

Recent Advances in Hydrogels for Sustainable Agriculture

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Agriculture accounts for about 70% of global freshwater withdrawals, yet only 30–50% of applied nitrogen is recovered by crops, while substantial portion being lost through leaching, volatilization, denitrification and runoff. Increasing rainfall variability intensifies both losses, particularly in rainfed and semi-arid regions, which account for a large share of India's cultivated area. Hydrogels, three-dimensional networks of hydrophilic polymers stabilized by chemical or physical crosslinks, address these losses simultaneously by acting as water and nutrient reservoirs in the root zone. The first generation of agricultural superabsorbent polymers (SAPs), based on crosslinked polyacrylate and polyacrylamide, is effective but environmentally persistent. The incubation of a polyacrylate superabsorbent hydrogels in four agricultural soils revealed main-chain mineralization of only about 0.12–0.24% over six months (Wilske *et al.*, 2014). Concerns over polymer accumulation and residual acrylamide have therefore redirected research towards biodegradable hydrogels.



Biodegradable Hydrogels

Biodegradable hydrogels are crosslinked hydrophilic biopolymer networks that absorb many times their dry mass in water, have emerged as multifunctional soil inputs. Hydrogels based on Cellulose, hemicellulose, starch, pectin, alginate, chitosan, lignin and proteins supply hydroxyl, carboxyl and amino groups that bind water through hydrogen bonding and ionic interactions. Many of these polymers can be recovered from rice straw, sugarcane bagasse, corn husk, fruit peels, coconut coir, soybean pulp (okara) and dairy whey, coupling hydrogel production with residue valorization. In India, where paddy-straw burning and surplus bagasse from sugarcane remain persistent disposal problems, this route offers a clear circular bio-economy opportunity. Conventional crosslinkers such as glutaraldehyde, formaldehyde-based resins and *N,N'*-methylenebisacrylamide yield robust networks but can leave toxic residues. Bio-based alternatives include citric acid, which forms ester linkages with polysaccharide hydroxyl groups on heating. Hydrolysable ester and glycosidic linkages offers biodegradability, whereas crosslink density, porosity and particle size control swelling capacity, mechanical strength and degradation rate. Life-cycle assessments indicate approximately 35% lower CO₂-equivalent emissions and production costs for agro-waste-derived hydrogels than for petrochemical SAPs.

Applications of Hydrogels

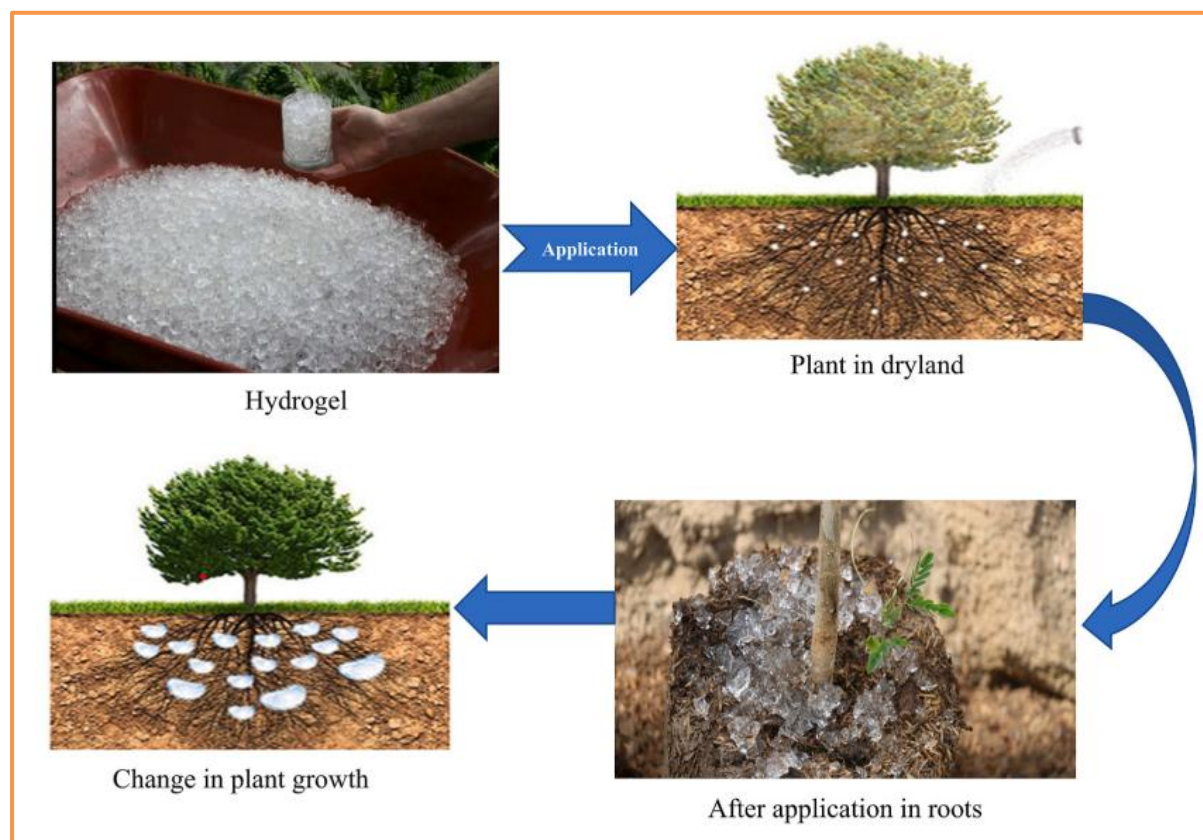
The principal agronomic functions of biodegradable hydrogels, their mechanisms and their outcomes are summarized in Table 1.

Table 1. Agronomic functions of biodegradable hydrogels: mechanisms and representative outcomes

Function	Mechanism	Representative outcomes
Soil conditioner	Water uptake during wetting and release as matric potential declines; swell–shrink cycles create macropores	Soil water retention increased by 20–50%, irrigation demand reduced by 15–40% and yield raised by 10–35% under water limitation (50–150 kg ha ⁻¹)
Nutrient carrier	Diffusion, swelling–deswelling and network erosion retard nutrient release	HPMC/PVA hydrogel released 87% of urea in 44 days against 97% in 4 days for uncoated urea; nitrate leaching and N ₂ O emissions reduced by up to 80%
Microbial carrier	Hydrated, protective matrix with gradual release of cells into the rhizosphere	Alginate–proline microcapsules achieved >99% encapsulation efficiency and released viable PGPR after 60 days of storage at room temperature
Stimuli-responsive system	pH, ionic strength or moisture-dependent changes in network charge and swelling	pH-sensitive network released 90% of its nutrient load at pH 5.5 against 50% at pH 7

Soil water retention

Hydrogels absorb water during irrigation or rainfall and release it as the soil dries, increasing plant-available water and lengthening irrigation intervals; the largest effects are observed in coarse-textured soils. In a two-year field study in the Indo-Gangetic plains, Pusa Hydrogel, a semi-synthetic cellulose-derivative superabsorbent applied at 2.5 kg ha⁻¹, improved the productivity, water productivity, rooting behaviour and profitability of the soybean–wheat system under water stress (Rajanna *et al.*, 2022). Excessive rates, conversely, can impair soil aeration and depress growth.



Controlled release of nutrients

When swollen in fertilizer solutions or polymerized around fertilizer granules, hydrogels release nutrients through diffusion, swelling–deswelling and progressive network erosion, thereby synchronizing supply with crop demand. In a 130-day pot experiment, urea-loaded cellulose hydrogels prepared from waste paper and applied to upland rice as a single basal dose of 90 kg N ha⁻¹, equivalent to 75% of the recommended rate, produced the highest grain yield and improved nitrogen uptake and use efficiency relative to split-applied conventional urea (Abg Ahmad *et al.*, 2023).

Delivery of beneficial microbes

Encapsulation in alginate, chitosan or gelatin matrices protects plant growth-promoting rhizobacteria (PGPR) from desiccation, ultraviolet radiation, acidity and competition, extends inoculant shelf life and permits gradual release into the rhizosphere. A carboxymethyl chitosan–sodium alginate–CaCl₂ hydrogel carrying the endophytic strain *Ensifer* sp. C5 enhanced colonization of *Brassica napus* roots, modulated suberin deposition in endodermal cells, and improved plant growth and adaptation to acidic soil (Feng *et al.*, 2025). Alginate encapsulation has similarly improved germination and early vigour of wheat (*Triticum aestivum*) inoculated with auxin-producing *Bacillus* strains.

Stimuli-responsive hydrogels

In pH-responsive networks, deprotonation of carboxyl groups increases fixed-charge density and electrostatic repulsion, expanding the network, whereas protonation collapses it; amino-functional networks behave in the opposite manner, so that release can be tuned to rhizosphere pH. Elevated ionic strength screens these charges and suppresses swelling, which limits conventional hydrogels in saline soils. A salt-tolerant hydroxyethyl starch hydrogel overcame this limitation, increasing soil water-holding capacity and reducing evaporation (Xiong *et al.*, 2022). Other designs release ameliorants once soil electrical conductivity exceeds a threshold or act as moisture-actuated irrigation sensors, although most remain at laboratory or pilot scale.

Biodegradation and Soil Health

Biodegradation proceeds through enzymatic hydrolysis of glycosidic, ester or peptide linkages, followed by microbial assimilation and mineralization to CO₂, water and humified organic matter. Its rate depends on the backbone, crosslink type and density, additives such as lignin or minerals, application format, and soil moisture, temperature and microbial biomass.

Table 2. Reported soil biodegradation of selected agricultural hydrogels

Hydrogels	Reported biodegradation	Dominant controlling factor
Crosslinked polyacrylate SAP	Virtually none over 6 months	Recalcitrant C–C backbone; high crosslink density
Alginate–chitosan polyelectrolyte complex	Complete within 6 weeks	Readily cleaved glycosidic bonds; high water uptake
Alginate/ <i>O</i> -carboxymethyl chitosan (Ca ²⁺ -crosslinked)	21.4–25.5% mass loss in 30 days	Reversible ionic crosslinks slow disintegration
Chitosan/CMC/silk fibroin blend	78% mass loss in 14 days	Enzyme-cleavable domains
Starch-based hydrogel from rice-cooking wastewater	34.6% in 120 days	Hydrolisable starch fraction within a copolymer
Lignin-based agro-hydrogels	9.5–14.5% mass loss in 40 days	Aromatic, hydrophobic lignin domains

Field studies report degradation within a single season without detectable microplastic residues or adverse effects on earthworms, together with improvements in porosity, aggregate stability, soil organic carbon and enzyme activity. Carbon-rich hydrogels applied at high

rates may transiently immobilize mineral nitrogen, and networks that degrade too quickly lose function before crop maturity. Semi-interpenetrating networks that combine a labile component with a more durable matrix are being developed to match service life to the cropping season.

Future Directions

Production costs and scalability of agro-waste-derived polymers must improve; long-term, multi-location field trials quantifying cumulative effects on soil health, nutrient dynamics and yield remain scarce; and the absence of standardized protocols for efficacy and soil biodegradability limits comparison across studies and regulatory approval. Priority areas include nanocomposite hydrogels reinforced with nanoclay, silica or nanocellulose; multifunctional formulations integrating water storage, nutrient release and biocontrol; multi-omics analysis of hydrogel–rhizosphere–microbiome interactions; and techno-economic and life-cycle assessments under farm conditions. For smallholders, targeted placement in planting pits, furrows or seed coatings at optimized low doses is more economical than broadcast application.

Conclusion

Biodegradable hydrogels have advanced from simple water-absorbing soil conditioners to tunable delivery systems for water, nutrients and beneficial microbes. Progress in bio-based polymers, green crosslinking and stimuli-responsive design now allows functional performance and degradation behaviour to be engineered together, while the use of crop residues as feedstock links these materials to the circular bio-economy. Translating this promise into routine practice will require long-term field validation, harmonized biodegradability standards and cost-effective production, after which biodegradable hydrogels can become a key input for climate-resilient and resource-efficient agriculture in India.

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