SSRG International Journal of Agriculture & Environmental Science
ISSN: 2394-2568/ https://doi.org/10.14445/23942568/IJAES-V13I3P102

Volume 13 Issue 3, 8-13, May-Jun 2026

Original Article

Development and Evaluation of HEC-Agar-Citric Acid-Based Hydrogel for Soil Moisture Retention

Abhitha Madhav Kumar

Delhi Public School, Bangalore North, Karnataka, India.

Corresponding Author : abhithakumar13@gmail.com

Received: 11 April 2026 Revised: 13 May 2026 Accepted: 29 May 2026 Published: 13 June 2026

Abstract *- Agriculture is facing a serious challenge due to water scarcity, especially in arid areas with low water retention capacity. The present study involves the preparation of the biodegradable hydrogels using Hydroxyethyl Cellulose (HEC), Agar, and Citric Acid for enhancing the water holding capacity of soil. The hydrogel was formulated with different concentrations of the polymer (120 formulations) and was tested for swelling and desiccation. The most effective formulations were tested on soil in the field for 14 days. The results showed that the water-retaining ability of the soil was enhanced by the use of the hydrogel and that some formulations showed water retention and water desiccation for a longer period of time. The best were Sample 96 and Sample 99. This study highlights the potential of biopolymer-based hydrogels as a sustainable substitute for chemical soil conditioners and the significance of formulation and long-term performance as a guide for their use in agriculture.*

Keywords *- Biodegradable Hydrogels, Hydroxyethyl Cellulose, Agar, Citric Acid, Water Retention, Soil Conditioners.*

1. Introduction

The problem of water scarcity has become one of the most important global issues of the twenty-first century, and agriculture is the primary consumer of freshwater on the planet, accounting for over 70 percent of the total freshwater. The effects are particularly dire in arid and semi-arid areas, where low rainfall and low soil quality already limit the productivity of crops. In such circumstances, it is necessary to have proper management of soil moisture in order to not only maintain agricultural production but also save water and reduce risks associated with drought. The increasing intensity of climate change and changes in rain patterns have made the development of sustainable agricultural systems that can enhance soil water retention a pressing issue. This situation is further aggravated by the fact that drylands, which comprise more than 40 percent of the Earth, feed about 2.5 billion people and play a major role in world food production, thus making them especially susceptible to the growing drought conditions [1]. In addition, the sandy soils that dominate these areas make the task even more difficult since they have low water and nutrient retention levels, which intensify the impact of water scarcity, causing considerable decreases in the agricultural production and endangering food security [2].

A potential method to improve soil moisture and water-use efficiency is the use of polymeric hydrogel materials that can absorb and release moisture over time (hydrogels). However, most commercially available agricultural hydrogels are synthetic, costly, and recalcitrant, which is of concern when considering the environmental impact over the long term. The recent literature reviews highlight the importance of using eco-friendly biopolymer-based hydrogels that are produced using natural polysaccharides, such as cellulose derivatives, starch, and chitosan, and are crosslinked with natural compounds like citric acid, which possess improved water-holding capacity, nutrient retention capacity, and crop resilience in arid and semi-arid soils [3][4][5][6]. An example is biopolymeric superabsorbent hydrogels, which can be used to enhance crop growth and to allow for better water use in dry regions, as well as formulations that contain hydroxyethyl cellulose and citric acids that absorb a lot of water and which decompose naturally, enabling them to be used as soil conditioners [7][8]. Hydrogels made of agarose have also demonstrated the possibility of seed germination and moisture retention in soil [9]. Therefore, this study aims to investigate the development of an environmentally friendly and biodegradable Hydroxyethyl Cellulose (HEC), Agar, Citric Acid (CT) based hydrogel to overcome these drawbacks. While these issues have been dealt with on their own, their capacity to be used together as a means to manage soil moisture in agriculture has not been studied extensively.

The proposed approach is novel because it works toward filling in this gap by suggesting an alternative to synthetic hydrogels that is both ecologically friendly and offers an improved supply of water, efficiency of water usage, and increased crop productivity within drought-stressed systems.

The main aim of the research is to develop and test biodegradable hydrogels made of Hydroxyethyl Cellulose, Agar, and Citric Acid with improved water retention capacity to be used in agriculture in arid and semi-arid areas.

2. Materials and Methods

2.1. Chemicals and Reagents

Agar powder (60 g; LR grade, Brew Lab Food and Beverage) was the main gelling agent, as it can create stable, biodegradable Hydrogel Networks. Hydroxyethyl Cellulose (HEC) powder (60 g; BRM Chemicals) was used as a thickening and stabilizing agent, which enhanced the viscosity and flexibility of the hydrogel matrix. To improve structural integrity, citric acid (30 g; food grade, Ori) was added as a mild crosslinking and stabilizing agent. The solvent and medium of hydrogel formation and swelling studies were tap or well water.

2.2. Glassware and Apparatus

The mixing and preparation of hydrogel solutions was done in a 1 L heat-resistant Pyrex measuring cup with a pouring spout to guarantee the safety of working with boiling liquids. The volume measurements were made accurate with the help of a measuring cylinder.

Hydrogel samples were cast in molds made of petri dishes (90 x 15 mm; n = 30) to standardize samples. Throughout the experiment, precise mass measurements were made using an analytical weighing balance (accuracy ±1 g). Water was heated in a kettle until it boiled. Mixing and homogenization were done using standard laboratory utensils like spoons and forks.

2.3. Materials for Absorption and Desiccation Studies

In the absorption and desiccation experiments, the samples of hydrogel were stored in twelve containers (capacity of at least 1 cup) during absorption and drying. Paper towels were used to clean and remove the remaining materials. Well-mixed potting soil (without vermiculite and perlite) was packed into 16 small pots to be used in potential application-based observations. All the experimental data and qualitative observations were documented in a laboratory notebook systematically.

2.4. Methodology

2.4.1. Experimental Design

The experiment was conducted in two phases. Phase I involved the synthesis of 120 hydrogel formulations by systematically changing the concentrations of agar, Hydroxyethyl Cellulose (HEC), and citric acid, and testing their water absorption and retention. The shortlisting was done based on predetermined selection criteria. During Phase II, the formulations chosen in the previous phase were evaluated on their ability to improve soil water retention in natural-like conditions.

2.4.2. Phase I: Hydrogel Synthesis and Screening

Hydrogel Preparation

Agar and Hydroxyethyl Cellulose (HEC) were used as the main polymeric matrices to produce a biodegradable hydrogel with citric acid as the stabilizing and crosslinking agent. One hundred and twenty different formulations were made by varying the concentrations of these components systematically to determine their effect on the properties of the hydrogel.

The independent variables investigated in this study included agar (0.5–2.5% w/v), HEC (0.5–3.0% w/v), and citric acid (0.5–2.0% w/v). The solvent was distilled water, and the end volume of each formulation was kept constant at 100 mL, which was a controlled variable during all experimental runs.

The agar, HEC, and citric acid had to be weighed properly according to the formulation of each formulation and then moved into a heat-resistant container. The mixture was heated to boiling using distilled or tap water, which was then added slowly to the mixture until the final volume was 100 mL. The solution was stirred so that the polymers were completely dissolved, and a uniform solution of hydrogel precursors was obtained.

The solution was then centrifuged to remove any impurities and then measured in pre-labeled Petri dishes in equal amounts to ensure consistency in sample size and mass. The hydrogels were left to cool and gel at ambient temperature. The mixture was heated to a specific temperature and left to dry without stirring for at least 3 hours to ascertain the formation of the entire network before further analysis.

Fig. 1 Hydrogel samples prepared using HEC, agar, and citric acid

Water Absorption and Desiccation Analysis

A gravimetric method was used to determine the swelling behavior and the water retention capacity of the hydrogels.

All the hydrogel samples were gently taken out of the Petri dishes and put in preweighed containers, and the initial mass was noted. Samples were then left in water for 1 hour to attain equilibrium swelling.

After immersion, the mass of the completely swollen hydrogel was measured as the initial hydrated mass (Day 0). The samples were then kept under ambient conditions, and their mass was measured at 24-hour time intervals up to a span of 10–14 days to observe the desiccation behavior.

The rate of mass loss over time was used to determine the water retention capacity. Along with quantitative measurements, qualitative observations were made, including the change in texture, shrinkage, and structural integrity.

Selection of Optimal Hydrogel Formulations

The water holding and swelling capacity of hydrogel formulations were measured objectively, based on gravimetric swelling and desiccation studies. The primary criteria for the selection of formulations were the equilibrium swelling, desiccation rate, and integrity of the structure during the experiment. Particular emphasis was laid on the duration of water retention, or the duration of days the hydrogel could maintain the moisture content under ambient conditions.

Formulations with high swelling capacity, low desiccation, and a long water retention time were the formulations of choice. As well, the stability of the drying process was considered to ensure the hydrogels' practicality.

Based on these parameters, a subset of the best-performing formulations was selected from the initial 120 formulations. These hydrogels showed the best capacity for water retention during the course of the experiment and were chosen to be tested in soil. The formulations chosen are detailed in Table 1.

Table 1. Composition of Selected Hydrogel Formulations

Sample No.	Agar (% w/v)	HEC (% w/v)	Citric acid (% w/v)	Distilled water (mL)
19	0.5	2.5	1.5	100
96	2.0	3.0	2.0	100
99	2.5	0.5	1.5	100
107	2.5	1.5	1.5	100
108	2.5	1.5	2.0	100
109	2.5	2.0	0.5	100

2.4.3. Phase II: Soil-Based Evaluation of Selected Hydrogels

Soil Preparation and Hydrogel Incorporation

To determine the feasibility and practicality of the chosen hydrogel formulations, intervention studies were carried out in a red garden soil collected from a local nursery that had been homogenized. Garden soil was used because it is commonly used in horticulture and was chosen to be red to avoid the interference caused by other materials that hold water and to provide a uniform baseline moisture properties.

The experimental setup consisted of cylindrical pots of height 6.5 cm, diameter 7.2 cm, and volume of approximately 264.5 cm^3. The prepared red garden soil was added to each pot in an amount of 250 g with 50 g of the selected hydrogel formulation to ensure that each pot has a uniform amount of soil and hydrogel throughout the soil matrix. To obtain repeatability and comparability of results, the soil-to-hydrogel ratio was kept constant in all experimental groups.

Control plots with a red garden soil without any hydrogel were kept under the same environmental conditions to compare soil moisture retention behavior.

Soil Intervention Study and Moisture Monitoring

The effectiveness of the selected hydrogels in enhancing soil moisture retention was evaluated in a soil intervention study. Each hydrogel-treated soil sample was supplemented with a certain volume of water to keep the initial soil moisture content equal in all the pots.

The pots were then placed in an outdoor environment to allow the samples to be exposed to natural conditions of temperature, light, and air. The soil moisture content was measured after 14 days using a calibrated soil moisture meter.

The samples were recorded for the rate of moisture loss, and the effectiveness of each hydrogel formulation was assessed by how long it retained the moisture content in the soil as compared to the standard soil. This assessment provided insight into the potential use of hydrogels in water conservation in agriculture.

Assessment of Soil Water Retention

Moisture retention in hydrogel-treated soil was used to assess the effectiveness of hydrogels. Both quantitative (moisture content) and qualitative (soil texture, consistency, and apparent dryness) data were obtained.
Hydrogels with lower moisture loss and high stability in terms of soil moisture retention were considered to be more valuable in agriculture.

3. Results

3.1. Selection of High-Performing Hydrogel Formulations

From the initial pool of 120 hydrogel formulations, a subset of seven compositions was shortlisted based on their superior swelling capacity, reduced desiccation rate, and structural stability during drying. These formulations represent optimized combinations of agar, Hydroxyethyl Cellulose (HEC), and citric acid, enabling a comparative assessment of how compositional variations influence soil moisture retention.

3.2. Statistical Analysis of Hydrogel Performance

The statistical analysis of the performance of the hydrogels is shown. The performance of the hydrogels is analysed statistically.

Hydrogel composition was evaluated with respect to its retention performance using statistical analyses. Since both of these variables were continuous quantitative measures, they were analyzed using Pearson correlation analysis. Furthermore, to check the effect of the different levels of agar, HEC, and citric acid on the hydrogel retention performance, one-way ANOVA was performed for the different formulation groups. ANOVA F-value is the ratio between inter-group variance and intra-group variance, and higher values signify higher variance among the tested formulations.

Table 2. Water Uptake Capacity and Moisture Retention Profile of Prepared Hydrogel Samples During 15-Day Drying Study

Sample No.	Initial Dry	Initial Wet	Water Uptake (%)	Weight at Day 1	Weight at Day	Weight at Day	Weight at Day
19	60	67	11.67	67	64	61	60
96	58	69	18.97	69	64	59	58
99	60	74	23.33	74	71	66	60
106	59	73	23.73	73	70	64	58
107	60	74	23.33	74	68	60	60
108	62	79	27.42	79	72	66	61
109	62	81	30.65	81	76	70	67

3.3. Soil Moisture Retention Behaviour

The soil moisture retention profiles of hydrogel-amended samples and the control were monitored over a 14-day period under outdoor conditions.

Table 3. Soil Moisture of the 7 hydrogels and the control sample over 14 days

	Sample No.							
	19	96	99	106	107	108	109	Control
Day	Soil Moisture (%)							
0	88%	88%	88%	86%	88%	87%	88%	88%
1	87%	88%	87%	85%	85%	86%	88%	84%
2	87%	88%	87%	82%	84%	85%	88%	80%
3	86%	87%	85%	81%	80%	81%	85%	75%
4	86%	86%	85%	79%	76%	74%	81%	70%
5	82%	85%	80%	75%	74%	72%	78%	66%
6	76%	84%	74%	71%	71%	68%	71%	63%
7	72%	82%	71%	64%	68%	55%	68%	52%
8	68%	80%	66%	62%	61%	49%	65%	44%
9	62%	78%	63%	60%	55%	41%	64%	40%
10	55%	76%	60%	58%	48%	38%	58%	35%
11	48%	74%	55%	54%	45%	35%	54%	33%
12	43%	65%	53%	50%	42%	32%	48%	28%
13	32%	55%	52%	44%	36%	29%	46%	25%
14	31%	42%	47%	40%	31%	28%	41%	22%

All samples, including the control, exhibited comparable initial moisture content (~86–88%), confirming uniform saturation at the start of the experiment. However, a clear divergence in moisture retention behavior emerged over time. While all hydrogel-treated samples showed a gradual decline in moisture content, the control exhibited a consistently faster rate of desiccation, indicating the absence of any moisture-retaining matrix. By Day 7, the control moisture content had decreased to approximately 52%, whereas hydrogel-treated samples retained significantly higher moisture levels, ranging from ~55% to ~82%. This gap widened further toward the later stages of the experiment. By Day 14, the control reached ~22%, while hydrogel-treated samples maintained substantially higher moisture levels, ranging from ~28% to ~47%. These observations confirm that hydrogel incorporation significantly delays soil moisture loss compared to untreated soil.

3.4. Comparative Moisture Retention Performance

Sample 96 was the best-performing of the hydrogel formulations with regard to overall retention, as it retained relatively constant moisture levels at the beginning of the experiment, and the decline was slower than in the other samples and the control. Sample 99 exhibited a steady and slow decline in moisture content, and even in the later stages, it retained a relatively high moisture content. Sample 19 was intermediate, showing good initial retention but faster loss of moisture after Day 4. Intermediate behavior was observed in samples 106 and 107, with a consistent decrease in moisture that was consistently higher than the control during the study period. Sample 108 had the lowest retention of the hydrogel-treated samples, but still, it was much better than the control. Sample 109 was stable in the initial period and gradually decreased after that, performing better than the control at all times.

A steady biphasic pattern was evident in all the samples treated with hydrogel, with a slow-loss period and a rapid desiccation. Conversely, the control had a more monotonic and steep downward trend, without the initial stabilization period of hydrogel systems. This disparity underscores the importance of hydrogels in controlling the dynamics of water release.

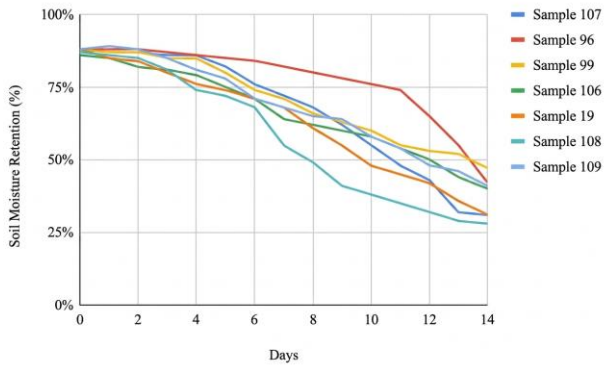

Fig. 2 Graph showing hydrogel performance in soil moisture retention

4. Discussion

The control data provide a good indication of the effectiveness of the hydrogel amendments on moisture retention. The moisture content of the control soil decreased gradually and rapidly, with a 66 percent loss in moisture content by Day 14. However, the moisture content in the hydrogel-treated samples was higher during the same time period, so hydrogel can act as a reservoir to retain moisture and to reduce moisture loss. The moisture retention in this comparative study can be attributed to the presence of the hydrogel network and not the environment.

The two phases of water release from the hydrogel-treated samples (and not from the control) also support the effect of hydrogels. The first stage is the swell of the hydrogel, and it is actually like holding water through hydrogen bonding and capillary pressure in the polymer network. The shrinking of the structure and the reduction in pore size in the second stage result in an increase in water release. In contrast, the control sample does not have such a structure, and, as a result, the water loss is instant. The present study demonstrates that the hydrogel is able to provide a buffering effect, thus reducing the instantaneous loss of water.

When compared to the controls, some of them, such as Sample 96 and Sample 99, are very encouraging. Sample 96 had almost twice the moisture content on Day 14 compared to the control, which meant it was able to retain water. This is because of the higher hydroxyethyl cellulose content, which enhances the hydrophilicity and polymer-water interactions. This has also been observed in cellulose-based hydrogels, where the interactions between the polymer and water are increased, and swelling and retention properties are increased [7][10]. However, the sustained water release of sample 99 was lower, likely due to the higher content of agar, which increases the stiffness of the hydrogel. Agar-based hydrogels have been reported to improve water retention of soils by maintaining the soil structure and sustained release of water [9].

The variations in the results of the samples treated with hydrogel and the control correspond to the previous studies on agricultural hydrogels. Biopolymer-based hydrogels are widely reported to have the ability to enhance water retention in soils and reduce water irrigation, particularly in dry and semi-dry regions [11][12]. This is in line with the reduction in the rate of water loss in the present work, and it shows that hydrogels can be used to increase the water-use efficiency in soil by a substantial margin. Additionally, the studies by Azeem et al. (2023) and Piccoli et al. (2024) also suggested that the biodegradable hydrogels can work as effectively as the synthetic ones and are environmentally friendly, which is also supported in the current study [3][4]. The outcomes of the different hydrogel formulations indicate that the performance closely relates to formulation, although it is generally better than the control. Sample 108 (and others) had a relatively high initial rate of moisture loss, suggesting that the network is not stable. However, moisture content is still significantly higher than the control in both cases, which shows that the use of hydrogels as a control is successful. The fast drying of the late-time samples in all samples shows that biodegradable hydrogels can undergo fatigue and lose their efficiency in retaining moisture. This observation has been made in other studies, where the drying effect results in a loss of effectiveness due to network breakdown [13].

From a practical perspective, including control data shows how hydrogels can be used to prevent soil drying. Hydrogel soils have a higher moisture content, which means that hydrogels can be used to reduce the irrigation frequency and to increase plant tolerance to drought. However, the final step to minimize moisture content means that hydrogels are not permanent or delaying solutions, and their application is maximized when used in combination with other practices of soil and water management. Overall, the control study not only confirms the effectiveness of the hydrogels but also the mechanism of action. These results are a good sign that biodegradable HEC-agar-citric acid hydrogels are able to increase soil moisture retention and that their potential use in farming is justified.

5. Conclusion

This research shows the successful preparation and evaluation of a biodegradable hydrogel of Hydroxyethyl Cellulose (HEC), agar, and citric acid to enhance the water retention ability of soil. The results confirm the improvement in the water-holding capacity of soil by incorporating hydrogel, particularly in the initial stage of drying, which leads to water preservation under controlled conditions. The best results were observed in Sample 96 and Sample 99, which suggests the importance of the composition of the polymer to achieve optimum water absorption, retention, and release.

The biphasic loss of moisture shows the two stages of moisture loss and the hydrogel structure; the first is the maintenance of moisture in a steady-state, and the second is the enhancement of moisture loss by shrinking and decreasing the water-holding capacity of the hydrogel. In particular, the use of naturally derived materials in this study highlights the sustainability and biodegradability of the resultant materials, making them potential materials for sustainable use in agriculture.

The findings are promising, but we should keep in mind some of the constraints. The study has been conducted for a short time (14 days), which limits the ability to assess the long-term stability of the hydrogel and its performance under repeated wet-dry conditions. Furthermore, the experimental setup has been conducted in a semi-controlled setup where the environment is not fully exposed to rain, wind, and temperature that can affect the system. Without statistical replication and characterization of the material, the statistical power and mechanistic understanding are also limited. The variability might also be attributed to the variability in soil properties and the distribution of hydrogel in the soil.

The current study should be extended to include field studies in longer time frames over various climatic and soil conditions to evaluate the persistence and field effectiveness of these hydrogels. Further physicochemical characterization of the hydrogels, such as swelling, mechanical, porosity, and degradation properties, will provide information on structure-property correlations. In addition, the studies on the swelling and deswelling of the hydrogels and the interaction with the plant growth factors will enhance the utility of the hydrogels in agriculture. Further applications should take compatibility with nutrient delivery systems, costs, and scalability into account. Overall, the study offers a good starting point to develop environment-friendly and biodegradable hydrogel-based systems to promote water-saving agriculture.

Ethical Considerations

Materials such as agar, hydroxyethyl cellulose (HEC), and citric acid were used and are generally considered to be non-toxic and environmentally friendly. The synthesis and testing of hydrogels did not involve the use of any hazardous chemicals or environmentally persistent additives.

Soil intervention tests were carried out in controlled outdoor conditions with the help of red garden soil and reduced environmental disturbance to examine the practicability of the soil interventions. Standard laboratory safety was used for the disposal of experimental waste.
No human being, animal, or clinical material was involved in this study, and thus, formal ethical approval was not required.

References

[1] Yingying Xing, and Xiukang Wang, "Precision Agriculture and Water Conservation Strategies for Sustainable Crop Production in Arid Regions," *Plants*, vol. 13, no. 22, pp. 1-23, 2024. [CrossRef] [Google Scholar] [Publisher Link]

[2] Sylus Kipngeno Musei et al., "Sandy Soil Reclamation Technologies to Improve Crop Productivity and Soil Health: A Review," *Frontiers in Soil Science*, vol. 4, pp. 1-13, 2024. [CrossRef] [Google Scholar] [Publisher Link]

[3] Muhammad Khalid Azeem et al., "Eco-Friendly Three-Dimensional Hydrogels for Sustainable Agricultural Applications: Current and Future Scenarios," *Polymers for Advanced Technologies*, vol. 34, no. 9, pp. 3046-3062, 2023. [CrossRef] [Google Scholar] [Publisher Link]

[4] Ilaria Piccoli et al., "Hydrogels for Agronomical Application: From Soil Characteristics to Crop Growth: A Review," *Agronomy for Sustainable Development*, vol. 44, no. 2, pp. 1-23, 2024. [CrossRef] [Google Scholar] [Publisher Link]

[5] Zaryab Tariq et al., "Significance of Biopolymer-based Hydrogels and their Applications in Agriculture: A Review in Perspective of Synthesis and their Degree of Swelling for Water Holding," *RSC Advances*, vol. 13, no. 35, pp. 24731-24754, 2023. [CrossRef] [Google Scholar] [Publisher Link]

[6] Yudi Wu, Simeng Li, and Gang Chen, "Hydrogels as Water and Nutrient Reservoirs in Agricultural Soil: A Comprehensive Review of Classification, Performance, and Economic Advantages," *Environment, Development and Sustainability*, vol. 26, no. 10, pp. 24653-24685, 2023. [CrossRef] [Google Scholar] [Publisher Link]

[7] Mohamed Mohamady Ghobashy et al., "Synthesis and Application of a Multifunctional Poly (vinyl pyrrolidone)-based Superabsorbent Hydrogel for Controlled Fertilizer Release and Enhanced Water Retention in Drought-Stressed Pisum Sativum Plants," *Scientific Reports*, vol. 14, no. 1, pp. 1-19, 2024. [CrossRef] [Google Scholar] [Publisher Link]

[8] Saja Kadhim, Awham M. Hameed, and Rashed T. Rasheed, "Effect of Crosslinking Agent (Zinc Chloride) on the Swelling Ratio and Water Retention Capacity of Polyacrylate and Polyvinyl Alcohol," *Journal of Applied Sciences and Nanotechnology*, vol. 2, no. 4, pp. 80-90, 2022. [CrossRef] [Google Scholar] [Publisher Link]

[9] Xin Tang et al., "Synthesis and Characterization of Agarose-Bacterial Cellulose Hydrogel for Promoting Seed Germination by Improving Soil Water Retention," *Polymer Bulletin*, vol. 81, no. 9, pp. 8215-8227, 2023. [CrossRef] [Google Scholar] [Publisher Link]

[10] Dipankar Das et al., "Synthesis and Characterization of Superabsorbent Cellulose-based Hydrogel for Agricultural Application," *Starch*, vol. 73, no. 1-2, 2021. [CrossRef] [Google Scholar] [Publisher Link]

[11] Dure Najaf Iqbal et al., "Nanocellulose/Wood Ash-Reinforced Starch-Chitosan Hydrogel Composites for Soil Conditioning and their Impact on Pea Plant Growth," *RSC Advances*, vol. 14, no. 13, pp. 8652-8664, 2024. [CrossRef] [Google Scholar] [Publisher Link]

[12] G.A. Rajanna et al., "Biopolymeric Superabsorbent Hydrogels Enhance Crop and Water Productivity of Soybean-Wheat System in Indo-Gangetic Plains of India," *Scientific Reports*, vol. 12, no. 1, pp. 1-18, 2022. [CrossRef] [Google Scholar] [Publisher Link]

[13] Alessandro Sorze et al., "Multifunctional Xanthan Gum/Wood Fibers-based Hydrogels as Novel Topsoil Covers for Forestry and Agricultural Applications," *Carbohydrate Polymer Technologies and Applications*, vol. 7, 2024. [CrossRef] [Google Scholar] [Publisher Link]