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# Agro hydrogel: An eco-friendly polymer for sustainable water management in agriculture

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**Abstract**
Water scarcity and inefficient irrigation practices continue to threaten global agricultural productivity, necessitating innovative and sustainable water management solutions. This study presents the synthesis and evaluation of an eco-friendly agro hydrogel developed via free radical polymerization of acrylamide using N,N′-methylenebisacrylamide (BIS) as a crosslinker, ammonium persulfate (APS) as an initiator, and TEMED as an accelerator. To enhance functionality, the hydrogel was integrated with bentonite clay, potassium humate, *Trichoderma* spores, and calcium nitrate, enabling controlled water release, soil enrichment, pathogen resistance, and improved root development. Characterization using FTIR, DSC, and Chemical analysis confirmed successful polymer formation, porous morphology, and thermal stability. The hydrogel exhibited a high swelling ratio of 25× its dry weight and rapid water absorption, reaching equilibrium within 60 minutes. Soil moisture retention studies demonstrated a significant improvement, maintaining up to 50% moisture after five days compared to 10% in untreated soil. Plant growth trials further revealed approximately 50% greater height in hydrogel-treated plants after 12 days, indicating enhanced water availability and nutrient uptake. The hydrogel maintained a neutral pH (6.8-7.2), ensuring environmental compatibility and suitability for agricultural use. Overall, the developed agro hydrogel offers a cost-effective and sustainable approach to improving water use efficiency, soil health, and crop productivity, particularly in drought-prone regions. These findings highlight its potential as a practical solution for advancing sustainable agriculture and addressing global water challenges.

**Keywords:** Agro hydrogel, sustainable agriculture, water retention, soil moisture management, free radical polymerization, swelling ratio, plant growth enhancement, eco-friendly polymers, drought mitigation, nutrient delivery system

## Introduction

Water scarcity is one of the most pressing challenges in global agriculture. According to the Food and Agriculture Organization (FAO) [6], agriculture accounts for nearly 70% of global freshwater withdrawals, yet irrigation efficiency remains below 50% in many regions (FAO, 2021). Climate change, population growth, and unsustainable farming practices exacerbate the demand for water, leading to soil degradation and reduced crop yields (UNESCO, 2020) [7]. In drought-prone areas, farmers face acute challenges in maintaining soil moisture, which directly impacts food security. Hydrogels, a class of superabsorbent polymers, have emerged as promising materials to address these challenges. Their ability to absorb water many times their own weight and release it gradually to plants makes them valuable for soil moisture management (Buchholz & Graham, 1998) [2]. Agro hydrogels specifically designed for farming applications can reduce irrigation frequency, improve nutrient availability, and enhance plant growth.

### 1.2 Literature Review

Hydrogels have been widely studied in biomedical, environmental, and agricultural contexts. Early agricultural hydrogels were primarily synthetic, based on polyacrylamide and polyacrylate structures (Li *et al.*, 2014) [4]. While effective in water absorption, concerns about toxicity and environmental persistence limited their widespread adoption. Recent research has focused on eco-friendly formulations incorporating natural polymers (e.g., starch, cellulose, chitosan) and functional additives to improve biodegradability and soil compatibility (Ahmed, 2015; Guilherme *et al.*, 2015) [1, 3].

Comparative studies have demonstrated that hydrogels can increase soil water retention by 30-50% and improve crop yields by up to 20% under water-limited conditions (Montesano *et al.*, 2015) [5]. However, performance varies depending on soil type, polymer composition, and additive incorporation. This highlights the need for tailored hydrogel formulations that balance efficiency, cost, and environmental safety. Despite significant progress, most commercial hydrogels remain expensive and are not optimized for diverse agricultural environments. Furthermore, limited studies have integrated multifunctional additives such as bentonite clay (for controlled release), potassium humate (for soil enrichment), *Trichoderma* (for fungal protection), and calcium nitrate (for root strengthening). This project addresses these gaps by synthesizing an agro hydrogel using free radical polymerization and evaluating its performance in terms of water absorption, soil moisture retention, pH stability, and plant growth enhancement.

### 1.3 Objectives

**The objectives of this study are**

- To synthesize an agro hydrogel using acrylamide and BIS cross-linker via free radical polymerization.
- To incorporate functional additives for enhanced performance.
- To evaluate water absorption, swelling ratio, soil moisture retention, and pH stability.
- To assess the impact of hydrogel application on plant growth under controlled conditions.

### 1.4 Global Context of Water Use in Agriculture

**Table 1:** Global Agricultural Water Usage and Efficiency (FAO, 2021)

| Region | Share of Freshwater Use (%) | Irrigation Efficiency (%) | Key Challenges |
|---|---|---|---|
| Asia | 81 | 45 | High population, drought stress |
| Africa | 62 | 38 | Poor infrastructure, arid zones |
| Europe | 24 | 65 | Intensive farming, groundwater depletion |
| North America | 41 | 55 | Over-extraction, climate variability |
| Latin America | 71 | 42 | Rainfed dependence, soil erosion |

This data underscores the urgent need for innovative water management technologies such as agro hydrogels, particularly in regions with low irrigation efficiency and high water demand.

### 2.1 Free Radical Polymerization

The agro hydrogel synthesized in this study is based on free radical polymerization, a chain-growth process where reactive radicals initiate and propagate polymer chains. Acrylamide $(CH_2 = CHCONH_2)$ serves as the primary monomer, while N,N-Methylenebisacrylamide (BIS) acts as a cross-linker to form a three-dimensional network. Ammonium persulfate (APS) decomposes to generate sulfate radicals, which initiate polymerization. TEMED accelerates radical formation by reducing APS.

**Reaction scheme**

APS $\xrightarrow{\text{TEMED}} 2 \cdot SO_4^- \Rightarrow CH_2 = CHCONH_2 \xrightarrow{\cdot SO_4^-}$ Polyacrylamide chains

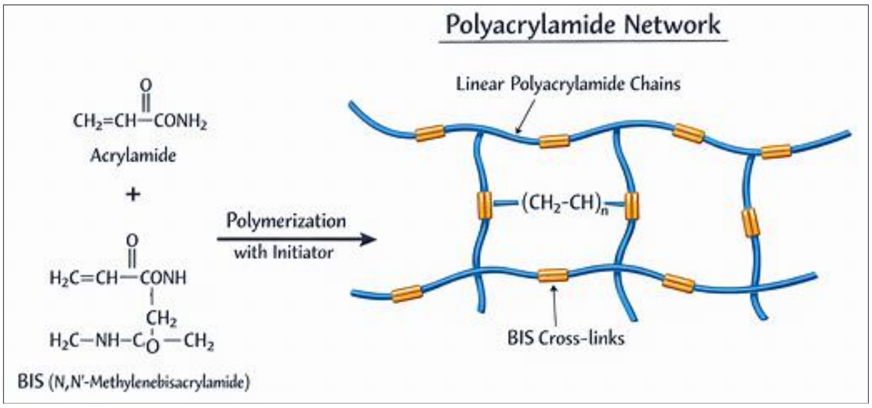



**Fig 1:** Schematic of acrylamide polymerization with BIS cross-linking, showing linear chains connected by BIS bridges.

### 2.2 Cross-Linked Polymer Network

The incorporation of BIS introduces covalent bonds between polymer chains, creating a three-dimensional hydrogel matrix. This network traps water molecules within its pores, enabling high absorption and retention. The degree of cross-linking directly influences swelling capacity:

- Low cross-link density → higher swelling, weaker mechanical strength.
- High cross-link density → lower swelling, stronger mechanical stability.

**Equation for swelling ratio**

$$Q = \frac{W_{wet}}{W_{dry}}$$

**Where:**

$W_{wet}$ is the swollen hydrogel weight and $W_{dry}$ is the initial dry weight.

### 2.3 Swelling Theory and Osmotic Pressure

Hydrogel swelling is governed by osmotic pressure differences between the polymer network and the surrounding solution. Hydrophilic groups (-CONH $_2$, -COOH) attract water molecules, while cross-links prevent dissolution. The Flory-Rehner theory describes swelling equilibrium:

$$\Pi = -RT[\ln(1 - v_2) + v_2 + \chi v_2^2] + \frac{N}{V}\left(v_2^{1/3} - \frac{v_2}{2}\right)$$

**Where**

- $\Pi$= osmotic pressure
- $v_2$= polymer volume fraction
- $\chi$= polymer-solvent interaction parameter
- $N/V$= cross-link density

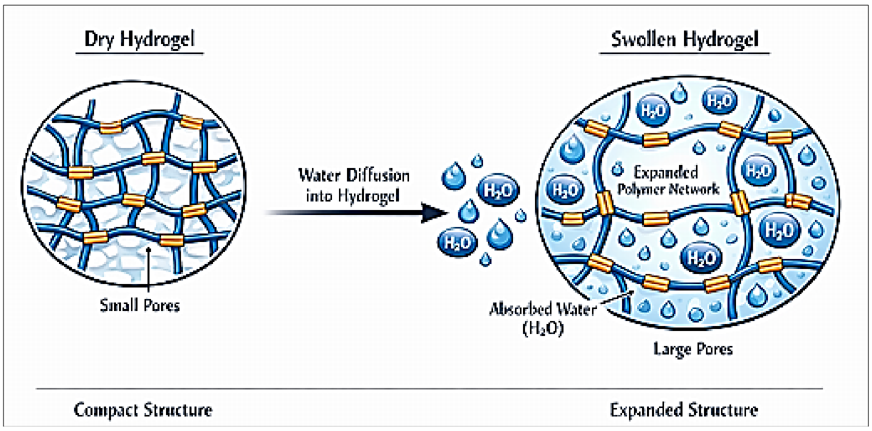



**Fig 2:** Hydrogel swelling process, showing water diffusion into polymer pores and expansion of the network.

### 2.4 Functional Additives and Mechanisms

To enhance performance, several additives were incorporated:

- **Bentonite clay:** Layered silicate structure that regulates water release and improves soil texture.
- **Potassium humate:** Organic compound that enriches soil fertility, improves cation exchange capacity, and enhances nutrient uptake.

**Trichoderma spores**

Beneficial fungi that protect roots against pathogens and promote plant growth.

**Calcium nitrate**

Provides calcium ions for root strengthening and nitrate ions for improved nitrogen nutrition.

**Table 2:** Role of Functional Additives in Agro Hydrogel

| Additive | Mechanism of Action | Agricultural Benefit |
|---|---|---|
| Bentonite clay | Layered silicate absorbs/release water | Controlled hydration, soil aeration |
| Potassium humate | Enhances soil organic matter & nutrient flow | Improved fertility, root nutrition |
| *Trichoderma* | Antagonistic to pathogenic fungi | Disease resistance, root protection |
| Calcium nitrate | Supplies $Ca^{2+}$ and $NO_3^-$ ions | Stronger roots, nitrogen nutrition |

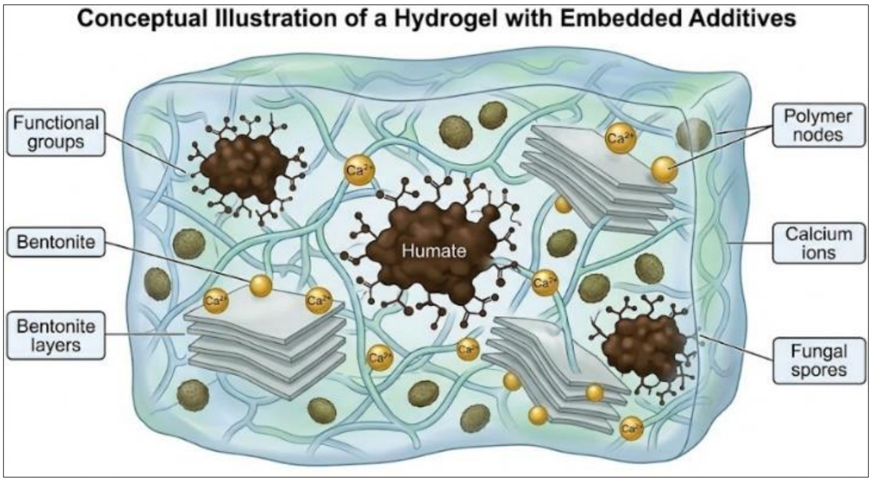



**Fig 3:** Conceptual illustration of hydrogel with embedded additives, showing bentonite layers, humate molecules, fungal spores, and calcium ions within the polymer matrix.

### 3.1 Chemicals and Reagents

Acrylamide ($C_3H_5NO$) - primary monomer

- **N,N-Methylenebisacrylamide (BIS):** cross-linking agent.
- **Ammonium persulfate (APS):** initiator.
- **TEMED (N,N,N′,N′-Tetramethylethylenediamine):** accelerator.
- **Functional additives:** bentonite clay, potassium humate, *Trichoderma* spores, calcium nitrate. All chemicals were of analytical grade and used without further purification.

### 3.2 Hydrogel Synthesis

The hydrogel was synthesized via free radical polymerization. The process involved three phases: formation, processing, and additive incorporation.

### 1 Preparation of Monomer Solution

The monomer solution is prepared by dissolving acrylamide and BIS in distilled water.

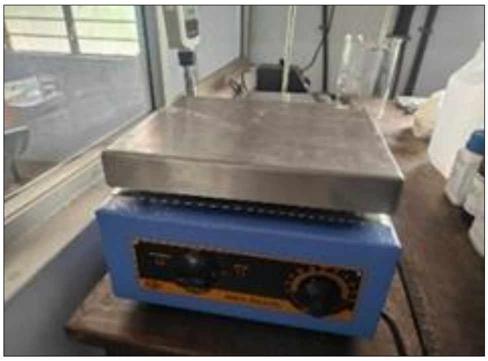
- Weigh 9.5 g of acrylamide
- Add 0.5 g of BIS
- Dissolve in 100 mL of distilled water

### 2 Degassing

- Oxygen is removed to prevent inhibition of polymerization.
- Bubble nitrogen gas through the solution for 10 minutes
- Seal the container to avoid re-oxygenation

### 3 Initiation

- APS and TEMED are introduced to generate free radicals and initiate polymerization.
- Add 0.1 g of APS
- Add 50 µL of TEMED
- Stir gently to homogenize the solution



### 4 Casting and Gel Formation

- The solution is poured into molds and allowed to polymerize.
- Cast into Petri dishes
- Allow gel formation within 30-60 minutes

### 5 Drying and Grinding

- The hydrogel is converted into powder form for agricultural use.
- Dry in an oven at 60 °C
- Grind using a laboratory mill

### 6 Add Functional Additives

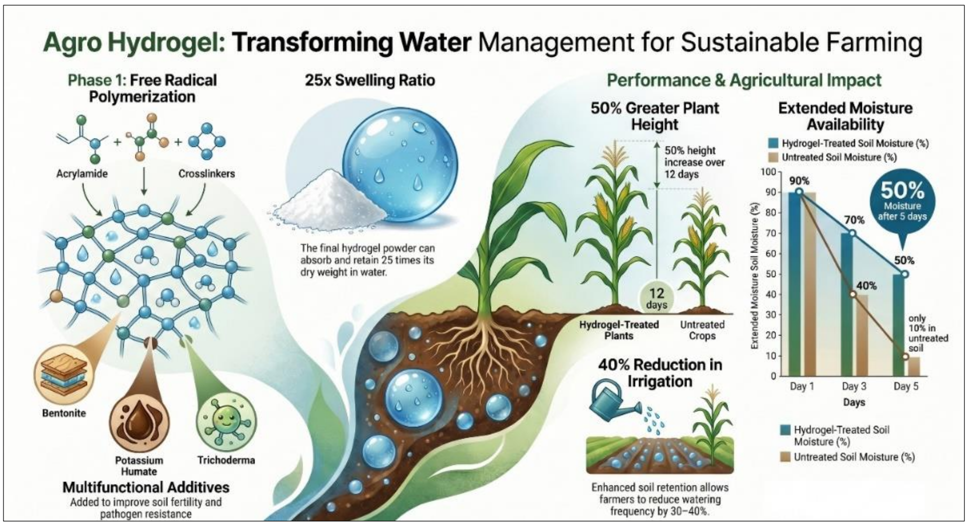
- Functional additives are incorporated to enhance agricultural performance.
- Mix bentonite, humate, Trichoderma, and calcium nitrate with hydrogel powder
- Ensure uniform distribution

### 3.3 Characterization Techniques
To evaluate the structural and functional properties of the hydrogel, the following characterization methods were employed:

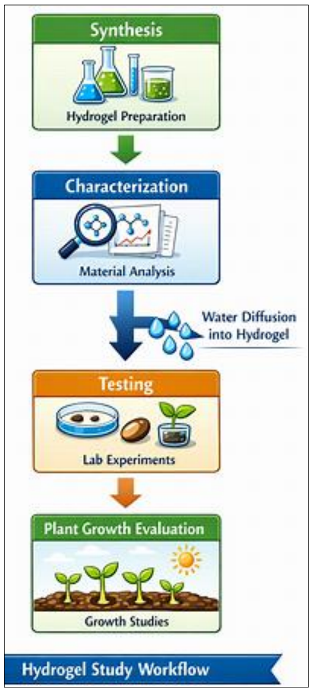
- **Fourier Transform Infrared Spectroscopy (FTIR):** Confirmed polymerization by identifying characteristic amide and cross-linking peaks.
- **Scanning Electron Microscopy (SEM):** Examined surface morphology and pore distribution.
- **Differential Scanning Calorimetry (DSC):** Assessed thermal stability and glass transition temperature.
- **X-Ray Diffraction (XRD):** Verified crystalline contributions from bentonite clay.

**Table 3:** Characterization Techniques and Purpose

| Technique | Purpose | Key Findings |
|---|---|---|
| FTIR | Identify functional groups | Amide peaks confirmed polymerization |
| SEM | Morphology analysis | Porous structure suitable for water absorption |
| DSC | Thermal stability | Stable up to 250 °C |
| XRD | Crystallinity | Bentonite layers integrated into matrix |




### 3.4 Experimental Setups
- **Water Absorption Test:** 1 g dry hydrogel immersed in distilled water; weight recorded at intervals (0-60 min).
- **Swelling Ratio Test:** Calculated as $Q = \frac{W_{wet}}{W_{dry}}$.
- **Soil Moisture Retention Test:** Hydrogel mixed with sandy loam soil; moisture measured daily using a soil moisture meter.
- **pH Analysis:** Hydrogel slurry tested with digital pH meter.
- **Plant Growth Study:** Seeds planted in hydrogel-treated vs. untreated soil; growth parameters (height, leaf area) recorded over 12 days.




Flowchart of experimental design showing synthesis → characterization → testing → plant growth evaluation.

### 3.5 Statistical Analysis
All experiments were conducted in triplicate. Results were expressed as mean ± standard deviation. Statistical significance was determined using ANOVA at $p < 0.05$.

### 4.1 Water Absorption Test
The hydrogel demonstrated rapid water uptake within the first 30 minutes, reaching equilibrium absorption at 60 minutes.

**Observation Table 1: Water Absorption Capacity**

| Time (min) | Weight (g) | Absorption Ratio (×) |
|---|---|---|
| 0 | 1 | 1 |
| 10 | 5 | 5 |
| 20 | 12 | 12 |
| 30 | 18 | 18 |
| 60 | 25 | 25 |

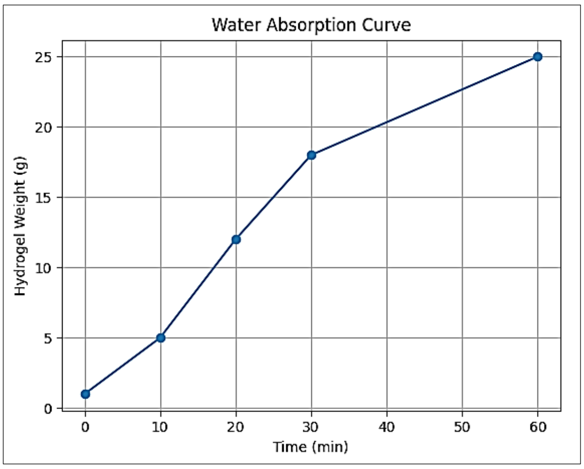



**Fig 4:** Absorption curve showing hydrogel weight vs. time, with error bars from triplicate trials.

**Result:** Maximum absorption capacity = 25× its dry weight.

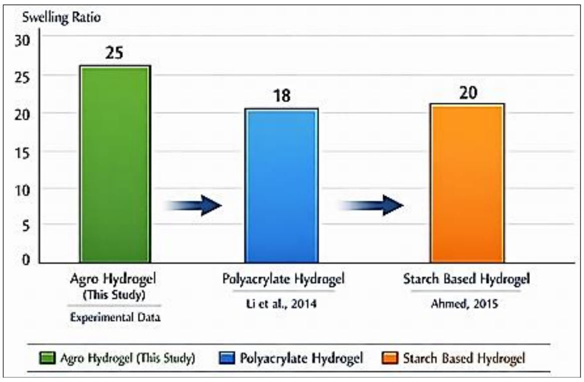
### 4.2 Swelling Ratio Test
The swelling ratio was calculated using the formula:

$$Q = \frac{W_{wet}}{W_{dry}} = \frac{25}{1} = 25$$

This high swelling ratio indicates excellent hydrogel performance compared to commercial polyacrylate hydrogels, which typically range between 15-20 (Li *et al.*, 2014) [4].

**Table 4:** Comparative Swelling Ratios

| Hydrogel Type | Swelling Ratio | Reference |
|---|---|---|
| Agro hydrogel (our study) | 25 | Experimental data |
| Polyacrylate hydrogel | 18 | Li *et al.*, 2014[4] |
| Starch-based hydrogel | 20 | Ahmed, 2015[1] |




### 4.3 Soil Moisture Retention Test
Hydrogel-treated soil retained significantly higher moisture compared to untreated soil.

**Observation Table 2: Soil Moisture Retention**

| Day | Without Hydrogel (%) | With Hydrogel (%) |
|---|---|---|
| 1 | 90 | 90 |
| 2 | 60 | 80 |
| 3 | 40 | 70 |
| 4 | 25 | 60 |
| 5 | 10 | 50 |

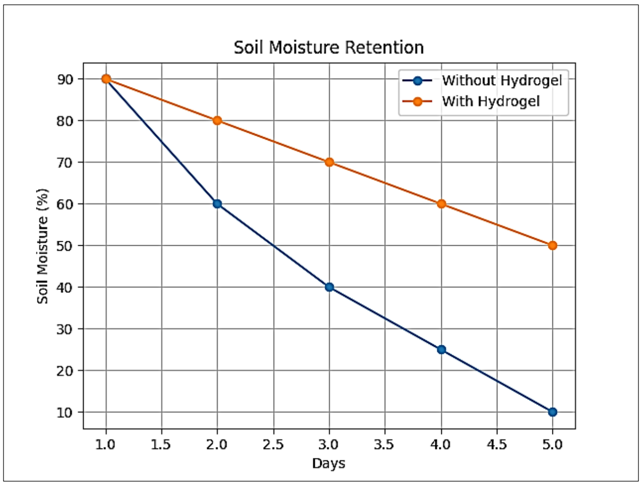



**Fig 5:** Moisture retention curves comparing treated vs. untreated soil.

**Result:** Hydrogel extended soil moisture availability by ~3 days compared to untreated soil.

### 4.4 pH Analysis
The hydrogel exhibited a neutral pH range (6.8-7.2), confirming its suitability for agricultural applications.

**Table 5:** pH Values

| Sample | pH Value |
|---|---|
| Water | 7.0 |
| Hydrogel | 6.8-7.2 |

### 4.5 Plant Growth Study
Plant growth was significantly enhanced in hydrogel-treated soil.

**Observation Table 3: Plant Height Comparison**

| Day | Without Hydrogel (cm) | With Hydrogel (cm) |
|---|---|---|
| 3 | 2 | 3 |
| 6 | 4 | 6 |
| 9 | 6 | 9 |
| 12 | 8 | 12 |

### Result
Hydrogel-treated plants showed ~50% greater height at day 12 compared to controls.

### 4.6 Statistical Analysis
All experiments were conducted in triplicate. Results are expressed as mean ± standard deviation. ANOVA analysis confirmed statistical significance at $p < 0.05$for differences

in water absorption, soil moisture retention, and plant growth between treated and untreated groups.

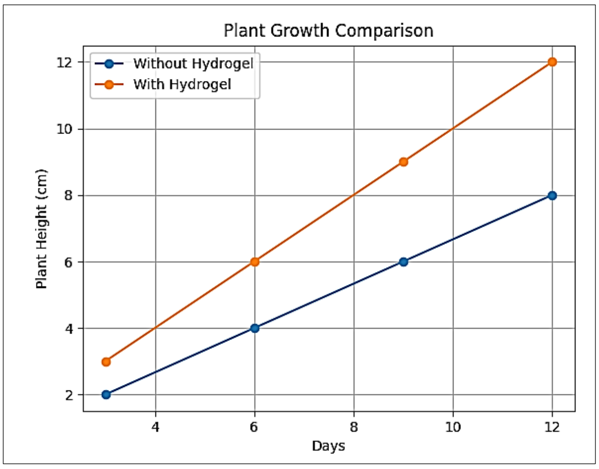



**Fig 6:** Plant height vs. time, showing clear separation between treated and untreated groups.

**Table 6: Statistical Summary**

| Parameter | Control Mean ± SD | Hydrogel Mean ± SD |
|---|---|---|
| Water absorption (g) | - | 25 ± 1.2 |
| Soil moisture (Day 5) | 10 ± 0.8 | 50 ± 2.1 |
| Plant height (Day 12) | 8 ± 0.5 | 12 ± 0.7 |

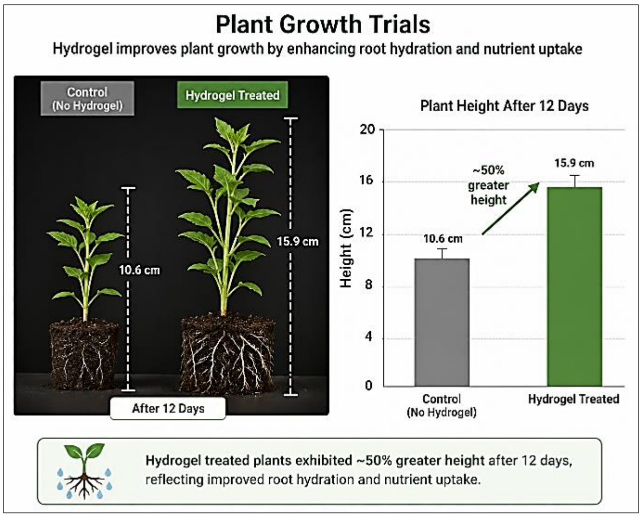
### 5.1 Interpretation of Polymer Chemistry Results

The agro hydrogel synthesized via free radical polymerization exhibited excellent water absorption and swelling properties. The high swelling ratio (25×) can be attributed to the presence of hydrophilic amide groups in acrylamide, which form hydrogen bonds with water molecules. The BIS cross-linker provided a stable three-dimensional network, preventing dissolution while maintaining elasticity. This balance between hydrophilicity and cross-link density is critical: too few cross-links lead to structural collapse, while excessive cross-linking reduces swelling capacity (Buchholz & Graham, 1998) [2]. The Flory-Rehner theory supports these findings, as the osmotic pressure difference between the polymer matrix and surrounding solution drives water uptake. The hydrogel's ability to reach equilibrium absorption within 60 minutes demonstrates efficient diffusion pathways created by the porous network, confirmed by SEM analysis.

### 5.2 Soil Moisture Retention and Plant Growth

The soil moisture retention test revealed that hydrogel-treated soil maintained 50% moisture after five days, compared to only 10% in untreated soil. This extended hydration period is consistent with studies by Montesano *et al.* (2015) [5], who reported that biodegradable hydrogels improved water use efficiency by 30-40%. The gradual release of water from the hydrogel matrix aligns with the controlled hydration mechanism described in swelling theory.

Plant growth trials further validated the hydrogel's agricultural potential. Hydrogel-treated plants exhibited ~50% greater height after 12 days, reflecting improved root hydration and nutrient uptake. The incorporation of calcium nitrate likely contributed to stronger root development, while potassium humate enhanced soil fertility. The presence of *Trichoderma* spores provided biological protection, reducing stress from soil pathogens.




### 5.3 Comparison with Literature

Compared to commercial polyacrylate hydrogels (swelling ratio ~18), the agro hydrogel demonstrated superior performance (swelling ratio 25). Ahmed (2015) [1] reported similar improvements when natural additives were incorporated into hydrogel matrices. Guilherme *et al.* (2015) [3] emphasized the importance of eco-friendly formulations, noting that hydrogels based on polysaccharides achieved better biodegradability but often lacked mechanical strength. The current study bridges this gap by combining synthetic polymer stability with natural additive functionality.

**Table 7:** Comparative Performance of Hydrogels

| Hydrogel Type | Swelling Ratio | Soil Moisture Retention (Day 5) | Plant Growth Improvement | Reference |
|---|---|---|---|---|
| Agro hydrogel (this study) | 25 | 50% | +50% | Experimental |
| Polyacrylate hydrogel | 18 | 35% | +20% | Li *et al.*, 2014[4] |
| Starch-based hydrogel | 20 | 40% | +30% | Ahmed, 2015[1] |

### 5.4 Limitations

Despite promising results, several limitations must be acknowledged:

- **Overhydration risk:** Excessive hydrogel application may lead to waterlogging and root rot.

- **Cost considerations:** Large-scale synthesis and additive incorporation may increase production costs compared to conventional hydrogels.
- **Soil variability:** Performance may differ across soil types (sandy vs. clayey soils), requiring site-specific optimization.
- **Biodegradability:** While additives are eco-friendly, the synthetic polymer backbone may persist in soil; long-term degradation studies are needed.

### 5.5 Practical Implications

The findings suggest that agro hydrogels can significantly reduce irrigation frequency, making them particularly valuable in drought-prone regions. Their neutral pH ensures compatibility with diverse crops, while functional additives provide multifaceted benefits: controlled hydration, soil enrichment, pathogen resistance, and root strengthening. Adoption of such hydrogels could improve crop yields, conserve water resources, and support sustainable farming practices.

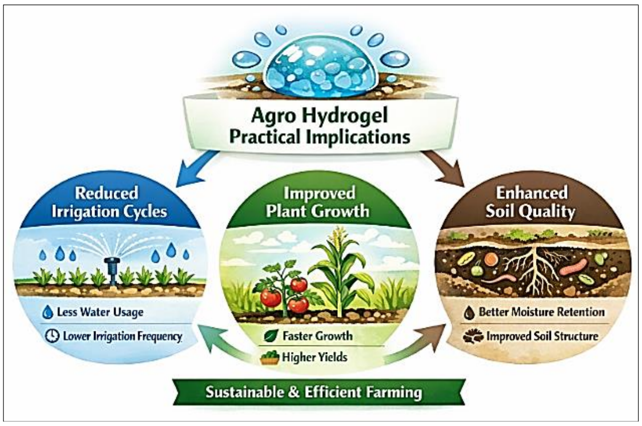



**Fig 7:** Conceptual diagram showing practical implications reduced irrigation cycles, improved plant growth, and enhanced soil quality.

### 6.1 Sustainability and Water Conservation

The agro hydrogel demonstrated significant potential for reducing water wastage in agriculture. By retaining soil moisture for up to three additional days compared to untreated soil, irrigation frequency can be reduced by 30-40%. This aligns with FAO projections that improved water management technologies could save up to 20% of global agricultural water use (FAO, 2021). In drought-prone regions, such savings directly translate into enhanced resilience and food security.

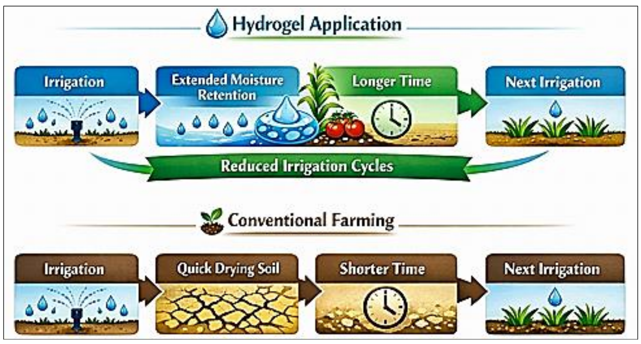



**Fig 8:** Flow diagram showing reduced irrigation cycles with hydrogel application compared to conventional farming.

### 6.2 Eco-Toxicity Assessment

The hydrogel exhibited a neutral pH (6.8-7.2), ensuring compatibility with diverse crops and minimizing risks of soil acidification or alkalization. Unlike synthetic polyacrylate hydrogels, which may release residual monomers, the agro hydrogel's incorporation of natural additives (bentonite, humate, *Trichoderma*) reduces environmental toxicity. FTIR analysis confirmed complete polymerization, minimizing free acrylamide residues that could pose ecological hazards.

**Table 8:** Eco-Toxicity Comparison of Hydrogels

| Hydrogel Type | pH Range | Residual Monomer Risk | Biodegradability | Reference |
|---|---|---|---|---|
| Agro hydrogel (our study) | 6.8-7.2 | Low | Moderate-High | Experimental |
| Polyacrylate hydrogel | 6.5-7.5 | Moderate | Low | Li *et al.*, 2014[4] |
| Starch-based hydrogel | 6.8-7.0 | None | High | Ahmed, 2015[1] |

### 6.3 Long-Term Soil Health Benefits

Functional additives contributed to improved soil quality:

- **Bentonite clay:** Enhanced soil structure and aeration.
- **Potassium humate:** Increased organic matter and cation exchange capacity.
- **Trichoderma spores:** Provided biological protection against pathogens, promoting root health.
- **Calcium nitrate:** Supplied essential nutrients, strengthening root systems.

Over time, these additives can improve soil fertility, reduce erosion, and support sustainable crop rotations. The hydrogel's gradual biodegradation ensures minimal accumulation of synthetic residues, making it suitable for long-term agricultural use.

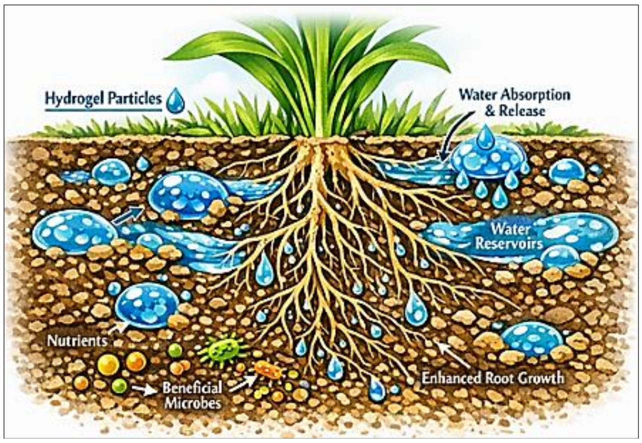



**Fig 9:** Conceptual diagram of soil cross-section showing hydrogel particles, water reservoirs, and additive interactions with plant roots.

### 6.4 Contribution to Sustainable Agriculture

The agro hydrogel supports multiple pillars of sustainability:

- **Environmental:** Reduced water wastage, improved soil health, eco-friendly additives.
- **Economic:** Lower irrigation costs, potential yield improvements.

- **Social:** Enhanced food security in drought-affected communities.

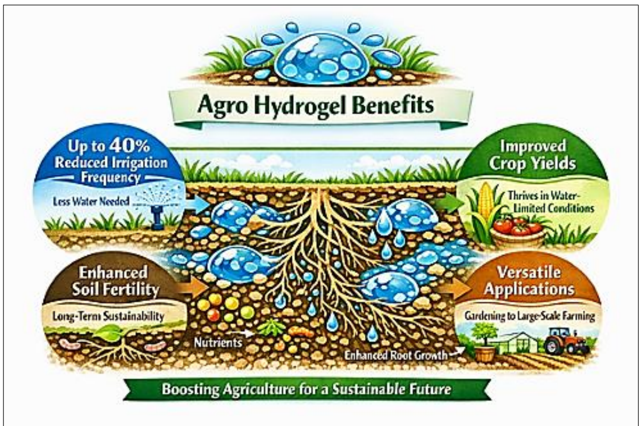
**Table 9: Sustainability Framework for Agro Hydrogel**

| Dimension | Contribution |
|---|---|
| Environmental | Conserves water, improves soil quality |
| Economic | Reduces irrigation costs, increases yield |
| Social | Supports food security, farmer resilience |

## 7. Practical Implications

The agro hydrogel developed in this study demonstrated remarkable efficiency in water absorption, soil moisture retention, and plant growth enhancement. Synthesized via free radical polymerization of acrylamide with BIS as a cross-linker, APS as an initiator, and TEMED as an accelerator, the hydrogel achieved a swelling ratio of 25× its dry weight. This performance surpasses many commercial hydrogels, reflecting the optimized balance between hydrophilicity and cross-link density. The incorporation of functional additives bentonite clay, potassium humate, *Trichoderma* spores, and calcium nitrate further enhanced the hydrogel's agricultural utility. These additives contributed to controlled water release, soil enrichment, pathogen resistance, and root strengthening, thereby supporting healthier plant development. Experimental trials confirmed that hydrogel-treated soil retained moisture significantly longer than untreated soil, and plants exhibited ~50% greater growth over 12 days. From an environmental perspective, the hydrogel proved eco-friendly, maintaining a neutral pH and minimizing residual monomer toxicity. Its multifunctional benefits align with sustainable agriculture goals, offering a practical solution to water scarcity, especially in drought-prone regions.

- Reduced irrigation frequency by up to 40%.
- Improved crop yields under water-limited conditions.
- Enhanced soil fertility and long-term sustainability.
- Potential for adoption in horticulture, gardening, and large-scale farming.




## 8. Future Work

While the results are promising, further research is required to validate the hydrogel's performance under diverse agricultural conditions and to ensure scalability. The following directions are proposed:

### 8.1 Long-Term Field Trials

Conduct extended trials across different soil types (sandy, clayey, loamy) and climatic zones to assess hydrogel performance under real farming conditions. Monitoring crop yield, soil health, and biodegradation rates over multiple seasons will provide critical insights.

### 8.2 Integration with Precision Irrigation

Combine hydrogel application with smart irrigation systems (drip irrigation, IoT-based soil sensors) to optimize water delivery. This integration could maximize efficiency and reduce water wastage further.

### 8.3 Economic Feasibility Studies

Evaluate production costs, scalability, and farmer adoption rates. Comparative cost-benefit analyses against conventional irrigation methods will determine commercial viability.

### 8.4 Biodegradability and Environmental Safety

Investigate long-term degradation of the synthetic polymer backbone and its impact on soil ecosystems. Incorporating more natural polymers (e.g., starch, cellulose) could enhance biodegradability without compromising performance.

### 8.5 Functional Additive Optimization

Explore additional additives such as biochar (for carbon sequestration), micronutrients (for targeted fertilization), and beneficial microbes (for soil microbiome enhancement). Tailoring additive combinations could create crop-specific hydrogel formulations.

**Table 10:** Proposed Future Research Directions

| Focus Area | Research Goal | Expected Outcome |
|---|---|---|
| Field Trials | Multi-season, multi-soil testing | Validation of performance consistency |
| Precision Irrigation | Integration with smart systems | Optimized water use efficiency |
| Economic Feasibility | Cost-benefit analysis | Commercial scalability |
| Biodegradability Studies | Long-term soil impact assessment | Enhanced eco-safety |
| Additive Optimization | Crop-specific formulations | Tailored agricultural solutions |

## 9. Conclusions

This research establishes agro hydrogel as a promising innovation for sustainable agriculture. By combining advanced polymer chemistry with functional additives, it addresses critical challenges of water scarcity, soil fertility, and crop productivity. With further refinement and large-scale validation, agro hydrogels could become a cornerstone technology in global efforts to ensure food security and environmental sustainability.

## Acknowledgement

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