

Review

Sustainable Gels from Polysaccharides in Agriculture

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Abstract: Polysaccharide-based materials are a highly promising bioresource in the realm of biomaterial technologies due to their unique properties and versatility. Cellulose gels leverage the renewability, biocompatibility, and biodegradability of cellulose, a glucose polymer, making them ideal for various applications. This review examines various types of cellulose gels, a well-known polysaccharide used in agriculture, including natural (such as non-wood and bacterial cellulose gels), regenerated cellulose gels, and gels derived from cellulose derivatives. The properties of these cellulose gels, advanced technologies used in their potential fabrication, and their utilization techniques are comprehensively summarized based on a comprehensive systematic literature review to provide an in-depth understanding of the research theme, identify research gaps, and highlight future research directions. The review also explores the various applications of cellulose gels in agriculture, from fundamental research to practical implementations. Cellulose gels are versatile materials that can be used for soil conditioning, controlled release of fertilizers, water retention, and other important purposes. This exploration aims to provide a comprehensive understanding of the current state of cellulose gels in agriculture, bridging the gap between fundamental advances and their real-world applications.

Keywords: cellulose; hydrogels; biomaterials; agriculture; polysaccharides



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1. Introduction

Polysaccharides stand out as an excellent raw material for a great variety of products due to their abundance, biocompatibility, and sustainable nature. In addition to cellulose, the cell walls of plants contain other important polysaccharides, such as hemicellulose and pectin, which contribute to their structural integrity and functional properties.

Cellulose, a typical polysaccharide derived from wood and cotton cell walls (Figure 1), can be sourced from annual plants, seaweed, and bacteria [1], and also from paper [2,3] and food and agricultural wastes [4,5]. Furthermore, alternative sources like rapeseed stalks [6], corn stalks [7], wheat straw [8], rice straw [9], flax fibers [10], soybean stems [11], Jerusalem artichoke stems and leaves [12], fruit peels [13], sago pith waste [14], tea leaf residues [15], coconut coir, and palm sugar gomuti [16] contain a sufficient amount of cellulose (20–42%).

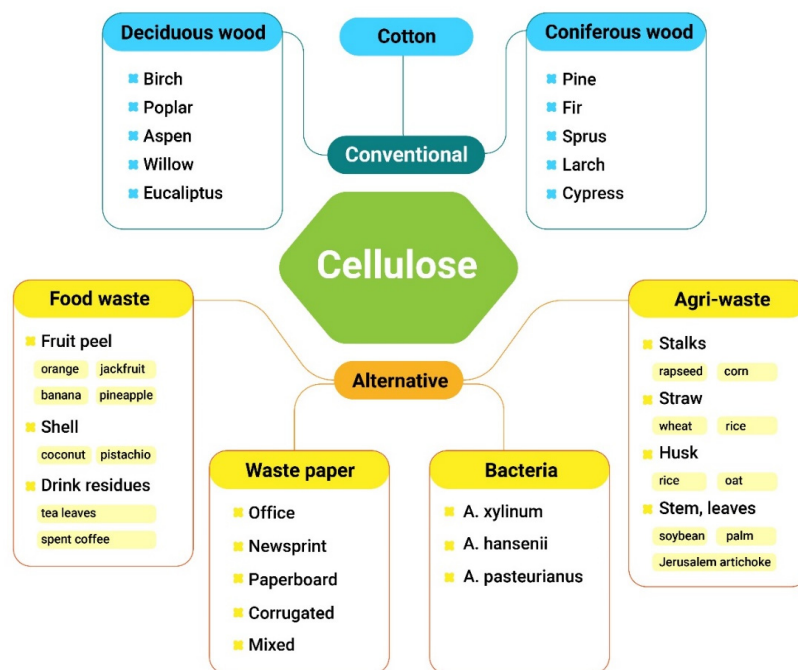


Figure 1. Raw materials for cellulose extraction.

Cellulose-based gels find significant application in modern agriculture due to their versatile properties, making them valuable materials in the development of advanced and eco-friendly technologies [17]. These gels, derived from abundant and renewable polysaccharide sources, offer unique advantages such as water retention, soil stabilization, and nutrient delivery [18].

Hydrogels are three-dimensional, hydrophilic polymer networks capable of absorbing and retaining large amounts of water or biological fluids without dissolving. This is due to their cross-linked structure, which provides mechanical stability while allowing for significant swelling. In the case of cellulose-based hydrogels, the polymer matrix is typically composed of cellulose or its chemically modified derivatives, in which hydrophilic functional groups (e.g., $-OH$, $-COOH$, $-CH_2CH_2OH$) facilitate water uptake and interaction with solutes [18].

Plant-derived cellulose is not commonly used in hydrogel preparation in its native form due to its limited solubility in common solvents. However, it can be dissolved in specialized solvents and processed into hydrogels through physical or chemical cross-linking [18]. To further enhance its solubility and make it more suitable for hydrogel formation, chemical modifications like esterification, etherification, and oxidation are often employed [19]. Non-derivatized cellulose hydrogels can also be obtained using cross-linking agents such as epichlorohydrin, aldehydes, and urea derivatives [1,20]. Additionally, hydrogels made from nanocellulose and bacterial cellulose have gained interest in recent research due to their enhanced properties [21,22].

In agriculture, cellulose-based hydrogels serve as effective water-retention agents, especially in arid and drought-prone regions. They can absorb and retain large amounts of water, releasing it gradually to plant roots, thus ensuring consistent moisture levels and promoting plant growth even under water-stressed conditions (Figure 2). Furthermore, cellulose-based gels contribute to soil stabilization by enhancing soil structure and preventing erosion. They form a gel-like matrix when mixed with soil, improving their water-holding capacity, nutrient retention, and overall fertility [23]. This leads to better crop yields and healthier plant growth and development.

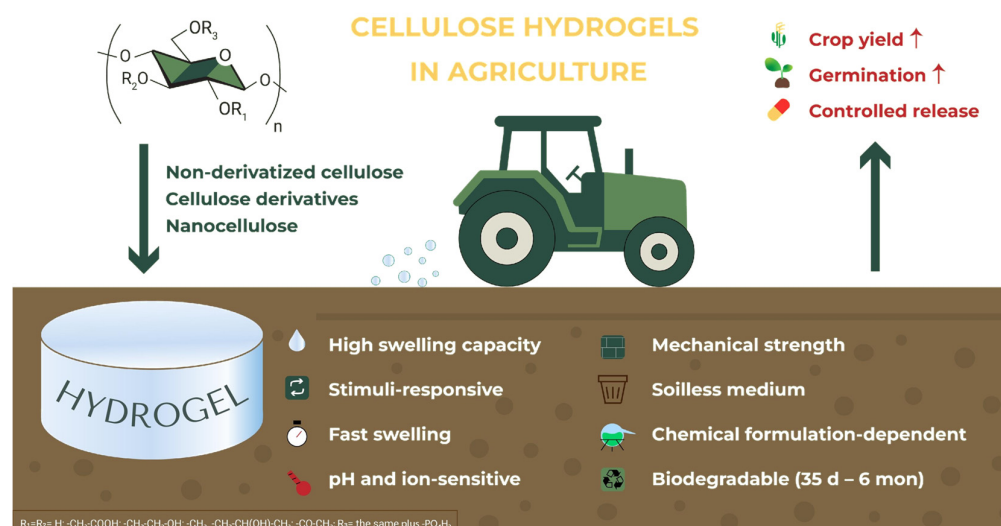


Figure 2. The role of polysaccharide-based hydrogels in sustainable agriculture.

To expand the functional capabilities and to improve the structural properties, cellulose and its derivatives are often copolymerized with other polymers [24] or subjected to various treatments, such as ultrasonification [25–27] or sonochemistry [28]. In agricultural applications, the combination of cellulose-based polymers with poly(acrylic acid) is commonly used [18,29,30].

In this review article, we aim to explore the multifaceted applications of cellulose-based gels in agriculture, particularly as carriers for essential agricultural inputs such as fertilizers, pesticides, and growth promoters. Our focus is to comprehensively analyze existing fundamental research and advancements in the real-life application of cellulose-based gels to encapsulate these substances. Through the literature review, we seek to shed light on the primary challenges encountered in current research, which play a crucial role in optimizing the effectiveness of agricultural cellulose hydrogels.

2. Fundamental Research on Cellulose Gels Used in Agriculture

Cellulose, the structural backbone of plant cell walls, has surpassed its natural role to become a key player of innovation in sustainable agriculture fields.

In its native form, cellulose's water-resistant crystalline structure transforms into a drought-fighting tool when cross-linked into hydrogels. These sponge-like networks trap water and agrochemicals, releasing them slowly to crops in arid soils—slashing irrigation needs and curbing fertilizer runoff.

Chemically modified derivatives expand their utility. Based on the present study and several recent research articles, the most commonly discussed cellulose derivatives are summarized in Table 1, highlighting their structural modifications and potential applications in agricultural systems.

Water-soluble carboxymethyl cellulose (CMC) and hydroxyethyl cellulose (HEC) cloak seeds in protective, nutrient-rich coatings or stabilize pesticides for even foliar application. Hydrophobic cellulose acetate, meanwhile, encases pesticides in slow-release capsules, balancing efficacy with environmental safety. Phosphorylated cellulose goes further, scavenging phosphate nutrients from the soil while neutralizing toxic heavy metals—a dual-action remedy for fertility and pollution.

At the nano-scale, nanocellulose marries strength and precision. With a surface area rivaling activated carbon and strength exceeding steel, it reinforces biodegradable mulches and delivers micronutrients like zinc directly to crops, targeting “hidden hunger” with unmatched accuracy. Bacterial cellulose, synthesized microbially, offers purity and

flexibility. Its gel-like matrix nurtures roots in hydroponic systems and shields plant wounds, accelerating healing while blocking pathogens.

Table 1. Cellulose derivatives discussed in the current study.

Derivative	Substituent Groups	Substitution Positions	Key Properties
Carboxymethyl Cellulose (CMC)	-CH ₂ -COOH (carboxymethyl)	C2, C3, and/or C6	Water-soluble, forms viscous solutions, used in food/pharma as thickener/stabilizer
Hydroxyethyl Cellulose (HEC)	-O-CH ₂ -CH ₂ -OH (hydroxyethyl)	C2, C3, and/or C6	High water solubility, biocompatible, used in drug delivery and biomedical fields
Hydroxypropyl Methylcellulose (HPMC)	-O-CH ₃ (methyl) and -O-CH ₂ -CH(OH)-CH ₃ (hydroxypropyl)	C2, C3, and/or C6	Thermogelling, hydrophilic, used in coatings, controlled-release pharmaceuticals
Cellulose Acetate	-O-CO-CH ₃ (acetyl)	C2, C3, and/or C6	Hydrophobic, thermoplastic (with plasticizers), used in films/fibers/pharma coatings
Phosphorylated Cellulose	-PO ₄ H ₂ (phosphate)	C6 (primary)	Flame-retardant, high charge density (6608 mmol/kg), used in adhesives/adsorbents

Together, these innovations epitomize sustainability: cross-linked cellulose conserves water, derivatives enable precision delivery, nanocellulose replaces plastics, and bacterial cellulose supports high-tech farming. Emerging advances, like pH-responsive nutrient release systems, hint at a future where cellulose autonomously adapts to crop needs.

2.1. Non-Derivatized Cellulose

Direct or non-derivatizing solvents, such as ionic liquids, *N,N*-dimethylacetamide with lithium chloride (DMAc/LiCl), *N*-methylmorpholine *N*-oxide (NMMO), and alkaline solvents—are capable of dissolving cellulose without prior derivatization and induce covalent modification of the cellulose structure. This leads to changes in the inter- and intramolecular hydrogen bonding system, resulting in a structural change from cellulose I to cellulose II, a process known as cellulose regeneration. Following the dissolution of cellulose molecules through physical intermolecular interactions, precipitation is achieved by inducing an anti-solvent effect using substances such as coagulants or water [31]. The resulting material can take on a gel-like form, which is subsequently converted into a hydrogel by rinsing with water [10]. Table 1 illustrates examples of the use of hydrogels derived from cellulosic agricultural waste and waste paper by dissolution in various solvent systems. The effect on plant growth and development has been investigated, as well as their efficacy in serving as slow-release or controlled-release fertilizers.

Ibrahim et al. prepared a hydrogel based on cellulose obtained from rice straw and acrylic acid (AA), using *N,N'*-methylene bisacrylamide (MBA) as a cross-linking agent and potassium persulfate as a polymerization initiator [9]. In a field experiment, the resulting rice straw hydrogels (HS) were compared with the commercially available acrylamide hydrogel (HA) as growth promoters for maize plants under different irrigation conditions. The study revealed that irrigation rate, hydrogel application, and their interaction signifi-

cantly affected the maize plant yield, outperforming commercially available HA (Table 2, N1). While using HA allowed a decrease in irrigation rate, HS exhibited slow water release. The use of HA increased the biological yield with irrigation every 2 days, whereas HS increased it with irrigation every 3 days. HA led to higher maize root length compared with HS. Grain yield increased more with HA, possibly due to its higher swelling ratio (247.6 g/g) compared with HS (215.0 g/g). Hydrogel application reduced differences between irrigation methods, and the decline caused by water stress became smoother. Irrigation water use efficiency was significantly affected by both hydrogels, with HA showing better results. HA application increased N, P, and K use efficiency in the soil by 25.5% compared with HS application, suggesting that HA directly improved nutrient uptake or indirectly enhanced maize root development compared with HS.

Cellulose fibers extracted from sago pith waste were dissolved in an aqueous-based solvent system of NaOH/urea to produce hydrogels with varying swelling abilities, influenced by cellulose concentration [14]. The hydrogel exhibited the highest swelling ability at a cellulose concentration of 5% (Table 2, N2). A further increase in cellulose content to 6% led to increased self-entanglement of chains through hydrogen bonds, limiting available space for swelling. Samples with lower cellulose percentages (3% and 4%) demonstrated lower swelling abilities (2.4 g/g and 2.0 g/g, respectively) due to fewer available pores. The 5% hydrogel, whether dried or swelled, is an excellent potting medium for maize seed germination, showing no significant difference in germination rate percentages compared with the control with regular watering.

In another study, a semi-interpenetrating polymer hydrogel, based on wheat straw, represented a cellulose-g-poly(acrylic acid) network combined with linear poly(vinyl alcohol) and containing nitrogen and phosphorus fertilizers, was prepared using the solution polymerization method [32]. The swelling and fertilizer release properties were influenced by the dry hydrogel's particle sizes, salt solutions, ionic strength, and pH variations. The hydrogel rapidly swelled within the first 60 min in water before reaching equilibrium. Similarly, the release patterns of nitrogen and phosphorus followed this trend. It is worth noting that smaller hydrogel particles retained more water due to their larger surface area (Table 2, N3). Additionally, smaller hydrogel particles released fertilizer more rapidly, resulting in a higher total release compared with larger particles. This can be attributed to their increased interstitial volume and interfacial area with water.

Additionally, the hydrogel exhibited pH responsiveness, reaching an equilibrium water absorbency until pH reached 7, after which a decline occurred [32]. Notably, release patterns for phosphorus and nitrogen fertilizers demonstrated opposite trends. With an increase in pH from 2 to 12, phosphorus release initially increased and then decreased, while nitrogen release exhibited the opposite pattern. The product exhibited optimal swelling in neutral conditions, with cations and anions influencing swelling in the order of $\text{Na}^+ > \text{K}^+ > \text{Ca}^{2+}$ and $\text{Cl}^- > \text{SO}_4^{2-}$. The diffusion coefficients for fertilizers suggested that the impact of cations on fertilizer release mirrored their effect on swelling. Moreover, under neutral conditions, nitrogen release was lower, and phosphorus release was faster compared with strong acidic or alkaline conditions. The diffusion coefficients for the product in various sizes indicated that using larger hydrogel sizes could improve the controlled-release effectiveness, primarily by reducing leaching loss [32].

A more complex system, based on cellulose extracted from a widely available agricultural waste, cotton straw, enhanced with bentonite—aluminum phyllosilicate clay—was produced in another study. A semi-interpenetrating polymer network consisting of cellulose-g-poly(acrylic acid)/bentonite network was employed to incorporate polyvinylpyrrolidone and urea, resulting in the production of a slow-release nitrogen fertilizer in the form of a hydrogel [26]. Factors such as microwave treatment (power and

irradiation time) and the composition of hydrogels (CS-groups content, bentonite, and polyvinylpyrrolidone proportion) had an impact on the water absorption of the hydrogels.

The evaluation included swelling in distilled water and saline solutions (Table 2, N4). The swelling rate constants decreased with the rise in concentration and the number of positive charges of the cation in the salt (Na^+ , Ca^{2+} , Al^{3+}), as it was in the previous example. The resulting hydrogel exhibited a low leaching loss of nitrogen (4.8%) in comparison to urea (43%). The hydrogel affected seed germination rate, plant height, root length, fresh weight, and dry weight of cotton (Table 2, N4). All these plant characteristics showed improvement with the hydrogel compared with plants treated conventionally with pure urea. It is worth noting that the cost of the hydrogel was calculated to be \$833.5 per ton.

The next example represents two types of hydrogels obtained from another type of waste—paper waste—without any synthetic polymer components. The effect of hydrogels on the response of tomatoes to water and NO_3^- ions in soil was investigated, considering two different levels of irrigation (95% and 75% available water content (AWC)) [33]. The researchers produced freeze-dried hydrogels (FDH) and oven-dried hydrogels (ODH) from waste paper using a direct dissolution method in a NaOH/aqueous/urea system without cross-linkers. The re-swelling ratio of FDH beads in water was 18.5% higher than that of ODH (Table 2, N5). After preparation, the hydrogels were loaded with a commercial NPK fertilizer. The results revealed that the FDH with 95% AWC treatment resulted in the highest average crop yield, surpassing the ODH and control treatments (Table 2, N5). This trend was also observed for total plant biomass. Only the FD with 95% AWC hydrogel significantly outperformed the control sample in terms of yield, with a measure of 2.00 compared with 1.59 kg/plant, respectively (Table 2, N5). The findings for plant height, stem diameter, and leaf area indicated minimal differences among the different combinations of hydrogel and AWC treatments. Notably, the FDH with 95% AWC treatment exhibited noticeably higher water use efficiency compared with the ODH and control treatments. The results indicated that under FDH and ODH treatments, excess nitrate was stored in the soil vacuoles and remobilized for uptake by the plant roots. The same solvent system (NaOH/urea) with citric acid as a cross-linker was applied by Zainal and colleagues to obtain hydrogels from office waste paper [34]. The swelling ratio of the hydrogels decreased from 18 to 6% when the initial heating temperature was raised from 30 to 50 °C and increased from 15 to 18% with a subsequent temperature increase from 60 to 70 °C. The authors propose the hydrogel as a non-toxic and biodegradable agricultural medium. Additionally, Jong et al. reported an elevated seed germination rate of 53% when utilizing cellulose hydrogel obtained from waste paper (Table 2, N6), following the same method, as a seed germination medium [35].

Another study performed on waste paper to prepare hydrogels by direct dissolution in a DMAc/LiCl system and regenerating it from solutions [3,36] demonstrated that the hydrogels' swelling ability ranged from 14.35 to 45.74 g/g depending on the raw material (cardboard or newsprint paper) and the conditions of the solubilization (Table 2, N7). The hydrogels were dense, semi-transparent materials with color ranging from gray to brown, featuring a well-developed pore system (Figure 3a,b).

Upon exposure to air and soil, the hydrogels gradually released water, with the process slowing down in the soil. During air drying (9–11 h), the hydrogels underwent hornification, losing their ability to swell again. However, when being lyophilized, the hydrogels demonstrated moderate re-swelling capacity (Table 2, N7). The adsorption capacity of the hydrogel manufactured from cardboard for a mineral fertilizer solution containing $\text{Ca}(\text{NO}_3)_2$, $\text{Mg}(\text{NO}_3)_2$, and KNO_3 with a total salt concentration of about 20% was 0.15 g/g. It was found that the hydrogel adsorbed 16.8% of the total available fertilizer (dry weight). Moreover, the desorption of fertilizer from the hydrogel into water was 52.7% of the initially adsorbed amount, demonstrating the hydrogel's effectiveness. The

impact of adding the hydrogel on the yield of mustard and water evaporation in closed-ground conditions was investigated. The experiment unequivocally demonstrated that the hydrogel not only failed to hinder seed germination or plant growth (Figure 3c–h), but also accelerated pea seed germination. In the soil, the hydrogel underwent rapid biodegradation, losing between 84–92% of its mass within 2 weeks (Table 2, N7).

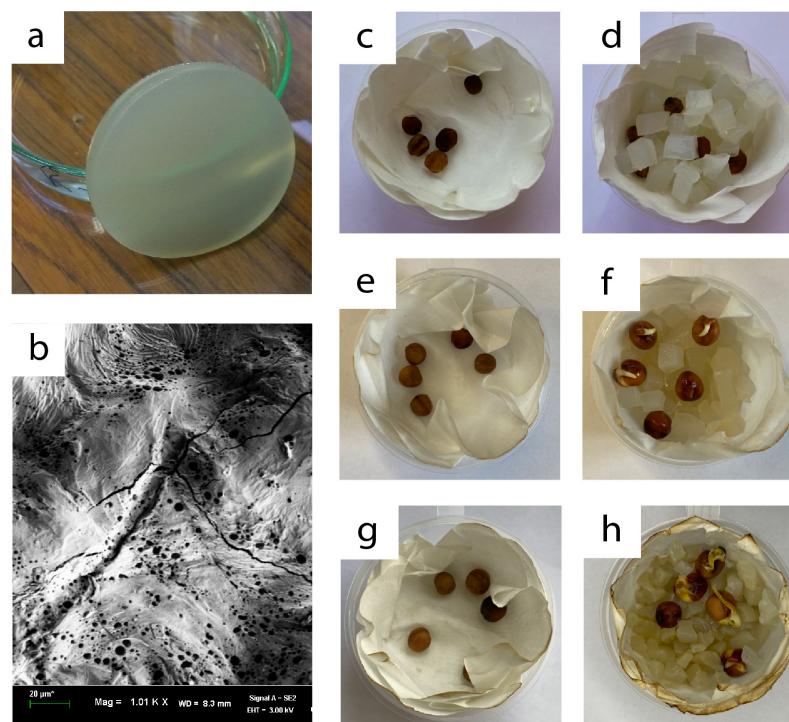


Figure 3. Digital image of the hydrogel obtained from waste paper (a), pore system visible in the SEM micrograph of the corresponding lyophilized hydrogel (b). Germination of pea seeds in the control plate with regular watering (c,e,g) and in the plate with hydrogel (d,f,h) after 1 day (c,d), 4 days (e,f), 12 days (g,h).

Table 2. Formulations and “agricultural” properties of the hydrogels based on non-derivatized cellulose extracted from waste.

Number	Precursors and Additives	Cross-linker	Purpose	Swelling Ability	Critical Agricultural Characteristics	Reference
1	Rice straw +AA (HS).	MBA	Water reservoir	215.0 g/g for HS, 247.6 g/g for HA	Ear yield: 3875, 3747, and 3160 kg/fed; biological yield: 6557, 6335, and 5339 kg/fed; root length: 23.8, 22.0, and 17.3 cm; Nitrogen uptake for soil: 106.0, 101.4, and 82.8 kg/fed. phosphorus uptake: 13.25, 12.98, and 9.04 kg/fed; potassium uptake: 92.11, 82.02, and 68.47 kg/fed, for HA, HS, and control soil without any hydrogel, respectively. All data are mean values related to the factors of irrigation frequency and rate.	[9]
2	Sago pith (in NaOH/aq./urea solvent system)	ECH	Water reservoir	19.7 g/g for 5% hydrogel, 8.1 g/g for 6% hydrogel	Both dry and swollen hydrogel applications facilitated maize seed germination without inhibitory effects	[14]

Table 2. Cont.

Number	Precursors and Additives	Cross-Linker	Purpose	Swelling Ability	Critical Agricultural Characteristics	Reference
3	Wheat straw +AA, PVA. NP fertilizer: urea, potassium dihydrogen phosphate	MBA	Slow-release and controlled-release fertilizer, smart material	183–243 g/g in water (depending on particle size), 32–124 g/g in NaCl solution (depending on concentration)	Phosphorus fertilizer release in water: 55–70% after 20 min, 70–75% after 60 min. Nitrogen fertilizer release in water: 50–62% after 20 min, 60–65% after 60 min.	[32]
4	Cotton stalks + AA. Additives: polyvinylpyrrolidone, bentonite. NK fertilizer: urea, potassium persulfate	MBA	Slow-release fertilizer	1018.4 g/g in distilled water and 71.3 g/g in 0.9 wt.% NaCl solution	60% of nutrients were released after 30 days. Cotton plant performance: germination rate 80.36 and 58.32%, plant height 22.48 and 19.95 cm, root length 6.15 and 4.75 cm, fresh weight 2.58 and 1.84 g, and dry weight 0.23 and 0.15 g for treatment with the hydrogel and with pure urea, respectively.	[30]
5	Waste paper cellulose (in NaOH/aq./urea solvent system): freeze-dried (FD) and oven-dried (OD) hydrogel beads. NPK fertilizer: commercial “Miracle Grow”	None	Slow-release fertilizer	Re-swelling ratio *: 415.62% for FD and 224.16% for OD hydrogel (roughly, it is 4.2 g/g and 2.2 g/g, respectively)	Crop yield: 0.88 kg/plant for FD + 95% AWC, 0.32 kg/plant for OD + 95% AWC, and 0.4–0.53 kg/plant for control. Total biomass: 2.00 kg/plant for FD + 95% AWC, 1.08 kg/plant for OD + 95% AWC, 1.59 kg/plant for control; 1.65 kg/plant for FD + 75% AWC, 1.03 kg/plant for OD + 75% AWC, 1.69 kg/plant for control. Water use efficiency: 3.91, 1.47, 1.51 kg/m-plant for FD + 95% AWC, OD + 95% AWC, and control, respectively	[33,37]
6	Waste paper cellulose (in NaOH/aq./urea solvent system). Additive: CMC	ECH	Water reservoir	3.55, 4.66, 3.20, and 2.10 g/g for the hydrogels with 2, 3, 4, and 6 wt% concentration, respectively	Soil moisture level: 12.3% for the loamy soil, 7.1% for the clayey soil, and ~9% for clay and river sand soils amended with 35% of the hydrogel. The germination rate of the paddy seeds after 30 days was 53%, 35%, 27%, and 18% on the hydrogel, loamy soil, river sand, and clayey soil, respectively	[35]
7	Waste paper cellulose (in DMAc/LiCl solvent system): cardboard (C) and newsprint paper (NP)	None	Water reservoir	29.13–45.74 g/g for C hydrogel and 14.35–37.17 g/g for NP. 4.65 g/g—re-swelling capacity of lyophilized C hydrogel	0.15 g/g—adsorption capacity of C for a mineral fertilizer solution. 52.68%—desorption of fertilizer from the hydrogel into water. Not phytotoxic. Biodegradation: 84–92% of total mass lost in soil within 2 weeks.	[3,36]
8	Cellulose+ glycerol (in aqueous zinc chloride/glycerol solvent system)	None	Water reservoir	160%	Germination percentage increased by 21.88%. The average number of leaves on wheat plants increased 100% after 21 days. The water uptake of the plants improved by 94.7%.	[38]

AA—acrylic acid, MBA—*N,N'*-methylene bisacrylamide, NK—nitrogen and potassium fertilizer, NPK—nitrogen, phosphorous, and potassium fertilizer, HA—commercially available acrylamide hydrogel, HS—rice straw hydrogel, AWC—available water content, ECH—epichlorohydrin, PVA—poly(vinyl alcohol). * Re-swelling ratio (RSR) was calculated as $RSR (\%) = \frac{W_s}{W_d} * 100$ [27,31], while common formula for swelling calculation is different: $Swelling (g/g) = \frac{W_s - W_d}{W_d}$ [17], where W_d is the dry weight of the regenerated hydrogel and W_s is the weight of the swelled hydrogel.

2.2. Cellulose Derivatives

Cellulose derivatives offer unique properties that go beyond the inherent characteristics of cellulose. These properties include enhanced water solubility, increased reactivity resulting from additional functional groups, and improved adsorption capabilities. Cellulose derivative hydrogels are produced through cellulose esterification or etherification, often coupled with chemical or dual-network cross-linking [16]. For example, the introduction of phosphorus groups adds sufficient surface anionic charges to cellulose, enabling the binding of cationic ions from macro- and micronutrients [39]. Carboxymethylation, on the other hand, enhances the water absorption capacity and enables solubility in water for carboxymethyl cellulose (CMC) [40]. Hydroxyethyl cellulose (HEC), another ether, can be combined with CMC to produce hydrogels that are well suited for agricultural applications. CMC forms intramolecular cross-links rather than intermolecular ones, resulting in improved water retention properties of the hydrogels [41].

Demitri and colleagues from the University of Salento (Italy) have successfully introduced polyelectrolyte hydrogels derived from CMC and HEC as potential water reservoirs in agriculture [42]. The concentration of cellulose was found to have a notable impact on the sorption properties of the hydrogels. The highest sorption capability, reaching 75 g/g, was observed for an optimal cellulose concentration of 4%. This phenomenon was attributed to the specific cross-linking process employed, which was expertly designed to achieve maximum efficiency. Excessive concentration (5%) resulted in an abundance of cross-linking points, while insufficient concentration (3%) led to loosely cross-linked networks with limited sorption capacity. The hydrogel took approximately 30 min to achieve complete swelling, a timeframe deemed acceptable for agricultural applications.

The study on cherry tomatoes clearly demonstrates that soil enhanced with hydrogel has superior water retention capacity compared with the control soil without hydrogel (Table 3, N1). Based on their findings, the authors suggest a sensor that relies on hydrogel to track soil moisture, which can be combined with special software capable of triggering an automatic irrigation system when the moisture level in the hydrogel and soil drops to a critical threshold.

Table 3. Formulations and “agricultural” properties of the hydrogels based on cellulose derivatives.

Number	Precursors and Additives	Cross-linker	Purpose	Swelling Ability	Critical Agricultural Characteristics	Reference
1	CMC + HEC	WSC, CA—catalyst	Water reservoir, smart material	75 g/g when pH = 7, 95 g/g when pH 10, sensitive to ionic strength variations	1% of the hydrogel triplicated the time length of the soil humidity; the plant survival time increased to 22 days; 6 months is the degradation time of the hydrogel in soil	[42]
2	HPMC, PVA, glycerol. Fertilizer: urea.	-	Slow-release fertilizer	17.2 g/g in distilled water, 14.4 g/g in tap water	Water retention ratio of soil: 54.6 (2nd day), 0.8 (5th day); control 51.9 and 0.04, respectively; Cumulative release of urea in water: 37%, 82.2%, and 85.4% at 1, 6, and 24 h; in soil: 27.1%, 64.5%, and 67.1% at 6, 30, and 44 days.	[43]
	HPMC, PVA, glycerol. Fertilizer: urea. Coating: HPMC + blended paper.	-		15.6 g/g in distilled water, 15.2 g/g in tap water	Water retention ratio of soil: 56.2 (2nd day), 1.0 (5th day); with control 51.9 and 0.04, respectively; Cumulative release of urea in water: 28.6%, 59.6%, and 64.4% at 1, 6, and 24 h; in soil: 30.8%, 82.3%, and 87.0% at 6, 30, and 44 days.	

Table 3. Cont.

Number	Precursors and Additives	Cross-Linker	Purpose	Swelling Ability	Critical Agricultural Characteristics	Reference
3	CMC. Micronutrient: Zn.	FeCl ₃	Controlled-release fertilizer	1.1–4.0 g/g	Water retention of soil: about 85% (10th day), 38% (20th day). Zinc release in soil: 13.5% on the 3rd day, 25.3% on the 5th day, and 65.3% on the 10th day. Improved the plant height, germination rate, fresh weight, and dry weight.	[44]
4	Sulfonated CMC + AA. Additives: polyvinylpyrrolidone, silica nanoparticles. NPK fertilizer: urea, ammonium phosphate, potassium dihydrogen phosphate	MBA	Slow-release and controlled-release fertilizer, smart material	~700–850 g/g in distilled water, ~120–120 g/g in saline solution (0.1 M NaCl), ~600–800 g/g when pH = 8, ~100 g/g when pH = 2	Water retention of soil: ~70% (10th day), 40% (25th day). NPK fertilizer release in water: 11.2% (1st day), 32.1% (7th day), 65.3% (30th day), release in soil: 29% (1st day), 56.4% (7th day), 83.6% (30th day)	[24]
5	CMC+ AA (HG). Additives: hydrochar (HC-HG). P fertilizer: phosphate solution	MBA	Controlled-release fertilizer	Swelling: ~70 g/g in water and P-solution at 30 °C, Water retention during 5 h of deswelling: 83 and 78% (water-loaded) and 81 and 80% (P-solution loaded) for HG and HC-HG, respectively	Germination vigor: 56.7% for HG, 78.3% for HC-HG with 80% for control; germination ratio: 60.0% for HG, 80.0% for HC-HG, and 83% for control; Length of stem: ~58 cm for both hydrogels, ~60 cm for control when treated with water, ~50, ~60, and ~58 cm for HG, HC-HG, and control, respectively, when treated with P-solution	[45]
6	CMC. Fertilizer: urea	Mixed CaCl ₂ , FeCl ₂ , FeCl ₃	Slow-release fertilizer	-	Urea release in water: coconut husk hydrogel: 0.13% (1st day), 0.60% (5th day), 4.05% (20th day), for palm sugar hydrogel: 2.69% (1st day) with the relatively high release in the following days	[16]
7	CMC. Additives: different types of clay. Herbicide: acetochlor	Fe(NO ₃) ₃	Controlled-release of herbicide	Swelling ratio: 1.30–2.26 g/g depending on the clay type	151–522 h—50% of acetochlor was released depending on the clay type, 2.18–14.0 h—50% of acetochlor was released depending on the cross-linking times	[46]
8	Cellulose acetate + Urea+ NaH ₂ PO ₄ . NP fertilizer: urea, NaH ₂ PO ₄	-	Water reservoir, smart material	17.3–48.1 g/g in water, 7.2–12.4 in saline solution	Germination occurs and at the 7th day the plant length was about 3 cm, in the control experiment the seeds did not germinate	[47]

CMC—Carboxymethyl cellulose, HEC—hydroxyethyl cellulose, CA—citric acid, WSC—1-ethyl-3-(3-dimethylaminopropyl) carbodiimide hydrochloride, HPMC—hydroxypropyl methylcellulose, PVA—poly (vinyl alcohol), AA—acrylic acid, MBA—*N,N'*-methylene bisacrylamide, NPK—nitrogen, phosphorous, and potassium fertilizer.

Kareem et al. investigated the hydrogels composed of hydroxypropyl methylcellulose, poly(vinyl alcohol), and glycerol with and without blended paper as a second covering layer [43]. The hydrogels exhibited a slightly higher swelling ability in distilled water when compared with tap water (Table 3, N2). This difference was attributed to the increased osmotic pressure contrast between the polymeric network and the immersion medium, which was influenced by the ions present in the swelling medium. The presence of Mg²⁺, Ca²⁺, and Na⁺ in tap water increased the ionic cross-linking density of the matrix blend, resulting in a reduction in water absorption. The swelling equilibrium, which is not favorable for the intended purpose of retaining water post-irrigation, occurred within 72 h

(48 h for one of the samples). The hydrogel added to the sandy soil resulted in an increase in its water retention, as demonstrated in Table 3, N2. In contrast, the soil without the hydrogel completely lost all of its water by the sixth day. Also, the coated hydrogels appeared to contribute to a slower release of urea in water compared with the uncoated hydrogels, as shown in Table 3, N2. This effect may be attributed to the paper creating a physical barrier in the form of a membrane in the matrix, resisting osmotic pressure and causing a slower release through diffusion due to concentration and/or pressure gradients. The hydrogel with paper coating exhibited a higher cumulative percentage release, facilitated by water absorption that dissolved the urea in the matrix. Consequently, it resulted in a maximum release of 87% of encapsulated urea after 44 days, compared with 67.1% for uncoated hydrogel during the same period.

Sodium carboxymethyl cellulose hydrogels loaded with micronutrient Zn have been shown to have a moderate water absorbency of 110–400% (i.e., 1.1–4.0 g/g) (Table 3, N3). However, this absorption decreases as the amounts of polymer and cross-linker increase [38]. The use of these hydrogels significantly improved the soil's water retention capacity, with the best result being twice as high as that of the control soil without hydrogel (25 days vs. 12 days until drying, respectively). The study reveals that the cumulative release values at equilibrium were slightly lower in soil than in water. The release of zinc in water persisted for 30 h, with a decline as the polymer and cross-linker content increased, resulting in a higher network density. The hydrogels loaded with zinc demonstrated significant positive effects on wheatgrass germination and growth (including length, fresh, and dry weight) compared with the control group without any treatment.

Olad and colleagues presented a superabsorbent nanocomposite hydrogel prepared through in situ graft polymerization of sulfonated carboxymethyl cellulose with acrylic acid (AA) in the presence of polyvinylpyrrolidone and silica nanoparticles. The hydrogel was enriched with nitrogen, phosphorus, and potassium (NPK) as fertilizers [24]. The samples, when placed in distilled water, exhibited swelling, and when exposed to a saline NaCl solution, underwent deswelling (Table 3, N4) with consistent absorption–desorption patterns. Additionally, the hydrogel demonstrated pH-dependent swelling reversibility: the samples swelled owing to anion–anion electrostatic repulsion in an alkaline medium, while in an acidic medium, they promptly shrank due to the protonation of carboxylate groups (Table 3, N4). These characteristics classified the hydrogels as smart materials due to their sensitivity to both salt concentration and pH levels. When incorporated into loamy sand soil, the water retention of the soil increases by over twofold compared with unaltered soil (Table 3, N4).

The presence of polyvinylpyrrolidone and silica nanoparticles in the hydrogel formulation enhanced the water retention characteristics of the hydrogel network. The hydrogel demonstrated controlled release of the fertilizer, with less than 15% being released on the first day and a maximum of 75% being released after a month. The absorbed water caused the fertilizer to dissolve, which was then gradually released through the polymeric shell due to the dynamic exchange of water within the hydrogel and the release medium. The release rate of the fertilizer was primarily influenced by the contrast in soluble material concentration between the interior and exterior of the hydrogel. As this difference decreased over time, the release rate slowed down [25].

The composite hydrogel, which incorporated municipal sludge-derived hydrochar into carboxymethyl cellulose-g-poly(acrylic acid), maintained a comparable swelling ratio to the initial hydrogel at 30 °C (Table 3, N5). However, the values decreased as the temperature of swelling increased [39]. The water loss rate in phosphate solution or water showed a more pronounced temperature response (7.9–15.0 folds) for the loaded hydrogel than for the initial one (8.2–10.0 folds). The phytotoxicity assessment results demonstrated that the

hydrochar in the composite hydrogel effectively mitigated the inhibitory effects of the AA component on rape germination (Table 3, N5). Furthermore, plant growth was significantly enhanced over a period of 28 days.

Carboxymethyl cellulose produced from agricultural wastes—coconut coir and palm sugar gomuti—was used for the fabrication of CMC–urea hydrogels cross-linked with a mixture of FeCl_2 , FeCl_3 , and CaCl_2 [16]. The study demonstrated that the type of initial raw material affected the production of carboxymethyl cellulose, and subsequently, the properties of its hydrogel, among which was the release rate of urea. The variation in question might be attributed to the degree of substitution during the carboxymethylation of the raw material, as performed in laboratory conditions. The authors hypothesized that the palm sugar hydrogel, which is characterized by a lower density than the coconut coir hydrogel, resulted in reduced contraction in urea particles within its hydrogel structure.

The study of CMC gels with various types of clay (activated by acid, pillared with metal hydroxides, and saturated with organic cations) was applied as controlled-release formulations of the herbicide acetochlor [40]. The release rate of acetochlor was assessed based on various formulation parameters, such as the amount and type of clay, cross-linking time, and drying of the hydrogel formulations.

The study found that the time required for 50% of acetochlor release varied widely, ranging from 151 to 522 h (Table 3, N7) for dried gel formulations, with the highest value observed in the formulation containing aluminum hydroxide pillared clay within CMC gels. The release rate of acetochlor from the gel formulations decreased as the hydrogels' cross-linking time increased. Controlled-release formulations of acetochlor increase safety for users and non-target organisms while significantly reducing herbicide application rates and soil leaching.

Phosphorylated porous cellulose beads capable of forming water-swellaable hydrogels were synthesized through a one-step thermal reaction involving urea and sodium dihydrogen phosphate dihydrate in a cellulose acetate dimethyl sulfoxide solution [47]. The beads, dried under vacuum, exhibited a maximum swelling ratio of around 50 g/g (Table 3, N8), which was carefully controlled by adjusting the reaction time and reagent composition. The swelling process demonstrated a rapid initial stage, reaching equilibrium at approximately 30–40 min—an advantageous feature for agricultural applications. Radish seed germination and plant growth were observed on the hydrogel beads within one week. Phosphate and carbamate in the formulation of the hydrogel might have affected germination through the osmo-priming effect. Overall, these results demonstrate the effectiveness of the hydrogel beads in promoting plant growth.

Significantly higher results in the swelling ability of the carbohydrate-based hydrogels were achieved by Qi and co-authors by utilizing commercial CMC in combination with beta-cyclodextrin to obtain an epichlorohydrin-cross-linked hydrogel [48]. The resulting material exhibited an extraordinary water absorption capacity of 8725 g/g in deionized water. The hydrogel's absorbency behavior was highly responsive to pH, ionic strength, and ionic species. The hydrogel demonstrated an impressive adsorption capacity of 3342.84 g/g in a urea solution. At 80 °C, urea retention in soil lasted for approximately 5 h. Furthermore, the material exhibited a degradation rate of about 98.2% in the presence of *Aspergillus niger* on the third day, reaching 77.2% and 61.7%, respectively, in soil and sewage by the 14th day.

2.3. Nanocellulose Hydrogels

Nanocellulose is confidently categorized into three main types: nanofibrillated cellulose (with particles 10–40 nm in width and several microns in length), nanocrystalline cellulose (particles 5–10 nm in width and a few hundred nanometers in length), and bacterial cellulose (fiber diameter of 10–100 nm). It has been proven to be an ideal material for

producing hydrogels for various applications [49,50]. Bacterial cellulose can be manufactured using numerous agro-industrial wastes. Bacterial cellulose is highly recommended for applications where chemical purity is crucial, such as in the biomedical and food industries. Additionally, it is utilized in the manufacture of membrane filters for environmental purification [45]. Although less commonly offered in agriculture, hydrogels made from bacterial cellulose are still a viable option due to their exceptional properties.

Nanocellulose is an excellent choice for hydrogel formulation due to its high surface area, aspect ratio, crystallinity, and strength, which make it an extremely effective reinforcing filler. Additionally, nanocomposite cellulose hydrogels have the potential to act as a superior reservoir for enhancing irrigation efficiency and promoting plant growth [51]. Integrating nanocellulose biopolymer into slow/controlled-release fertilizers and super-absorbent hydrogels improves biodegradability while maintaining intended functionality. The significant surface-to-volume ratio of nanocellulose enables strong interaction with fertilizer compounds. Effective chemical surface modifications, such as grafting, coupling, acetylation, and cationic modulation, enhance compatibility with the matrix [52].

TEMPO-oxidized cellulose nanofibers were dissolved in NaOH/urea aqueous solution and cross-linked with epichlorohydrin to prepare cellulose anionic hydrogels [53]. The hydrogels obtained possessed varying carboxylate contents: 0 (CH), 0.7 mmol/g (CH₇), and 1.5 mmol/g (CH₁₅). As shown in Table 4, N1, the equilibrium swelling ratios of the hydrogels in distilled water at 37 °C increased with the rise in the number of carboxyl groups. The hydrogels with appropriate carboxylate contents were found to enhance the germination rate of sesame seeds when planted directly on the hydrogel surface, as seen in Figure 3. CH₇ exhibited the highest germination rate, achieving 100% within four days of sowing. In contrast, seeds on CH did not fully germinate until the sixth day, while seeds on CH₁₅ showed an increase in germination to 75% by the third day, with no further increase. As a control experiment, seeds were planted in soil, where 100% germination was achieved by the fifth day. This exceptional germination efficiency of CH₇ can be attributed to its uniform macroporous structure and the optimal carboxylate contents, which facilitate significant water retention. The seedlings germinated and grew on CH₇, displaying a longer root and heavier fresh weight compared with those on CH and CH₁₅, but presented similar lengths of root and fresh weight compared with soil seedlings (Table 4, N1). The findings indicated that cellulose hydrogels, containing appropriate carboxylate levels, proved beneficial as plant growth regulators. Moreover, they demonstrate effective antifungal properties during the breeding and growth of sesame seeds. Therefore, hydrogels can be used as soilless culture media for plant growth.

Incorporating metal-organic frameworks [MIL-100(Fe): FeCl₃·6H₂O, H₃BTC (trimesic acid), and *N,N*-dimethylformamide] into the cellulose-based hydrogel, a pH-sensitive nanocellulose/sodium alginate hydrogel (CAM) was developed [54]. Carboxylated nanocellulose was obtained from the *Eucalyptus* pulp waste using the TEMPO catalytic oxidation method. The hydrogel exhibited notable water adsorption capacity corresponding to changes in pH, with the minimum at pH 3 (17 g/g) reaching the highest value (100 g/g) at pH 11. Additionally, a pH-sensitive urea slow-release fertilizer (U-CAM) was formulated to enhance its performance in alkaline environments and exhibit a slower release rate at lower pH values (Table 4, N2). The soil moisture loss was delayed by 18 days when using U-CAM compared with unmodified soil, which took only 15 days. As the quantity of MOFs in the hydrogel increased, the hydrogel demonstrated enhanced efficiency in the gradual release of urea. Among the other groups, U-CAM, containing 10% of MOF, exhibited the most effective performance, releasing only 50% of urea by the 30th day. The positive impact of U-CAM on wheat growth was evident in the germination rate, number of leaves (Table 4,

N2), photosynthetic rate, and chlorophyll content of the crop, supporting its potential application in farming.

Table 4. Formulations and “agricultural” properties of the hydrogels with nanocellulose in the formulations.

Number	Precursors and Additives	Cross-Linker	Purpose	Swelling Ability	Critical Agricultural Characteristics	Reference
1	Cellulose nanofibers (in NaOH/urea aqueous solution), the hydrogels had different carboxylate contents: 0 (CH), 0.7 (CH ₇), and 1.5 mmol/g (CH ₁₅)	ECH	Water reservoir, cultivation media	Swelling ratio: 80%, 174%, 309%, for CH, CH ₇ , and CH ₁₅ , respectively.	Germination rate on the hydrogel substrate: 100% seeds within 4 days for CH ₇ , 6 days for CH, and 75% for CH ₁₅ within 3–7 days; control—100% seeds within 5 days for soil without hydrogels. Root length 5.5, 8, and 1.5 cm, shoot length 3, 2, and 2.5 cm on CH, CH ₇ , and CH ₁₅ hydrogels, respectively. Control (in soil)—7 cm for root and 3 cm for shoot. Weight of seeding at fresh (30, 35, and 12 mg for CH, CH ₇ , and soil CH ₁₅ , respectively) and dry states (about 5 mg for CH, CH ₇ , and soil and 2 mg for CH ₁₅).	[53]
3	Cellulose nanofibrils+ sodium alginate + MOF. Fertilizer: urea.	-	Slow-release and controlled-release fertilizer, smart material	Swelling: 25–55 g/g depending on the amounts of MOF; Moisture content: 95.94–96.28%,	Urea release in water: 80–90% at pH 3, 68–85% at pH 11 after 25 h; Soil water-retention capacity: soil dried in 15–30 days when enhanced with the hydrogels (12 days for unmodified soil); Germination rate: 92.5% and 65.0% for the hydrogel-treated and urea-treated wheat seeds. Number of leaves per plant on the 60th day: 188 and 82 for the hydrogel-treated and urea-treated plants. Not phytotoxic. Improved germination and growth of cucumber.	[54]
4	CMC. Additive: nanocellulose. NPK fertilizer: commercial	Citric acid	Slow-release and controlled-release fertilizer	~18.3 g/g—CMC; 25, 29, 19, and 19 g/g for 1, 3, 5, and 10 wt% of NC	72 h—release of NPK in water from CMC hydrogel; up to 300 h continued the gradual release in water for CMC-NC. Nine days was the duration of release in soil; for CMC-NC, it was slower and more gradual than for CMC.	[55]

ECH—epichlorohydrin; MOF—metal-organic frameworks; CMC—carboxymethyl cellulose; NPK—nitrogen, phosphorous, and potassium fertilizer; NC—nanocellulose.

Another example involved the use of 4% CMC hydrogels reinforced with nanocellulose (NC) produced from *Eucalyptus* residues obtained after harvesting and cutting and prepared by ball milling [55]. The swelling behavior exhibited a consistent pattern across CMC and CMC-NC: an initial increase in water absorption, reaching approximately 15 g/g within the first few hours, followed by equilibrium at 18–29 g/g after 150 h. Incorporating low concentrations of nanocellulose (1–3 wt%) into composite hydrogels significantly enhanced swelling (Table 4, N3).

The same effect was reported in a previous study [56], where the swelling capacity of CMC-g-poli(acrylic acid-co-acrylamide) in water increased from 245.8 to 458.7 g/g with the addition of carboxylated cellulose nanofibrils up to 2.5 wt%.

This might be attributed to the greater number of available free hydroxyl groups, facilitating interaction and water retention within the hydrogel structure. Higher contents of nanocellulose led to a reduction in swelling capacity, likely due to the involvement of nanocellulose in the cross-linking of the CMC chains, resulting in fewer available hydrophilic groups and increased cross-linking density [55].

Carboxylated anionic nanocomposite hydrogels presented better responsive behavior in relation to pH presence and have increased water retention capacity at different temperatures [56]. The CMC hydrogel, enriched with a commercial NPK fertilizer (with equivalent amounts of nitrogen (N), phosphorus (P_2O_5), and potassium (K_2O) as 10-10-10), maintains release stability in water after 72 h (Table 4, N3) [49]. The study confirms a rapid release of NPK molecules from the hydrogel structure, facilitated by the absence of physical impediments. The nanocellulose filler in CMC-NC contributed to a slower and controlled release of NPK in both water and soil, possibly due to the high negative surface area of nanocellulose, allowing interaction with cations. During the pot experiment, the presence of hydrogels did not hinder cucumber seed germination, indicating no phytotoxicity. The addition of CMC-NPK hydrogel slightly accelerated seed germination and plant length compared with the control experiment, while CMC-NC with added fertilizer significantly promoted the development of cucumber plants [55].

3. Commercial Hydrogels in Agriculture and Perspectives for Scaling Up Cellulose-Based Hydrogel Production Technologies

Commercially available water-absorbing hydrogels have been proven effective in conserving water for soil use. One of the drawbacks of those products is that their high water retention capacity carries a risk of overuse, making it crucial to determine appropriate amounts and application rates for different conditions and plant species [57]. Another drawback is that the majority of commercial products, being acrylate-based, are not biodegradable or degrade very slowly [57–59].

Currently, it is easy to purchase industrially produced superabsorbent hydrogels for agricultural purposes. For example, potassium polyacrylate (SOCO, Zhangjiagang, China) is widely marketed as a means to transport seedlings, improve their survival during replanting, and reduce the need for watering when used at a dosage of 15 to 30 kg per 0.5 ha of land. The water retention capacity of this polymer (according to the manufacturer) is ≥ 350 g/g, performance in the soil is guaranteed for up to 5 years, and the cost is approximately 300 euros for 25 kg (as of 25 January 2024). The manufacturer asserts that the product is environmentally friendly, claiming it will decompose into carbon dioxide and water “over time”, but without providing any supporting evidence.

Scientific groups have been researching the biodegradation of polyacrylates in field experiments, but these studies are affected by drastic differences in climate characteristics for various regions of the world, types of soil, contamination levels, etc. Additionally, the duration of the research is usually limited.

The consequences of the widespread use of synthetic hydrogels and the accumulation of microplastics in the soil are yet to be determined. As an outcome of these limitations, the results of such a study may differ significantly from real-life conditions, similar to the distinction between laboratory methods and actual production processes. Consider one of the research groups that studied the decomposition of polyacrylate films covering granules of slow-release fertilizer in soil [60]. They synthesized several polyacrylate films in the laboratory and performed burial tests in the soil for one year without comparing the results with industrial hydrogels.

The composition of commercially sold hydrogels is a trade secret, making it challenging to check the similarities between laboratory-made polyacrylates and industrial hydrogels. Furthermore, the placement of hydrogel films (with a thickness and diameter of about 2.0 and 10 mm, respectively) at a burial depth of 10 cm from the soil surface, separated by 10 cm horizontally, does not closely resemble the conditions faced by farmers, where the hydrogel layer can be much thicker and unevenly distributed, forming agglomerates. The authors concluded that the polymer network structure of polyacrylate became

loose over a burial time of 1 year. The polymer network could incorporate and blend with a number of inorganic groups, such as nutrient and metallic elements, in the soil. Eventually, the authors speculate that polyacrylate may become a component of the soil [54]. In light of the above considerations regarding differences in real-life conditions, this conclusion does not sound too optimistic.

In another study on the behavior of commercial potassium and sodium polyacrylate hydrogels, the authors conducted a thorough analysis of the hydrogel characteristics, evaluating their properties [61]. However, this study did not include the results of polyacrylate degradation in the soil. The results indicated a deterioration of the polymer's properties (absorption, moisture retention, service life, as well as physicochemical changes) over time in different types of water and saline solutions, potentially indicating degradation of the polymer net.

In concluding their research, the authors noted that the observed changes in hydrogel properties could be unfavorable from the standpoint of environmental cross-contamination. Therefore, they advocate for the development of hydrogels from renewable and truly biodegradable sources, such as biomass, to ensure objectivity and balance in evaluating their environmental impact.

The market transition to cellulose-based hydrogels has not yet occurred. However, these hydrogels not only match but even surpass commercial synthetic hydrogels in terms of consumer properties.

In their study, Womack et al. [62] compared two commercially available hydrogels (Idrostop, Criado, Recco, Italy) made of 90% polyacrylamide (CI) with a laboratory-made hydrogel based on carboxymethyl cellulose, supplemented with montmorillonite (50% *w/w*) and humic acid (30% *w/w*) (cellulose-based hydrogel), as reported in [63]. The impact of both hydrogels on the pore structure and swelling behavior of sand, sandy loam, and clay soils was confidently assessed. The soil treated with hydrogels exhibited a significant increase in porosity, specifically those exceeding 12% for the pores > 828 μm (macroporosity), in comparison to the control. Both hydrogels induced a volume change in the soil, ranging from -37% (shrinkage) to $+6\%$ (swelling). It is worth noting that CI induced shrinkage in all examined soils, while the cellulose-based hydrogel did not exhibit this effect, possibly due to the soil-strengthening properties of cellulose, clay minerals, and humic acids integrated into its structure.

Unlike synthetic hydrogels, cellulose-based materials provide an environmentally friendly alternative and exhibit superiority in certain properties. However, the higher production costs compared with oil-based products that are manufactured on an industrial scale have limited their market presence. It is desired to see renewable and biodegradable cellulose hydrogels in the market in the near future, on par with synthetic ones. To examine the development in this direction, this section provides a brief review of several startups that offer cellulose-based hydrogels for agriculture.

Sannino and colleagues successfully developed and patented biodegradable microporous cellulose-based superabsorbent hydrogels capable of absorbing one liter of water per gram of dry material. They also scaled up the technology, establishing a pilot-scale production plant in 2000–2010 in Italy [63,64]. The hydrogels were shaped and charged with nutrients for controlled release. Their findings demonstrate that the addition of small quantities of the hydrogel increases soil moisture retention by over four times compared with untreated soil.

AEH (UK) has developed Gelponics, a hydrogel substrate made from cellulose, for use in vertical farms, greenhouses, horticulture, and traditional farming [65]. The hydrogel is lightweight, easily disposable and disinfected, and has high biodegradability (95%), with the remaining 5% being compostable. Gelponics is available in the form of sheets, plugs,

powder, and granules, which offer different physical forms and properties suitable for various applications in hydroponic systems. The latter is used to increase the soil moisture content, as well as the carbon and nitrogen content of the soil; additionally, slow-released biostimulants can be loaded in the hydrogel. Figure 4 presents seeds initially planted on the surface of the hydrogel substrate, highlighting the interaction between the hydrogel and the seeds. Despite the seeds starting on the surface, the roots were gradually incorporated into the body of the hydrogel due to its gel-like structure, demonstrating how the physical form of the hydrogel influences seed development over time. Gelponics eventually results in a yield increase of 20–30% and water savings of almost 20%, as the founder of AEH claims. The start-up was initiated in 2019 with the support of Manchester University and several industrial partners. Currently, trials on lettuce, basil, pea shoots, and microgreens are being conducted. The partners helped with refining the product and preparing it for market launch, and now the manufacturing facility is being established in Birmingham with the support of industrial partners of AEH [66].

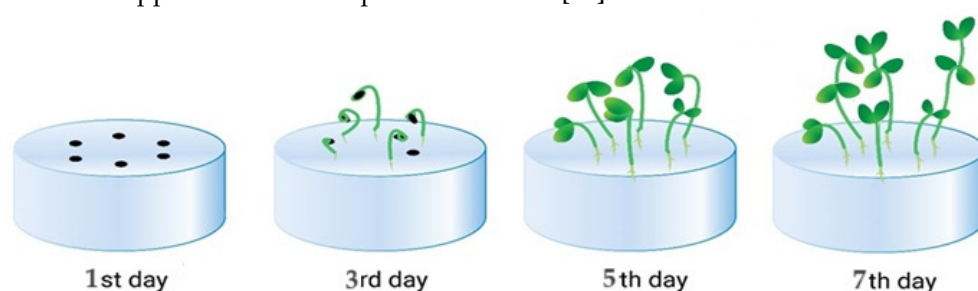


Figure 4. Seeds planted on the surface of the hydrogel substrate after 1, 3, 5, and 7 days (adapted from Mikhailidi et al., 2024 [18]).

Bios Hydrogel, an agro-technological startup in Italy, introduces a cellulose-based hydrogel made from up to 80% waste materials, including clay and humus [67,68]. This hydrogel is capable of absorbing water up to 200 times its weight and can serve as a growing medium or a soil additive, exhibiting slow-release fertilizer properties, promoting faster germination, and enhancing plant rooting effects. As indicated, the improvement in average germination time and plant growth correlates with the number of hydrogel capsules inserted into the substrate at the time of sowing, influencing soil microbial colonization. Bios Hydrogel is completely biodegraded in the soil within 35 days, making it suitable for short cultivation intervals. The founders estimate the product's cost at 8 euros per kg, compared with the commercial synthetic polymer-based hydrogel costing 5–10 euros/kg. Currently, on 15 January 2025, according to the product's launching page, the project is in the pilot plant stage and is seeking industrial partners for further development. Unfortunately, the project's website has not been updated for some time, so it is not entirely clear if it has reached the implementation stage. For the moment, Bios Hydrogel is unavailable for purchase.

Thus, it is evident that commercial hydrogels based on polyacrylates are widely accessible on the market, while high-tech startups focusing on the commercialization of their scientific findings in the field of cellulose hydrogels for agriculture are relatively few. These innovative products have received awards in various competitions and enjoy support from academia, foundations, and some enterprises, demonstrating their potential for continued evolution and success. Scaling up laboratory technology for larger production is a difficult yet achievable task. It is crucial to find an interested industrial partner to achieve this goal, despite the challenges that come with it [69].

4. Conclusions

Cellulose-based hydrogels, including derivatives, nanocellulose, and regenerated cellulose, sourced from paper and agricultural wastes, are highly promising for agricultural applications [70]. The key property of hydrogels is to swell in water and saline solutions and retain it for some time, gradually releasing it into the soil. It is worth noting that cellulose hydrogels have an impressive swelling capacity of several dozen grams of water per 1 g of dry polymer. Some of the reviewed materials exhibited the ability to repeatedly swell and shrink under different stimuli, functioning as smart water reservoirs. The factors influencing the swelling ability of cellulose-based hydrogels include the following:

- **Concentration of cellulose:** initially increasing concentration has a positive impact, but beyond a threshold value (3–4%), it negatively affects it due to an increased cross-linking degree.
- **Formulation of the hydrogel:** grafting acrylic acid or additives like silica nanoparticles significantly improves swelling ability, commonly to about 1.000 g/g but, in some reported cases, up to 8.000 g/g, while other additives, such as clays or hydrocarbons, may reduce swelling ability.
- **Concentration of chemical cross-linkers:** initially improves swelling capacity, but reaching a specific limit becomes a negative factor due to the excessive density of the cross-linked hydrogel. Nanocellulose additives follow this trend as they also act as cross-linkers of the gel.
- **pH of the solution, ionic strength, and ionic species:** These factors enable the control of the hydrogel swelling state by varying the medium.

Assessing the swelling kinetics is crucial for the successful application of hydrogels as water reservoirs, with an optimal rate observed in the range of 30–40 min.

Cellulose-based hydrogels have been shown to demonstrate significant enhancements (up to threefold) in soil water retention capacity [71]. Additionally, their improved mechanical properties can play the role of a soilless potting medium. These hydrogels not only enhance critical soil properties for crop cultivation but also hold the potential for integration into smart plant care systems, including automatic irrigation.

Both NPK fertilizers and herbicides were proved to be successfully loaded into cellulose hydrogels. The release rate is lower in soil compared with water and decreases with higher gel content and cross-linking density in both mediums. Various coatings may serve as physical barriers, causing a delay in release through diffusion driven by concentration and/or pressure gradients. Moreover, the addition of clay in the hydrogel formulation allowed slowing down the release of the herbicide by up to 50 times.

In general, plants do not experience a phytotoxic effect after hydrogels obtained from agri- and paper waste are applied. Furthermore, cellulose-based gels have been reported to improve the germination rate, root and shoot length, number of leaves, total biomass, crop yield, and some other parameters. Therefore, the application of these hydrogels as water reservoirs, soil amendments, and also as an independent soilless substrate is a highly effective method for enhancing plant growth and yield. Hydrogels containing acrylic acid have been observed to inhibit seed germination, but this effect can be mitigated by adding hydrochar to the hydrogel composition, which reduces toxicity.

Biodegradation was assessed for various formulations of cellulose-based hydrogels ranging from 35 days to 6 months in soil. This indicates that these materials are better suited for plants with relatively short life cycles, such as greens and vegetables.

Thus, at the level of laboratory research and pot experiments, cellulose hydrogels from waste are unequivocally recommended for production, as they indeed accelerate plant growth and even increase crop yields. Unfortunately, production lines and even high-tech startups in the cellulose hydrogel sector for agriculture are currently limited, although they

show great promise and receive recognition in competitions supported by foundations. Despite the challenges in scaling up, these startups actively seek industrial partnerships to advance their innovative technologies.

The findings are further supported by the extensive applications of cellulose hydrogels reviewed by Kundu et al. [72], which demonstrate their versatility in domains such as agriculture, biomedical sciences, and environmental sustainability. Moreover, other research emphasizes the environmental sustainability of cellulose hydrogels and their potential to substitute for hazardous petroleum-based hydrogels, a perspective that aligns with our emphasis on agricultural applications of cellulose-based hydrogels [73]. Collectively, these insights provide a framework for the development of innovative solutions that utilize cellulose hydrogels to contribute to a sustainable future.

The economic viability of cellulose-based hydrogels is largely determined by the cost of raw materials—cellulose and chemical reagents—and the processing steps involved in their production. The overall price is also influenced by the scale of production and the intended application. In specialized fields such as nanomaterials, where only small quantities are required, higher production costs are justified due to the precision and complexity of the synthesis process [74]. However, for large-scale agricultural applications—where cellulose hydrogels may be applied at rates of hundreds of kilograms per hectare—the cost per unit significantly decreases due to economies of scale [69]. Bulk production methods, streamlined processing, and the use of agricultural or industrial waste as feedstock further drive down costs, making these materials a feasible and cost-effective alternative to traditional soil amendments and water-retention agents.

The future of hydrogels used in ecological agriculture is supported by the increasing emphasis on sustainable practices and renewable resources. With a focus on non-toxicity, biocompatibility, and biodegradability, along with cost-effectiveness [75], these biogels reduce reliance on fossil fuels and mitigate greenhouse gas emissions, potentially contributing to soil remediation [76]. By integrating sustainable development goals across technological, material, energy, and economic domains, we anticipate a surge in innovative products and applications.

As modern techniques continue to evolve, simultaneously with the rise of cellulose-based hydrogels [64], we foresee the emergence of novel agricultural solutions, leveraging the exceptional properties of hydrogels and promoting sustainable management practices for the benefit of communities, industries, and the environment [77].

Together, these cellulose-based materials form a toolkit for Millennium III agriculture. Cross-linked hydrogels combat water scarcity, derivatives enable precision agrochemical delivery, while nanocellulose drives nano-scale efficiency, and bacterial cellulose supports cutting-edge horticulture. They collectively reduce reliance on synthetic inputs, mitigate pollution, and enhance resilience against climate volatility.

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