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Formaldehyde-crosslinked GIPANA–polyacrylamide hydrogel improves root-zone soil moisture, infiltration, and crop yield under arid irrigation in the Turkistan Region

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Abstract

This study evaluated a superabsorbent polymer (SAP) hydrogel synthesized from hydrolyzed polyacrylonitrile (GIPANA) and an anionic polyacrylamide component cross-linked with formaldehyde for improving soil water status and crop performance under arid field conditions in the Turkistan Region (Saryagash District, Kazakhstan) during the 2024 growing season. A randomized complete block design with three replicates tested three crops (rice, wheat, saffron) under three hydrogel treatments: control (T0), 0.2% (w/w) hydrogel (T1), and 0.4% (w/w) hydrogel (T2), with identical crop-specific irrigation inputs across treatments. Soil moisture was monitored using TDR at 0–10, 10–20, and 20–40 cm depths over time; field infiltration, wetting depth, and a retention coefficient were determined using double-ring infiltrometry; and laboratory swelling capacity was measured for unmodified and Ca–P modified hydrogels. The experimental soil remained non-saline and chemically stable across the season, enabling attribution of observed responses primarily to hydrogel amendment. Hydrogel application increased volumetric soil water content in a consistent dose-responsive manner acrss crops and depths, with the largest and most persistent gains under T2, particularly in the 20–40 cm layer in rice later in the season. In parallel, infiltration rate, wetting depth, and retention coefficient increased substantially with hydrogel dose. Laboratory tests confirmed rapid swelling and high absorption capacity, which further increased with Ca–P modification. Improved soil water availability translated into enhanced vegetative growth (plant height and leaf number) and higher yields in all crops, with T2 providing the most consistent agronomic benefits. Overall, the results demonstrate that GIPANA–polyacrylamide hydrogel amendment can improve root-zone moisture dynamics, soil water transmission, and crop productivity in arid irrigated systems, supporting its use within integrated water-saving soil management strategies.

Keywords: Superabsorbent polymer, Hydrogel, Soil moisture, Infiltration, Arid irrigated agriculture.

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Introduction

Arid and semi-arid irrigated agroecosystems are increasingly exposed to soil water deficit because potential evapotranspiration commonly exceeds precipitation during the growing season, while irrigation water availability and delivery efficiency remain limiting (Ingrao et al., 2023; Nilahyane et al., 2023). In southern Kazakhstan, including the Turkistan Region, high summer evaporative demand and episodic heat stress can accelerate the depletion of plant-available water between irrigation events and reduce yield stability (Tokbergenova et al., 2025). Under these conditions, improving the capacity of the root zone to retain and

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redistribute irrigation water is a practical pathway to increase water productivity and buffer crops against short-term drought episodes. In parallel, regional water-management constraints are intensifying interest in alternative irrigation resources and quality management, because water scarcity and soil degradation pressures are particularly acute in arid zones and can interact with salinity/sodicity risks when marginal waters are used (Bulanbayeva et al., 2025).

Superabsorbent polymer (SAP) hydrogels are cross-linked polymer networks that absorb large quantities of water and release part of the stored water as the surrounding soil dries (Chang et al., 2021). When incorporated into soil, SAPs can increase the water retained at agronomically relevant matric potentials, stabilize short-term fluctuations in soil moisture, and reduce non-productive losses (surface evaporation and deep percolation) depending on soil texture and irrigation management. Recent synthesis and applications reviews highlight broad interest in SAPs for sustainable agriculture, particularly in water-limited regions where small improvements in root-zone water availability can translate to measurable yield gains (Rizwan et al., 2021; Chang et al., 2021; Palma et al., 2024). Dose is a key determinant of agronomic response; for instance, a synthesis of published results reports that ~0.5% SAP (w/w) showed no clear effect on maize seedling height while inhibiting root growth, and 1% SAP caused negative effects on both height and root development—indicating that excessive rates can be counterproductive and supporting the need to test moderate application windows such as 0.2–0.4% (w/w) (Krasnopeeva et al., 2022). Field evidence from Kazakhstan further supports strong SAP responsiveness in coarse media: in sand-dune soil containing >95% sand, polymer hydrogels showed maximum water absorption up to ~201 times their own weight and significantly increased both full moisture capacity and smallest moisture capacity across polymer–sand mixtures, with potassium polyacrylate reporting the highest moisture-capacity gains (Naushabayev et al., 2022). In addition, field-scale evidence from semi-arid cropping systems indicates that SAP benefits can be amplified when the amendment is integrated with improved agronomic practices and optimized application methods (e.g., seed treatment or slurry application), leading to measurable gains in system water productivity and, in some cases, profitability under water-limited conditions (Rajanna et al., 2024). Likewise, coupling deficit-irrigation scheduling with SAP hydrogel has been reported to enhance yield and water productivity in Brassica juncea under semi-arid conditions, emphasizing that SAPs are most effective when evaluated as part of an integrated irrigation–soil management strategy rather than as a stand-alone input (Rathore et al., 2020).

Recent field evidence further indicates that management context and application pathway can modulate practical benefits: under drip irrigation in red cabbage, a split-plot experiment comparing full (100% ETc) and reduced (75% ETc) irrigation reported ~3–6% higher root-zone SWC with SAPs and improvements in crop and irrigation water productivity (reported CWP +14% and IWP +8–14% under reduced irrigation), with root dipping often performing comparably or better than soil application (Kishor et al., 2024). In a two-year soybean–wheat system, modified low-dose application approaches (seed coating and slurry) improved system productivity (reported 8.1–26.7%) and system water productivity (17.6–33.8%), and increased wheat yield (8.0–32.2%) while using ~10 cm less irrigation water than the no-hydrogel control (Adireddy et al., 2024).

The effect of SAPs on soil hydrophysical behavior is not unidirectional. By swelling, SAP particles occupy pore space and modify pore-size distribution, which can increase water retention but also alter infiltration and hydraulic conductivity. Under some conditions, swelling reduces saturated hydraulic conductivity and limits rapid drainage, supporting water conservation but requiring careful matching of dose and placement to avoid restricting water entry or aeration. For example, under deficit irrigation, hydrogel addition increased soil water content and improved some hydrophysical indicators, while also decreasing saturated hydraulic conductivity in a soil-dependent manner (Abdelghafar et al., 2024). Conversely, engineered hydrogel networks can be designed to slow water movement through coarse media and increase retention time, which may improve water availability to roots when irrigation inputs are pulsed (Abdelgelil et al., 2025). A two-year field study under drip irrigation further showed that SAP hydrogels can increase root-zone soil water content (SWC) by approximately 2–6% depending on hydrogel type, and that application mode (root dipping vs soil application) can significantly modulate the magnitude and persistence of this moisture benefit (Kishor et al., 2024). Consistent with this integrated view, a deficit-drip case study on bean reported that combining hydrogel amendment with reduced irrigation levels can maximize crop water productivity and improve water-use efficiency indices, reinforcing the rationale for evaluating SAPs within deficit-irrigation frameworks in water-scarce regions (Satriani et al., 2018).

Hydrogel formulation is also critical. Mineral or composite modification is increasingly used to tune swelling kinetics, mechanical stability, and water release behavior. Composite hydrogels that incorporate mineral additives or clays can increase the density of hydrophilic interaction sites and improve structural integrity, often improving soil water retention and plant performance under arid conditions. A polyacrylamide–Fuller's earth composite, for instance, was reported to improve soil water retention and crop yield, illustrating how inorganic fillers can complement polymer networks (Rajanna et al., 2022). In parallel, cellulose-based and other biodegradable hydrogel platforms are being developed to provide similar agronomic functions with improved environmental profiles (Das et al., 2025). This shift is partly driven by concerns that many conventional SAPs rely on petroleum-based, poorly degradable polymers, motivating the development of bio-derived networks that can deliver water-buffering benefits with improved end-of-life behavior. In a recent cellulose-derivative hydrogel system (NaCMC/HEC crosslinked with citric acid), soil amendment with 2% hydrogel increased total porosity (reported ~57% vs ~53% in the unamended soil) and reduced bulk density (reported ~1.06 vs ~1.16 g cm^{-3}), while improving plant-level water-use efficiency by roughly 25–46% depending on crop and season (Das et al., 2025). These findings support the premise that biodegradable hydrogel platforms can simultaneously enhance soil physical condition (aeration/porosity) and water productivity—traits that are highly relevant for arid irrigated systems.

In addition, semi-synthetic SAPs (natural polymer backbones grafted/modified with synthetic chains) are highlighted as especially promising for agriculture because they can combine the biocompatibility/biodegradability advantages of natural polymers with the higher absorbency/retention of synthetic polymers, and they can be engineered as matrices for slow nutrient release—an attribute particularly relevant for dry regions (Krasnopeeva et al., 2022).

Against this background, the present study evaluated a GIPANA- and polyacrylamide-based hydrogel cross-linked with formaldehyde under arid field conditions in the Turkistan Region (Kazakhstan) using three contrasting crops (rice, wheat, and saffron) and two application rates (0.2% and 0.4% w/w). The experiment integrated measurements of baseline and end-of-season soil status, TDR-derived volumetric soil water content by depth and time, soil water transmission indicators (double-ring infiltration, wetting depth, and a retention coefficient), laboratory swelling capacity, and crop growth and yield. This integrated approach enables assessment of whether hydrogel amendment improves the soil water regime in situ and whether those changes translate into agronomically meaningful benefits under practical irrigation management.

Material and Methods

Study site and experimental period

The field experiment was conducted in Kazakhstan (Turkistan Region, Saryagash District) during the 2024 growing season (April–October). The area is characterized by an arid to semi-arid continental climate with high summer evaporative demand, such that soil water deficit is a primary limitation for crop growth and yield stability under field conditions.

Soil sampling and laboratory analyses

To characterize the experimental field and quantify seasonal and treatment-related changes, composite soil samples were collected before treatment establishment (baseline) and after harvest (end of season) from each plot at 0–20 cm and 20–40 cm depths using a soil auger. Samples were air-dried, gently disaggregated, and passed through a 2-mm sieve prior to laboratory determination of chemical and physical properties. Organic matter (humus) content was determined by the Tyurin method (GOST 26213-91). Soil reaction (pH) was measured in a salt extract prepared following the TSINAO method (GOST 26483-85), and electrical conductivity (EC) was measured in a 1:1 soil-to-water extract following Rowell (1996). Total carbonates ($CaCO_3$) were analyzed using the Scheibler calcimeter (Loeppert and Suarez, 1996), while cation exchange capacity (CEC) was determined according to Chapman (1965). Particle-size distribution (granulometric composition) was measured using standardized laboratory procedures for grain-size determination (GOST 12536-2014). Key physical parameters, including bulk density, total porosity, and water permeability, were determined using standardized methods for soil physical characteristics (GOST 5180-2015).

Experimental design and treatments

The trial was established as a randomized complete block design (RCBD) with three blocks (replicates). Three crops (rice, wheat, saffron) and three hydrogel treatments were evaluated, yielding 27 plots (3 crops × 3 treatments × 3 blocks). Each plot measured 5 × 2 m (10 m^2), with 1 m spacing between adjacent plots and 2 m spacing between blocks. Treatments were randomized within each block to minimize spatial effects. The hydrogel treatments were T0 (control, no hydrogel), T1 (hydrogel at 0.2% w/w), and T2 (hydrogel at 0.4% w/w).

Crops and agronomic management

The studied crops were rice (Oryza sativa L.), wheat (Triticum aestivum L.), and saffron (Crocus sativus L.). Crop husbandry followed local agronomic practice. All management operations (land preparation, planting, weed control, and crop protection) were kept uniform across treatments, and hydrogel dose was the only planned factor differing among plots within each crop.

Hydrogel synthesis and preparation

The superabsorbent hydrogel was synthesized via a condensation/crosslinking route based on hydrolyzed polyacrylonitrile (GIPANA; 33% aqueous solution) and an anionic polyacrylamide (PAA) component, using aqueous formaldehyde (formalin) as the chemical crosslinker to form a three-dimensional polymer network, following published procedures for GIPANA–PAA–formaldehyde systems with minor operational adjustments. In brief, the required amounts of GIPANA solution and anionic PAA were dispersed in distilled water and stirred continuously for 25–30 min to obtain a homogeneous reaction mixture. The reaction medium was then heated and maintained at ~80 °C, after which formalin was added to initiate crosslinking. Throughout network formation, the pH was controlled and stabilized below pH 9 by careful neutralization with sulfuric acid to maintain appropriate reaction conditions and prevent alkaline destabilization of the developing gel structure. Ammonium sulfate was incorporated during synthesis as a mineral additive to enhance water-holding behavior and absorption kinetics by modifying the ionic environment and interaction sites within the polymer matrix. After completion of crosslinking, the gel was repeatedly washed with distilled water to remove residual reactants and soluble by-products, then neutralized. The purified hydrogel was dried to constant mass, mechanically ground, and sieved to obtain granules in the 1–3 mm size fraction for subsequent field application.

Hydrogel material and field application

The prepared hydrogel granules (1–3 mm) were applied to field plots at two rates (0.2% and 0.4% w/w, calculated on a dry soil mass basis for the 0–20 cm layer) and incorporated uniformly into the upper soil (0–20 cm) prior to sowing/planting. Incorporation was performed under the same tillage conditions for all plots to ensure consistent mixing and placement within the effective root zone. This application strategy was selected to maximize contact between swelling hydrogel particles, infiltrating irrigation water, and developing roots, thereby improving short-term water storage and moisture redistribution within the crop rooting zone.

Irrigation management

Irrigation schedules were crop-specific and followed local practice, but within each crop the irrigation regime was kept identical across hydrogel treatments (i.e., irrigation was not adjusted by hydrogel dose). Rice received 600 m^3 ha^{-1} per irrigation event, applied twice per week throughout the irrigated period. Wheat and saffron each received 400 m^3 ha^{-1} per irrigation event, also applied twice per week. This approach ensured that observed differences among treatments could be attributed to hydrogel amendment rather than to differential irrigation inputs.

Measurements and data collection

Soil moisture monitoring (TDR): Volumetric soil water content was measured using time-domain reflectometry (TDR) at 0–10, 10–20, and 20–40 cm depths. Measurements were scheduled by crop and expressed as days after the start of monitoring: rice at 30, 60, and 90 days, wheat at 30 and 60 days, and saffron at 30 days. Within each plot, multiple probe readings were taken at representative positions and averaged to obtain a plot value. For each crop × treatment × depth × sampling time, values were then aggregated across the three blocks (n = 3) to derive treatment means for reporting and visualization.

Infiltration, retention coefficient, and wetting depth: Field infiltration was measured at the plot scale using a double-ring infiltrometer and expressed as m day^{-1}. During the same field procedure, wetting depth (cm) was determined as the depth of observable wetting/redistribution associated with the infiltration event. A retention coefficient (dimensionless) was derived from plot measurements using a consistent calculation approach applied to all plots; the coefficient was computed from the measured infiltration/wetting observations to represent the soil's capacity to retain and redistribute infiltrated water under the field conditions of the trial. Measurements were conducted for all crop × treatment combinations with replication corresponding to the RCBD structure.

Hydrogel swelling (laboratory absorption) test: Hydrogel water absorption was evaluated under laboratory conditions for the unmodified material and for hydrogel material modified with Ca–P mineral additive at different inclusion rates. Samples were immersed in water and absorption was recorded as g g^{-1} at 5, 30, and 60 minutes to capture the early uptake phase and near-equilibrium behavior.

Plant growth measurements: Vegetative growth was assessed 7–10 days before harvest. Plant height (cm) and leaf number (count) were recorded from 10 randomly selected plants per plot using uniform sampling criteria across treatments.

Yield and yield components: At maturity, crop yield was harvested from the full plot area (10 m^2) and converted to t ha^{-1}. In addition to grain yield, total aboveground mass (t ha^{-1}) and 1000-unit mass (g) were determined from representative harvest subsamples following standard agronomic procedures to quantify treatment effects on biomass accumulation and grain filling.

Statistical analysis

The experiment followed a randomized complete block design (RCBD) with three blocks (replicates). For each crop, treatment effects on soil moisture (by depth and sampling date), infiltration rate, wetting depth, retention coefficient, swelling capacity, growth traits (plant height and leaf number), and yield components were evaluated using analysis of variance (ANOVA) under the RCBD framework, with hydrogel treatment considered as a fixed factor and block as a random factor. When repeated measurements were available over time (e.g., TDR soil moisture), each sampling date was analyzed separately within each depth to avoid pseudo-replication, and treatment means were compared within the same date × depth stratum. Mean separation was performed using Tukey's HSD test at $p < 0.05$. Prior to ANOVA, residual normality and homogeneity of variance were checked using the Shapiro–Wilk and Levene tests, respectively. When assumptions were not met, data were log- or square-root transformed as appropriate; if assumptions remained violated, the nonparametric Kruskal–Wallis test followed by Dunn's post-hoc procedure (with multiplicity adjustment) was used. Results are reported as means ± standard error (SE) unless otherwise stated.

Results

Soil baseline and end-of-season status

Across the 2024 field season, the experimental soil remained non-saline and exhibited only modest, agronomically small shifts in its key chemical and physical properties (Table 1). Overall, the data indicate that the trial was conducted on a slightly acidic to near-neutral sandy loam, with moderate cation exchange capacity and relatively stable structural indicators, providing a consistent baseline for evaluating hydrogel-driven changes in soil water dynamics and crop performance.

In the surface layer (0–20 cm), soil pH increased slightly from 6.4 at the start of the season to 6.5 at the end, reflecting a minimal shift toward neutrality (Table 1). Electrical conductivity rose from 0.45 to 0.48 dS m^{-1}, remaining well below thresholds commonly associated with salinity constraints for most field crops, and confirming that treatment responses observed later in the study occurred under non-saline conditions. Organic matter showed a similarly small seasonal increase from 3.1% to 3.2%, consistent with modest within-season variability and/or minor residue inputs during crop growth. Importantly, carbonate content remained constant (3.5% $CaCO_3$) and CEC was stable at 19 cmol(+) kg^{-1}, suggesting that the soil's buffering capacity and exchange sites did not change materially during the experimental period (Table 1). Bulk density decreased slightly from 1.32 to 1.30 g cm^{-3}, but this change was small and the overall magnitude indicates a soil with moderate compaction status typical for cultivated sandy loam systems.

The subsurface layer (20–40 cm) displayed the same overall stability (Table 1). pH remained constant at 6.4, while EC increased marginally from 0.40 to 0.42 dS m^{-1}, again confirming the absence of salinity accumulation across the season. Organic matter increased from 3.0% to 3.1%, consistent with minor seasonal fluctuations rather than a substantive change in carbon status. Carbonate content (3.5% $CaCO_3$) and CEC (17 cmol(+) kg^{-1}) remained unchanged, and bulk density shifted only slightly from 1.35 to 1.34 g cm^{-3}. Texture was essentially stable at both depths, with the surface soil classified as 45–35–20% (sand–silt–clay) and the deeper layer as 40–38–22%, indicating no detectable redistribution of particle-size fractions over the study period (Table 1).

Taken together, these results demonstrate that the experiment was conducted under chemically stable baseline conditions, with no evidence of salinization or major shifts in texture, CEC, or bulk density during the season. This stability supports attributing the observed differences in soil moisture dynamics, infiltration behavior, and crop responses primarily to hydrogel application rather than to confounding changes in underlying soil chemical status (Table 1).

Table 1. Soil properties at the start and end of the season.

Depth, cm	Time	pH	EC, dS m^{-1}	OM, %	$CaCO_3$, %	CEC, cmol(+) kg^{-1}	Bulk density, g cm^{-3}	Texture		
								Sand, %	Silt, %	Clay, %
0–20	Start	6.4	0.45	3.1	3.5	19	1.32	45	35	20
0–20	End of season	6.5	0.48	3.2	3.5	19	1.30	45	35	20
20–40	Start	6.4	0.40	3.0	3.5	17	1.35	40	38	22
20–40	End of season	6.4	0.42	3.1	3.5	17	1.34	40	38	22

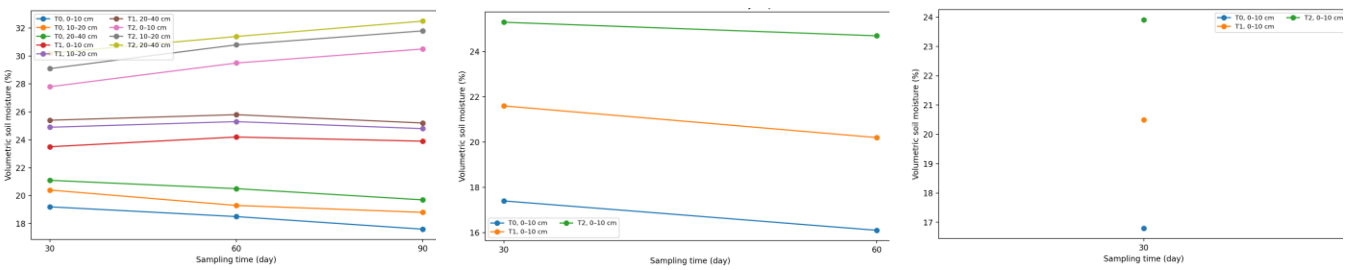
Soil moisture dynamics

Hydrogel incorporation produced a clear, dose-responsive increase in TDR-derived volumetric soil water content across crops and monitored depths, with T2 (0.4% w/w) consistently maintaining the highest moisture and T1 (0.2% w/w) showing an intermediate response relative to the control (Figure 1). Values shown represent treatment means aggregated across the three RCBD blocks (n=3).

In rice, treatment effects were evident at all depths (0–10, 10–20, and 20–40 cm) and became more pronounced as the season progressed (Figure 1a). At 30 days, volumetric moisture increased from 19.2% (T0) to 27.8% (T2) at 0–10 cm, from 20.4% to 29.1% at 10–20 cm, and from 21.1% to 30.2% at 20–40 cm. By 60 days, the moisture advantage under T2 was maintained or increased (e.g., 31.4% at 20–40 cm under T2 vs 20.5% in T0). By 90 days, the separation was strongest, particularly in the subsoil: at 20–40 cm, volumetric moisture reached 32.5% under T2 compared with 19.7% in the control, while T1 remained intermediate at 25.2% (Figure 1a). This pattern indicates that the hydrogel not only increased surface water content but also supported deeper wetting and moisture persistence within the effective root zone over time.

In wheat, the hydrogel effect was also distinct at the monitored 0–10 cm layer (Figure 1b). At 30 days, moisture increased from 17.4% (T0) to 25.3% (T2), with T1 at 21.6%; at 60 days, T2 maintained 24.7% compared with 16.1% in the control (T1: 20.2%). These results suggest that hydrogel-amended plots buffered the seasonal decline in near-surface soil moisture that typically occurs under high evaporative demand.

For saffron, the single available sampling point at 30 days similarly showed a dose-response at 0–10 cm (Figure 1c), where volumetric moisture increased from 16.8% (T0) to 23.9% (T2) (T1: 20.5%). Collectively, the moisture profiles in Figure 1a–c confirm that hydrogel addition improved soil water status, with the higher dose delivering the most persistent benefits under field conditions.



(a) (b) (c)

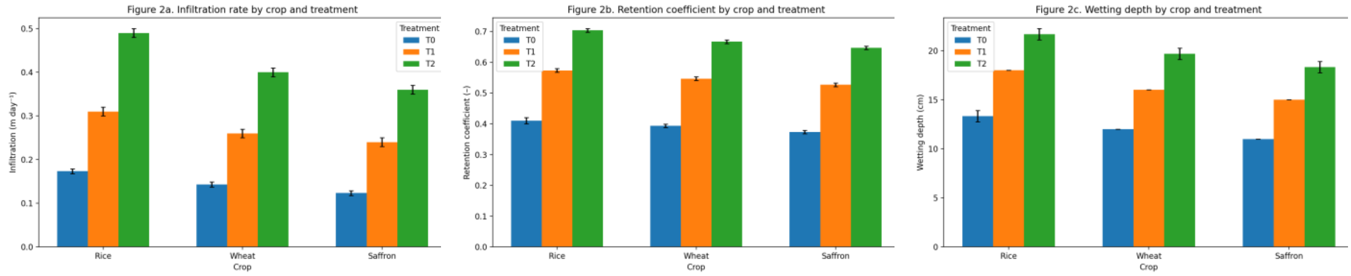
Figure 1. TDR-derived volumetric soil water content (%) measured at three depths (0–10, 10–20, and 20–40 cm) under hydrogel treatments in the 2024 field experiment in the Turkistan Region (Kazakhstan). Treatments were T0 (control, no hydrogel), T1 (0.2% w/w hydrogel), and T2 (0.4% w/w hydrogel). The x-axis represents sampling time expressed as days after the start of the monitoring period. (a) Rice, measured at 30, 60 and 90 days; (b) Wheat, measured at 30 and 60 days; (c) Saffron, measured at 30 days. Values are treatment means across the three blocks (n = 3).

Infiltration and wetting depth.

Hydrogel incorporation produced a strong, dose-dependent improvement in soil water transmission parameters across all crops, as reflected by higher infiltration rate, retention coefficient, and wetting depth (Figure 2). In all three metrics, T2 (0.4% w/w) consistently outperformed T1 (0.2% w/w), indicating that the hydrogel effect scaled with application rate.

In rice, infiltration increased from 0.17 ± 0.01 m day^{-1} in the control (T0) to 0.31 ± 0.01 m day^{-1} under T1 and 0.49 ± 0.01 m day^{-1} under T2 (Figure 2a), corresponding to an approximate 79% (T1) and ~183% (T2) increase relative to T0. This was accompanied by a marked rise in the retention coefficient from 0.41 ± 0.01 (T0) to 0.57 ± 0.01 (T1) and 0.70 ± 0.01 (T2) (Figure 2b), together with deeper wetting, increasing from 13.3 ± 0.6 cm (T0) to 18.0 ± 0.0 cm (T1) and 21.7 ± 0.6 cm (T2) (Figure 2c). These combined shifts indicate improved downward redistribution of irrigation water and greater moisture penetration into the effective rooting zone under hydrogel-amended conditions.

Comparable dose-responsive responses were recorded for wheat and saffron. In wheat, infiltration rose from 0.14 ± 0.01 m day^{-1} (T0) to 0.26 ± 0.01 m day^{-1} (T1) and 0.40 ± 0.01 m day^{-1} (T2), while wetting depth increased from 12.0 ± 0.0 cm to 16.0 ± 0.0 cm and 19.7 ± 0.6 cm, respectively (Figure 2a,c). In saffron, infiltration increased from 0.12 ± 0.01 m day^{-1} (T0) to 0.24 ± 0.01 m day^{-1} (T1) and 0.36 ± 0.01 m day^{-1} (T2), with wetting depth increasing from 11.0 ± 0.0 cm to 15.0 ± 0.0 cm and 18.3 ± 0.6 cm (Figure 2a,c). Retention coefficients followed the same consistent ranking (T2 > T1 > T0) in both crops (Figure 2b), supporting the interpretation that hydrogel amendment enhanced both water entry into the soil and the soil's capacity to retain and redistribute infiltrated water under arid field conditions.



(a) (b) (c)

Figure 2. Hydrogel effects on field-scale soil water transmission parameters measured in the 2024 experiment in the Turkistan Region (Kazakhstan). Treatments were T0 (control, no hydrogel), T1 (0.2% w/w hydrogel), and T2 (0.4% w/w hydrogel). (a) Infiltration rate (m day^{-1}) determined using a double-ring infiltrometer; (b) retention coefficient (dimensionless) calculated from plot measurements as defined in the Methods; (c) wetting depth (cm) assessed during the infiltration measurements. Bars represent treatment means across crops (rice, wheat, saffron) and error bars indicate standard deviation across blocks (n = 3).

Hydrogel swelling capacity

Laboratory swelling tests confirmed that the synthesized hydrogel behaved as a fast-acting superabsorbent, exhibiting rapid initial water uptake followed by a high, sustained absorption capacity over the 60-min observation window (Table 2). Across all formulations, the steepest increase occurred within the first 30 min, indicating that the material can quickly capture available water after irrigation or rainfall events and subsequently function as a short-term reservoir within the soil matrix.

For the unmodified hydrogel, absorption increased from 55 g g^{-1} at 5 min to 160 g g^{-1} at 30 min—an almost threefold increase—before reaching 195 g g^{-1} at 60 min (Table 2). This pattern suggests that a large proportion of the swelling potential is realized rapidly, while the additional increase from 30 to 60 min reflects continued water diffusion into the polymer network and progressive equilibration of the gel structure.

Incorporation of the Ca–P mineral additive consistently enhanced swelling performance relative to the unmodified material, both during the early uptake phase and at longer immersion times (Table 2). At a 5% additive rate, absorption increased from 72 g g^{-1} at 5 min to 210 g g^{-1} at 30 min and 250 g g^{-1} at 60 min. Compared with the unmodified hydrogel, these values correspond to improvements of approximately +31% (5 min), +31% (30 min), and +28% (60 min), demonstrating that mineral modification strengthened the hydrogel's water-binding capacity without delaying its uptake kinetics.

A further improvement was observed at the 10% Ca–P rate (Table 2). At 5 min, absorption reached 85 g g^{-1}, indicating a substantially higher initial uptake than both the unmodified and 5% formulations. By 30 min, absorption increased to 245 g g^{-1}, and by 60 min it reached 290 g g^{-1}, representing the maximum swelling recorded in this study. Relative to the unmodified hydrogel, the 10% Ca–P modification increased absorption by approximately +55% at 5 min, +53% at 30 min, and +49% at 60 min (Table 2). These consistent gains across time points indicate that Ca–P modification increased the effective number of hydrophilic/ionic interaction sites and/or improved network structure such that the polymer could accommodate more water at equilibrium while still swelling quickly.

Overall, the swelling results demonstrate that the hydrogel has strong water uptake capacity and that Ca–P mineral modification further amplifies this capacity in a dose-dependent manner (Table 2). From an agronomic perspective, the combination of rapid early swelling and high sustained absorption is desirable under arid-field irrigation regimes, where efficient capture of episodic water inputs and gradual release to the root zone can improve plant-available water during periods of high evaporative demand.

Table 2. Laboratory water absorption (swelling) of the hydrogel (g g^{-1}).

Sample	Mineral additive (%)	Time (min)	Absorption (g g^{-1})
Unmodified hydrogel	0	5	55
Unmodified hydrogel	0	30	160
Unmodified hydrogel	0	60	195
Ca–P modified hydrogel	5	5	72
Ca–P modified hydrogel	5	30	210
Ca–P modified hydrogel	5	60	250
Ca–P modified hydrogel	10	5	85
Ca–P modified hydrogel	10	30	245
Ca–P modified hydrogel	10	60	290

Plant growth responses.

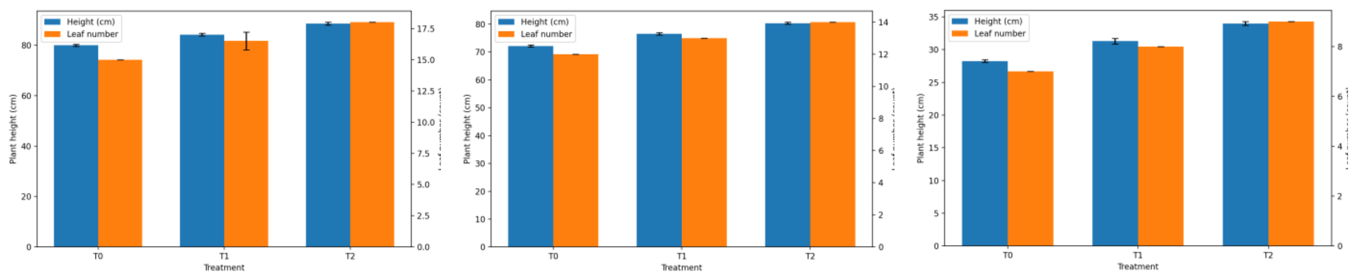
Hydrogel application consistently enhanced vegetative growth in all crops, with a clear dose response (T2 > T1 > T0) for both plant height and leaf number (Figure 3a–c). Overall, the growth benefits mirrored the improvements observed in soil moisture and infiltration, indicating that hydrogel-mediated changes in the soil water regime translated into measurable gains in canopy development.

In rice, the effect was pronounced (Figure 3a). Mean plant height increased from 79.90 ± 0.42 cm in the control (T0) to 84.50 ± 0.71 cm under T1 and 88.50 ± 0.57 cm under T2, corresponding to a net gain of approximately +8.6 cm at the higher dose. Leaf number followed the same ranking, increasing from 15.0 ± 0.0 (T0) to 16.0 ± 0.0 (T1) and 17.0 ± 0.0 (T2). The simultaneous increase in height and leaf production suggests improved plant water status during the main vegetative period, supporting more sustained tillering/canopy expansion in hydrogel-amended plots.

In wheat, growth responses were similarly dose dependent (Figure 3b). Mean height increased from 46.00 ± 0.28 cm (T0) to 54.35 ± 0.21 cm (T1) and 60.00 ± 0.14 cm (T2), representing an overall increase of about 30% at T2 relative to the control. Leaf number increased from 5.0 ± 0.0 (T0) to 6.0 ± 0.0 (T1) and 7.0 ± 0.0 (T2), indicating a consistent improvement in early canopy establishment and leaf area formation under hydrogel treatments.

For saffron, the hydrogel effect remained evident despite lower absolute growth values (Figure 3c). Mean plant height increased from 33.00 ± 0.14 cm (T0) to 41.00 ± 0.28 cm (T1) and 49.00 ± 0.71 cm (T2), while leaf number rose from 9.0 ± 0.0 to 11.0 ± 0.0 and 13.0 ± 0.0, respectively. These changes imply improved shoot development under hydrogel-amended conditions, consistent with enhanced near-surface moisture availability observed earlier in the season.

Collectively, the results confirm that hydrogel incorporation—particularly at 0.4% (w/w)—promoted more vigorous canopy development across contrasting crops, supporting the interpretation that improved soil water availability and retention contributed to stronger vegetative growth (Figure 3).



(a) (b) (c)

Figure 3. Effects of hydrogel treatments on crop vegetative growth in the 2024 field experiment in the Turkistan Region. Treatments were T0 (control, no hydrogel), T1 (0.2% w/w hydrogel), and T2 (0.4% w/w hydrogel). Bars represent mean plant height (cm; left y-axis) and mean leaf number (count; right y-axis). Error bars indicate standard deviation (SD) across blocks (n = 3). (a) Rice, (b) wheat, and (c) saffron. Height and leaf number are shown in different colors for visual separation.

Yield responses

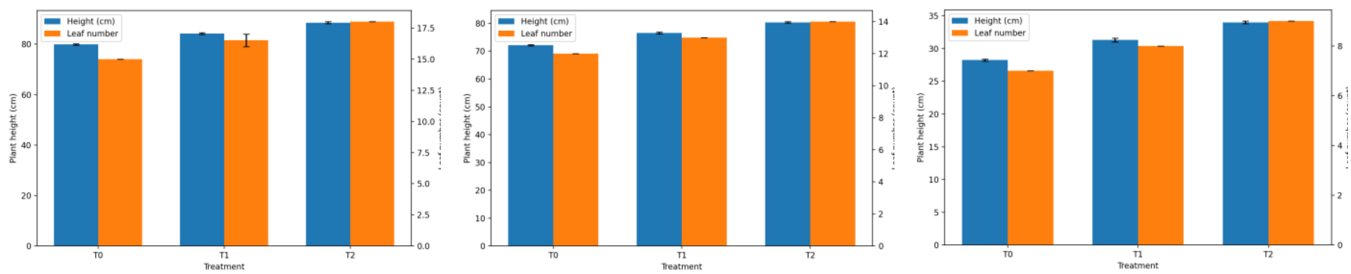
Yield responses closely tracked the improvements in soil water availability and transmission capacity observed under hydrogel treatments. Across all crops, both hydrogel doses increased yield relative to the control, and the higher dose T2 (0.4% w/w) delivered the largest and most consistent gains (Figure 5a–c). The intermediate dose T1 (0.2% w/w) produced a clear stepwise response between T0 and T2, indicating a dose-dependent agronomic benefit rather than a threshold-only effect.

In rice, mean grain yield increased from 6.12 ± 0.05 t ha^{-1} (T0) to 6.90 ± 0.03 t ha^{-1} (T1) and 7.61 ± 0.04 t ha^{-1} (T2), corresponding to approximately +13% and +24% increases over the control, respectively (Figure 5a). Yield improvement was accompanied by higher total aboveground biomass and improved grain filling indicators; for example, total mass increased from 9.38 ± 0.04 t ha^{-1} (T0) to 10.93 ± 0.04 t ha^{-1} (T2), while the 1000-unit mass rose from 28.35 ± 0.21 g to 30.55 ± 0.07 g (Figure 5a). These changes are consistent with prolonged moisture availability in the effective rooting zone, particularly at deeper layers later in the season, as reflected by the higher subsoil moisture maintained under T2 (Figure 1a) and the larger wetting depth (Figure 2c).

In wheat, grain yield increased from 4.24 ± 0.02 t ha^{-1} (T0) to 4.81 ± 0.02 t ha^{-1} (T1) and 5.34 ± 0.03 t ha^{-1} (T2), equivalent to roughly +14% and +26% gains over the control (Figure 5b). Concomitantly, total mass increased from 7.08 ± 0.04 to 8.38 ± 0.04 t ha^{-1}, and the 1000-unit mass increased from 39.55 ± 0.07 to 41.45 ± 0.07 g (Figure 5b), suggesting enhanced canopy function and assimilate partitioning under improved soil moisture regimes.

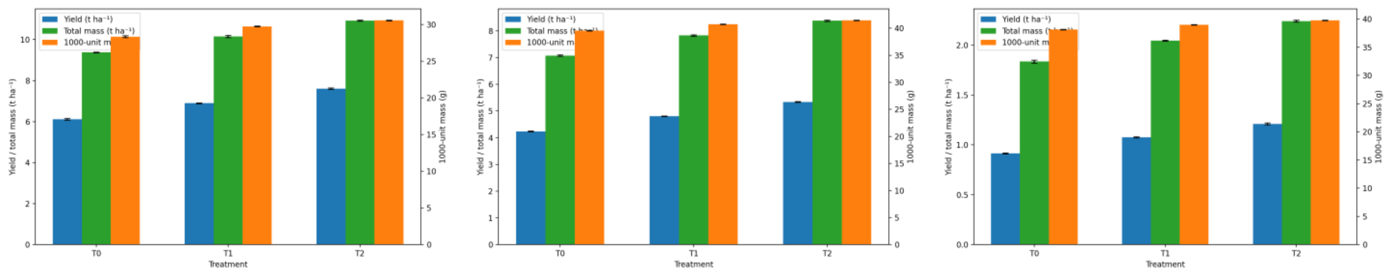
For saffron, although absolute yields were smaller due to crop type, the proportional response was substantial: yield increased from 0.92 ± 0.01 t ha^{-1} (T0) to 1.08 ± 0.01 t ha^{-1} (T1) and 1.21 ± 0.01 t ha^{-1} (T2), representing approximately +18% and +32% improvements (Figure 5c). The parallel increase in total mass (from 1.84 ± 0.02 to 2.24 ± 0.01 t ha^{-1}) and modest increases in 1000-unit mass (38.15 ± 0.07 to 39.75 ± 0.07 g) further support that hydrogel addition improved growth conditions and yield formation (Figure 5c).

Collectively, the yield data confirm that hydrogel incorporation—especially at 0.4% (w/w)—provided agronomically meaningful gains across contrasting crops under arid-field conditions, consistent with the observed improvements in soil moisture retention (Figure 1) and enhanced infiltration and wetting depth (Figure 2).



(a) (b) (c)

Figure 4. Effects of hydrogel treatments on vegetative growth parameters of the tested crops in the 2024 field experiment in the Turkistan Region. Treatments were T0 (control, no hydrogel), T1 (0.2% w/w hydrogel), and T2 (0.4% w/w hydrogel). For each crop, bars represent mean ± standard error (SE) for plant height (cm; left y-axis) and leaf number (count; right y-axis) across blocks (n = 3). (a) Rice, (b) wheat, and (c) saffron. Height and leaf number are shown in different colors for visual separation.



(a) (b) (c)

Figure 5. Effects of hydrogel treatments on yield and yield components of the tested crops in the 2024 field experiment in the Turkistan Region (Kazakhstan). Treatments were T0 (control, no hydrogel), T1 (0.2% w/w hydrogel), and T2 (0.4% w/w hydrogel). Bars represent mean ± standard error (SE) for grain yield (t ha^{-1}) and total aboveground mass (t ha^{-1}) shown on the left y-axis, and 1000-unit mass (g) shown on the right y-axis. The three parameters are displayed in different colors for clarity. (a) Rice, (b) wheat, and (c) saffron.

Discussion

Baseline soil stability and implications for interpreting hydrogel effects

The experimental soil remained chemically stable and non-saline throughout the season (Table 1), with only modest changes in pH, electrical conductivity, and organic matter at both 0–20 and 20–40 cm. This stability matters for two reasons. First, it reduces the likelihood that treatment responses were confounded by concurrent changes in salinity or carbonate chemistry. Second, hydrogel swelling and water retention performance can be suppressed when salinity increases because ionic strength reduces osmotic gradients and can alter polymer hydration; thus, the consistently low EC supports the conclusion that differences in soil moisture dynamics, infiltration behavior, and crop performance were driven primarily by hydrogel amendment rather than by a shift in baseline soil chemical constraints.

Texture and baseline water-holding capacity are among the strongest moderators of SAP performance. The sandy-loam character of the study soil is representative of soils where SAPs are expected to provide measurable gains because the unamended matrix retains comparatively little water at plant-available potentials. Consistent with this principle, Omar and Alsharaeh (2024) showed that a high-performance SAP hydrogel improved water retention and reduced water stress in sandy soils, while Abdelgelil et al. (2025) demonstrated that a fabricated superabsorbent hydrogel can reduce water flow rate in sandy media, increasing residence time and retention. The present field results align with this broader evidence base that SAP benefits are particularly detectable in coarse-textured, moisture-limited settings.

Soil moisture dynamics and rooting-zone moisture persistence

Hydrogel incorporation produced a clear, dose-responsive increase in TDR-derived volumetric soil water content across crops and monitored depths (Figure 1), with the higher dose (0.4% w/w) consistently maintaining the highest moisture and the intermediate dose (0.2% w/w) showing an intermediate response relative to the control. The depth-resolved patterns—particularly in rice where treatment separation became strongest later in the season and at 20–40 cm—suggest that hydrogel amendment did not merely increase near-surface water storage but also promoted deeper wetting and persistence of moisture within the effective rooting zone. From a functional standpoint, deeper and more persistent wetting is advantageous under arid conditions because it reduces exposure of stored water to surface evaporation and stabilizes water supply during periods of high atmospheric demand.

Comparable improvements in root-zone soil moisture under SAP amendments have been reported across different polymer chemistries and management contexts. Notably, a precision subsurface co-application approach that placed a hydrogel–fertilizer mixture at 20 cm increased total soil water retention by 14.3% and raised subsoil (20–40 cm) moisture by 9.0 percentage points, confirming an in-situ "water reservoir" function under arid field conditions; this mechanistic pattern is consistent with the deeper-layer moisture persistence observed in our rice profiles at 20–40 cm under T2 (Manabaev et al., 2026). Under deficit-irrigation conditions, Abdelghafar et al. (2024) reported that superabsorbent hydrogel additions increased soil water content and water availability, with the magnitude depending on soil type and irrigation level. Under contrasting irrigation regimes, Adjuik et al. (2022) observed improved soil moisture and higher water-use efficiency in wheat and cluster bean when hydrogels were applied, supporting the interpretation that hydrogels can buffer soil moisture decline between irrigations. Consistent with this interpretation, Kishor et al. (2024) reported improved seasonal soil water distribution and higher SWC under drip irrigation in red cabbage, with the effectiveness varying by hydrogel formulation and application pathway, reinforcing the need for dose- and method-specific optimization in arid field management. In a multi-season soybean–wheat system, optimized SAP deployment (including seed treatment and slurry application) increased near-surface soil moisture and improved system water productivity while reducing irrigation inputs, underscoring that "how" SAPs are applied can be as important as "how much" is applied when targeting field-scale moisture persistence and water saving (Rajanna et al., 2024).

Mechanistically, the observed moisture persistence is consistent with rapid swelling immediately following irrigation and subsequent gradual release as soil matric potential decreases. The laboratory swelling kinetics measured here support this mechanism: absorption increased sharply within 30 minutes and remained high at 60 minutes (Table 2), indicating that the hydrogel can capture water rapidly during irrigation events and store substantial quantities for subsequent release. Similar rapid uptake and high storage capacity are commonly identified as key design targets for hydrogels intended for arid-land agriculture and drought buffering (Chang et al., 2021; Palma et al., 2024).

Infiltration, wetting depth, and retention: reconciling hydraulic responses

In addition to increasing soil moisture, hydrogel amendment improved plot-scale indicators of water transmission and redistribution: infiltration rate, wetting depth, and retention coefficient all increased with dose across crops (Figure 2). The co-occurrence of higher infiltration and deeper wetting suggests that hydrogel-amended soils accepted irrigation water effectively and redistributed it downward into the profile, increasing the probability that water entered and remained within the root zone rather than being lost rapidly as runoff or shallow evaporation. This interpretation is aligned with evidence that polymer hydrogels are used not only to increase water-holding capacity in sandy soils, but also to reduce water runoff and increase field infiltration rates—functions that are directly relevant to the direction of change observed in our double-ring infiltration measurements (Naushabayev et al., 2022).

At first glance, improved infiltration may seem inconsistent with reports that SAP swelling can reduce saturated hydraulic conductivity. In practice, both responses can occur depending on (i) the water state (unsaturated vs near-saturated), (ii) the spatial scale of the measurement, and (iii) whether the dominant limitation is crusting/surface sealing versus internal drainage. Abdelghafar et al. (2024) documented reductions in saturated hydraulic conductivity following hydrogel addition, yet simultaneously reported improvements in soil water availability. This combination is plausible: restricting rapid drainage can increase the time water remains in the profile, while infiltration under field conditions can still increase if hydrogels improve near-surface structure, reduce sealing, or enhance wettability. A complementary explanation is that some hydrogel systems measurably decrease bulk density and increase porosity after amendment, which can promote intake and redistribution under field conditions; for example, cellulose-based hydrogel modification increased soil porosity and lowered bulk density in a controlled soil–plant study (Das et al., 2025). The present double-ring infiltration measurements integrate near-surface intake and early redistribution under field conditions; thus, the observed increases likely reflect improved intake and effective wetting front propagation rather than purely saturated flow through a fixed pore network.

The increase in retention coefficient observed in parallel with higher infiltration and deeper wetting supports the interpretation that hydrogel treatments improved not only water entry but also the effective fraction retained for redistribution and plant use. Reviews of hydrogel behavior in soils emphasize that successful field performance is typically expressed as a coupled response—higher retained water in the root zone together with a moderated rate of water movement—rather than a single directional shift in any one hydraulic parameter (Rizwan et al., 2021; Chang et al., 2021).

Mineral modification, swelling capacity, and linkage to field behavior

The swelling tests demonstrated that Ca–P mineral modification increased absorption relative to the unmodified hydrogel at 5, 30, and 60 minutes (Table 2). This indicates that mineral addition enhanced water-binding capacity without compromising rapid uptake. Composite and mineral-modified hydrogels are widely used to tune swelling, mechanical stability, and water release behavior, particularly under repeated wetting–drying cycles. Consistent with this concept, a polyacrylamide–Fuller's earth composite hydrogel improved soil water retention and crop yield, illustrating how inorganic fillers can strengthen polymer networks and support agronomic function (Rajanna et al., 2022).

From an agronomic perspective, rapid early swelling combined with high sustained absorption is desirable under arid irrigation schedules because water is delivered in discrete pulses. The stepwise increases in field moisture (Figure 1) and the improved transmission and wetting indicators (Figure 2), together with the swelling kinetics (Table 2), support the conclusion that the hydrogel functioned as a short-term reservoir that captured irrigation water quickly and enhanced its redistribution and persistence in the rooting zone. This mechanism is consistent with current design principles for hydrogels intended for arid-land agriculture (Palma et al., 2024).

Translation to crop growth and yield and implications for water productivity

The agronomic responses mirrored the hydrophysical improvements. Hydrogel treatments increased vegetative growth (plant height and leaf number; Figure 4) and yield and yield components (Figure 5) in a consistent dose-dependent pattern. Such coupling is expected: stabilizing root-zone moisture supports stomatal conductance, canopy expansion, and assimilate production, which in turn increases biomass and harvestable yield. The presence of an intermediate response at 0.2% w/w suggests that benefits scale with dose within the tested range, rather than being expressed only above a narrow threshold.

Comparable crop responses have been reported for SAP systems under water limitation. In wheat and cluster bean, hydrogels improved plant growth and water-use efficiency under different irrigation regimes, indicating that hydrogel-mediated moisture buffering can translate into physiological and yield benefits (Adjuik et al., 2022). In sandy soils, SAP hydrogels reduced water stress and improved plant performance by increasing water retention and slowing water movement (Omar and Alsharaeh, 2024; Abdelgelil et al., 2025). In addition, cellulose-based biodegradable hydrogels have been reported to improve soil water retention and enhance plant growth, suggesting that similar functional benefits can be achieved with alternative material platforms (Das et al., 2025). Importantly, field evidence also indicates that SAPs can be leveraged explicitly for water-saving: under deficit drip irrigation in bean, hydrogel amendment was associated with maximized crop water productivity and improved WUE indices at reduced irrigation levels (Satriani et al., 2018). Similarly, in Indian mustard grown under semi-arid conditions, combining irrigation scheduling with hydrogel use improved seed yield and increased marginal/gross water productivity particularly under limited irrigation or rainfed scenarios, with concurrent economic gains (Rathore et al., 2020).

A further implication is the potential synergy between water retention and nutrient dynamics. Multifunctional hydrogels developed for controlled fertilizer release can couple water storage with regulated nutrient supply, which may further enhance productivity under arid conditions. For example, a PVP-based SAP hydrogel used as a carrier for controlled fertilizer release improved soil water retention and supported plant development in pea (Pisum sativum L.) (Ghobashy et al., 2024). Consistently, a major SAP review summarizes evidence that porous polyacrylamide (PAM) hydrogels can be loaded with urea and exhibit measurable release behavior, and that hydrogel addition (e.g., 10 g m^{-2} in sandy soil) increased time to wilting of bean plants—supporting the concept that SAPs can deliver coupled benefits via water storage and (in engineered systems) nutrient delivery (Krasnopeeva et al., 2022). While fertilizer release was not a factor manipulated in the present field design, the consistent gains in yield components (including 1000-unit mass) are compatible with improved water availability during grain filling, which can also influence nutrient uptake and assimilate partitioning.

This study was conducted at one site in one growing season, and SAP performance can vary with soil texture, salinity, irrigation method, and interannual climate variability. The experimental design intentionally maintained identical irrigation inputs within each crop to isolate hydrogel effects; future work should explicitly test whether irrigation volumes can be reduced while maintaining yield, thereby quantifying water productivity gains and identifying an economically optimal dose under regional water constraints. A practical benchmark for such optimization is emerging from localized subsurface placement studies, where a "30 kg ha^{-1} hydrogel + 50% P/K" configuration delivered stable wheat yield increases (23.32–27.05%) while simultaneously achieving 50% fertilizer savings and a 57% reduction in hydrogel use relative to broadcast application—illustrating that placement strategy can materially improve input efficiency, not only agronomic response (Manabaev et al., 2026). Building on recent agronomic innovations, future trials in the Turkistan Region could compare incorporation with lower-dose application pathways (e.g., seed coating/slurry or root dipping) that have been shown to increase productivity and water productivity while reducing irrigation water requirement in other semi-arid systems (Adireddy et al., 2024; Kishor et al., 2024). This hypothesis is supported by multi-season field data where SAP use improved system water productivity and economic returns alongside reduced irrigation inputs, indicating that irrigation "saving" trials can be designed with realistic expectations of maintaining or increasing yield under optimized SAP application pathways (Rajanna et al., 2024), and by deficit-irrigation evidence where hydrogel-amended strategies maximized crop water productivity indices under reduced ET replacement (Satriani et al., 2018).

Environmental and durability considerations also warrant attention, particularly for polyacrylamide-based networks. Long-term persistence and performance under repeated wetting–drying cycles should be evaluated, together with any risk associated with residual monomers or degradation products. Recent literature highlights active development of alternative or hybrid systems, including biodegradable cellulose-based hydrogels (Das et al., 2025) and engineered networks designed to regulate water flow in sandy soils (Abdelgelil et al., 2025), which may offer pathways to improve environmental compatibility while maintaining agronomic function. However, even biodegradable platforms can present practical constraints: degradation rates may be slow and dependent on soil temperature, moisture, and microbiota; repeated applications could lead to transient accumulation, and some systems may increase risks of fungal growth or waterlogging in fine-textured soils if water retention becomes excessive (Das et al., 2025). In addition, salinity can reduce water-absorbing capacity and potentially intensify osmotic stress as soils dry, while incomplete degradation may alter porosity/compaction and thereby affect infiltration, drainage, and root penetration (Das et al., 2025). Field-relevant evidence indicates that persistence can decline within a single season: hydrogel losses attributable to biodegradation over a three-month vegetation period may exceed 30% under irrigated arid conditions, and this biodegradation is concluded to be one of the most important factors decreasing hydrogel efficiency in actual soils (Krasnopeeva et al., 2022). At the same time, some commercial SAPs are described as sensitive to microbiological degradation (reported as ~10–15% per year) and as having low bioaccumulation potential because macromolecules are too large to be absorbed into plant tissues (Krasnopeeva et al., 2022).

Taken together, the present findings and the supporting literature indicate that SAP hydrogels can provide agronomically meaningful improvements in arid irrigated systems by increasing rooting-zone moisture, improving water transmission and redistribution, and enhancing crop growth and yield. Under Turkistan Region conditions, the higher application rate (0.4% w/w) delivered the most consistent benefits across all measured hydrophysical and agronomic indicators. These results support the practical use of hydrogel amendment as a component of integrated water-saving strategies in irrigated agriculture, while highlighting the need for site-specific optimization and long-term assessment of performance and environmental behavior.

Conclusion

Hydrogel amendment using a GIPANA–polyacrylamide network cross-linked with formaldehyde produced clear, consistent improvements in soil water status and crop performance under arid field conditions in the

Turkistan Region. Because the soil remained chemically stable and non-saline throughout the season, the observed treatment differences can be attributed primarily to the hydrogel.

Across rice, wheat, and saffron, the hydrogel increased TDR-derived volumetric soil water content in a dose-responsive pattern (T2 > T1 > T0) and supported deeper and more persistent moisture within the effective rooting zone, especially evident in rice at 20–40 cm later in the season. Field-scale hydraulic indicators improved concurrently: infiltration rate, wetting depth, and the retention coefficient increased markedly with hydrogel dose, indicating that the amendment enhanced both water entry and effective retention/redistribution in the profile. Laboratory swelling tests corroborated the proposed mechanism, showing rapid water uptake and high absorption capacity, with further gains under Ca–P mineral modification.

These hydrophysical improvements translated into agronomically meaningful responses. Hydrogel treatments increased vegetative growth (plant height and leaf number) and yield across all three crops, again with the most consistent benefits at 0.4% (w/w). Within the tested range, the results support the practical use of SAP hydrogel amendment as a component of arid-zone irrigation management aimed at stabilizing root-zone moisture and improving productivity. Future work should quantify whether irrigation volumes can be reduced without yield penalties under Turkistan Region conditions, and should assess multi-season durability, environmental behavior, and the economic optimum dose and application pathway for field deployment.

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