

Advancing Sustainable Agri-Food Systems with Biopolymer Hydrogels: From Soil Enhancement to Edible Applications

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Abstract

Biopolymer hydrogels derived from natural polymers like chitosan, alginate, cellulose, and starch are emerging as sustainable solutions for agri-food systems, addressing critical challenges in water scarcity, soil degradation, and food preservation. These hydrogels, synthesized through cross-linking methods such as chemical grafting or ionic interactions, exhibit exceptional water retention (up to 400× their dry weight) and controlled-release properties, making them ideal for soil conditioning and nutrient delivery. Recent studies demonstrate their efficacy in agricultural applications: crosslinked xanthan-guar gum hydrogels improved soil water retention over 12 wet-dry cycles, while starch-polyacrylamide hybrids enhanced nitrogen use efficiency in wheat by 20–30%, reducing fertilizer leaching. In food systems, chitosan-thyme oil hydrogel coatings extended the shelf life of fresh-cut fruits by 3–5 days by mitigating moisture loss and oxidative spoilage, and alginate-chitosan encapsulation boosted probiotic survival by 2–3 log units during digestion. Environmental benefits include a 30–50% reduction in greenhouse gas emissions compared to synthetic polymers, alongside biodegradability and waste valorization potential (e.g., dairy byproduct acid whey used in hydrogel synthesis). Future research should prioritize large-scale field trials to validate long-term agroecological impacts and optimize cost-effective production methods for global scalability. Despite challenges like variable mechanical strength, advancements in stimuli-responsive (pH/temperature-sensitive) hydrogels and precision agriculture integration promise to further optimize their performance. Collectively, biopolymer hydrogels represent a transformative approach to sustainable agri-food systems, balancing ecological and economic demands while aligning with global sustainability goals.

Keywords: Biopolymer hydrogels; Sustainable agriculture ; Soil enhancement ;Edible coatings; Food preservation