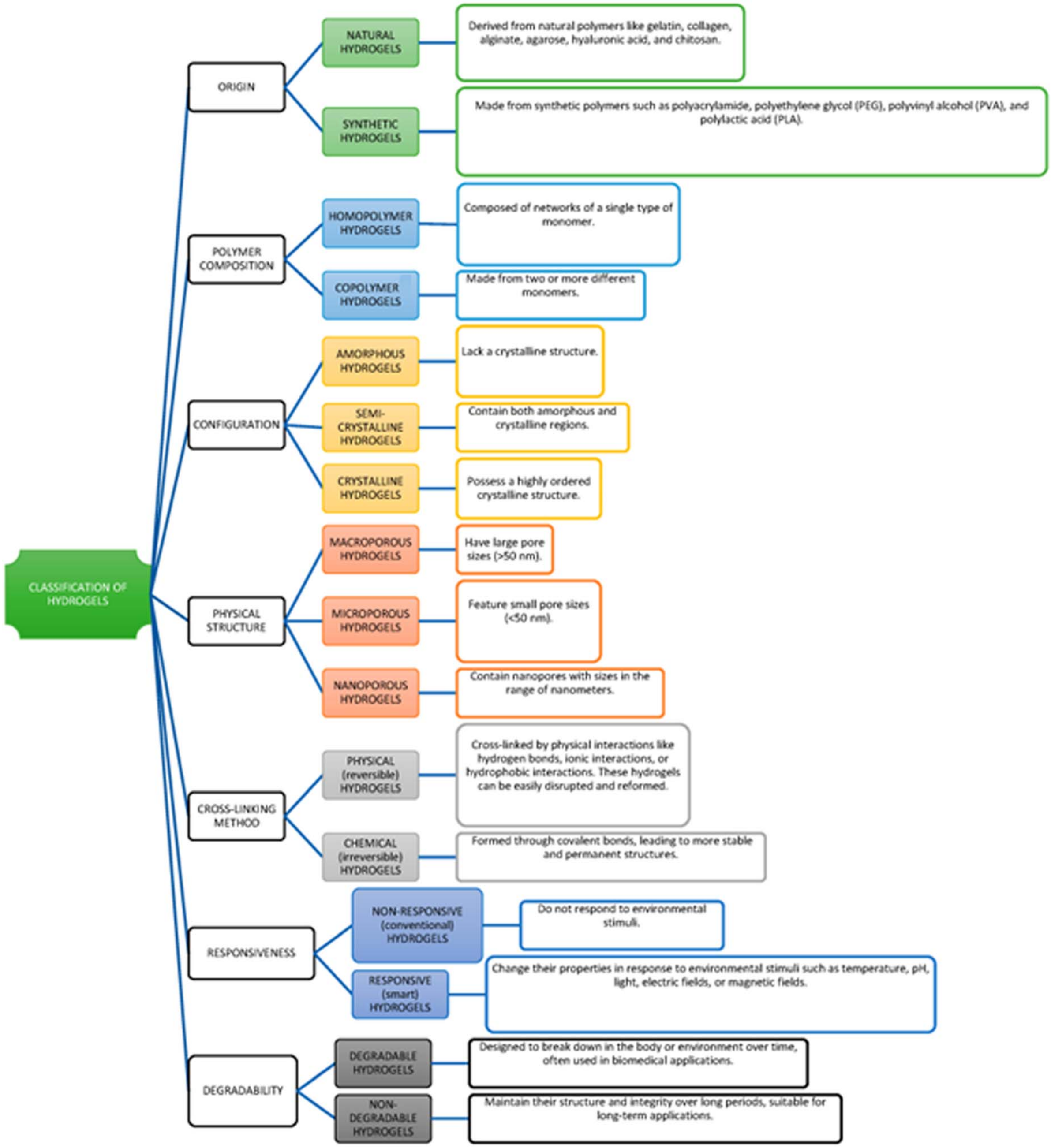

Fig. 1 Classification of hydrogels.[6]

Radiation crosslinking is an effective method for formulating hydrogels from natural polymers, utilizing high-energy radiation such as gamma rays, electron beams, and X-rays to induce crosslinking, eliminating the need for chemical crosslinkers.[57] The differences and challenges of each of these methods are illustrated in Fig. 2.

2.2 Functional properties of hydrogels relevant to agriculture

2.2.1 Swelling capacity and water retention. Owing to the 3D structure of hydrogels created by the crosslinking process and the presence of hydrophilic groups, they absorb and retain a large amount of liquid. Swelling is the characteristic response of hydrogels upon contact with water, ionic liquids and biological fluids. Temperature, pH and the type and density of crosslinking decides the amount of swelling.[6] The ability of hydrogels to improve nutrient transfer and irrigation efficiency, and function as soil conditioners is due to their ability to absorb and retain water. Furthermore, their ability to retain water reduces their loss due to drainage and evaporation, which reduces the cost of irrigation. When the soil is dry, hydrogels release the water retained earlier along with the nutrients encapsulated within their polymer matrix, functioning as both

Table 1 Categorization of hydrogels based on their origin

Classification	Examples	Key characteristics	Citation
Natural hydrogels	Cellulose, chitosan, alginate, collagen, starch, gelatin, lignin, agarose	Biodegradable, biocompatible, derived from polysaccharides/proteins	37–39
Synthetic hydrogels	Polyacrylamide (PAM), polyvinyl alcohol (PVA), polyethylene glycol (PEG) Pyrrolidone	High water absorption, durable, non-biodegradable	38, 40 and 41
Hybrid/Composite hydrogels	Gelatin-alginate, chitosan-hyaluronic acid, collagen-chondroitin sulfate	Tailored properties (*e.g.*, antimicrobial, stimuli-responsive), combine natural and synthetic polymers	42 and 43

Table 2 Overview of the methods for the preparation of hydrogels[54]

Preparation methods		
Physical methods	**Chemical methods**	**Radiation crosslinking**
• Ionic interactions	• Sol–gel transition	
• Crystallization	• Double network	
• Hydrogen bonding	• Schiff base reaction	

a slow-release fertilizer hydrogel and soil conditioner (Fig. 3).[25] The factors directly affecting the extent to which hydrogels swell are their degree of cross-linking, number of hydrophilic groups, and available space in their matrix to accommodate, absorb and retain water molecules owing to their hydrophilic nature.[58,59]

2.2.2 **Biodegradation.** The 3D structure of hydrogels can degrade upon exposure to the natural environment due to actions of enzymes and bacteria. Hydrogels behave like waste upon entering the humus cycle, making them suitable for sustainable agriculture.[25] Hydrogels made of natural polymers are susceptible to degradation, while synthetic hydrogels are non-biodegradable, contributing to environmental pollution.[21]

2.2.3 **Controlled release behavior.** Matrix-type delivery and reservoir-type delivery have been identified as the release mechanisms of nutrients and agrochemicals encapsulated in hydrogels. A matrix delivery system involves the dissolution or uniform distribution of active ingredient within the hydrogel, whereas in a reservoir delivery system, the active ingredient exists as small particles, often nanosized, encapsulated within the polymer matrix.[60] In matrix-type delivery, upon contact with water or moisture, the release of the active ingredient commences, which continues for several weeks. Alternatively, in reservoir-type delivery, water-soluble minerals in the polymer coating of the hydrogel break down or become permeable,

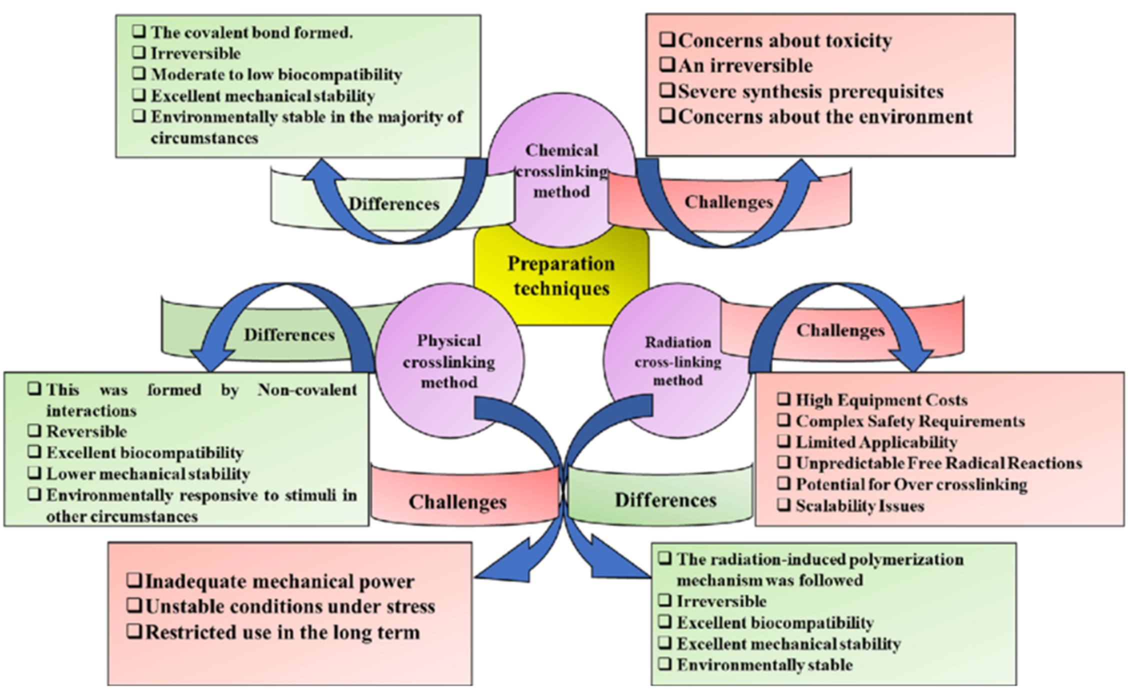

Fig. 2 Differences and challenges in hydrogel preparation techniques.[54]

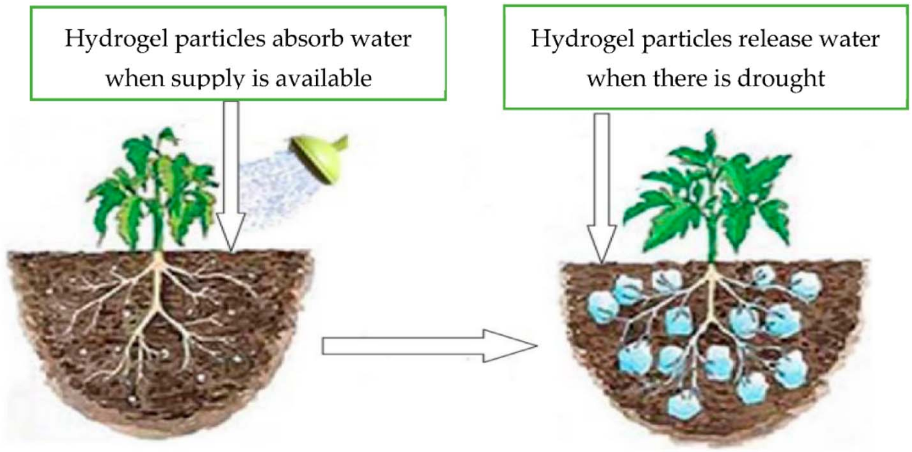

Fig. 3 Change in soil porosity upon swelling of the hydrogel.[21]

allowing the nutrients and agrochemicals to be released in response to external stimuli.[61,62]

The release mechanism of a hydrogel starts with water from the soil penetrating its coating, creating fissures and dissolving the encapsulated fertilizers. The continuous entry of water into the hydrogel affects osmotic pressure within the matrix, resulting in the collapse of its coating and abruptly releasing the entrapped fertilizers. Furthermore, another mechanism that results in the gradual release of fertilizers is upon absorbing water, the pores in the hydrogel matrix expand, which decreases the osmotic pressure and the rate of nutrient release (Fig. 4).[63,64]

2.2.4 Conductivity. The hydrophilic nature of hydrogels facilitates the dissolution of ions, enabling ionic conductivity. The incorporation of polymers, namely, polyaniline (PANI), polypyrrole (PPy), and poly(3,4-ethylenedioxythiophene) (PEDOT), as well as conductive nanomaterials such as carbon nanotubes (CNTs), graphene, and metal nanoparticles in the hydrogel matrix improves the conductivity of hydrogels, allowing them to detect environmental parameters in real time and act as soil sensors. Upon exposure to external stimuli, the electrical charges of conductive hydrogels provide measurable signals, reflecting the soil conditions. For example, the swelling of hydrogels is influenced by water absorption.[96]

2.3 Evolution of advanced hydrogels toward sustainability

Aligning with the current sustainable goals, hydrogels have shifted to more eco-friendly alternatives over the non-biodegradable and ecotoxic synthetic hydrogels derived from petroleum-based materials.[66] Therefore, naturally sourced hydrogels synthesized from renewable sources and agricultural residues, which offer biodegradability and soil compatibility, have attracted increasing interest.[67] Adapting to green synthesis approaches and formulating smart and responsive hydrogels to pH, temperature and moisture, which exhibit controlled nutrient release and higher water efficiency, have proven this shift toward sustainability.[68]

3 Eco-friendly and advanced hydrogels

3.1 Green synthesis and bio-based raw materials

Hydrogel synthesis involves the use of petroleum-based monomers and toxic crosslinkers. However, although synthetic and chemically crosslinked hydrogels are more advantageous in terms of their mechanical properties, they often pose certain environmental risks, hindering sustainability in agriculture. Thus, use of bio-based raw sources, non-toxic crosslinkers and

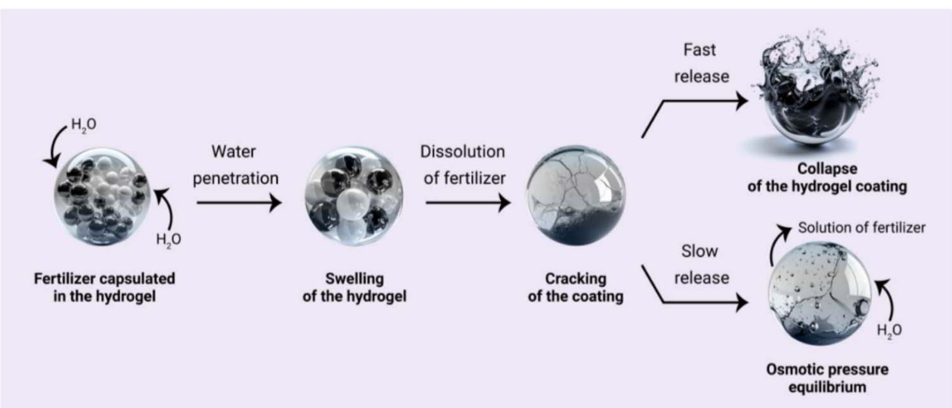

Fig. 4 Mechanisms of nutrient release from a hydrogel.[18]

environmentally benign solvents are green approaches in developing eco-friendly advanced hydrogels.[46,66,69] Starch, alginate, pectin, carrageenan, chitosan, collagen, carboxymethyl chitin, carboxymethylcellulose, dextran, agarose, and pullulan, are natural polymer-based sources that can be employed to synthesize hydrogels.[70–79] Guar gum, a non-toxic, biodegradable polymer, has been used to develop hydrogels through co-polymerization with acrylic acid using *N*,*N*-methylene-bis-acrylamide (MBA) or hexamine as cross-linkers, which exhibited excellent water retention and pH sensitivity. Furthermore, when grafted with acrylamide guar gum, hydrogels have shown increased soil water absorption, highlighting the importance of their use in arid regions as a sustainable agricultural application.[80]

Hydrogels based on chitosan obtained from seafood waste were prepared by Zhang *et al.*, which successfully showed the release of urea.[76] It was reported that a hydrogel derived from okra mucilage and soybean residue (okara) showed an increased water retention capacity and biocompatibility.[77,78] Crosslinking *via* citric acid and irradiation as alternatives to toxic chemicals in crosslinking is a greener approach toward eco-friendly hydrogels.[79] These eco-friendly approaches have emerged as promising ways to formulate hydrogels toward a sustainable agriculture.

3.2 Biodegradability and environmental compatibility

Hydrogels based on natural sources degrade readily when applied to the soil due to the presence of soil microorganisms, an eco-friendly characteristic compared to synthetic hydrogels.[80–82] Additionally, it has been reported in the literature that several species of microorganisms including bacteria and microfungi can secrete cellulase, an enzyme that can breaks down cellulose.[83] Besides, some bacteria species can secrete other enzymes such as amylase, in addition to cellulase which have the potential to degrade starch.[84]

Cellulose hydrogels derived from okara have been observed to completely degrade in soil within 28 days, showing their potential to be used in the application of fertilizers for short-term crops during their active vegetation period.[18,85] However, an increase in the crosslinking density in hydrogels may hinder the extent of their degradation. For example, Grabowska-Polanowska *et al.* reported that with an increase in the cellulose nanocrystal (CNC) content, the percentage of degradation of the hydrogel significantly decreased. This proves that the degradation period of hydrogels can be altered by adjusting their degree of cross-linking, customizing it to specific plant cultures.[86]

Synthetic hydrogels show limited degradability in soil and resistance to microbial degradation, and thus it has been proposed that by combining them with natural polymers, resulting in hybrid hydrogels, they can be eliminated.[23,87–89] Hybrid hydrogels show characteristic advantages in terms of adsorption capacity, cost-effectiveness and multiple swelling and drying cycles, while the presence of natural polymers endow the extra advantages of biodegradability and eco-friendliness.[87–89] It has been reported that natural polymers combined with acrylates are biodegradable composites. For example, it was reported that the degradation of a starch-modified poly(acrylic acid) hydrogel by microorganisms resulted in a higher mass loss (60%) when the concentration of starch was increased, while the hydrogel containing only poly(acrylic acid) without starch additive only showed 10% degradation.[90]

3.3 Smart and responsive hydrogels

A notable aspect of hydrogels is the evolution of smart hydrogels, which possess the collective properties of polymer hydrogels, together with the ability to be responsive toward variations in pH, temperature, light, ionic strength, osmotic pressure, or changes in magnetic or electric field, enabling precise control of the rate of release of their encapsulated materials.[18] This dynamic behavior of hydrogels allowing them to function as intelligent materials has resulted in a paradigm shift in this field.[90] They respond to external stimuli by undergoing structural and volume phase transitions, revolutionizing the field of responsive materials and positioning them as stimuli-responsive hydrogels (SRH).[91,92] The agriculture sector can utilize the stimuli-responsive swelling behavior of smart hydrogels triggered by external factors.

The pH-responsive behavior of hydrogels is a crucial characteristic for controlled pesticide release. Under alkaline conditions, the ability to ionize their carboxyl or amine functional groups allows increased water absorption and expansion of their polymer matrix, eventually releasing the pesticides entrapped within the hydrogel matrix.[93,94] Zha *et al.* developed dopamine-modified ATP combined with sodium alginate to achieve the pH-dependent release of glyphosate, which showed 60% release of glyphosate at pH 8.5 within 24 h, compared to only 20% under neutral or acidic pH owing to the ionization of carboxyl groups in sodium alginate, causing the microspheres to swell and release glyphosate.[95]

The precision and effectiveness of agrochemical delivery systems can be integrated by incorporating other responsive mechanisms such as temperature, redox and light. Poly(*N*-isopropylacrylamide) (PNIPAM) is a polymer known for its ability to undergo phase transitions, where its characteristic lower critical solution temperature (LCST) allows it to swell according to the changes caused by temperature and pH.[96] Additionally, multi-responsive hydrogel systems have been developed to respond to multiple stimuli. Zheng *et al.* developed a multi-responsive grafted copolymer hydrogel, incorporating the photothermal material semi-coke to introduce light responsiveness, allowing the generation of heat. This induced a phase transition in PNIPAM, eventually creating a smart hydrogel responsive to light, temperature and pH conditions.[97]

Furthermore, advanced hydrogels developed by integrating multilayer coatings with nanoparticles or encapsulating biochar have been studied, which showed increased nutrient use efficiency and improved precision release, resulting in enhanced soil health.[97]

Lang *et al.* developed a magnesium-encapsulated biochar-based fertilizer hydrogel, combining magnesium-enriched biochar with polyacrylic acid (PAA). This hydrogel achieved significant water absorption of 1395 g g^{-1} (gram of water per

Table 3 Examples of recent smart hydrogel applications in agriculture[109]

Smart hydrogel type	Mechanism	Agricultural application	Benefits
Temperature-sensitive	Swelling/deswelling in response to temperature changes	Heat stress management in crops	Protects crops from high temperatures, conserves water
pH-sensitive	Swelling/deswelling in response to soil pH	Targeted nutrient release in variable pH soils	Optimizes nutrient availability, reduces fertilizer use
Moisture-sensitive	Swelling/deswelling in response to soil moisture	Precision irrigation in water-scarce regions	Reduces irrigation frequency, conserves water
Ion-sensitive	Response to ionic concentration in soil	Salinity management in coastal or arid regions	Protects crops from salt stress, improves yield

gram of dry weight of polymer) and enhanced nutrient release, with approximately 62.1% of nitrogen released over 30 days, addressing the inherent problems of rapid leaching and volatilization associated with conventional fertilizers.[97,98] The incorporation of multilayer coatings and nanoparticles, acting as barriers to nutrient release, ensured prolonged released, while nanoparticles increase the mechanical strength, nutrient retention, and functional interactions within the hydrogel matrix.[97] Lu *et al.* formulated this type of system, with a PVA/starch hydrogel membrane enhanced with iron oxide nanoparticles and a bio char outer layer, which showed a reduction in nitrogen leaching from 31.03% to 24.99% and phosphorus leaching from 37.92% to 36.74%, while enhancing the mechanical strength, swelling capacity, and hydrophilicity of the hydrogel membrane, ensuring the gradual and consistent release of the encapsulated nutrients.[99]

Recent research has highlighted the emerging trends in smart agriculture, focusing on sensor technologies and advanced delivery systems for agrochemicals and water management. Smart sensors are being developed to monitor plant health, fruit conditions, and environmental factors crucial for crop growth.[100] Nanobiosensors and nanoformulations are advancing precision agriculture by enabling the real-time detection of plant stresses and targeted delivery of agrochemicals.[101] Smart materials, integrated with data science and nanosensors, are enhancing site-specific crop management and environmental monitoring.[102] Furthermore, data-driven tools and technologies together with hydrogels in precision agriculture play a pivotal role in targeted nutrient and moisture delivery.[6,103] Soil-moisture sensors and hydrogels can collectively fine-tune irrigation schedules by analyzing real-time data to decide when and in what amount water is needed by crops, thus sustaining their productivity.[104] The precise delivery of nutrients and water to targeted areas of fields by incorporating hydrogels in automated irrigation systems ensures the efficient use of resources, minimizing nutrient and water waste.[105] The use of hydrogels in precision agriculture is not only beneficial for improving crop performance but also contributes to sustainability by minimizing inputs and the environmental impact.[106] In the study carried out by Chen *et al.*, they designed a plant-wearable fluorescence sensor, CdTe QDs@PVA@AG, which constructed by embedding CdTe quantum dots in polyvinyl alcohol (PVA) and an agarose (AG)-co-assembled double-network hydrogel to transmit on-the-scene pesticides residues messages in and used to quantitatively detect the pesticide thiram. CdTe QDs@PVA@AG was tightly pasted onto the surface of a leaf to achieve the *in situ* and non-destructive detection of thiram residue owing to its excellent flexibility and high adhesion. Also, the degradation of thiram was monitored by obtaining dynamic residue data at different intervals. This fulfilled the need for monitoring pesticide residue information during the crop growth process, while opening a new path in smart hydrogel integration.[107]

Going a step further, the large amount of biomass generated as residues from agricultural processes can be utilized to formulate stimuli-responsive hydrogels. This innovative step not only ensures sustainability by adding value to otherwise burned agricultural residues but also leads the way toward synthesizing invaluable materials especially in biomedicine and environmental engineering.[108] As discussed by El-Sayed *et al.*, bagasse, straw, rice straw and wheat straw have potential to formulate cellulose-based stimuli responsive hydrogels. These raw materials, which are environmentally friendly and are renewable sources, assure sustainability, while having the potential to synthesize hydrogels responsive to an array of stimuli including light, temperature, magnetic field, electric field, pH, and chemical and biological triggers.[108] Table 3 summarizes some of the recent smart hydrogel applications in agriculture.

Researchers are exploring smart hydrogels responsive to multi-stimuli that can adapt and respond to multiple responses at the same time. However, although smart hydrogels are considered a promising solution, there are still some challenges such as scaling up their application, the high production costs for advanced hydrogels, and the need for comprehensive and long-term field studies to fully assess the impacts of hydrogels on the soil ecosystem.[110]

These remarkable developments show the importance of advanced smart hydrogels in driving agriculture toward sustainability. However, these advanced hydrogels may have environmental risks if developed using synthetic materials alone, and thus formulating them using natural polymers will facilitate achieving complete sustainability in agriculture.

4 Applications of eco-friendly hydrogels in sustainable agriculture

The ability of hydrogels to absorb, retain and slowly release encapsulated water and agrochemicals make them ideal

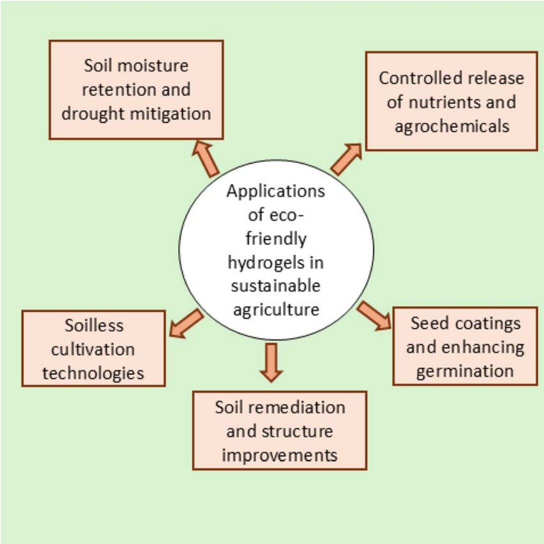

Fig. 5 Applications of eco-friendly hydrogels in sustainable agriculture.

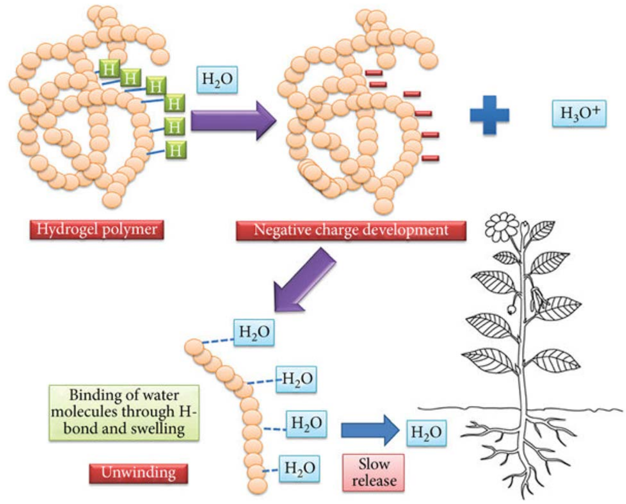

Fig. 6 Role of hydrogel in water retention mechanism.[164]

candidates for numerous applications in agriculture, as summarized in Fig. 5.

4.1 Soil moisture retention and drought mitigation

Plants undergo oxidative stress and increased lipid peroxidation when subjected to limited water availability and drought stress.[21] Water is becoming scarce in many regions due to climate change, highlighting the need for improved water management techniques in agriculture. Not all the water applied to plants through traditional irrigation methods is utilized, where a fraction is lost due to evaporation, while another portion along with the dissolved nutrients, moves into deeper layers of the soil, hindering effective water utilization and causing water stress in plants.[111–113]

Owing to the characteristic of hydrogels to absorb and retain a large amount of water, they have the ability to act as "water-holding reservoirs", which release their stored water when the soil is dry, ensuring an uninterrupted water supply to plants.[21,23] It is noteworthy that hydrogels are classified according to the way they associate with water, which is important to understand how they behave during agricultural applications, including free water, bound water, and intermediate water.[56,114] Free or non-bound water is loosely held within the hydrogel network and is the first to be released when the hydrogel dries out, playing a pivotal role in the swelling and deswelling dynamics.[115] Bound water is strongly associated with the polymer chains *via* hydrogen bonds or ionic interactions, which remain intact even under low-humid conditions, contributing to the strength and structural integrity of the hydrogel.[106] Intermediate water exhibits qualities between non-bound and bound water, retaining the polymer network and affecting the overall performance of the hydrogel *via* water retention and release.[116] Fig. 6 illustrates how the 3-dimensional structure of hydrogels functions as water-reservoirs for plants by absorption, retention and gradual release of water upon changes in the soil moisture conditions.

Hydrogels can improve the water holding capacity of soil due to their characteristic swelling behavior. However, although the water retention capacity of synthetic hydrogels is comparatively higher than that of natural hydrogels, they possess lower mechanical strength.[117] In contrast, bio-based hydrogels show higher mechanical strength despite their lower water retention capacity, particularly when reinforced with additives such as nanocrystalline cellulose.[118] However, studies show that natural eco-friendly hydrogels can reduce the water loss, improve the water use efficiency, and overall reduce the cost of irrigation. In areas that are susceptible to droughts or depict irregular rainfall patterns, the application of hydrogels is beneficial for maintaining soil moisture and the uninterrupted continuation of vegetation.[120] The characteristic slow and sustained release mechanism exhibited hydrogels reduces the frequency of irrigation, conserving water and diminishing the impact of droughts, eventually contributing advantageously to crop cultivation.[121]

In the study conducted by El-Aziz *et al.*, they concluded that eco-friendly hydrogels formulated using the polymers pectin, starch and pectin-starch mitigated the issues related to water shortage and improved the quality of tomato fruits without having any negative impact. Additionally, this study proved that the soil water retention has increased by 35%, while the growth of tomato plants and the quality of their fruits were enhanced under normal and drought conditions.[119] Chen *et al.* reported that a locust bean gum/borax hydrogel had the good water absorbing capacity of 130.29 g g^{-1} within 30 min, soil water retention ability for 14 days, good soil optimization ability and low adverse environmental impact, concluding that this hydrogel can enhance plant growth by improving the water retention capacity of sandy soil in arid areas.[122] Durpekova *et al.* designed a renewable and biodegradable hydrogel based on acid whey and cellulose derivatives blended with poly(lactic acid) (PLA), which showed a swelling ratio of up to 500%, proving its potential as a sustainable water reservoir for plants, while improving the water retention capacity of the soil by 30%.[89]

In the study carried out by Abd *et al.*, they synthesized a nano-silica hydrogel, which was reported to have improved soil water retention, crop yield and increased crop water productivity (CWP) under reduced irrigation conditions when applied to rice and clover, outperforming the control silica hydrogel-treated crops. In the first season, the nano-silica hydrogel enhanced the rice yield, with a maximum yield of 10.76 tons per ha with 90% irrigation and 119 kg ha^{-1} of hydrogel compared with other treatments. In the second season, the clover yields were also positively affected, with the highest fresh forage yield of 5.02 tons per ha with 90% irrigation and 119 kg ha^{-1} nano-silica hydrogel. The higher yield and better water efficiency observed for both rice and clover signified its importance in sustainable agriculture.[123]

In a recent study carried out by El-diehy *et al.*, they formulated Na-CMC/PAAm hydrogels *via* gamma radiation-initiated copolymerization and further modified them by KOH treatment, which showed enhanced swelling capacity and possessed high gel content, while remaining best for long-term water retention. Additionally, in the field trials conducted for sugar beet under very dry conditions, the shoot length increased by 18%, the root length increased by 32%, the shoot fresh weight increased by 15% and the shoot dry weight increased by 15%. The protein content increased by 19%, resulting in an increase in leaf chlorophyll levels to a maximum of 12% and carbohydrate production was enhanced by 13%, increasing the crop yield. Thus, these modified hydrogels have been demonstrated to be promising solutions to mitigate effects of drought conditions and obtain enhanced crop yield in regions with limited water availability.[124]

4.2 Controlled release of nutrients and agrochemicals

Conventional fertilizers exhibit low nutrient use efficiency, whereby a considerable percentage of nitrogen (40–70%), phosphorus (80–90%), and potassium (50–70%) from applied fertilizers is lost to the environment through leaching, runoff or volatilization, causing environmental pollution.[125,126] However, although a large proportion of fertilizers is lost, overfertilization is not a viable solution given that it pollutes the environment. Therefore, environmentally benign techniques to apply fertilizers in a controlled manner are required in path toward sustainability.

The ability of hydrogels to transition between swelling and deswelling is utilized to load small molecules such as nutrients and other agrochemicals, which cause them to release gradually.[48,127] Slow release fertilizers (SRF) use hydrophobic coatings, and in controlled release fertilizers (CRF), fertilizers are encapsulated and the rate, pattern and duration of their release are controlled.[59,65] This gradual release commences from the deswelling process of hydrogels, in which water diffuses, and fertilizers are transported through the pores of the polymer matrix to the outside environment.[128] The release of encapsulated nutrients from these polymer networks occur in response to the soil moisture levels. The gradual and sustained release of nutrients ensure improved fertilizer use efficiency and alleviate nutrient leaching compared to the inherent disadvantages of conventional fertilizers.[106] The release profiles of the encapsulated nutrients can be tailored in accordance with the growth stages of crops, ensuring that the plant crops receive the correct amount of nutrients at the correct time.[130]

It has been reported that hydrogels encapsulated with essential nutrients and micronutrients increase their availability to plants, enhancing crop growth and leading to increased yield.[131] By addressing specific nutrient deficiencies in plants, the overall crop health and productivity are improved.[132] Fig. 7 shows the mechanism occurring in response to moisture conditions upon the application of fertilizer-encapsulated hydrogels to soil. It demonstrates that the sustained and gradual release of nutrients reduce the need for frequent fertilizer application, while minimizing the nutrient loss through runoff.

A hydrogel was developed using starch grafted with poly(-acrylic acid) and urea was entrapped in it, which showed a slow-release pattern, where 25% of the fertilizer was released during the initial 1–5 days after applying it to the soil, within a period of 5–20 days, over 64% of the urea was released, and in the next 20–30 days, nearly all the urea (90–99%) was released.[23] Combining fertilizers with nanomaterials results in the formation of nanofertilizers, which are readily available, making them a sustainable option given that they reduces the frequency of fertilizer application.[23]

In the study carried by out Kottegoda *et al.*, they reported that urea-modified hydroxy apatite nanoparticles encapsulated in a cellulose matrix demonstrated the release of nitrogen in a slow and sustained manner for more than a 60 days period and field trials using paddy indicated an improved crop yield compared to the trials carried out with a conventional fertilizer.[133]

A novel slow-release and water-retention nitrogen (N) fertilizer (SRWRNF) was developed using moldy steamed bread-based starch-*g*-poly(acrylic acid-*co*-acrylic amide) (SBS-*g*-P(AA/AM)) as the matrix and urea–formaldehyde oligomers (UF) as the slow-release N source *via* a semi-interpenetrating method. SRWRNF exhibited high water absorbency (104.2 g g^{-1}) and enhanced soil water retention by 15.3–17.6%, while nitrogen release studies proved its gradual nutrient supply, improving the maize yield by 20.3% over urea. These findings highlight the potential of SRWRNF in large-scale agricultural applications, particularly in enhancing crop productivity together with soil water management.[134]

The study carried out by Khanam *et al.* introduced a method to convert rice straw into a slow-release hydrogel containing nitrogen, phosphorus, and potassium (NPK) fertilizers, which involved a series of acid-base pretreatments to enhance the rice straw reactivity, followed by graft copolymerization with acrylamide (AM) and *N*,*N'*-methylenebisacrylamide (MBA) to form a three-dimensional network that retains water and plant nutrients. This hydrogel system ensured the slow release of NPK fertilizers, proving to enhance the nutrient use efficiency and providing water to plants, which resulted in over 98% atom

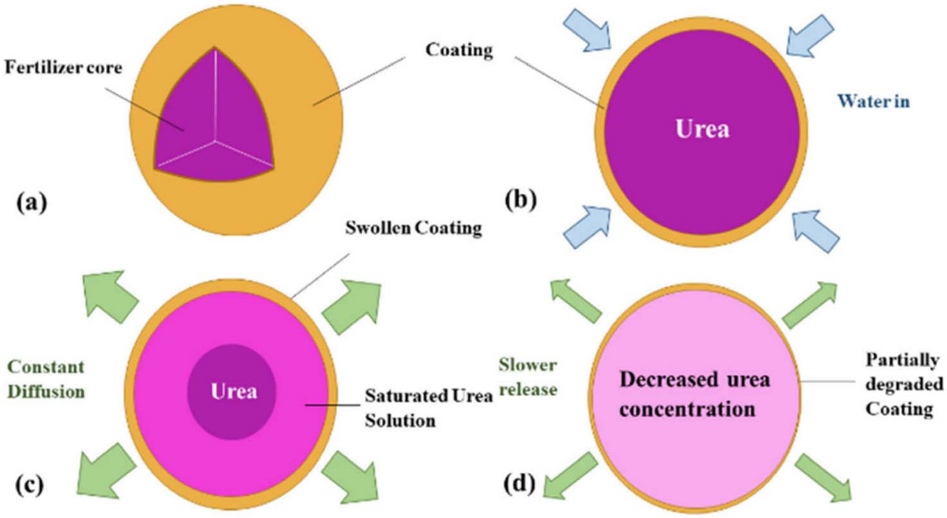

Fig. 7 Controlled nutrient release from hydrogel-encapsulated fertilizers. (a) Granule of a controlled-release fertilizer. (b) Initial phase involving water infiltration through the coating into the core. (c) Accumulation of internal pressure leading to the steady release of nutrients into the surroundings. (d) Final stage where the concentration gradient diminishes, causing a reduced release rate.[64]

economy. This indicates that this hydrogel formulation process is a zero effluent system, signifying its suitability for agricultural applications as a sustainable approach.[135]

In a study carried out by Nandal *et al.*, they synthesized a natural polysaccharide κ-carrageenan and guar gum-based hydrogel crosslinked with epichlorohydrin to examine its effectiveness as a slow-release fertilizer for urea and dipotassium hydrogen phosphate, in which tomato was used for the plant study, enabling the controlled release of water, nitrogen, and phosphorous from the fertilizer system, while reducing irrigation frequency and promoting efficient water management. The synthesized hydrogel-treated tomato plants depicted significant growth, where the plant height and leaf width were observed as parameters.[136]

Saragih *et al.* reported the successful synthesis of a chitosan-based slow-release fertilizer hydrogel, in which chitosan was derived from black soldier fly (BSF) pupa shells and acted as a crosslinking agent in the synthesized polymer-based hydrogel. Furthermore, it was understood that chitosan from BSF pupa shells has the properties of 83% degree deacetylation, a semi-crystalline and slightly amorphous structure, pores that enhance water absorption capacity, and high thermal stability. These properties make chitosan an effective crosslinking agent, improving the hydrogel stability and extending the nutrient release duration eventually, contributing as a potential material in sustainable agriculture.[137]

4.3 Seed coatings and enhancing germination

The application of hydrogel additives around plant seeds is intended to protect them from external factors such as drought, salinity, and pathogens and ensure water availability for a longer time, while providing the optimal conditions for the growth and performance of plants, especially in challenging environments.[128,129,138] The active ingredients entrapped in seed coating hydrogels are delivered in a targeted and regulated manner, whereby the germination of seeds is improved, seedlings survive, and the overall growth of plants is sustained, which also reduces the misuse and decomposition of fertilizers and agrochemicals.[6,139]

Before the seed is planted, it is covered with a dry hydrogel and a mixture of active components; this coating is formulated with a binder for adhesion and fillers such as clay or talc.[140] As shown by Pathak and Ambrose, covering seeds allows plants to survive through the seed germination stage and develop their seedlings.[141] The distribution of AI and plant growth enhancement were caused by hydrogel seed coatings formulated using biopolymers such as gelatin, gums and starch, which are eco-friendly hydrogels.[142]

Dry seeds undergo swelling and change their shape during the imbibition process, when the uptake of water takes place, causing the embryo to expand. Later, the stored reserves in the hydrogels are mobilized along with the release of retained water within the hydrogel.[143] Jampi *et al.* proved this using cellulose hydrogel as a medium for maize seeds to germinate.[144] Saberi Riseh *et al.* developed hydrogels or sodium alginate formulations encapsulated with bacteria, serving as biological control agents while ensuring biodegradation.[145]

The addition of nutrients, microorganisms and biopesticides to formulate hydrogel seed coatings has shown advantages in improving the nutritional value in soil, thus enhancing plant development, while not causing any residual effect on the immediate environment.[146] The presence of moisture for a prolonged period facilitates the growth of both the roots and shoots of plants. For example, it was reported that the shoot length of maize increase compared to the control group on day 7 of the experiment when a carbohydrate-based hydrogel was applied.[147] Furthermore, Iftime *et al.* observed an increase in the growth of plants by approximately 70% when chitosan-based hydrogels were applied compared to the reference soil.[148] This characteristic is advantageous, especially in arid environments where water is scarce, and irrigation deficits occur. Thus, eco-friendly hydrogels play an imperative role in the application of seed coating, not only in seed germination but overall plant growth and yield.

The study carried out by Zhang *et al.* utilizing cellulose-based hydrogels demonstrated that a higher carboxyl group content, such as CH07 (carboxylate content of 0.7 mmol g^{-1} of hydrogel), exhibited superior water absorption (309% $\pm$ 6%) due to its hydrophilic nature, ensuring the adequate presence of moisture for seed germination and early seedling development. The experimental results revealed that sesame seeds germinated faster on CH07, achieving 100% germination within four days, significantly outperforming the other hydrogel variants. The optimal water retention and macroporous structure of CH07 facilitated early root development and greater fresh weight, which were comparable to seedlings grown in soil. Furthermore, the cellulose anionic hydrogel demonstrated antibacterial activity, ensuring a clean and protective environment for seed growth.[98]

4.4 Soil remediation and structure improvements

The application of hydrogels is beneficial to enhance the structure and stabilization of soil, control erosion and overall increase the soil fertility.[21,149,150] Owing to the repeated swelling and shrinkage of hydrogels, they have a positive relationship with the permeability, bulk density, texture and aeration of the soil.[149,150] Besides, larger tubules in the soil structure are mechanically obscured by the hydrogels when the micro-capillaries thrive, restricting the evaporation and release of water due to gravity, and eventually hindering the loss of nutrients.[151] Hydrogels help the soil particles to bind by increased agglomeration, which reduces the risk of soil erosion caused by wind and water.[152] This is beneficial in areas with loose, sandy soils or steep slopes, where erosion can lead to the significant deterioration of soil, thus hydrogels contribute to achieving soil cohesiveness.[154] Also, by improving the soil cohesion, hydrogels contribute to maintaining the soil structure and fertility, ensuring sustainable land management practices. Hydrogels are concurrently applied with other soil stabilizers such as mulch and geotextiles to enhance their effectiveness. Hydrogel-applied agricultural lands have demonstrated higher resistance to erosion, especially during heavy rainfalls.[155] This is advantageous for areas where reforestation and land reclamation are done to establish vegetation in which soil structure is promoted by hydrogel application.[6]

A study showed that a chitosan hydrogel could increase the water retention capacity of soil by up to 154% in comparison to the control without hydrogel.[148] Although biopolymeric hydrogels biodegrade and are eco-friendly, their ability to infiltrate the soil is less pronounced compared to synthetic hydrogels, highlighting that a larger application content is essential for biopolymeric hydrogels.[86] Thus, further research to optimize the composition of bio-polymeric hydrogels is needed for their function in improving soil structure and fertility.

4.5 Soil-less cultivation technologies

Soil is the preferred option as a potting medium due to its convenience and availability, although it possesses the risk of soil-borne diseases, and scalability difficulties in large-scale production.[24] Alternatively, lightweight materials such as sphagnum moss, rockwool, cocopeat, and perlite are used as media in soil-less culture, which require a continuous supply of water, increasing operational costs for production. Thus, to overcome these irrigation costs, act as a soil-conditioner and reduce water run-off and soil-erosion, hydrogels are introduced as a potting medium. Due to their continuous supply of water and nutrients and positive impact on plant growth, hydrogels have emerged as a promising alternative for soil-less cultivation. By introducing cellulose hydrogels into a perlite substrate, while maintaining the high air capacity of the perlite substrate, the water retention was improved in 27.9% and 47.7% compared to the unchanged substrate with the use of 1% and 2% hydrogel concentrations, respectively. Biodegradable hydrogels have attracted significant interest in modern urban farming given that they offer flexibility when mixed with cellulose-based non-toxic materials such as cellulose derivatives, sawdust cellulose, rice ash, wheat straw, pineapple peel, and oil palm empty fruit bunch in their formulation.[59,153,156,157] Bio-polymeric hydrogels are important for urban farming as a medium in soil-less cultivation due to their benefits of water retention, improved nutrient efficiency and increased crop yield.

5 Benefits and challenges associated with eco-friendly hydrogels

5.1 Agronomic and environmental benefits

The benefits of using eco-friendly and advanced hydrogels have increased importance in achieving sustainability in agriculture given that they address some urgent issues in modern agriculture such as water scarcity, irrigation cost, efficient nutrient use, enhancing soil health and overall impact on the environment. Table 4 summarizes a series of case studies from different regions and agricultural systems, highlighting the practical benefits gained from using hydrogels in real-world applications.

In the study carried out by Barros *et al.*, they synthesized and examined a hydrogel based on a natural polymer derived from cashew gum (*Anacardium occidentale*) on the growth, chemical composition, and mineral content of cactus pear genotypes, where the plant study was carried out together with controls of no hydrogel and a commercial hydrogel. It was conducted in a completely randomized design with a 3 $\times$ 3 factorial arrangement (n = 36), involving three hydrogel types $\times$ three cactus pear genotypes [Elephant Ear (*Opuntia stricta*); Giant (*Opuntia ficus-indica*); and Sweet (*Nopalea cochenillifera*)]. This study demonstrated that the synthesised hydrogel promoted greater plant growth and improved the chemical and mineral composition, making it an eco-friendly alternative to synthetic hydrogels.[158]

A chitosan-based biopolymeric hydrogel was reported to have shown the water holding capacity of up to 154% and improved the nitrogen content in the plant medium, which was

Table 4 Summary of the key case studies on hydrogel applications in agriculture[109]

Region	Crop type	Hydrogel benefits	Yield improvement	Water savings
Sub-Saharan Africa	Maize	Improved drought resilience, higher soil moisture retention, reduced irrigation frequency	20% increase	Reduced irrigation frequency
Semi-Arid India	Pearl millet	Enhanced water retention, better soil structure, prolonged root hydration	30% increase	40% less water usage
Southern Europe	Grapes	Consistent moisture during berry development, improved fruit quality	15% increase	25% less water usage
Middle East	Tomato	Better fruit quality, reduced soil salinity, enhanced nutrient uptake	18% increase	30% less water usage
North America	Strawberries	Improved fruit firmness, longer shelf life, reduced irrigation needs	12% increase	20% less water usage

twice that of the control treatment.[148] The efficient use of nutrients diminishes the negative impact caused by over-fertilization, chemical run-off and leaching, and contamination of the soil and water, while reducing the cost of excessive fertilizer usage. The encapsulation of nutrients and agrochemicals and developing SRF and CRF minimize the need for fertilizer application repeatedly, offering more economical value. Furthermore, the use of eco-friendly hydrogels poses the additional benefit of biodegradation, given that hydrogels made of natural biopolymers and agro-waste decompose naturally without leaving harmful residues in the environment. Agro-waste-derived hydrogels such as lignin-cellulose blend-based hydrogels lowered greenhouse gas emissions by 15–20% through reduced fertilizer runoff and their biodegradable decomposition.[114–159] Also, the lower cost of their raw materials is an advantage, given that eco-friendly hydrogels are derived from abundant and renewable sources in contrast to the higher cost of petrochemical-based monomers used in synthetic hydrogels.[86]

The use of eco-friendly advanced hydrogels maintains optimal moisture and nutrient levels and enhances seed germination and early plant growth, ensuring overall crop development and increased yield and supporting food security globally.[6]

Furthermore, in an area where water resources are minimum, the use of hydrogels decreased the need for supplemental irrigation by 25%, contributing positively to water conservation.[26] This positive observation of hydrogels has inspired further research on the use of hydrogels for high-value crops such as olives and citrus fruits in the Mediterranean region.[104]

Extensive field trials in arid conditions in Uzbekistan and the temperate climate in the Moscow region evaluated composite gel-forming soil conditioners, such as "Aquapastus" a patented polymer. These trials revealed an increase in the yield of potato tubers by 30% and above with 30–50% savings in irrigation. The hydrogels also provided antipathogenic protection, enhancing the crop resilience.[160]

Additionally, in the pursuit of improving water management, soil conditioning and crop productivity, hydrogels have become invaluable materials, while commercially available hydrogels have contributed to integrating agricultural practices. AQUASORB, a cross-linked copolymer of acrylamide and potassium acrylate, has been reported to have a water absorbing capacity of 100–200 times its weight, while releasing nutrients and water for optimal plant intake.[161]

Agra Gel (T-400), a hydrogel synthesized utilizing organic cross-linked co-polymers with water-binding groups based on potassium, has the ability to absorb and retain water several 100 times its weight, highlighting its importance in soil conditioning and water retention.[162]

Alsta Hydrogel is an eco-friendly polymer, which is beneficial for reducing water usage, while ensuring robust plant health, which is designed for lush green harvests, even under arid conditions. It has been reported to have a water absorbing capacity of up to 500 times its weight.[111]

PUSA (Indian Agricultural Research Institute, India) hydrogel is a semi-synthetic, cross-linked, derivatized cellulose-*graft*-anionic polyacrylate superabsorbent polymer, which has exhibited high water absorbency together with absorbency at relatively high temperatures (40–50 °C, suitable for arid and semi-arid regions). Additionally, PUSA hydrogel has low application levels (2.5–3 kg ha^{-1}) and is reasonably priced (US$ 14–18 per kg) compared to other contemporary commercial hydrogels, making it more appealing for large-scale applications.[162]

However, the high cost of production and complex manufacturing processes are challenges in the commercialization of hydrogels. Thus, to yield agronomic benefits, it is necessary to develop green protocols for formulating hydrogels with a considerably decreased cost and well-defined benefits.[162]

5.2 Limitations and challenges

It has been observed that hydrogels made of natural polymers exhibit lower water retention capacity compared to synthetic hydrogels. This should be addressed by focusing on the composition and the degree of crosslinking, given that the properties of hydrogels are largely attributed to the type and concentration of crosslinking.[18] This can also hinder the effectiveness of hydrogels under field conditions. Natural polymers have shown limited monomer solubility in aqueous and non-aqueous solvents during the synthesis of hydrogels, which requires the excessive use of hydrogels to enhance the agricultural yield.[163]

The water retention ability of hydrogels is largely dependent on the soil pH, which is an aspect that can be addressed by tailoring hydrogel compositions according to the soil type and crop requirements.

Lower mechanical strength is identified as an inherent disadvantage of hydrogels based on natural polymers compared to their synthetic counterparts, which hinders their effectiveness in applications where maintaining structural integrity is crucial. The brittleness and softness of natural polymer-based hydrogels are factors limiting their applicability. Accordingly, the strategies of crosslinking, composite formation and nanomaterial integration have been explored to address these shortcomings and improve their mechanical properties.[54] Gong *et al.* synthesized a new material category of hydrogels in the form of a "double network", which was derived from several cross-linking processes between two polymer networks. Some of the energy is released through the bundles of the polymer network when it is mechanically stretched, and the other network remains unchanged.[165] The integration of hydrogel compositions with nanomaterials has been reported to result in higher strength and improved flexibility than conventional hydrogels.[54]

Additionally, practical difficulties such as absence of uniformity across batches and raw materials in formulating hydrogels based on natural polymers result in inconsistencies in their performance. This challenge occurs due to the variability in polymer composition, molecular weight, and purity, which eventually affect the key characteristics of hydrogels, which are strength, degradation kinetics, and swelling dynamics. Given that these inconsistencies in performance affect the overall effectiveness of hydrogels, standardizing the raw material quality, refining extraction processes, and using advanced characterization techniques are imperative to alleviate the shortcomings and improve the performance of hydrogels.[54]

Advancing hydrogels by incorporating features of responsiveness to pH, temperature, or biological stimuli is essential to increase their versatility, especially in formulating smart-sensor hydrogels.[166] However, maintaining structural integrity upon imparting these advanced functionalities is a challenge given that the balance between mechanical strength and introducing responsive features often leads to weakened networks or change in degradation rates, disrupting the overall efficacy of hydrogels. Therefore, sophisticated research on formulating hydrogels while preserving both their performance and responsiveness is timely.[54]

Natural polymer-based hydrogels are widely acknowledged for their eco-friendliness and contribution to attaining sustainability. However, the processes used to extract, purify, and modify natural polymers are typically intricate, lengthy, and costly. The purification of raw materials is necessary to ensure consistency in quality, while chemical modifications are required to improve functional properties, mechanical strength and durability, increasing the cost of production. As a result, this makes the conveniently produced synthetic fertilizers more appealing for scaling up in industrial applications over natural polymer-based hydrogel fertilizer applications.[54,167]

Additionally, the cost-effectiveness of hydrogels depends on several factors, including crop type, soil properties, and climate, which makes it difficult to generalize their economic benefits across diverse agricultural systems.[6] Thus, intensive research to improve their practicality by cost-effective extraction methods and scalable modification techniques is crucial to overcome these challenges. The cost of advanced technologies to promote precision agriculture is challenging, especially for small-scale farmers, further highlighting the need for affordable and scalable solutions that can be widely adopted.[109] However, although these sensor technologies offer significant potential for sustainable agriculture, their successful implementation requires farmer education and extensive field trials to ensure effectiveness in real-world conditions.

Additionally, commercializing hydrogels, maintaining a consistent profile of nutrient release, overcoming the limitations of bearing load and tensile strength, and conducting field trials for improved efficacy are challenges that need to be addressed to achieve sustainability.[114]

6 Future directions

Developing cost-effective biodegradable hydrogels and making them accessible to farmers, especially in developing regions, are priorities in directing agriculture toward sustainability through eco-friendly hydrogels.[164]

Although smart hydrogels have attracted significant interest in recent times, improving their responsiveness and reliability for a prolonged period, while ensuring a consistent performance requires extensive research.

Combining hydrogels with digital farming technologies, allowing the real-time monitoring of soil conditions and nutrient levels, will support precision agricultural practices.[131,168] Tailoring the characteristics of hydrogels according to the crop requirements and soil condition remains an avenue for further study in precision farming.

The possibility of integrating hydrogels that can respond to multiple stimuli effectively will not only support precision agriculture but also help to attain sustainability. The "all-in-one gel" is proposed as a potential development to address this, which can dynamically respond to external environmental stimuli, while modulating the release of entrapped nutrients and agrochemicals (Fig. 8).[96]

The integration of novel nanocomposites to improve the performance of hydrogels can be further studied to enhance their properties.[104] Infusing natural nanomaterials, such as polysaccharide-based nanoscaffolds, and inorganic compounds, such as kaolin, MMT, and attapulgite, will address the high cost of hydrogels, which is a major challenge, while not

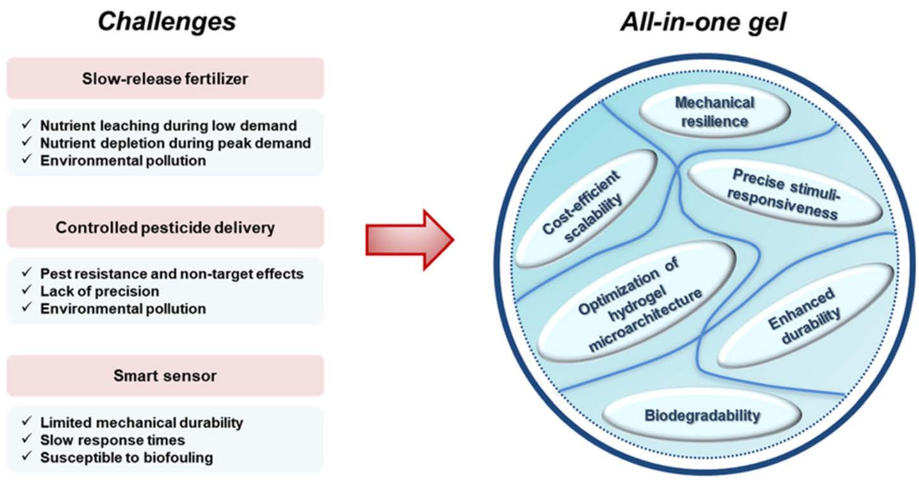

Fig. 8 Challenges in current hydrogel-based agriculture practices and the solution of all-in-one gel.[96]

compromising their essential properties such as mechanical strength, swelling degree, and nutrient and water release. Integrating functional nanocomposite slow-release fertilizer hydrogels that have the potential to improve the water absorbing capacity with nanoparticles to enhance their properties such as thermal stability, porosity, swelling kinetics, and release dynamics is a path to explore in attaining sustainability in agriculture.[169] The continuous development of eco-friendly advanced hydrogels requires collective efforts from multiple disciplines including materials scientists, agronomists, and environmental scientists.[109]

7 Conclusion

The increasing global population demands increased food production, whereby agriculture requires innovation and sustainability to cater to the growing food needs, while conserving the environment. In this case, hydrogels address some major challenges in the agricultural sector including water conservation, nutrient use efficiency, maintaining soil health, and eventually eliminating the risks associated with environmental pollution. Eco-friendly and advanced hydrogels can overcome the limitations in modern agricultural practices, while acting as a sustainable tool. These hydrogels integrated with advanced formulations have attracted significant interest in recent times, with numerous applications showing promise in alleviating challenges associated with agricultural practices. Although there are some limitations and gaps to address, through extensive research, the effectiveness and usability of hydrogels can be enhanced, thus attaining sustainability in agriculture.

Data availability

As this is a review paper, no new data was generated or analysed during this study. All data discussed in this review are derived from previously published studies, which are cited appropriately in the manuscript.

Author contributions

Loshini Rodrigo-investigation, writing-original draft. Imalka Munaweera-conceptualization, writing-review and editing, supervision.

Conflicts of interest

The authors declare that there is no conflict of interest.

Acknowledgements

The authors received no specific funding for this work.

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