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Review Article

Use of Hydrogel in Agriculture for Improvement in Soil Properties and Sustainable Crop Production- A Review

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ABSTRACT

Agriculture is one of the major water consumers, as more than 80% available water resources are used by this sector. Agriculture has recently begun to experience the effects of water scarcity and accompanying desertification due to climate change. The use of modern technologies to enhance water and nutrient use may become increasingly crucial in the future, particularly in arid and semi-arid regions where water availability is constrained. Hydrogels are cross-linked hydrophilic water-soluble polymers that have the ability to absorb and hold a large amount of water, up to a hundred times the amount of dry matter provided, and desorb the water under stress. The hydrogel polymer compound appears to be quite helpful as a soil conditioner, promoting crop tolerance and growth in sandy or lightweight gravel soils. It has been discovered that hydrogels enhance the physical properties of soils (viz., porosity, bulk density, water-holding capacity, soil permeability, infiltration rate, etc.) and biological/microbial activities in soil, thereby increasing oxygen/air availability in the plant root zone. Similarly, it improves seed germination, seedling emergence rates, root growth and density, and helps improve crop growth and yield in field crops and vegetables. Numerous studies have recommended using hydrogel in various doses based on soil structure and other soil properties, atmospheric conditions, irrigation methods, and, most importantly, the quality of irrigation water to be used. The hydrogel application method depends on the place where it can be used, such as field crops, nursery beds, potting and crop transplanting. Many factors, such as the type and size of the polymer, dose and application method, environmental temperature, soil texture, the polymer's biodegradation nature, and salt concentration in water and soil solution, affect the efficiency of the hydrogel.

Key words: Hydrogel, Agriculture, Water conservation, Soil parameters, Plant growth, Crop yield

Introduction

About 85% of the available water resources are used by agriculture, making it one of the biggest water consumers (Calcagnile *et al.,* 2019). As a result of climate change, the agricultural sector has begun to experience water scarcity and related desertification in recent years. This increases the urgency of creating new sustainable materials for water management. Utilizing modern technologies to improve water and nutrient use may become increasingly important in the future, especially in arid and semi-arid countries where water availability is limited. In the agricultural sector, polymers are used as structural materials to create environment that is favourable to plant growth and to improve irrigation water efficiency (Dehkordi, 2017). Hydrogels have been widely employed over the past 20 years to improve water availability for plants. By enhancing the water-holding capacity of soil and growing media, the usage of hydrogel polymers may be an effective method to increase the efficiency with which water and nutrients are used (Dehkordi and

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Seyyedboveir, 2013). In addition to preventing water waste and improving irrigation efficiency, superabsorbent polymers can enhance several soil physical properties (Montesano *et al.,* 2015). To improve crop tolerance and growth in sandy or lightweight gravel substrates, the hydrogel polymer compound appears to be highly beneficial when utilised as a soil conditioner in the agricultural sector. To boost agricultural output and reduce soil water loss, hydrogel polymers have gained acceptance as soil conditioners (Ovalesha *et al.,* 2017). Farmers who cultivate crops in rainfed or water-scarce areas will benefit greatly from the technology's efficiency. Hydrogel application reduces irrigation frequency in practically all crops, including cereals, legumes, vegetables, and flowers, saving time and money on irrigation, as well as on labour and water expenditures. The aim of the paper was to increase understanding of the use of hydrogels in agriculture to improve soil health and sustainable crop production. It also offers references and recommendations for agricultural research in order to thoroughly assess agronomic benefits.

Hydrogel and its Classification

Networks of polymer chains, called hydrophilic gels (also known as hydrogels), are occasionally found as colloidal gels in which water serves as the dispersion medium (Ahmed *et al.,* 2013). Cross-linked hydrophilic water-soluble polymers known as hydrogels have the capacity to absorb and retain a significant amount of water, up to a hundred times the amount of dry matter provided, and desorb the water under stress (Ahmed, 2015). Hydrogels are polymers which have a three-dimensional cross-linked structure that allows them to absorb, store and release water molecules (Ahmed, 2015), can be classified on various bases, which are shown in Fig. 1.

The source of a hydrogel is a crucial factor in its classification. Polymers come in two origins: synthetic and natural. More consideration is being given to using biodegradable polymers (of natural origin) in agriculture for environmental conservation purposes. Some examples of natural polymers are displayed in Table 1.

Key Characteristics of Agricultural Hydrogels

Agricultural hydrogels are natural polymers containing a cellulose backbone. They are suitable for arid and semi-arid environments since they can function effectively at high temperatures (40–50°C).

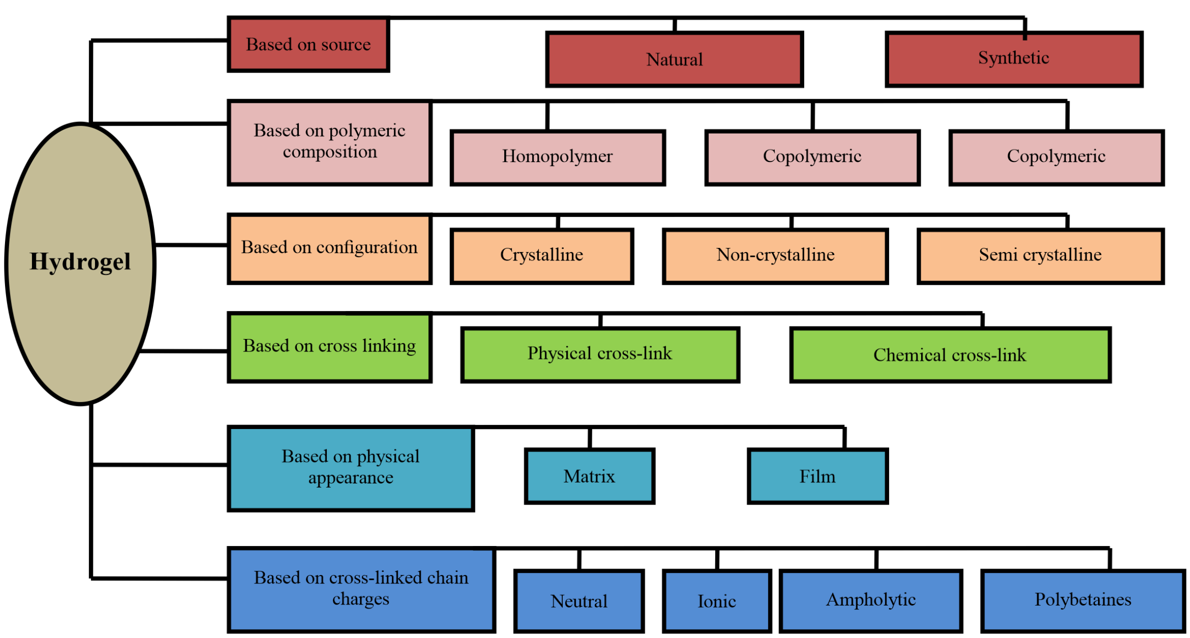

Fig. 1. Graphic presentation of hydrogel classification

Table 1. Some examples of natural polymers

Name of polymer	Functional group	Gelations
Agarose	-OH	Gelation during cooling due to coli helix transition
Alginate	-COOH; -OH	Chemical cross linking; Ionic cross linking
Carboxymethyl Cellulose	COOH; -OH	Chemical cross linking; Ionic cross linking
Chitason	$-NH_2$; -OH	Chemical cross linking; Ionic cross linking
Fibrin		Assembling and covalently cross linking of fibril from thrombin cleavage of fibrinogen
Gelatin	-COOH; $-NH_2$; -OH	Chemical cross linking; Ionic cross linking
Silk fibroin	COOH; $-NH_2$	Sol-gel transition in presence of acid and ions

They are capable of absorbing at least 400 times of their dry weight in pure water, releasing it gradually as the crop plant requires. It has been discovered that hydrogels enhance the physical qualities of soils (viz. porosity, bulk density, water holding capacity, soil permeability, infiltration rate, etc.). Improved seed germination and seedling emergence rates, as well as increased root growth and density due to less compacted soil, are all benefits of increased porosity. It also increases biological/microbial activity in the soil, thereby increasing oxygen availability in the plant's root zone. Hydrogels help plants withstand prolonged moisture stress by delaying the onset of permanent wilting point and reducing crop irrigation requirements by reducing water loss through evaporation. Leaching of nutrients from the soils and the crop root zone is decreased. Agricultural hydrogel can be used for all crops and all soil types. Its advantages are most evident in nurseries, seedling beds, crops vulnerable to moisture stress, crops requiring a lot of water, and container gardens and pot cultures.

Raw hydrogel Water soaked hydrogel

Fig. 2. Status of raw and water-soaked hydrogel

Mechanism of Water Absorption and Release by Hydrogel

Hydrogels are hydrophilic in nature and contain carboxylic groups, enabling them to bind cations and adsorb water. Many factors affect the absorptive capacity of hydrogels for water, including their tolerance to ionic solutions, the tension at which they bind water, and the rate at which they degrade in the field. Raw hydrogel granules and hydrogel granules after soaking in water are shown in Fig. 2.

Hydrogels are special materials for a range of applications because of their capacity to absorb and store large amounts of water and water solutions (El-Ashmar, 2017). The process of diffusion of water from polymer capsules takes place in several stages, such as (1) the water from rainfall present in the soil solution migrates inside the hydrogel, (2) the stored water causes an increase in pressure inside the capsule, and (3) causes gradual release of water into the soil. The thickness and material of the polymer coating play a very important role in the controlled release of water (Shavit *et al.,* 2003).

Hydrogel can absorb more than 400 times of its weight of water in this mode. When its surroundings begin to dry out, the hydrogel gradually dispenses up to 95% of its stored water. When exposed to water again, it will rehydrate and repeat the process of storing water. The bio-degradable hydrogel decomposes after this process, which can span 2 to 5 years.

Methods of Hydrogel Application

The hydrogel application method depends on the place where it can be used such as:

- ***At field crops***: Make a hydrogel-to-fine-dry-soil admixture in a 1:10 ratio and apply it either with the seeds or fertilizer or in the prepared furrows

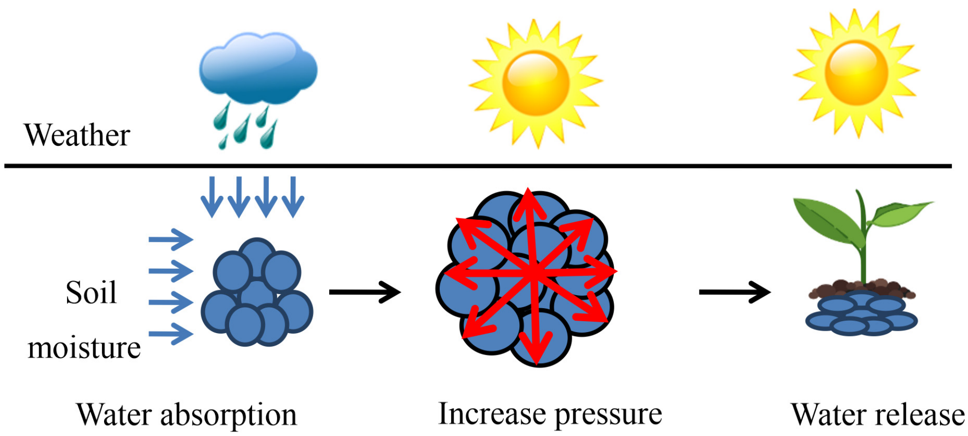

Fig. 3. Absorption and release of water by hydrogel

before to sowing. Hydrogel should be used in close proximity to the seeds for optimal effects.

- ***In nursery bed***: Apply 2 gm per m^2 or according to the recommended rate of hydrogel for nursery bed. Mix the hydrogel uniformly into the top 2 inches of the nursery bed soil.
- ***In pots***: In pot culture, mix 3–5 gm hydrogel kg^{-1} of soil before planting.
- ***While transplanting***: Prepare a free-flowing solution by thoroughly combining 2 g of the required dose of hydrogel per litre of water; let it settle for 30 minutes. Plant seedling roots should be dipped in the solution before transplanting into the field.

Application Rate of Hydrogel for Different Purposes under Different Conditions

In light of the foregoing information, it stands to reason that the more hydrogel is incorporated into the soil, the greater the water retention and enhanced soil moisture. The ideal quantity must be understood in order to achieve benefit-cost parity in irrigation practice and to justify the cost of hydrogel. Numerous studies have recommended using hydrogel in various ratios based on soil structure and other soil properties, atmospheric conditions, the type of crop being irrigated, and, most importantly, the quality of the irrigation water. Numerous studies have recommended the use of hydrogel at various levels (Table 2).

Application of Hydrogel in Agriculture and its Effect on Soil and Crop Yield

Effect of hydrogel on soil properties

According to Tayel and El- Hady's (1981), the gel decreased soil bulk density, quickly drained pores, hydraulic conductivity, mean pore diameter, intrinsic permeability, transmissivity, and evaporation while increasing total porosity, the ratio of micro to total or macro pores, void ratio, water holding pores, water retention, and available water. According to Lentz and Sojka (1994), applying 0.7 g kg^{-1} of super absorbent on average reduced soil erosion by 94 per cent in corrugation irrigation and increased infiltration rate by 15%. Chan and Sivapragasam (1996) reported significant improvements in soil physical properties, namely increased water-stable aggregation, reduced tensile strength, and reduced bulk density, in the treated soil at the lowest application rate (0.001%) and increased with increasing application rate. Additionally, hydrogels are good at preventing capillary water swelling, reducing cumulative evaporation, and correcting aggregation (Al-Omran *et al.,* 1997; Sivapalan, 2006). When hydrophilic polymer application and irrigation rates were tested on okra, Cookson *et al.* (2001) found that treated crops needed 25% and 50% less water in the summer and winter, respectively, than untreated crops. According to Kumaran *et al.* (2001), a hydrophilic polymer significantly reduced irrigation frequency in tomato plants by enhancing the soil's ability to hold water.

Table 2. Application of hydrogel under different conditions

Recommended doses of hydrogel	Conditions/purpose for hydrogel application	References
4.0-6.0 g kg^{-1} soil	For arid and semi-arid regions	Shooshtarian *et al.* (2011)
2.3 -3.0 g kg^{-1}soil	For all levels of water stress treatment and improved irrigation period	Nazaril *et al.* (2010)
0.2-0.4 g kg^{-1}soil or 0.8% of soil	To delay the permanent wilting point in sandy soil	Altarawneh *et al.* (2012)
2.0-4.0 g $plant^{-1}$ pit	To save irrigation water from 15-50%	El-Hadyand Wanas (2006)
0.5-2.0 g pot^{-1}	To improve the relative water content and increase leaf water use efficiency	Yan and Yan (2013)
0.2-0.4% of soil	To moderate the negative effects of drought stress	Keshavars *et al.* (2012)
225-300 kg ha^{-1}	To prohibit the bad effects of drought stress	Nazaril *et al.* (2011)
3% of soil	To decrease water stress	Oraee and Moghadam (2013)
2.5 kg ha^{-1}	For significantly higher growth and yield of aerobic rice	Rehman *et al.* (2011)
10- 20 g kg^{-1} seed	For significantly higher effective tillers, ear length, test weight, grain and stover yield of pearl millet	Singh (2012)
200 kg ha^{-1}	For significantly higher growth and yield of peanut in sandy soil with a hot and arid climate.	Langaroodi *et al.* (2013)
5.0 kg ha^{-1}	Wheat yield was increased by 8.48% in clay loam soil with 100% RDF	Borivoj *et al.* (2006)
20 kg ha^{-1}	Using prior to sprinkler irrigation increased infiltration rates and reduced runoff and erosion	Stern *et al.* (1992)
2 g kg^{-1}soil	Improved the water holding capacity of sand from 171% to 402 %	Johnson (1984)

According to Akhter *et al.* (2004), adding hydrogel to soils increased their ability to retain water and the amount of water available for wheat growth. Bhat *et al.* (2004) observed that the incorporation of 2g hydrogel reduced irrigation water use by 15 per cent, and the incorporation of 3g hydrogel reduced it by 30 per cent in cucumber under stress conditions. The use of a polymer reduced both particle density and bulk density. The soil's particle density was reduced by 8%, and the bulk density was reduced by 4-80% (Rifat and Ali, 2004). According to Sohrabi *et al.* (2005), adding 10 ppm of superabsorbent to irrigation water reduced soil loss by 78 per cent and increased overall water infiltration by 56 per cent. Crop production on the hydrogel-amended soils requires fewer irrigations overall, especially in the early stages of plant establishment. In addition, some plants initially appeared to benefit from the hydrogels' increased root growth and decreased irrigation frequency (Frantz *et al.,* 2005). For maize cultivation on soils with limited water holding capacity, where irrigation water and fertilizer frequently leak below the root zone in a short period of time, use of superabsorbent polymer (hydrogel) may be an efficient management method (Yazdani *et al.,* 2007).In sandy loam, loamy, and clay soils, respectively, application of high levels of Superab A200 addition at 2, 4, 6, and 8 g kg^{-1} increased available water content approximately 1.8, 2.2, and 3.2 folds over the control, and there were noticeable responses in the number of days to permanent wilting point as a result of polymer application (Jahangir and Jafar, 2006). According to Al-Rahim *et al.* (2007), application of hydrogel at 0.6 per cent concentration resulted in a 66 per cent delay in the time it took for water to evaporate from the soil, and seedlings grown in soil mixed with 0.6 per cent hydrogel survived three times as long as those grown in control soil, despite being statistically equivalent to soil mixed with 0.4 per cent hydrogel concentration. According to Koupai *et al.* (2008), the hydrogel treatment increased the time required (22 days) to reach the permanent wilting point (PWP) compared with the control (12 days). According to Karimi *et al.* (2008), using the Igita absorbent in the soil increased the amount of available water and the soil's ability to hold water, which in turn increased the water intervals. The need for irrigation was reduced by 50% when using Agrihope superabsorbent at a weight concentration of 0.4%. Longer intervals between irrigations were possible because the hydrogel enhanced water retention and moisture availability in the root zone when applied to sandy loam soils. When hydrogel was placed at 0, 2, 3, and 4 g hydrogel plant^{-1} pits, the water-holding capacity (20.15, 23.05, 27.10, and 33.75 per cent) and available moisture (4.82, 7.70, 10.62, and 12.47 per cent) were measured. The soil moisture was recorded as 12.78, 13.20, 12.21, 12.87, 11.03, 13.10, 12.83 and 13.31 percent as compared to control 9.88, 11.15, 10.09, 10.30, 10.45, 10.44, 9.59 and 10.03 percent at 21, 28, 35, 42, 53, 60, 77, and 84 days after sowing, respectively. They also reported that the application of hydrogel at 2.5 kg ha^{-1} improved the soil moisture content (El-Hardy *et al.,* 2009). Soil porosity and soil bulk density are typically thought of as opposing one another; as one increases, the other decreases. According to Dorraji *et al.* (2010), soil electrical conductivity decreased when polymer levels were increased. Nazarli *et al.* (2010) found that using superabsorbent polymer increased water retention capacity and provided drought protection. According to Ekebafe *et al.* (2011), adding polymers to coarse sand increased its water-retention capacity by 171-402 per cent. The soil bulk density fell by 3.42, 4.10, 7.53, and 13.57 per cent for concentrations of superabsorbent hydrogel nano-composite (SHNC) of 0.1, 0.2, 0.3, and 0.4 per cent, respectively, when soil wetness changed. Hydraulic conductivity was decreased by 16, 36, 48, and 63 per cent, respectively, by adding 0.1, 0.2, 0.3, and 0.4 percent of SHNC (Shahid *et al.,* 2012). The addition of SHNC also reduced hydraulic conductivity and slowed soil moisture loss, thereby postponing the wilting of seedlings. With SHNC concentrations of 0.1, 0.2, 0.3, and 0.4 w/w per cent, respectively, the beginning of permanent wilting point (PWP) was postponed by 5, 6, 7 and 8 days (Shahid *et al.,* 2012). At concentrations of 0.1, 0.2, 0.3, and 0.4 per cent, respectively, the soil pH decreased by 1.49, 2.43, 3.78, and 4.86 per cent compared to the control. In the meantime, the application of SHNC increased electrical conductivity (EC). In six oilseed rape genotypes, the hydrogel at a concentration of 7 per cent reduced the damaging effects of water scarcity by preserving and absorbing water, enhancing several agronomic characteristics, and increasing yield and its components, as well as decreasing plant water requirements (Moghadam *et al.,* 2013). Water-use efficiency with three irrigations at 2.5 or 5.0 kg ha^{-1} hydrogel is comparable to, but much greater than, that of no hydrogel (Shahid and Ram, 2016). At all growth phases of the fodder sorghum crop, the application of 5 kg ha^{-1} of hydrogel considerably enhanced soil moisture content at different soil depths (namely, 0-15, 15-30, and 30-45 cm) (Dass *et al.,* 2013). With the addition of hydrogel, soil bulk density was reduced by 10 and 11.5 per cent, and soil porosity was enhanced by 10.20 and 12.60 per cent (Dahri *et al.,* 2019). Based on improved traditional furrow irrigation technology, it was observed that using highly swell-able polymer hydrogels with a dose of 50 kg ha^{-1} under conventional agro technology conditions in automorphic soils can reduce irrigation water use by 15–17 percent in the first year, 12–14 percent in the second year, and 9–11 percent in the third year of experiments (Salokhiddinov *et al.,* 2020).

Since little is known about the beneficial impacts of superabsorbent application on soil biological and biochemical properties, the effects of superabsorbent polymers, such as hydrogels, on the soil microbial community remain poorly understood. The physical, chemical, and biological characteristics of soils are significantly influenced by microorganisms like bacteria, fungi, and actinomycetes. Enzyme activity might be regarded as a crucial metric for describing the biological activity of soil, as most biological processes in soil are enzymatic. Abd *et al.* (2004) and El- Hady *et al.* (2006) observed an increase in microbial population, as well as dehydrogenase and phosphatase enzymatic activity, in the root zone of plants treated with hydrogel. Future, Borivoj *et al.* (2006) confirmed that the application of hydrogel in sandy soils increases various enzymatic activities that are markers of microbial population in the soil (acid phosphatase, alkaline phosphatase, dehydrogenase, protease, and urease). El-Hady *et al*. (2011) found that rice straw-based hydrogels in sandy and sandy calcareous soils increased the numbers of beneficial bacteria, fungi, and actinomycetes, as well as hydrogenase and phosphatase activities in the rhizosphere soil. Achtenhagen and Kreuzig (2011) found that using highly absorbent polymers can greatly increase microbial activity. Li *et al.* (2013) found that at a 0.6% w/w rate, superabsorbent polymers (SAPs) had varying effects on soil microbial characteristics depending on water level. SAPs enhanced soil microbial biomass carbon from 22-24 mg kg^{-1} under high water-deficient circumstances. In contrast, under mild water-deficiency conditions, the rise was greater, ranging from 22 to 34 mg kg-[1]. A starch-based SAP hydrogel was found to improve soil biological properties, increasing bacterial activity by 16% and fungal activity by 18% compared to a control without SAP (Parvathy *et al.,* 2014). El-Saied *et al.* (2016) demonstrated that a paddy straw-based hydrogel improved soil biological activity by increasing the overall counts of bacteria and Azotobacter spp., phosphate-dissolving bacteria (PDB), fungi, and actinomycetes, as well as the activities of dehydrogenase and phosphatase. Saied *et al.* (2016) found that hydrogels increased soil microbial enzyme activity by 43-54%. Furthermore, Bokharaei *et al.* (2021) discovered that hydrogel served as a slow-release nutrition source, increasing soil microbial populations by 64%, fungi by 57.3%, and actinomycetes by 45.3% when treated at 0.6% w/w. Hydrogels can also change soil microbial populations, which influence enzymatic activities (Tomadoni *et al.,* 2020; Zhang and Guan*,* 2022).

Effect of hydrogel on plant growth parameters, crop yield and economic feasibility

Application of superabsorbent polymer could prevent water loss and increase soil water storage capacity, making more water available, increasing relative water content in leaves, and promoting plant development under water stress (Kramer, 1988). According to Sivapalan (2001), grain yields for soybeans grown in soil treated with 0.05, 0.1, and 0.2 per cent poly acrylamide (PAM) were 6, 9, and 14 times higher, respectively, than those for controls. According to Watt and Peake (2001), the soil-wetting polymers added to potato fields boosted water retention in the soil by 102% around the root zone, which resulted to a 25% increase in tuber output. Polymer enhanced seedling growth, increased nitrogen uptake, and decreased nitrogen loss through leaching of saline soils (Martinez *et al.,* 2004). According to Anupama *et al.* (2005), the application of hydrogel (0.5 per cent) to chrysanthemum plants showed the most noticeable development in terms of plant height, stem diameter, number of leaves per plant, number of flowers per plant, and flower size. Compared with the control, the modified soil with natural and synthetic polymers increased dry matter yields by 92 and 81 per cent, and maize yields by 36 and 31 per cent, respectively (Yangyuoru *et al.,* 2006). Applying 5 kg ha^{-1} of hydrogel to clay loam soil with the full prescribed amount of fertilisers increased wheat yield by 8.48 per cent compared to the control (Borivoj *et al.,* 2006). Compared to the control, which had 13.0 seedlings/pot, the addition of hydrogel to the potting media improved the emergence (20.4 seedlings per pot) and survival (80-100 per cent) of crested wheat grass seedlings (Mangold and Sheley, 2007). Application of hydrogel increased soybean grain production in soils susceptible to drought, and the yields were 1.77, 3.47, 4.98, and 6.41 q ha^{-1} with the application of super absorbent polymer at 0, 75, 150, and 225 kg ha^{-1}, respectively (Yazdani *et al.,* 2007). According to Al-Humaid and Moftah (2007), the application of polymer at a weight-based concentration of 0.4 to 0.6 per cent increased the water potential of buttonwood (*Conocarpus erectus* L.) seedlings in dry areas. Under drought stress, these seedlings fared three times better than the control. They added that the use of hydrogels considerably boosted root and shoot growth. According to Yazdani *et al.* (2007), the application of superabsorbent polymer considerably enhanced soybean seed yield (5495 kg ha^{-1}) compared to the control (4172 kg ha^{-1}). According to Eiasu *et al.* (2007), the pure gel polymer enhanced total and marketable tuber production, particularly at higher fertiliser rates. According to Abedi-Koupai *et al.* (2008), the amount of SuperabA-200 that had the greatest impact on Golden Privet (*Ligustrum ovalifolium* Hassk.) was 6 g kg^{-1}, even though 4 g kg^{-1} increased water consumption by 33 per cent compared to the control. According to

Ghasemi and Khushkhui (2008), the use of hydrophilic gels had a positive and significant impact on plant height, root fresh and dry weight, root/shoot proportion, and coverage area under drought stress. It also had a positive and significant impact on the number, diameter, fresh and dry weight, and number and area of leaves. For instance, the results showed that using 0.8 per cent of hydrogel as the control over a 5-day period increased the number of bush flowers by about 6.5 per cent, the number of leaves by 42 per cent, the area of the leaves by 29 per cent, the number of shoots by 24 per cent, and the height of the plant by 45 percent on average. According to Yazdani *et al.* (2008), water stress and superabsorbent polymer had the greatest impact on the qualitative and quantitative performance of soybean seed protein. Compared with soil treated with 2 g hydrogel (43.7 g plant^{-1}) or 2 kg compost (35.0 g plant^{-1}) individually, or with the control, soil incorporating hydrogel (1 g plant^{-1}) with 2 kg compost also boosted the dry weight of tomatoes (19.2 g plant^{-1}). When combined, the advantages of organic matter and hydrogel outweigh those of either conditioner separately (El-Hardy *et al.,* 2009). According to Orikiriza *et al.* (2009), adding hydrogel to soil improves the efficiency of water uptake and use by plants growing in soils with water contents close to field capacity. According to Ghamsari *et al.* (2009), the use of superabsorbent polymers increased the number and weight of grains in maize and mitigated the effects of drought. The addition of superabsorbent polymer can linearly enhance the weight of 1000 seeds of maize and soybean crops, according to Khadem *et al.* (2010). Agaba *et al.* (2010) suggested that hydrogel improves plant growth and significantly increases the shoot and root biomass compared to the control. When 65% cow dung and 35% superabsorbent polymer were applied (26 t ha^{-1} cow manure + 70 kg ha^{-1} superabsorbent polymer), grain yield increased by 16.2% compared to the control (Khadem *et al.,* 2010). High polymer content in the water supply led stomata to remain open for an extended period, resulting in increased CO_2 fixation and, in turn, increased dry matter production (Khadem *et al.,* 2010). According to Nazarli *et al.* (2010), the use of superabsorbents during the growth phase, particularly at the genesis stage, resulted in high moisture retention, which increased the rate of photosynthesis and lengthened the seed-filling time. Islam *et al.* (2011) observed that superabsorbent polymer at high and very high dosages considerably increased plant height, stem diameter, leaf area, biomass accumulation, and relative water content in maize, although the ideal dose of superabsorbent polymer for maize cultivation was 30 kg ha^{-1}. As compared to the control, the use of water absorbents considerably increases the emergence count (180 m^{-2}), plant height (79 cm), effective tillers (264 m^{-2}), grains per panicle (69), and grain yield (23.3 q ha^{-1}) of aerobic rice (Rehman *et al.,* 2011). Compared with the control and water-soaking treatments, coating pearl millet seed with 10 and 20 g of hydrogel per kg of seed increased the number of effective tillers, ear length, test weight, and grain and stover yields (Singh, 2012). When compared to control, seed coating with 20 g of hydrogel per kg of pearl millet seed produced the largest grain and stover yields, as well as the highest consumption of water and water use efficiency (Singh, 2012). According to Vijayalakshmi *et al.* (2012), tomato plants grown in sandy loam soil with 0.75 per cent (w/ w) water-soluble polymers and 50 per cent Attainable Moisture Depletion (AMD) provided the highest yield (59.6 t ha^{-1}) and most efficient use of water (153.6 kg m^{-3}).With sandy soil of Iran with a hot and arid climate, the results of applying 200 kg ha^{-1} of hydrogel to peanuts were shown to be noticeably superior in regard to all growth and yield features (namely seed yield, biomass yield, pod yield, number of branches per plant, and 100 seed weight) (Langaroodi *et al.,* 2013). According to Barihi *et al.* (2013), using superabsorbent polymer improved the performance of growth indices in greenhouse cucumbers. Superabsorbent polymers reportedly affected the yield of cash crops in dry and semiarid regions, according to Dabhi *et al.* (2013). According to Waly *et al.* (2015), application of 1 per cent hydrogel in dry rice resulted in the greatest harvest index, largest grain yield, highest biological yield pot^{-1}, highest number of grains panicle^{-1}, and highest protein percentage in grains. According to Kalhapure *et al.* (2016), three irrigations with 5 kg ha^{-1} of hydrogel produced a greater yield for the wheat crop than three irrigations without hydrogel and five irrigations without hydrogel. Pusa hydrogel, applied at 2.5 kg ha^{-1} in the furrow at the time of sugarcane planting, improved the vigour and germination of the crop, which increased cane yield, commercial cane sugar (CCS) yield, and Irrigation water use efficiency (IWUE) (Singh *et al.,* 2018). Superabsorbent polymers in the soil increased grain water-use efficiency by 10% and maize production by 12% compared to untreated plots (Wei Yang *et al.,* 2018). In comparison to the control and 2.5 kg ha^{-1} of hydrogel application, the drilling of hydrogel at 5.0 kg ha^{-1} before planting produced considerably greater pod plant^{-1} (66.5), grain yield (1210 kg ha^{-1}), and net return (Rs. 27507 ha^{-1}) of lentil, respectively (Ram *et al.,* 2018). Compared to the non-hydrogel-treated plots, the plant population in the hydrogel-treated plots rose by 22%. The application of hydrogel significantly increased the effective tillers, plant height, ear length, and grains per ear. After hydrogel amendment, both the overall yield and grain yield greatly increased (Roy *et al.,* 2019).In semi-arid agro-ecologies, the application of hydrogel under rainfed conditions and deficit irrigation has the potential to increase Indian mustard production, profitability, and bio-energy output (Rathore *et al.,* 2020). Pusa hydrogel application at 100% recommended dose of hydrogel (RDH) 5 kg ha^{-1}) led to a significant improvement in plant height and the number of spikes, which translated into a higher seed yield of caster (1776 kg ha^{-1}) followed by 50% (2.5 kg ha^{-1}) RDH (1652 kg ha^{-1}) as compared to Control (1242 kg ha^{-1}) and may be a key practice to boost castor yield under rainfed conditions (Kumar Naik *et al.,* 2020).

Knowledge of the economic evaluation of hydrogel application across diverse crops worldwide is limited. Though some authors have published favourable results on yield improvement around the world, its economics have gotten little attention. According to Puoci *et al.* (2008), hydrogels improve the benefit-cost ratio by lowering input costs due to their ability to reduce irrigation and fertilizer, while enhancing crop productivity. Islam *et al.* (2011) indicated that the optimal dose of super absorbent polymer for significant maize production was 30 kg ha^{-1}, and lower (10-20 kg ha^{-1}) or higher (40 kg ha^{-1}) doses were insufficient and inefficient for increasing maize yield. Kumar *et al.* (2015) found a higher benefit-cost ratio of 2.15 without hydrogel treatment compared to ratios obtained when hydrogel was applied at 10 kg ha^{-1} (1.86), 15 kg ha^{-1} (1.72), 20 kg ha^{-1} (1.52), 25 kg ha^{-1} (1.36), and 30 kg ha^{-1} (1.24) in rabi maize. Furthermore, Jat *et al.* (2018) stated that increasing hydrogel application from 0 to 5 kg ha^{-1} increased mustard seed yield, but net returns and B:C did not increase significantly, most likely due to the higher cost of hydrogel, which increased cultivation costs, resulting in lower net returns and benefit: cost ratio. Ramanjaneyulu *et al.* (2018) determined that a minimum improvement in seed production of 200 kg ha^{-1} is required to offset the additional cost of hydrogel addition. Additionally, Singh *et al.* (2018) discovered that by applying Pusa hydrogel at a rate of 2.5 kg ha^{-1}, the cane yield (75.2 t ha^{-1}) was much greater than the control (69.5 t ha^{-1}). Hydrogels in water-scarce regions can provide a major economic benefit by improving soil moisture retention, thereby reducing water requirements and labour costs (Ashraf *et al.,* 2021). Large-scale hydrogels do have downsides, such as a lower benefit-cost ratio (Kaur *et al.,* 2023). Although hydrogels have economic benefits, their high initial cost remains a significant barrier to widespread use, particularly among low-income farmers in underdeveloped countries (Anuar *et al.,* 2025). Based on these assessments, the high cost of hydrogels has been a barrier to their widespread application in agriculture. Farmers can boost their economic returns, making hydrogels a viable, long-term alternative for improving water use efficiency, especially in dry and semi-arid regions.

Factors Affecting Super Absorbent Polymer Performance

Kind of polymer

There are three main categories of hydrogels (natural, synthetic and semi-synthetic). They vary greatly in overall absorbency, hydration time, structural stability, and soil lifetime. The full hydration of starch-graft co-polymers may take many hours. Cross-linked acrylamide-acrylate co-polymers have the gel strength and longevity that starch graft co-polymers lack (Grula and Huang, 1982). In contrast to cross-linked acrylamide-acrylate copolymers, which remain active for 5 to 7 years or longer, starch-graft copolymers often have a seasonal activity limit. Hydrogels within a group can also vary significantly. For instance, whilst many cross-linked arylamide-acrylate co-polymer hydrogels have an absorbency factor of 400x, some cross-linked acrylamide-arylate co-polymers can only absorb 30–40 times of their weight in deionised water. However, compared to their more absorbent cousins, these lower-absorbing co-polymers are less sensitive to salinity.

Size of the polymer's particle

Water-absorbing polymers come in a range of particle sizes, from fine granules smaller than 2 mm in diameter to powders. On root zone properties including oxygen diffusion rate and water absorption, the impact of powders versus coarse granules may be significantly different. The goal is to significantly increase the soil's ability to hold water while maintaining its ability to conduct gaseous exchange. Gas exchange to the roots may be significantly hampered if a continuous powder covering is applied. It is urgently necessary to conduct research comparing the ability of powders to influence gaseous exchange to fine and coarse-grade granules.

Soil texture

The potential benefit of polymers on water storage also depends on the soil texture. Therefore, in coarse-textured soils as opposed to fine-textured soils, a polymer could hold a larger amount of water. Compared with the control, the addition of polyacrylamide (PAM) decreased the bulk density of loamy and sandy soils and slightly increased that of clayey soil. In contrast, for clay loam and sandy soils, porosity increased with PAM rate. But in clay soil, macropore size grew, whereas in clay loam and sandy loam soils, it dropped (Uz *et al.,* 2008). With the highest 0.67 per cent PAM rate applied due to an increase in water content at field capacity (FC) and a drop in water content at wilting point (WP), the available water contents of loamy and clay soils exhibited highly significant increases of 108 per cent and 105 percent, respectively, in Sandy loam soil's plant-available water content rose by 55% as a result of the rise in water content at wilting point.

Salt concentration in water and soil solution

According to Johnson (1984), nature and the concentration of dissolved salts in irrigation water have a considerable impact on the water-holding capabilities of polymers. Saline water decreases water absorption and conservation. Akhtar *et al.* (2004) evaluated the effect of water quality on the amount and rate of absorption and reported that the maximum time for absorption with distilled water, tap water and saline water was 7, 4 and 12 hr, respectively and the amount of absorption in 1 hr was measured as 505, 212 and 140 g g^{-1}, respectively. In loamy sandy soils, an increase in water salinity of greater than 2.5 dS m^{-1} reduced the efficiency of polymers, and plants irrigated with 5 dS m^{-1} used 42 per cent more water than those irrigated with 1.6 dS m^{-1} (Bhat *et al.,* 2009). The inclusion of Al^{3+} prevented the hydration of a cross-linked polyacrylamide the most among several NO_3^- containing salts. Similarly, compared to monovalent cations (NH_4^+, Na^+, and K^+), divalent cations (Ca^{2+} and Mg^{2+}) showed a higher inhibitory effect on polymer expansion. Since the anion changed but the cation remained constant, the effect of NH_4^+ based salts on polymer expansion was significantly less. This suggests that the source of cations has a much bigger impact on polymer hydration than the source of anions. Overall, the amount of water absorbed by one gram of polymer ranged from 247-369 g in distilled water, 141-175 g in 50% Hoagland solution, and 120-155 g in irrigation water over a 5-240 min saturation period. The amount of water absorbed by the polymer decreased from 360 to 110 g g^{-1} as the electrical conductivity (EC) of the water source increased from 0.03 to 2.23 dSm^{-1} (Reddy *et al.,* 2015).

Application rate of polymers

Depending on the soil's characteristics, the slope, and the type of erosion being targeted, the polyacrylamide (PAM) application rates to the soil may need to be modified. Per acre, older PAM formulations called for hundreds of kg of PAM. But even at lesser rates, PAM using newer, longer-chain polymers is more efficient (Wallace and Wallace, 1986). The application of 20 kg ha^{-1} PAM before spray watering increased infiltration rates and decreased runoff and erosion, according to many researchers (Stern *et al.,* 1992). In some instances, overusing hydrogels can have the opposite effect of what was intended, as it lowers soil air, allowing the gel to inflate and fill any gaps. There are numerous accounts of gels having little or no effect on plant growth indices when used excessively in soil. The primary cause, as previously stated, results from the occupation of numerous unoccupied soil spaces, which causes severe soil ventilation issues (Abedi-Koupai and Mesforoush, 2009). In a trial with *Pinus sylvestris* L. seedlings, Sarvas *et al.* (2007) found that excessive use of superabsorbent in the soil increased the likelihood that plants would contract *Fusarium* infections, which ultimately led to their death. They recommended conducting research to determine the optimal hydrogel dosage across various environmental conditions and plant types. Pigeon pea was given a 28 kg water absorption polymer per hectare along with the prescribed rates of fertilizers, which increased the crop's seed production and nitrogen uptake by 12 and 10%, respectively, during the course of the crop's various growth phases in sandy loam soil (Mondal, 2011). Application of carboxymethyl cellulose at rates of 2 and 4 per cent with 5 tonnes of compost per hectare increased maize yield over untreated sandy soil by 25 and 34 per cent, respectively. In terms of nutrient and water use, the combined effects of the two soil conditioners were superior to their individual effects.

Polymers application method

The application technique also affects how efficiently the gel promotes plant development. It was established that mixing the hydrogels with the entire root zone or sprinkling them as dry granules did not work (Flannery and Busscher, 1982). When the hydrogels are piled, ideally a few inches below the soil surface, better outcomes appear to be attained. The types of gel, particle size, pace of application, and type of plant must all be taken into consideration when interpreting the results; therefore, generalizations should be avoided.

Bio-degradation nature of the polymer

The ability of a polymer to delay the release of water and nutrients in the soil may depend on how long it remains there. In general, synthetic polymers are more resistant to biological breakdown than naturally occurring polymers, which are easily broken down by soil microbes. Many of the chemical linkages in natural polymers can be disrupted by typical enzymatic hydrolysis in soils. Since soil bacteria have not yet evolved the polymer-specific enzymes necessary for rapid degradation, the synthetic polymers often exhibit far greater resistance to biological attack.

Ambient air temperature

Physical, chemical, biological and photo-chemical reactions cause polyarylamide polymers to break down in soil at rates of at least 10% annually (Tolstikh *et al.,* 1992). It is well known that high UV ray exposure outside accelerates breakdown rates. Using an ornamental plant (*Concarpus lancifolius*) in sandy soil, Bhat *et al.* (2009) investigated the effects of high temperatures on the performance of PAM polymers under three temperature regimes: variable ambient temperature (VAT, daily maximum and minimum temperatures ranging from 33-49^{o}C and 25-35^{o}C, respectively), environment-controlled greenhouse (GH), and indoor temperature regulation (LAB, daily maximum and minimum temperatures ranging from 21-26^{o}C and 20-24^{o}C, respectively). In VAT, GH, and LAB conditions, the plants grown at 0.4 per cent PAM required 33.8, 38.1, and 30.7 per cent less water than the control (no PAM), respectively. The breakdown of polymers caused by high temperatures and intense light may account for a significant portion of their decreased effectiveness under the VAT regime (Tolstikh *et al.,* 1992).

Disadvantages of Hydrogel in Agriculture

These hydrogels, or water-absorbing polymers, have been around for a while but are not as helpful to plant agriculture as they might first appear.

- If there are any ions in the water, the amount of water that hydrogels can absorb is significantly reduced. Typically, distilled water is used in the data for hydrogel water absorption. In the actual world, soils have ions from irrigation water and fertilizers that significantly lower the water absorption capacity of the hydrogels.
- The majority of soils have adequate water-holding capacities for plant growth. Insufficient rainfall causes the soil water to become depleted. Hydrogels won't be able to fix that issue.

- Due to their high price, hydrogels are only useful for high-value crops such as potted ornamental plants, landscape trees, and home gardens. According to one study, adding peat moss at the same cost as the recommended amount of Hydrogel increased potting soil's water-storage capacity by the same amount.

Future Research Thrust for Hydrogel Polymer

Recently, the application of hydrogel polymer in agriculture has demonstrated significant growth potential. Additionally, in dry and semiarid locations, the use of hydrogel polymer to boost crop yield and increase soil water retention is drawing significant interest (Dar *et al.,* 2017). On the other hand, the majority of these components, particularly those for slow-release nutrients, are currently being obtained utilizing natural ingredients (Dar *et al.,* 2017). Future research should examine how the use of superabsorbent polymers reduces fertiliser use and increases yield for seasonal crops and vegetables grown under conventional farming practices.

- In India, it is necessary to quantify the dosage of hydrogel for various soil types and crops under various agro climatic conditions.
- In-depth research is required on the mechanism underlying the hydrogel's water absorption and release pattern.
- It is possible to design agricultural machinery for applying hydrogel in the subsoil layers, particularly in *Kharif* crops where irrigation is not recommended for 30-40 days after sowing and crops start drying, and if irrigation provided the crop roots did not developed fully, which put harmful effect on yield of crop specially cotton.

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