Agri Articles
(e-Magazine for Agricultural Articles)
Volume: 03, Issue: 04 (JULY-AUGUST, 2023)
Available online at http://www.agriarticles.com

Hydrogels in Agriculture to Increase Crop and Water Productivity in Conditions of Water Sufficiency

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Due to the low rainfall and irregular spatial and temporal distribution that severely threatens the viability of agriculture in the world's arid and semiarid climates, water scarcity is a major environmental issue. Under moisture stress conditions, various physiological changes have been noted, including a decrease in water potential, stomatal closure, a decrease in photosynthetic rate, a decrease in morphological rate, and a reduction in decile yield and quality of the plant by limiting overall plant growth. The modern method of water-saving deficit irrigation technologies is regarded as a crucial element in conditions of limited water supply to ensure favorable soil moisture balance in the root zone with increased water use efficiency without compromising crop yield and its quality. The problems can currently be resolved by drastically reducing irrigation water consumption and improving water use efficiency thanks to the development of modern micro-irrigation technologies like low-pressure micro sprinklers and plastic mulching in addition to drip irrigation systems with ideal irrigation scheduling. These high-tech tools, however, are specifically used in high-value crops and demand sufficiently high capital expenditures, ongoing operational expenditures, and specialist skills from the farmers. In order to overcome the soil moisture stress and increase production, alternative irrigation technology using highly expandable polymer materials is another solution to the pressing problems. Due to its numerous benefits, including excellent water absorption and water retention, hydrogel polymer technology has recently become widely used in agriculture as a soil conditioner. The polymers continue to have very high water swelling and moisture-releasing capacities in the presence of water deficits, which improves plant growth and crop yield by reducing evaporation loss, deep water percolation, and nutrient leaching in arid and semiarid climates around the world.

Hydrogel also referred to as "root watering crystal," "water retention granules," or "raindrops," is an amorphous, quasisolid-phase substance. It has specially designed absorbency and biodegradability thanks to three-dimensional networks of loosely held cross-linked versatile hydrophilic macromolecules connected by covalent bonds or physical interactions.

When in contact with freely available water, these organic polymers have the unusual ability to absorb a significant amount of moisture in their super-absorbent structure in a short amount of time. When the soil dries, these materials uniformly release the trapped moisture to the surrounding soil and rhizosphere zones over time.

Functional Characteristics of a Hydrogel

The following characteristics of the ideal hydrogel materials should be present:

1. High water absorption capacity
2. Desired absorption and desorption rates in accordance with plant requirements

3. Lowest solubility and remaining monomer
4. High biodegradability and biocompatibility
5. High durability and stability during swelling and storage
6. High performance over a broad temperature range
7. Water's pH becomes neutral after swelling
8. Non-toxic, colorless, and odorless
9. Increase the physical, chemical, and biological qualities of the soil
10. Photostability, longer-lasting rewetting, inexpensive material, and environmental friendliness

How Does a Hydrogel's Water Retention and Release Behaviour Operate?

(i) The hydrophilic groups of the polymer chain, such as acrylamide, acrylic acid, acrylate, carboxylic acid, etc., are what allow a hydrogel to absorb water.

(ii) Osmosis allows water to enter the hydrogel system through the polymers, where it reacts with hydrogen atoms to produce positive ions.

(iii) This process leaves behind a number of negative ions along the length of the polymer chain. Figure 1 illustrates how these repelling negative charges cause the polymer chain to unwind and open up. Additionally, they draw water molecules and bind them with hydrogen bonds.

(iv) The hydrogel can absorb 400–1500 times its dry weight in water during this process without changing the soil's physicochemical characteristics.

Usage of Hydrogel in Agriculture

Hydrogel is used in agriculture as a small water reservoir and as a pesticide and fertilizer delivery system to improve the physical characteristics of the soil. Water in the soil is crucial for vegetation and different types of plants. One of the best solutions for agricultural water shortage issues is the development of hydrogels. Due to their superior capacity for retaining water and utilizing nutrients, amendments like hydrogel polymers have been a promising option in areas with limited water availability. In the world's semi-arid and arid regions, water management has become one of the most pressing issues. In the agricultural sector, hydrogel polymers are beneficial in a variety of ways because they reduce land erosion and have an incredibly high water-holding capacity.

1. Water reservoir: The excellent ability of hydrogels to absorb and retain large amounts of water in their structure (up to hundreds of times their weight) without dissolving is the reason for their widespread use. A further benefit of hydrogels is their ability to release almost 95% of the water they have absorbed into their surroundings. Once they have dried out, they can be rehydrated by being exposed to water. As they are primarily used as soil conditioners in the agricultural sector, they can control soil moisture content and are also in charge of providing water to plants. They are also used to increase the water storage capacity close to the roots, the field capacity of various types of soils, and the quantity and availability of water, which reduces water stress in plants and enhances performance, thereby promoting growth.

2. Plant growth: Water availability is crucial for the establishment to succeed, but in arid and semi-arid areas, it is constrained by the low soil moisture content. Hydrogel polymers expand to increase the soil's capacity to hold water and lengthen the time it takes for plants to wilt, which improves plant growth and increases the survival rate of plants under water stress. Hydrogels are also used to create water reservoirs close to plant roots, which lower soil osmotic pressure, increase plant water availability, boost plant growth, increase overall yield, and lower crop production costs. The viability of plants is increased through the use of hydrogels, which also improve seed germination, ventilation, and root development in dry environments.

3. Controlled delivery of micronutrients: Combining hydrogels and fertilizers would reduce the need for irrigation while limiting fertilizer loss and environmental impact, particularly for nitrogen-based compounds. Protective agents like pesticides and herbicides may consider a career in the polymer.

Techniques for Applying Hydrogel in Agriculture

Hydrogels are used as soil conditioners to improve soil structure at greater depths by aggregation, stabilize surface soils to prevent the formation of crusts, increase water-holding capacity, and promote plant growth and development. The soil texture affects how quickly hydrogel is applied in agriculture. It is 2.5 kg ha-1 at a soil depth of 6 to 8 inches for clay soil and up to 5.0 kg ha-1 at a soil depth of 4 inches for sandy soil. Generally, there are only two ways to apply hydrogels to soils:

(i) Dry method to subsoil: a dry polymer, such as polyallylamine (PAAm) or polyvinyl alcohol (PVA), is mixed with sandy soil to a depth of 15 to 25 cm, moistening the soil for swelling before cultivation. The soil structure is enhanced, and water penetration and retention capacity are increased after the polymer has swollen.

(ii) Wet method of topsoil: The topsoil is initially wetted, the polymer solution is sprayed onto it, it is dried for water-stable aggregate stability, and then it is immediately seeded. This wet method can improve soil hydraulic conductivity, decrease soil erosion, and use less water. The hydrogel can also be combined with micronutrients and pesticides in the spray method.

Hydrogel Polymer Effect on Soil Properties

The following ways the hydrogel can be used as soil conditioners or amendments to improve the soil properties of arid and semiarid regions:

(i) Alter the physical (such as porosity, bulk density, water-holding capacity, soil permeability, percolation and infiltration rate, soil temperature, etc.), chemical (such as CEC), and biological environments to improve the structure of coarse-textured soil through aggregation, stabilization, and solidification.

(ii) Prevent crust formation

(iii) Create a hospitable growth environment by decreasing soil bulk density, improving ventilation, and maintaining a consistent moisture level to support plant viability, growth, and yield

(iv) Improve soil water retention, plant root water supply, and water uptake efficiency; decrease irrigation frequency due to a decline in water losses from leaching and evaporation; and safeguard plants from soil water stress.

(v) Reduce soil losses from water and wind erosion and runoff.

(vi) Control seepage by creating soil membranes that control the downward movement of water and nutrients, increase soil permeability and infiltration, improve aeration and soil drainage, and prevent salt toxicity injury to plants.

(vii) Improve plant water and nutrient use efficiency and water conservation

Advantages of Hydrogel in Agriculture

(i) Hydrogels serve as "miniature water reservoirs" close to a plant's root zone. When there is a water shortage, it can absorb 400–1500 times its weight in both natural and supplied water and release it gradually.

(ii) It can perform the cyclic process of water absorption and desorption, provide the maximum amount of plant-available moisture for rapid seed germination and seedling establishment, and increase the growth and high yield of the crop.

(iii) In cold climates, the use of hydrogels prevents the moisture absorbed in the structure from freezing and makes it accessible to the plants, regulating the temperature of the growing seedlings and preventing death by freezing.
(iv) It can reduce soil osmotic moisture, reduce the need for irrigation, labor, and production costs, reduce crop irrigation needs, lessen the severity of drought conditions, prevent water and nutrient runoff and leaching, increase plant water and nutrient use efficiency, and restore soil microorganisms and enzymes.
(v) Delaying the start of the plant's eventual permanent wilting can help the plant withstand prolonged moisture stress.
(vi) It can lessen the use of excessive amounts of minerals, such as micronutrient fertilizers and pesticides.
(vii) It can improve soil aeration, prevent soil compaction, and release nutrients found in soil.
(viii) It can promote healthier, stronger plant growth and marketable yield.

Conclusion

In arid and semiarid areas, water is increasingly the limiting factor for sustainable crop production. The use of hydrogel as a soil conditioner can enhance the hydrophysical, physicochemical, and biological conditions of the soil, as well as its capacity to hold and release water. Additionally, it can improve crop yield and quality, increase irrigation, water, and nutrient use efficiency, and maintain environmental quality. This hydrogel technology may develop into a practically useful and revolutionary technology in water-stressed areas in terms of increased yield (cereals, vegetables, oilseeds, flowers, spices, plantations, etc.) and lowering soil moisture stress.