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Review Article

Prospects of Hydrogels in Agriculture for Enhancing Crop and Water Productivity under Water Deficit Condition

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In arid and semiarid regions and under rainfed conditions, water availability is one of the principal ecological constraints that hinder agriculture's sustainability. The super absorbent polymer (agricultural) is water-absorbing and is cross-linked to absorb aqueous solutions through bonding with water molecules. It is a new approach to water management under water-stressed conditions to conserve soil moisture in the active rooting zone of crops by reducing the evaporation, deep percolation, and runoff losses. Agricultural hydrogels are water retention granules which swell their original size to numerous intervals when they come in contact with water. It can absorb and retain a huge amount of moisture under plentiful rainfall and irrigation events and release it back to the soil for mitigating crop water demand when the rhizosphere zone dries up under drought conditions. It plays multifarious roles in agriculture including soil-water retainer, nutrient and pesticide carriers, seed coating, soil erosion reducer, and food additives. It has the extraordinary ability in improving different physicochemical, hydrophysical, and biological properties of soil, simultaneously decreasing irrigation frequency, enhancing the water and nutrient use efficiencies, and increasing the yield and quality of the field, plantation, ornamental, and vegetable crops. These biodegradable materials are nontoxic to the soil, crop, and environment. Hence, the addition of the hydrogel polymer will be a promising and feasible technological tool for augmenting crop productivity under moisture stressed conditions.

1. Introduction

In the arid and semiarid climates of the world, water scarcity is a major environmental problem due to the low amount of rainfall with irregular spatial and temporal distribution which seriously hampers the sustainability of agriculture. Different physiological changes have been observed under moisture stress conditions, like reduction of water potential, stomatal closure, reduction of photosynthetic rate, morphological rate and, thus, decile yield and quality of the plant by restricting overall plant growth [1, 2]. In limited water supply conditions, the modern approach of water-saving deficit irrigation technologies is considered a critical component to ensure favourable soil moisture balance in the root zone with increased water use efficiency without hampering crop yield and its quality [3, 4]. Presently, the advancement of modern microirrigation technologies such as low-pressure microsprinkler and drip irrigation systems with optimum irrigation scheduling coupled with plastic mulching can solve the problems by reducing drastically the consumption of irrigation water and improved water use efficiency [5–7]. However, these high-techs are explicitly employed in high-value crops and require sufficiently large capital investment, recurring operational expenditure and expertise skills of the farmers. Another solution of the burning issues is to explore alternative irrigation technology of using highly swellable polymer materials to overcome the soil moisture stress for increasing production [8]. Recently, hydrogel polymer technology has been widely used in the agricultural sector as soil conditioner because of its multifunctional roles in excellent water absorbency and water-retaining ability. The polymers maintain a very high water swelling and releasing capacity of moisture under water deficit conditions and consequently enhance water and nutrient use efficiency by checking evaporation loss, deep water percolation, and nutrient leaching under the arid and semiarid climates of the world by improving plant development and crop yield [9–11].

Hydrogel, popularly known as "root watering crystal," "water retention granules," or "raindrop," is a quasisolid-phase amorphous material. It has three-dimensional networks of loosely held cross-linked versatile hydrophilic macromolecules interconnected by covalent bonds or physical interactions with specially designed absorbency and biodegradability. These are organic polymers and have a unique capability to absorb a large amount of moisture in their super absorbent structure within a short period when it comes in contact with freely available water. These materials desorb the stored moisture to the surrounding soil and rhizosphere zones during the soil drying process in a uniform manner over an extended period [12, 13]. Having more available water in the soil helps in avoiding water stress at the time of moisture scarcity when it occurs for a longer period. The capacity of the hydrogel in capturing moisture arises from the hydrophilic functional groups attached to the polymer backbone while their resistance to dissolution arises from cross-links between network chains [14]. The super absorbent polymers are both naturally occurring and of synthetic origin generally made from petroleum products. However, the synthetic polymers have a unique character of showing high degrees of swelling and shrinking in connection with the changes that occur in the external environment.

However, much emphasis is now given to natural polysaccharide polymers over synthetic polymers because of controlled release systems, safety to the environment, cost-effectiveness, easy accessibility, and biodegradability [15]. Super absorbent hydrogels with fascinating structures and properties can be prepared from the polysaccharide with abundant hydroxyl groups. Polymer hydrogels that originated from cellulose have high absorbency, high strength, good salt resistance, nontoxicity, excellent biodegradability, and biocompatibility as compared with the synthetic polymer hydrogels [16]. Hydrogel forms an amorphous gelatinous mass on hydration when applied in soil, and it is capable of cyclic adsorption and desorption of water for a longer period. Hence, it is considered an effective tool in conserving adequate amounts of water quickly in soil and providing water and dissolved nutrients slowly to the plants over an extended period when the surrounding soil near the crop root zone starts drying up [17]. The specific objective of this review work was to find out the efficacy of hydrogel on soil water retention and release characteristics for alleviating drought stress and simultaneously improving crop production under moisture stress conditions.

2. Functional Characteristics of a Hydrogel

The features of the ideal hydrogel materials should include the following:

(i) The high water absorption capability

(ii) The desired rate of absorption and desorption capacity according to plant requirement

(iii) Lowest soluble content and residual monomer

(iv) High durability and stability during swelling and storage

(v) High biodegradability and biocompatibility

(vi) High performance over a wide temperature range

(vii) After swelling, water becomes neutral in pH

(viii) Colourlessness, odorlessness, and nontoxic

(ix) Upscale the soil's physical, chemical, and biological properties

(x) Photostability, rewetting capability for a longer time, low-cost material, and eco-friendly

3. How Do Water Retention and Release Behaviour Work in a Hydrogel

(i) The hydrophilic groups, *viz.*, acrylamide, acrylic acid, acrylate, carboxylic acid, etc., of the polymer chain are responsible for water absorption in a hydrogel

(ii) When the polymers come in contact with water, the water penetrates the hydrogel system by osmosis, and hydrogen atoms react and come out as positive ions

(iii) This process leaves several negative ions along the length of the polymer chain. These negative charges repel each other and force the polymer chain to unwind and open up (Figure 1) and attract water molecules and bind them with hydrogen bonding [14]

(iv) The hydrogel can absorb more than 400-1500 times their dry weight of water in this process

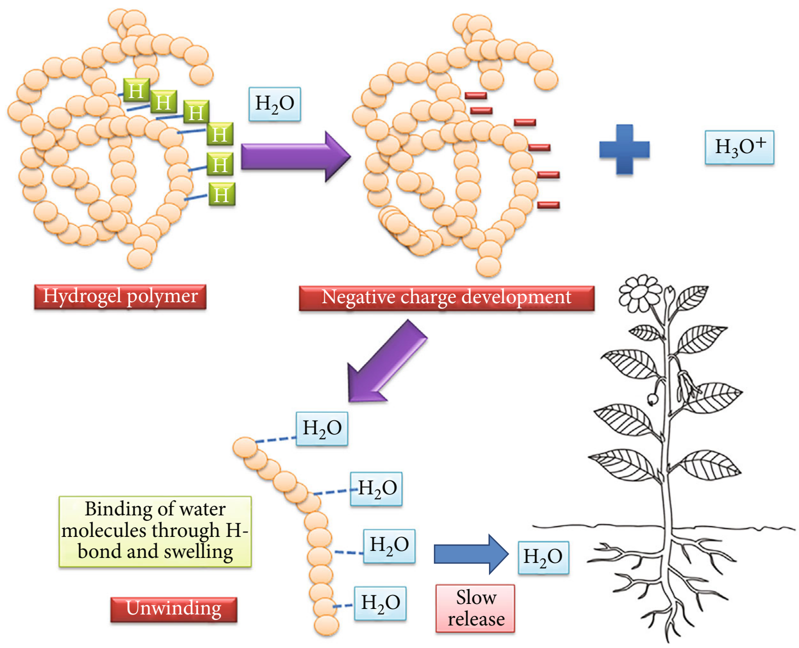

Figure 1: Mechanism of action of hydrogel upon soil-based application.

and act as a miniature water reservoir. When the surrounding around the root zone begins to dry up, the hydrogel gradually dispenses up to 95% of its stored water to plant absorption [18, 19]

(v) Under exposition to rewetting condition, rehydration starts and the process of storing water continues

(vi) This polymer has the ability to increase water retention in soil which facilitates higher water uptake and water use efficiency, thus helping in reducing the water stress of plants and increasing crop growth and yield

(vii) These undergo volume transition in response to physical and chemical stimuli depending on the prevailing environmental conditions [20]

(viii) The hydrogels are biodegradable and decompose in the soil after working for 2-5 years and thus do not alter the physicochemical properties of the soil

4. Classification of Hydrogel

Based on the source, hydrogel for agricultural use is classified into three types: (i) natural hydrogel, (ii) semiartificial hydrogel, and (iii) artificial hydrogel [21]. The petroleum-based synthetic or artificial hydrogels available in the market are categorized mainly into three types based on their chemical composition and configuration as follows:

(i) Starch-polyacrylonitrile graft polymers (starch copolymers)

(ii) Vinyl alcohol-acrylic acid copolymers (polyvinyl alcohols)

(iii) Acrylamide sodium acrylate copolymers (cross-linked polyacrylamides)

5. Usage of Hydrogel in Agriculture

The soil water availability is the most important environmental factor for the survival of plants and the microbiological population and also significantly determines the agricultural activity in the water-scarce region. Climate-resilient low-water-requiring crops and varietal selections, efficient water management practices through microirrigation with proper irrigation scheduling, and alternative use of soil conditioners like super absorbent polymers are some of the technological interventions judiciously applied in agriculture for managing water in the soil and relieving the growing plants from adverse drought conditions. Hydrogels are white sugar-like hygroscopic crystalline granules or tiny beads that swell manifolds in water or aqueous solution to form a clear gel made of separate individual particles. The synthetic polymers are prepared by polymerizing acrylic acid with a cross-linker. Potassium polyacrylate is the major element used in hydrogel technology and is marketed as a hydrogel for agriculture. The swelling capacity and gel modulus depend greatly on the quantity and type of cross-linker used. These are nontoxic, nonirritating, and noncorrosive in nature with a biodegradation rate of 10-15% per annum. Biodegradability depends on the chemical configuration of these polymers as well as the chemical and the biological environment of the soil. The super absorbent polymers have great potential to absorb and store water several hundred times their own original dry weight and can serve as a "miniature water reservoir" in soil under witness and then readily release up to 95% of absorbed water from these tiny tanks to thirsty plants under moisture stress or drought condition through osmotic pressure difference as the binding forces of water in the hydrogels are lower than the suction force of roots [19, 22]. Hydrogels are extensively used in arid and semiarid regions as a soil conditioner for the improvement of soil physical properties, reservoirs of water and nutrients, planting and transplanting gels, seed coatings for controlled seed germination, increased leaf water and leaf chlorophyll content, soil aerators, and in soil sterilization [10]. These polymers are widely used in farming for their capability for holding higher soil water retention for longer periods and slow release of water and nutrients to plants, serving as buffers against temporary drought stress in adverse weather conditions to reducing the risk of plant failure during crop establishment, promoting growth and development of the plant, reducing the evapotranspiration rate, and obtaining higher yield and quality of harvests [23]. In spite of direct contact with the soil matrices, hydrogels form aqueous gels, and this aqueous gel acts as a water reservoir for the plant-soil system. The roots of the plant go through the matrix of these hydrogelled particles and draw water from them when required [24]. These materials are nontoxic and eco-friendly to the environment [25]. Some of the effects of the hydrogel on soil and plant properties are listed as follows.

5.1. Soil Amendments. For the improvement of soil properties, the application of suitable soil conditioners increases for a common solution [26]. Hydrogel polymers are known as hydrophilic, 3-dimensional, and cross-linked multifunctional polymers [27, 28] enabling them to hyperaccumulate excess soil-water accounts for volume hundreds of times their own weight [29]. The application of hydrogel (absorbent polymers) in agriculture is crucial because it can soak up water and make it available to plants over the long run [30]. Nowadays, hydrogel polymers are being applied as soil additives in agriculture to reduce water loss and nutrient conservation in soil and ameliorate the negative effects of dehydration and moisture stress on crops [31]. In particular, the use of hydrogel polymers in soils has several advantages, such as (i) it can absorb hundreds of times more water than its own weight and can act like a long-lasting gel [29], (ii) it can protect the soil from runoff flow, (iii) it is an effective soil fertilizer performance improver [32], and (iv) finally, it can improve the microbial activity in the soil [31]. Barakat et al. [33] have reported that problems related to conventional irrigation procedures can be bypassed with the application of some polymers. Several recent researches have reported the importance of using some hydrogel polymers to help absorb and retain water. Most importantly, hydrogel polymers can prevent water loss through percolation and act as a reservoir in the main root-zone region [34]. There are some more basic issues related to the importance of using hydrogel polymers to improve the effectiveness of soil fertilizers and increase the activity of microbial organisms in the soil. The application of hydrogel polymers can improve the physicochemical properties of the soil as well as the fertilization capacity [35]. Alternatively, the potential effects of hydrogel polymers on soil water conservation, fertilizer conservation, and reduction of their losses have also been taken under consideration [36]. Similarly, the use of hydrogel polymers plays an essential role in the growth of soil germ communities [37]. Yin et al. [38] researched recently to explore the biological effects of polyglutamic acid, an innovative hydrogel polymer component for the growth of corn and the improvement effects of beneficial soil microorganisms. The use of this organic polymer has proven that it can enhance soil conservation water, increase corn seedlings, and increase the population of plant growth-promoting microbial bacteria, such as Bacillus, Pseudomonas, and Burcholderia [39].

5.2. Reduction of Drought Stress. Drought occurrences because of reduced water content in the soil can proceed to oxygen radicals and lipid peroxidation [40] production. This may have some detrimental effects on plant morphology, such as loss of plant height, reduction of leaf area, and ultimately leaf damage. Therefore, the application of hydrogels can serve as saving tools for higher plant growth and crop yield even in adverse climatic conditions [41]. Bearce and McCollum [42] have observed that hydrogel reduces the need for frequent irrigation and increases the shelf life of potted plants. Several researchers have reported the profits of hydrogel in horticulture; in addition, it may increase the water-holding capacity of the soil [42] and increase the water storage capacity of porous soils, reducing the chances of wilting for plants [41]. MacPhail et al.'s [43] greenhouse tests have shown the significance of using different doses of "Vitera 2 Hydrogel" to improve the survival of turfgrass and bluegrass under moisture stress conditions. Tomášková et al. [44] studied the effects of hydrogel treatment with sawdust, organic manure, compost, wheat straw, subsoil, and subsoil with a coating on the survival, growth, and physiological characteristics of 20 plant species and observed that all treatments have significantly improved drought-sensitivity amongst species. They also summarized that adding hydrogel at the time of planting is regarded to be an effective way for tree species in this region to combat high temperature and moisture stress conditions [44].

5.3. Enhancement of Fertilizer Availability. Hydrogels can also be made as fertilizer components with the help of potassium and nitrogen ions. In particular, the chemicals that remain in the polymer network do not wash off immediately but are slowly released into the soil and then absorbed by the plants. Konzen et al. [45] studied the combined effects of hydrogels with different types of fertilizers based on the traditional herbaceous NPK, superphosphate, and potassium chloride and observed on *Mimosa scabrella* seedlings that their growth was increased because of higher water retention and nutrient uptake.

5.4. Importance of Hydrogel for Plant Performance

5.4.1. Seed Germination. Hydrogel treatment has no parallel effect on seed germination [46]. Ismail et al. [47] reported that the super absorbent hydrogel composed of acrylamide and acrylic acid on starch using polyethene glycol (PEG) has a positive effect on the germination of maize seeds and growth of young plants than seeds without hydrogel [46]. Alternatively, hydrogel-treated plants show satisfactory effects for the fresh and dried weight of leaves and roots [48]. Elshafie et al. [46] also experimented on the biological activity of some natural substances and/or antimicrobial hydrogels on the germination of seeds of *Phaseolus vulgaris* and concluded that the hydrogen gel-based oregano essential oil with the assistance of *Burkholderia gladioli* bacteria is superior in seed germinations.

5.4.2. Plant Growth. The effects of different concentrations of hydrogels on Turfgrass and Baron Kentucky bluegrass were found as confirmed by MacPhail et al. [43]. They observed that seedling growth in concentrations between 0 and 50 kg per 100 m^2 was not negatively affected. In addition, Akhter et al. [30] concluded that the application of hydrogels has increased the plant growth by increasing the water-holding capacity of soil, particularly in sandy soils. However, Konzen et al. [45] recorded that use of hydrogel can improve the plant height, collar diameter, and fresh organic matter of *M. scabrella* seedlings under greenhouse conditions. Filho et al. [49] showed that two-stage brightness of 50% and 100% and 10 doses of hydrogel ranging between 0 and 6 $g\,L^{-1}$ for setting seedlings of *Enterolobium contorticilicum* are helpful by evaluating the most appropriate dose of the hydrogel. They also found that the two tested doses of 2 and 3 $g\,L^{-1}$ showed optimal development of seedlings even in full sun and shady environments, respectively. Similarly, the application of 6 $g\,L^{-1}$ hydrogel at the level of *Corymbia citriodora* was able to improve the plant height and stem diameter by 23% [50]. In contrast, Sarvas et al. [51] registered that 7 $g\,L^{-1}$ of hydrogel per *Pinus sylvestris* led to plant death.

5.5. Impact of Hydrogel on Soil Microflora. Microorganisms like bacteria, fungi, and actinomycetes populations are greatly influenced by the physical, chemical, and especially biological environments of soil which are responsible for the modification and decomposition of plant residues and other organic substrates leading to the formation of humus and release of nutrient elements to the soil for facilitating plant growth and development [52]. When the superabsorbent hydrogel polymers are incorporated in moist soil, it becomes swollen after absorbing and storing a large quantity of water and nutrients within a short period and allows the absorbed water and nutrients within it slowly to the soil, mitigating the water and nutrient requirements of the plant especially when the drought stress condition around the root zone periphery prevails. The peculiar water-nutrient reservoir and lending characteristics of the hydrogel polymers for the soil-plant system have been widely applied in the agricultural domain for substantial water and nutrient saving and ecological restoration [53]. Actually, the effects of superabsorbent polymers like hydrogel on the soil microbial ecosystem are not yet well understood as there is little information available about the positive effect of the superabsorbent application on the soil's biological and biochemical properties. The experimental findings of El-Hady et al. [52] indicated that the efficiency of applying the lower rate of rice straw-based hydrogels in sandy and sandy calcareous soils is better for improvement of soil conditioning in increasing the beneficial bacteria, fungi, and actinomycete counts and hydrogenase and phosphatase activities in the rhizosphere soil without harmful effects on plant growth. Achtenhagen and Kreuzig [54] reported that super absorbent polymer application can significantly increase the sorption of ^{14}C-imazalil in soils and stimulate microbial activity. Generally, hydrogel polymers contain certain functional/carbon sources, such as carboxylic acid, carboxamide, hydroxyl, amine, and amide groups, which may catalyze the activity of soil enzymes and interact with microorganisms for pesticide degradation or the soil matrix buildup [55–57]. Soil microorganisms are very active in the interactions with plants and soil systems and always play important roles in the nutrient cycle in soil by involving with the assessment of soil ecosystem services, such as community structure and abundances [58, 59]. The use of SAPs could enhance the soil's physical properties, control the water loss, improve some soil microbial activities, and promote Chinese cabbage growth [53]. One of the hydro-absorbents, namely, Terra Cottemis, is a mixture of more than twenty components having nutritive, root growing activators, and carrier material which are all assisting the plant growth processes in a synergic way. This hydro-absorbent can not only play an important role in germination and growth rate but could also impact the soil properties including those of a biological and biochemical nature [60]. Hydrogel-based biofertilizers increase the shelf life of microorganisms. Wheat seeds treated with hydrogel-based bioinoculants and the consortium also enhanced the plant growth positively via a multiplicity of synergistic mechanisms compared to liquid- and lignite-based microbial consortia [61]. The coapplication of super absorbent polymer with biofertilizer (rhizobacteria) in both drought stress and normal condition increased maize grain yield [62]. Soil amendment with starch-based SAP hydrogel complemented with irrigation at 3-day intervals was found beneficial to improve the biological property of soil in terms of increased bacterial (16%) and fungal (18%) populations as well as superior plant growth as compared to those of control without SAP [63]. The addition of hydrogels that may cause adverse effects or not on the soil ecosystem is an important issue for consideration. Johnson and Hummel [64] described how the addition of hydrogels to soil could decrease the amounts of mycorrhizal root associations. However, nitrogen-fixing microbes can benefit from the application of the hydrogel [65]. The imposition of functional polymers in the hydrogels (mannan-containing hydrogels) and its application in the potential root zone could positively influence the rhizobacteria colonization and plant growth and is emerging as a new tool to stress tolerance and crop production [66].

6. Novel Characteristics of Hydrogel for Agricultural Use

The hydrogels as soil conditions have the following characteristics -

(i) Resistant to salt concentrations in soil

(ii) Improve the physical, chemical, and biological properties of soil

(iii) Promote seed germination, seedling growth, root growth, plant density, and yield

(iv) Higher water absorption in water excess and gradual release under drought stress

(v) Alleviate the plants from moisture stress and can tolerate prolonged moisture stress

(vi) Delay onset of the permanent wilting point under intense evaporation in the arid environment

(vii) Render more efficient water consumption

(viii) Enhance water use efficiency by minimizing evaporation and leaching loss of water

(ix) Reduce irrigation frequencies, fertilizer requirement of crop, and irrigation cost

(x) Maximum stability and durability in soil

(xi) No environmental hazards

(xii) High performance at high temperatures (40-50°C), hence suitable for hot and dry climates

7. Methods of Hydrogel Application in Agriculture

Hydrogels as soil conditioners are used for stabilizing surface soils to inhibit crust formation, to improve poor structure soil at greater depths by aggregation, to increase water-holding capacity, and to enhance plant growth and development. The rate of application of hydrogel in agriculture depends upon the soil texture. In clay soil, it is 2.5 kg ha^{-1} at 6-8″ soil depth, and for sandy soil, it is up to 5.0 kg ha^{-1} at 4″ soil depth. There are mainly two methods for applying hydrogels in soils:

(i) *Dry method to subsoil*: a dry polymer such as polyallylamine (PAAm) or polyvinyl alcohol (PVA) is applied to the subsoil by mixing with sandy soil to 15-25 cm depth, moistening the soil for swelling before cultivation. After the polymer has swollen, the soil structure is improved and water penetration and retention capacity are increased

(ii) *Wet method to topsoil*: the polymer solution is sprayed onto initially wetted topsoil, followed by drying for water-stable aggregate stability and immediate sowing. This wet method can reduce water consumption, decrease soil erosion, and increase soil hydraulic conductivity. In the spray technique, the hydrogel can also be mixed with micronutrients and pesticides

8. Impact of Hydrogel Polymer on Soil Properties

The application of the hydrogel as soil conditioners or amendments can improve the soil properties of the arid and semiarid regions [10, 67] in the following ways:

(i) Improve the structure of coarse-textured soil by altering the physical (viz., porosity, bulk density, water-holding capacity, soil permeability, percolation and infiltration rate, soil temperature, etc.), chemical (CEC, etc.), and biological environments through aggregation, stabilization, and solidification

(ii) Prevent crust formation

(iii) Accomplish favourable growth medium by reducing soil bulk density, providing better ventilation and moisture regime for supporting plant viability, growth, and yield

(iv) Increase soil water retention capacity, higher water supply to plant roots, and efficient water uptake; reduce the frequency of irrigation because of the decline of water losses by leaching and evaporation and protect the plants against soil water stress

(v) Inhibit soil losses by water and wind erosion and runoff

(vi) Control seepage by the formation of membranes in soil that regulate the movement of water and nutrient downwards, increase soil permeability and infiltration, improve aeration and soil drainage, and prevent salt toxicity injury to plants

(vii) Increase water and nutrient use efficiencies and water saving to plants

(viii) Play havoc roles in light as well as heavy soils, where water scarcity prevailed

9. Benefits of Hydrogel in Agriculture

(i) Hydrogels act as "miniature water reservoirs" near the root zone of plants. It can absorb both natural and supplied water 400-1500 times of its own weight and release it slowly on water shortage conditions by root capillary suction mechanism

(ii) It can perform the cyclic process of absorption and desorption of water, can supply optimum plant-available moisture for quick seed germination and seedling establishment, and can increase the growth and high yield of the crop

(iii) In cold regions, the use of hydrogels does not freeze the moisture absorbed in the structure and makes easy accessibility to the plants, thereby regulating seedling growth temperature and preventing death by freezing

(iv) It can decrease soil osmotic moisture; save irrigation water, labour, and production cost; reduce irrigation requirement of crops; mitigate drought conditions; prevent leaching and runoff of water and nutrients; improve water and nutrient use efficiencies in plants; and restore soil microorganisms and enzymes

(v) It can help the plant to withstand the prolonged moisture stress by delaying the onset of permanent wilting of the plant

(vi) It can reduce the overuse of minerals including micronutrient fertilizers and pesticides

(vii) It can prevent soil compaction, improve soil aeration, and release soil mineral nutrients

(viii) It can enhance stronger and healthier plant growth and marketable yield

10. Drawbacks of Using Hydrogel in Agriculture

There are many factors which affect the absorptive capacity of hydrogel for water and limit its usefulness in agriculture in many cases as below:

(i) Water hardness has some influence on water absorption by the hydrogel. With increased hardness due to increasing concentrations of Ca^{2+} and Mg^{2+} ions mainly coming from fertilizers and irrigation water sources, the water absorption capacity of the hydrogel is substantially reduced. When hydrogel absorbs water, these ions react with negative sites in the polymeric chain resulting in the formation of nonsoluble salts which block the negative ion sites. This blockage increase with the increased salinity of water and further cycles of wetting and drying [14]

(ii) Most of the soils can hold reasonable amounts of water for plant growth. If there is any scanty rainfall, the soil water is depleted and the hydrogel will not clear up the problem. Similarly, under the condition of good distribution of rainfall during the cropping period, it will not work at all

(iii) The cost of the hydrogel is usually too high and becomes an inhibiting factor to modify the active rooting depth. Hence, its potential use is confined only to high-value crops to minimize the irrigation frequency or to lessen the stress between irrigations, particularly where plant or crop quality and value deteriorate by water stress. Unless costs are brought down drastically, its use is limited to the government and other well-funded organizations, leaving out the private farmers and agriculturists who can reap the benefit from its judicious use

(iv) The efficiency of hydrogel depends on the soil texture, type of polymer, method and time of application, and the nature of crop species. Generally, the polymers should be applied in the soil near the root zone at 10 cm depth through dibbling

(v) Innumerable evidence showed that there were no or little negative and positive effects of the hydrogel on soil amendment with regard to moisture conservation and yield improvement in several crops [30, 34, 68]. In water-stressed conditions, instead of supplying water to plants, sometimes, it may rather absorb water irreversibly from the biological system causing withering of plant stands

11. Practical Assessment of Hydrogel in Agriculture

The beneficial effects of varying levels of hydrogel application on the yields of various crop, soil moisture conservation, and water use efficiencies under different sets of soil, crop, and climatic conditions are summarized in Table 1. The experimental results reported that the increase in yield due to the addition of a hydrogel-concerning control (without hydrogel) was 11.0-27.8% for sunflower, 14.8-51.3% for wheat, 27.8% for onion, 15.0% for apple, 55.7% for lemon, 6.2% for aerobic rice, 33.0% for castor, 45.0% for soybean, 21.9-23.3% for pearl millet, 14.9% for banana, 5.3% for mustard, 50.3% for lentil, 20.9-250% for tomato, and 36.6% for sugarbeet. The increase in water use efficiency in hydrogel treatment over control was found to be 14.43% for wheat, 9.0% for pearl millet, 5.52% for mustard, 100-216% for tomato (greenhouse), and 33.5% for sugar beet. Likewise, the soil water retention in hydrogel treatment over control was observed to be 15.4-29.2% for sunflower, 5.9% for lemon, 23.7-37.2% for aerobic rice, 13.0% for pearl millet, 20.0% for banana, and 15-25% for lentil and 1.6-2.1-folds for tomato (greenhouse). This amply indicates that soil application of hydrogel increased the yields of various crops which could be due to adequate availability of water by the polymer and indirect supply of nutrients to the plants under moisture stress conditions, which resulted in adequate translocation of water, nutrients, and photosynthates and finally higher economic yield [10, 24, 69].

The higher soil water availability as a result of hydrogel application helps to escape water stress during prolonged periods of water scarcity. During the phase of water release by the hydrogel, free pore volume will be set up within the soil, offering additional space for root growth and air and water infiltration and storage. It also strongly resists soil pressure at high soil depth without losing its swelling capacity. Concurrently, water is stored in the rhizosphere so that water and plant nutrient losses due to deep percolation and nutrient leaching can be ignored. In this way, water and nutrients can be made available to the plant for a long period [70]. The seed germination, seedling emergence,

Table 1: Effect of hydrogels on crop yield, water use efficiency, and soil water conservation under water-stressed conditions.

Year & season	Soil texture	Test crop	Variety	Condition	Treatment	Yield (t ha^{-1})	Yield increase over without hydrogel (%)	WUE (kg ha-mm^{-1})	WUE increase over control (%)	Soil moisture increase over control (%)	Reference
2015-16 (*Kharif*)	—	Sunflower	—	Rainfed	100% RDF (80 : 60 : 30 kg NPK ha^{-1})+hydrogel at 2.5 kg ha^{-1} in seed furrows	1.24	27.8 (w.r.t. 100% RDF)	—	—	28.4	Gaikwad et al. [13]
2014-17 (*Kharif*)	—	Sunflower	—	Rainfed	100% RDF (80 : 60 : 30 kg NPK ha^{-1})+hydrogel at 2.5 kg ha^{-1} in seed furrows	1.26	11.0 (w.r.t. 100% RDF)	—	—	15.4-29.2	Ghatol et al. [73]
2012-14 (*Rabi*)	Sandy loam	Wheat	HD 2733	Subtropical semiarid	Two types of irrigation at tillering and flowering with hydrogel at 2.5 kg ha^{-1}	3.31	14.9 (w.r.t. two types of irrigation at tillering and flowering)	15.38	14.43		Singh et al. [74]
2017 (*Rabi*)	Sandy loam	Wheat	HS-507	Drought stress	Pusa hydrogel at 5.0 kg ha^{-1}	2.24	51.3	—	—	—	Roy et al. [69]
2012-13	Clayey	Wheat	AKAW-4627		100% NPK +hydrogel at 5.0 kg ha^{-1}	2.51	18.3 (w.r.t. without hydrogel)	—	—	—	Mahla and Wanjari [75]
2014-16	Sandy loam	Wheat	Locullus	Warm and temperate	Hydrogel at 30 kg ha^{-1}	9.29	14.8	—	—	—	Grabinski and Wyzinska [76]
2013-15	Sandy loam	Onion	Giza 20	Coastal desert	240 : 140 : 240 kg NPK ha^{-1} + 25 kg ha^{-1} hydrogel	37.2	27.8	—	—	—	Soubeih [25]
2016	Clay loam	Apple	Granny smith	Arid	Hydrogel at 200 g tree^{-1}	133 g fruit weight	15.0	—	—		Keivanfar et al. [8]
2008-12	Gravely sand	Assam lemon	—	Hot and humid	Hydrogel (stockosorb/ raindrop/ agrosorb) at 100 g plant^{-1}	130.2 fruits plant^{-1}	55.7	—	—	5.9	Pattanaaik et al. [70]
2009 (*Kharif*)	Sandy loam	Aerobic rice	Super basmati		Hydrogel at 2.5 kg ha^{-1}	2.39	6.2	—	—	23.7-37.2	Rehman et al. [68]

Table 1: Continued.

Year & season	Soil texture	Test crop	Variety	Condition	Treatment	Yield ($t\,ha^{-1}$)	Yield increase over without hydrogel (%)	WUE ($kg\,ha\text{-}mm^{-1}$)	WUE increase over control (%)	Soil moisture increase over control (%)	Reference
2016 (*Kharif* rainfed)	Medium black	Castor	DCH-177	Arid	Pusa hydrogel at 2.5 $kg\,ha^{-1}$	1.65	33.0	—	—	—	Kumar Naik et al. [77]
2003 (spring & summer)	Silty loam	Soybean	Cult L_1	Drought stress	Tarawat A 200 hydrogel at 225 $kg\,ha^{-1}$	6.42	45.0	—	—	—	Yazdani et al. [17]
2006-08 (*Kharif*)	Sandy loam	Pearl millet	ICMH-356	Arid	Seed coating 20 g hydrogel +thiourea (0.1%)+DMSO (0.01%) kg^{-1} seed	2.21	23.3	9.28	9.0	13.0	Singh [78]
2015 & 2016 (summer)	Loamy sand	Pearl millet	Gujarat hybrid Bajara 732	Semiarid and subtropical	Hydrogel at 5.0 $kg\,ha^{-1}$	4.49	21.9	—	—	—	Saini et al. [11]
2012-14	Sandy	Banana	Grand Nain	Arid desert	Hydrogel at 150 g $plant^{-1}$ with 80% irrigation requirement	27.82 kg $bunch^{-1}$	14.9	—	—	20	Barakat et al. [33]
2014-16 (*Rabi*)	Sandy loam	Mustard	NRCDR 2	Temperate	Hydrogel at 2.5 $kg\,ha^{-1}$	1.27	5.3	9.08	5.52	—	Bharat et al. [79]
2015-18 (winter)	Clay loam	Lentil	—	Temperate	Hydrogel at 5 $kg\,ha^{-1}$	1.03	50.3	—	—	15-25	Shankarappa et al. [80]
2017 & 2018	Sandy loam	Tomato (greenhouse pot expt.)	—	Arid desert	Irrigation at 100, 75, and 50% FC +cellulose/starch polymer at 2 $g\,kg^{-1}$ soil	168, 147, and 81 g pot^{-1} at 100, 75, and 50% FC, respectively	20.9, 50.0, and 92.9% at 100, 75, and 50% FC, respectively, over 100% FC	6.2, 7.2, and 6.0 $g\,m^{-3}$ at 100, 75, and 50% FC, respectively	100, 148, and 216% at 100, 75, and 50% FC, respectively, over control	1.6-, 1.8-, and 2.1-folds for cellulose/starch polymer at 100, 75, and 50% FC over control	Ahmed and Fahmy [15]
2012-13	Sandy	Tomato			Hydrogel at 5 $g\,kg^{-1}$ soil	35 fruits $plant^{-1}$	250		—	—	Sultana et al. [81]
2013-14	Sandy	Sugar beet	Baraka	Arid	Hydrogel at 40 $kg\,ha^{-1}$	80.0	36.6	123.5	33.5	—	El-Karamany et al. [82]

and its vigour, stability of plant growth, and yield can be guaranteed in drought stress when the soil is treated with super absorbent polymers [71, 72].

Under limited or scarce water conditions, the application of hydrogel minimizes the irrigation requirements of several crops by improving the water-holding capacity of the soil [41,40]. Furthermore, the incorporation of super absorbent polymers into soil enhances the physical property and water availability, resulting in promoting plant growth and yield by reducing crop irrigation requirements [17]. The addition of the hydrogel amendments as cultural practice in coarse sandy loam soil improved the soil water storage, reduced evaporation loss and irrigation requirement, and enhanced seedling growth of wheat and barley as compared with untreated soil and thus is useful for enhanced plant establishment under drought-prone environments [30]. Zangooinasab et al. [83] reported that hydrogel could fully conserve moisture and increase crop yield and quality when it was applied in combination with proper irrigation. Pattanaaik et al. [70] found that the Assam lemon crops suffered from severe water stress during the period from October to March resulting in low crop water productivity. However, the application of stockosorb at 100 g per plant increased the yield to 130.2 fruits per plant from 83.6 fruits per plant obtained in the control plot, and the water-holding capacity of the soil increased from 28.74 to 34.63%. The increasing yield is because of hydrogel application which might be because the soil was wet for a longer time causing increased microbial activity and reduced fruit drops due to water stress. "Grand Nain" banana plants showed that the application of hydrogel enhanced bunch weight and fruit yield under the water regime of 87.5% of the recommended amount of irrigation [84]. Liu et al. [85] reported that superabsorbent polymers promoted gaining total dry weight, chlorophyll, and soluble sugar in the leaves of the coffee tree. The seed yield increase in rainfed castor with the application of 2.5 kg ha^{-1} of hydrogel in medium black soil was 33% when compared with the no hydrogel condition [77]. In another study, Ramanjaneyulu et al. [86] found that hydrogel application failed to enhance the seed yield of rainfed castor in alfisols due to its long duration, intermediate nature, and inherent ability to withstand short-term droughts. Salokhiddinov et al. [87] noticed that the use of highly swellable polymer hydrogels under conditions of automorphic soils based on improved traditional furrow irrigation technology had made it possible to reduce water consumption for irrigation by 15-17% in the first year, by 12-14% in the second year, and by 9-11% in the third year of experiments in cotton crop. Due to the longer duration of moisture conservation in the soil, the period between irrigations was extended by 10-12 days; the number of irrigations is reduced. Conversely, Austin and Bondari [88] found that the addition of hydrogel to peat moss, pine bark, or soil did not improve plant growth, yield, or berry weight. There was little or no economic benefit from adding hydrogel to organic matter for soil amendments; rather, it could create a potentially lethal hazard for young blueberry plants. Likewise, Meena et al. [89] observed no wheat yield improvement with hydrogel application. However, despite its limitations, the hydrogel is considered a low-cost alternative water management tool which helps to bring a congenial environment for the improvement of the efficiency of soil and water management in agriculture as well as the horticulture sector.

12. Prospects of Nano-Based Hydrogel in Agricultural

Nanotechnology is the modern tool for precision input utilization in modern agriculture practice for accomplishing higher resource use efficiency for crops [90, 91]. This technology raises hope for innovation in the field of soil management and agricultural application [92]. According to Duncan [93], the nanotechnology term itself is defined as a material that synthesizes or prepares, characterizes, and manipulates its structures and devices in such type of dimensional scale where particular or specific materials are reduced from macrodimensions to nanodimensions and their physical and chemical properties are improved manifold. By using this technology, various opportunities are opened up in the agriculture field with the use of different products containing nanoparticles (NPs), and the benefits of NTs are tremendously manufacturing nanofertilizers, nanopesticides, nanoherbicides, and nanosensors for sustainable agriculture with low environmental impact [93, 94]. Water is becoming a limiting natural resource because of incessant human and livestock population growth, numerous anthropogenic activities, and continuous global climate change. This vital problem can be overcome by using those designed materials possessing good water absorption and retention capacities like nanocomposite hydrogels under high pressure or temperature [95]. Hydrogels are generally a 3D cross-linked polymer network structure which contains both hydrophilic and hydrophobic parts. They generally swell when placed in moist conditions by increasing their size without changing their inherent properties [96, 97]. Keeping these soil moisture absorption and retention capacities as the focal point, Vundavalli et al. [91] synthesized a novel biodegradable poly(acrylamide-co-acrylic acid)/silver-coated superabsorbent hydrogel nanocomposite for agricultural use. Electron microscopy scanning showed that the nanoparticles had a mean diameter of 200 nm which was akin to those reported earlier by Liu et al. [98] and Bajpai et al. [99]. The water absorbency rate of silver-coated hydrogel nanoparticles is comparatively higher in distilled water and tap water as compared to 1% sodium chloride solution whereas the water-holding ratio was 7.5% and 3.5% higher in the soil with silver-coated hydrogel and soil with hydrogel, respectively, when compared to original soil [91]. Hence, the silver-coated hydrogel had excellent water absorbency, improved water retention, and moisture preservation capacity of the soil and can be effectively employed for the enhancement of growth and yield of the plant. The nanocomposite is synthesized and characterized by Kayalvizhy [100] who reported that the swelling rate depends always on the duration of time determined by the diffusion mechanism which reduces the osmotic pressure between internal and external superabsorbents that lead to reducing the swelling rate and capacity. Some of the traditional nanocomposite hydrogels are nonbiodegradable and regarded as pollutants for the soil. Because of environmental protection issues, biodegradable hydrogels became more important for commercial application in agriculture [101]. The preparation procedure is simply in chitosan-based hydrogel beads which have higher loading capacity which is achieved through increasing porosity, expanding polymer chains, increasing surface area, decreasing crystallinity, and improving access to internal sorption sites [102, 103]. Peng et al. [104] noticed that the adsorption process was accelerated and improved in chitosan-halloysite nanotube composite hydrogel beads than in pure chitosan hydrogel beads. Montesano et al. [105] also reported that due to high water retention properties of cellulose-based hydrogels for the growing media in vegetable crops make them highly useful in crop production. The association of fertilizer with the hydrogel nanomaterials brought about a new vista in crop production processes as these composites are fully accessible and readily available to plants rather than the conventional fertilizers. Nanoparticles of chitosan are an interesting material for use in controlled fertilizer release systems [106]. Nanofertilizers are loaded and/or capsulated by easily soluble hydrogel nanoparticles, allowing a slower release of nutrients into the soil. Nanofertilized biodegradable hydrogels are slowly diffused into roots easily *via* symplastic and apoplastic pathways and translocated via xylem tissue to the above-ground parts of the plants including the stems and leaves [107]. However, the nanofertilizers for encouraging the growth of plants should be used in low concentrations, as there can be significant toxic effects to plant, animal, and human health; food-web contamination; and, above all, environmental damage in high concentrations [108]. In addition, SAPs have been employed in combination with pesticides to control their release rates to promote the efficient use of both pesticides and water [109].

13. Conclusion

Water is becoming the most limiting factor for sustainable crop production in arid and semiarid regions. The application of hydrogel as a soil conditioner can improve the hydrophysical, physicochemical, and biological environments of the soil; increase the soil water retention and release capacity; improve irrigation, water, and nutrient use efficiencies; enhance the yield and quality of agricultural produce; and sustain the environmental quality. This hydrogel technology may become a practically convenient and radical technology in water-stressed areas in terms of increased yield (cereals, vegetables, oilseeds, flowers, spices, plantation, etc.) and in alleviating soil moisture stress. This review envisages that the beneficial application of hydrogel on a large scale could be a boon to the farmers and other stakeholders for the optimization of water resource management for higher yield in agriculture.

Data Availability

Data used in the article will be available after request.

Conflicts of Interest

The authors declare no conflict of interest.

Authors' Contributions

S.K.P., R.P., P.U.A., P.B., S.S., P.P., and B.B. were responsible for the conceptualization; S.K.P., R.P., P.U.A., P.B., S.S., P.P., and B.B. were responsible for the original draft preparation; M.S., M.B., V.B., P.O., and A.H. were responsible for review and editing; M.S., M.B. and A.H. were responsible for funding acquisition. All authors have read and agreed to the published version of the manuscript.

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