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Hydrogels in Agriculture

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Abstract

A hydrogel is a three-dimensional (3D) network of hydrophilic polymers that can hold a large amount of water by swelling while maintaining its structural integrity due to chemical or physical cross-linking of individual polymer chains. Hydrogels were first reported by Wichterle and Lím (1960). For a material to be called as hydrogel, at least 10% of the total weight (or volume) must be constituted by water. Hydrogels show similarity to natural tissue in terms of degree of flexibility, due to their significant water content. The hydrophilicity of the network is due to the presence of hydrophilic groups such as $-NH_2$, -COOH, -OH, -$CONH_2$, - CONH -, and $-SO_3H$. The presence of hydrophilic groups in the hydrogel structure is necessary to provide sufficiently high-water absorption and water retention abilities (Ghobashy, 2020).

Hydrogels are mainly formed from biopolymers and/or polyelectrolytes. Hydrogels can be divided into those formed from natural polymers and those formed from synthetic polymers. Similarly, hydrogels may be cationic, anionic, or neutral, depending on the ionic charges on the bound groups. The types of cross-linking agents also can be considered as the criteria for classification.

Hydrogels were first introduced for agricultural usage in early 1980s. Hydrogels play a significant role in agriculture, offering promising prospects and addressing various challenges. Let's delve into their applications:

1. **Drought Resistance**: Hydrogels can retain substantial amounts of water within their three-dimensional polymeric network. When irrigated (artificial irrigation or rainwater) on cultivated land, the hydrogel absorbs and retains water, preventing quick water loss to drainage and evaporation. Upon the drying of soil, the stored water is released from the hydrogel into the soil in a controlled manner via a diffusion mechanism, that allows the soil or the substrate to remain moist for extended period. So, these can be used for drought mitigation in the crops under the present unpredictable climate changing conditions, especially during frequent and long dry spells.
2. **Nutrient Reservoirs**: Hydrogel acts as a reservoir for critical nutrients. Hydrogels create a favorable microenvironment around plant roots by retaining water and nutrients, and gradually releasing them whenever needed. This helps to optimize availability and uptake of nutrient. The biodegradable nanoparticles type of hydrogels can spread into the entire food chain once it enters the plant via successive organisms. The hydrolyzed hydrogel releases urea 192 times slower than the control (pure urea). There are studies which shows urea release ratio may be successfully slowed down by hemicellulose hydrogels with high water retention ability (Hou *et al*., 2023).

3. **Seed Coating Agents**: Hydrogels can be used as a coating agent over the seeds since they create a protective layer that improves germination and early growth. The hydrogel coating ensures consistent moisture supply to the seed, ensuring seedling establishment. Beneficial bacteria can be encapsulated with hydrogels or sodium alginate formulations for biological control of diseases.
4. **Soil Conditioning**: Hydrogels can improve structure and water retention capacity of soil, and nutrient availability, thereby enhancing crop growth and productivity, especially in the arid regions.
5. **Increased Efficiency**: The use of hydrogels as carriers of biochemical, enhances the efficiency of agrochemicals usage by improving their targeting and uptake by plants. By delivering the chemicals directly to the crops root zone or targeted foliar surfaces, hydrogels ensure the maximum utilization of the active ingredients (ai), leading to better pest, disease and weed control, as well as improved nutrient uptake by the plants.
6. **Transplantation Success**: Hydrogels improve success rates of transplantation of seedlings. Use of hydrogels during transplanting, maintains soil moisture around the root ball, reducing transplanting shock and promoting healthy growth of the plants.
7. **Crop Protection (Pesticide and Herbicide Delivery**): Hydrogels can serve as carriers of pesticides and fertilizers, facilitating controlled release and reducing environmental impact. Hydrogels can be loaded with pesticides or herbicides and applied to the soil or crop foliage. These hydrogel-encapsulated chemicals are released slowly over time, providing controlled and targeted protection against pests and weeds while reducing the risk of runoff and leaching of harmful chemicals into the environment.
8. **Sustainable Agriculture**: Hydrogel-based crop production and protection aligns with principles of sustainable agriculture by reducing chemical usage, minimizing environmental impact of harmful chemicals, and promoting resource use efficiency. Hydrogel offers a more environmental friendly alternative to conventional spraying methods, thereby contributing to sustainable farming practices.

Applying hydrogels to the soil increases soil structure, density, and permeability, improving water infiltration and reducing evaporation rates, water run-off and erosion of soil, that improves crop productivity. Additionally, mixing a hydrogel with the soil will increase soil porosity that provides better oxygen circulation to the plant roots.

The network structure of hydrogels formed by physical interactions or chemical crosslinking can be customized to suit specific applications. However, challenges remain in modifying hydrogels for precise agricultural needs, but their potential impact on sustainable farming practices is promising. Since the global population is growing, but the water source remains constant, it is important to use water efficiently. Hydrogels offer a way to optimize water availability to the roots, enhance crop yield, and contribute to sustainable agriculture.

In terms of safety and sustainability, natural biopolymer-based hydrogels are advantageous over the synthetic polymers. Although natural polymers, such as polysaccharides, have undoubted advantages related to their biocompatibility, biodegradability, and low cost, they are inferior to synthetic polymers in terms of water absorption and water retention properties. In this regard, the most promising are semi-synthetic polymeric super-absorbents based natural polymers that remodified with additives or grafted chains of synthetic polymers. These can combine the advantages of natural and synthetic polymeric hydrogels. Ongoing research and innovation aims to further optimize hydrogel formulations and application methods for enhanced efficacy and adoption in commercial agriculture. Such semi-synthetic polymers are of great interest for agricultural applications, especially in dry regions, since they can be used for the slow release of nutrients into the soil, that are necessary to increase crop yields using environmentally friendly technologies.

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