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Localized subsurface placement of a polyacrylamide superabsorbent polymer improves soil moisture distribution and reduces irrigation requirement in wheat grown in Eastern Kazakhstan

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Abstract

Water scarcity and increased drought frequency threaten irrigated cereal production across arid and semi-arid regions. Superabsorbent polymers (SAPs) can improve soil water retention and reduce non-productive losses, but field-scale effectiveness depends strongly on placement strategy and soil conditions [1–5]. This study evaluated a commercially available cross-linked polyacrylamide SAP applied locally using a slitter-based implement at two rates (30 and 60 kg ha^{-1}) and two placement depths (20 and 40 cm) under irrigated wheat (Triticum aestivum L., cultivar 'Steklovidnaya-24') in Eastern Kazakhstan (April–June 2025). A randomized complete block design with three replications was used (6 × 4 m plots). Soil moisture was measured by depth (0–5, 0–20, 20–40 cm) using the thermostat–weight (oven-drying) method; soil reaction (pH) was measured in a salt extract prepared by the TSINAO method using a calibrated pH meter; and grain yield was assessed by whole-plot harvest and converted to a hectare basis. Localized SAP placement redistributed water downward, with a 3.6–3.8 percentage-point reduction in the 0–20 cm layer and a 3.2–3.6 percentage-point increase in the 20–40 cm layer, resulting in an 8–11% increase in root-zone moisture reserves. The number of irrigations decreased from two to one, reducing seasonal irrigation from 1,800 to 900 m^3 ha^{-1}, while crop growth indicators visibly improved relative to the control. Overall, 30 kg ha^{-1} placed at 20 cm provided the most favorable balance between agronomic benefit and input intensity, consistent with broader evidence that targeted subsurface SAP placement can enhance irrigation water productivity.

Keywords: Superabsorbent polymer, polyacrylamide, localized placement, slitting, soil moisture, irrigation water productivity, wheat, Eastern Kazakhstan.

Introduction

Climate change is increasing the frequency and severity of drought episodes and intensifying evaporative demand, thereby amplifying pressure on already limited irrigation water resources in arid and semi-arid agroecosystems. In this context, soil amendments that increase plant-available water, buffer short-term water deficits, and improve irrigation water productivity have attracted renewed scientific and practical attention. Superabsorbent polymer (SAP) hydrogels are cross-linked polymer networks capable of absorbing large quantities of water and releasing it gradually as the surrounding soil dries, potentially reducing non-productive water losses and stabilizing soil water supply to crops. For example, Ng'eno et al. (2023) reported that SAP amendments can increase plant-available water (PAW) under dryland conditions, while Takahashi

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et al. (2023) and Krasnopeeva et al. (2022) summarized the mechanistic basis of SAP water retention and release behavior across contrasting soil environments.

However, SAP effectiveness is not universal and is strongly conditioned by soil texture and structure, salinity and divalent cations, wet–dry cycling, and—critically—the spatial coincidence between SAP placement and the active root zone (Krasnopeeva et al., 2022; Takahashi et al., 2023; Omar and Alsharaeh, 2024). Omar and Alsharaeh (2024) demonstrated improved water retention in sandy soils with high-performance hydrogels, whereas broader syntheses emphasize that ionic strength and Ca^{2+}/Mg^{2+} can reduce swelling capacity and thereby diminish functional water storage (Krasnopeeva et al., 2022; Takahashi et al., 2023). Soil-dependent responses have also been highlighted in classic work; Narjary et al. (2012) showed that hydrogel-related improvements in water availability differ across soil types, indicating that "one-rate-fits-all" recommendations are unlikely to be robust.

A persistent implementation challenge is how SAP is applied. Broadcast incorporation can dilute SAP throughout the soil profile, often requiring higher rates and increasing the risk that stored water is not positioned where roots can readily access it (Ng'eno et al., 2023; Takahashi et al., 2023). Precision alternatives therefore emphasize localized or banded subsurface placement (e.g., via slitting/slotting) to target SAP directly into the functional rooting zone and reduce surface-layer evaporative losses. Evidence from field systems supports the agronomic importance of "root-zone proximity"; for instance, Kishor et al. (2024) showed that hydrogel-assisted strategies can improve soil water distribution and water productivity under contrasting drip-irrigation regimes, with performance varying by application method.

Beyond immediate water-retention effects, longer-term amendments may influence soil physical condition. Yang et al. (2021) documented that repeated SAP use (in combination with organic inputs) can affect soil structure and organic carbon distribution across layers, implying that placement strategy could have implications beyond a single season. In the steppe environments of Kazakhstan and neighboring regions—where irrigated cereal production is increasingly constrained by water scarcity and operational costs—localized subsurface placement offers a practical route to improve water productivity with manageable SAP inputs. Recent regional work by Manabaev et al. (2026a,b) demonstrated that integrating slit-based soil loosening with localized hydrogel placement can enhance moisture conservation and cereal performance under arid-steppe conditions, with optimal responses often observed at moderate rates and shallower placement depths.

Against this background, the present study evaluates a field-feasible protocol for slitter-based localized placement of a commercially available cross-linked polyacrylamide SAP in Eastern Kazakhstan under irrigated wheat (*Triticum aestivum* L.). The objective was to quantify (i) redistribution of soil moisture across profile layers, (ii) operational irrigation requirements under field practice, and (iii) crop growth and yield measurements under two SAP rates (30 and 60 kg ha^{-1}) and two placement depths (20 and 40 cm). We hypothesized that moderate SAP rates placed within the effective rooting zone would provide the best agronomic return, whereas deeper placement and/or higher rates would exhibit diminishing marginal benefits due to reduced SAP–root contact and constrained accessibility of stored water (Takahashi et al., 2023; Manabaev et al., 2026a,b).

Material and Methods

Study area and soil conditions

Field studies were conducted from April to June 2025 at a single irrigated wheat site in the Eastern Kazakhstan Region (Druzhba farm). The region represents a continental steppe–foothill environment where irrigated cereal production is practiced on soils commonly classified as chernozem and kastanozem (Wei et al., 2018; Jelen et al., 2020; Kalimov et al., 2024; Zharlygassov et al., 2025). Prior to treatment establishment, baseline soil sampling was performed from the 0–20 cm layer, and the initial agrochemical and physical characteristics of the experimental field were determined according to national regulatory standards (GOST series). The baseline results are presented in Table 1.

Specifically, humus content was determined by the Tyurin method (GOST 26213-91). Nitrate nitrogen (NO_3–N) was determined using TSINAO-based standardized procedures (GOST 26488-85). Available (mobile) phosphorus (P) and potassium (K) were determined by the Machigin method modified by TSINAO (CINAO) (GOST 26205-91). Mobile sulfur (S) was determined according to TSINAO methodology (GOST 26490-85). Soil reaction (pH) was measured in a salt extract prepared by the TSINAO method (GOST 26483-85). Granulometric composition (particle-size distribution) was determined using laboratory methods for grain-size distribution (GOST 12536-2014). The principal physical parameters reported in Table 1, including soil bulk density, total porosity, and water permeability, were determined using standardized laboratory methods for soil physical characteristics (GOST 5180-2015).

Table 1. Baseline soil characteristics at the Druzhba site, Eastern Kazakhstan (0–20 cm).

Parameter	
Humus, %	2.78
Mineral Nitrogen, mg/kg	8.23
Available Phosphorus, mg/kg	29.8
Available Potassium, mg/kg	488.00
Available Sulfur, mg/kg	9.0
pH	7.29
Texture Class	Medium loamy
Water permeability, mm/min	0.67
Soil bulk density, g/cm^3	1.03
Porosity, %	45-55

Superabsorbent polymer (SAP) and placement method

The superabsorbent polymer (SAP) was a commercially available high-capacity product based on cross-linked polyacrylamide. According to the manufacturer's specification, the material is designed for high water uptake and gradual release under soil drying. SAP was applied locally using a slitter-based soil-cultivating unit that enables placement at a specified depth and distribution along the treated band. The placement approach and depth verification are illustrated in Figure 1.

Figure 1. Local placement of SAP into soil using a slitter; placement depth verified with a ruler (cm)

Experimental design and treatments

The trial followed a randomized complete block design (RCBD) with three replications. Plot size was 6 × 4 m (24 m^2). The wheat cultivar was 'Steklovidnaya-24'. Five treatments were established: (i) Control (no SAP), (ii) 30 kg ha^{-1} at 20 cm, (iii) 60 kg ha^{-1} at 20 cm, (iv) 30 kg ha^{-1} at 40 cm, and (v) 60 kg ha^{-1} at 40 cm (Table 2).

Table 2. Field experimental treatments

Treatment	SAP rate (kg ha^{-1})	Placement depth (cm)
T1	0	—
T2	30	20
T3	60	20
T4	30	40
T5	60	40

Irrigation management

Irrigation was applied at 900 m^3 ha^{-1} per irrigation event according to regional practice. The number of irrigation events during the season and the inter-irrigation interval were recorded for each treatment.

Soil moisture measurement

Soil moisture content was determined by depth intervals (0–5, 0–20, and 20–40 cm) using the thermostat–weight (oven-drying) method, following the standardized procedure of GOST 28268-89. For each plot and each target depth interval, soil samples were collected using a consistent sampling protocol, placed in sealed containers to prevent moisture loss, and weighed to obtain fresh mass. Samples were then dried at 105°C to constant mass and re-weighed to obtain oven-dry mass. Gravimetric soil water content (θg, %) was calculated as:

$$\theta_g(\%) = \frac{W_{fresh} - W_{dry}}{W_{dry}} \times 100$$

where W_{fresh} is fresh soil mass (g) and W_{dry} is oven-dry soil mass (g).

To support rapid field assessment of moisture variation along the soil profile, a handheld Soil Moisture Meter (MC-7828) was additionally used to obtain complementary in situ measurements at the same depths. These instrument readings were used as supporting field-based observations, while the gravimetric measurements obtained under GOST 28268-89 served as the reference method for reporting soil moisture.

Plant growth and yield measurements

Plant growth was assessed using morphometric measurements. Plant height was measured within each plot using a measuring ruler during the active growth period (mid-season), using the same measurement protocol across treatments; an illustrative field measurement is shown in Figure 2.

For grain yield, all plants within each plot were harvested at maturity. Harvested biomass was threshed and grain mass per plot was recorded. Grain yield was converted to a hectare basis as:

$$Yield\,(kg\,ha^{-1}) = \frac{Grain\,mass\,(kg\,plot^{-1})}{Plot\,area\,(m^2)} \times 10{,}000$$

Figure 2. Field measurement of wheat plant height after SAP application (illustrative photograph)

Soil pH

Soil reaction (pH) was measured in a salt extract prepared by the TSINAO method (GOST 26483-85) using a calibrated pH meter.

Supporting datasets from related experiments

In addition to the main Druzhba field trial, three supporting datasets supplied with the study material were summarized for contextual comparison:

(i) A rainfed barley dataset (2023–2024) reporting soil moisture at 0–10 and 10–20 cm and grain yield under three SAP rates (0, 25, 35 kg ha^{-1}).

(ii) A controlled evaluation dataset reporting gravimetric moisture retention and early wheat growth metrics.

(iii) A swelling ratio dataset showing time-dependent swelling at pH 5.8 and 7.4.

Results

Climate context

Monthly precipitation and mean air temperature during the study period are presented in Figure 3. The climatic pattern is characteristic of the continental steppe environment of Eastern Kazakhstan, with progressive warming from early spring to early summer and an uneven seasonal distribution of rainfall. During the active wheat growth period (April–June 2025), mean temperature increased steadily, while precipitation events were episodic (Figure 3). This combination—rising evaporative demand together with intermittent rainfall—creates conditions under which short-term soil water deficits frequently develop in the upper soil layers, making irrigation scheduling and root-zone water conservation particularly important for maintaining crop growth.

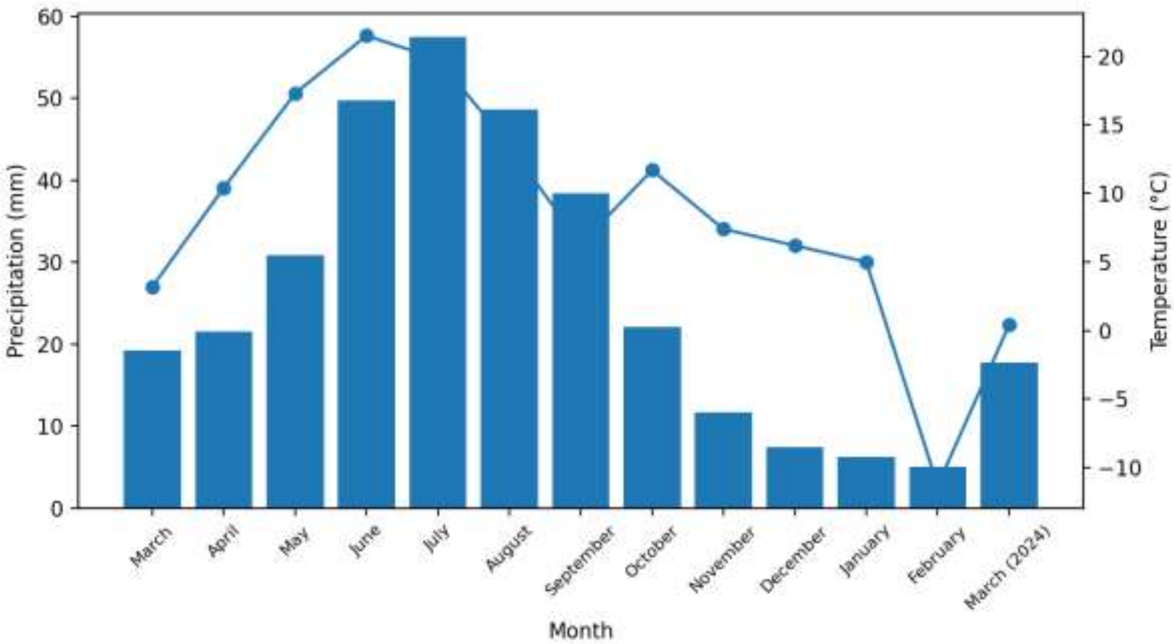

Figure 3. Monthly precipitation (bars) and mean temperature (line) for the study region during the study period.

Soil moisture redistribution under localized SAP placement

Field measurements showed that localized subsurface placement of SAP altered the vertical distribution of soil water relative to the untreated control. In the 0–20 cm layer, gravimetric moisture content was 3.6–3.8 percentage points lower than the control, whereas in the 20–40 cm layer moisture content was 3.2–3.6 percentage points higher. The net effect was an increase in root-zone moisture reserves by 8–11% compared with the control.

This redistribution pattern indicates that SAP placement promoted greater water storage at depth within the effective rooting zone while limiting moisture persistence in the near-surface layer. Agronomically, the observed shift in soil water toward the 20–40 cm layer is consistent with reduced exposure of stored water to direct evaporative losses and improved buffering against short-term peaks in atmospheric demand. A synthesized summary of the reported redistribution is provided in Figure 3.

Irrigation requirement and operational impacts

Localized SAP placement had a clear operational effect on irrigation scheduling. Relative to the control, SAP-treated management required one fewer irrigation event during the season, with the number of irrigations decreasing from two to one. Accordingly, total seasonal irrigation volume was reduced from 1,800 to 900 m^3 ha^{-1}, corresponding to an approximate 50% reduction in applied irrigation water under the conditions of this study. Beyond irrigation, SAP treatment also reduced field operations. The number of mechanical tillage operations decreased from two to one, indicating a practical reduction in operational inputs under improved soil moisture buffering.

Crop growth response and optimal treatment

Across treatments, SAP application was associated with visibly improved crop vigor compared with the control, reflected by taller stems and a denser canopy during the active growth period. Among the tested combinations, 30 kg ha^{-1} placed at 20 cm (T2) provided the most favorable balance between agronomic benefit and application intensity. In contrast, increasing the SAP rate to 60 kg ha^{-1} and/or placing SAP at 40 cm did not yield a clearly proportional additional improvement in crop vigor under the study conditions, suggesting diminishing marginal returns beyond moderate rate and shallower placement. A representative field measurement of wheat plant height illustrating the morphometric assessment approach is shown in Figure 2.

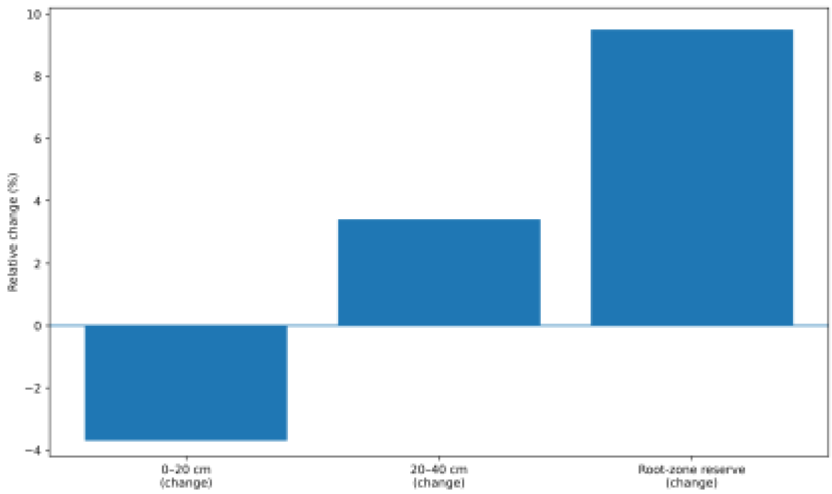

Figure 4. Summary of soil moisture redistribution under localized SAP placement.

Supporting datasets from related experiments

To complement the primary RCBD field trial, three additional datasets supplied with the study material were summarized to contextualize SAP/hydrogel performance under rainfed and controlled conditions. These datasets are reported descriptively and should be interpreted as supportive evidence rather than direct extensions of the main experimental design.

Supporting rainfed barley dataset (2023–2024): soil moisture and yield response to SAP rate

A rainfed barley dataset (2023–2024) indicates a positive response of soil moisture and yield to SAP application rate (Table 3). Compared with the control (0 kg ha^{-1}), SAP at 25 kg ha^{-1} increased soil moisture from 8.5 to 8.7% in the 0–10 cm layer (+0.2 percentage points) and from 14.9 to 17.5% in the 10–20 cm layer (+2.6 percentage points). The 35 kg ha^{-1} rate produced a larger increase, particularly in the surface layer (10.6%, +2.1 percentage points vs. control) and in the 10–20 cm layer (18.5%, +3.6 percentage points vs.

control) (Table 3). Grain yield increased from 14.6 c ha^{-1} (control) to 18.7 c ha^{-1} at 25 kg ha^{-1} (+4.1 c ha^{-1}; ∼+28%) and to 18.9 c ha^{-1} at 35 kg ha^{-1} (+4.3 c ha^{-1}; ∼+29%) (Table 3). The marginal yield gain from 25 to 35 kg ha^{-1} was small (+0.2 c ha^{-1}), suggesting diminishing returns at the higher rate under those rainfed conditions.

Table 3. Supporting rainfed barley dataset: effects of SAP rate on soil moisture and yield (2023–2024).

Rate (kg ha^{-1})	Soil moisture 0–10 cm (%)	Soil moisture 10–20 cm (%)	Yield (c ha^{-1})	Yield increase (c ha^{-1})
0	8.5	14.9	14.6	0.0
25	8.7	17.5	18.7	4.1
35	10.6	18.5	18.9	4.3

Controlled evaluation: moisture retention and early wheat growth

A controlled evaluation dataset indicates that hydrogel/SAP treatment increased moisture retention and improved early wheat growth (Table 4). Gravimetric moisture retention increased from 80 ± 5% (control) to 95 ± 3% (treatment). Seedling height was higher in the treated condition at all time points (days 7, 14, and 30), and germination time was shortened from 10 ± 2 to 7 ± 1 days (Table 4).

Table 4. Supporting controlled evaluation: effect of hydrogel treatment on moisture retention and early wheat growth (mean ± SD).

Parameter	Control Plot	Experimental Plot
Gravimetric moisture retention (%)	80 ± 5	95 ± 3
Moisture release temperature (°C)	60 ± 2	70 ± 4
Test chamber temperature (°C)	25 ± 2	25 ± 2
Effect on soil moisture (%)	15 ± 3	25 ± 4
Wheat seedling growth (plant height, cm) after 7 days	4 ± 1	6 ± 1
Wheat seedling growth (plant height, cm) after 14 days	10 ± 2	12 ± 3
Wheat seedling growth (plant height, cm) after 30 days	22 ± 3	28 ± 4
Germination stimulation (germination time, days)	10 ± 2	7 ± 1
Fertilizer effect with zeolite-containing agrominerals (yield impact, %)	10 ± 4	25 ± 6

Swelling ratio dynamics under different pH conditions

Swelling ratio dynamics provided for soil samples at pH 5.8 and pH 7.4 show a rapid initial uptake phase followed by stabilization over time (Figure 5). Swelling was higher under the alkaline condition (pH 7.4) than under the slightly acidic condition (pH 5.8), consistent with greater swelling capacity at higher pH in the supplied dataset.

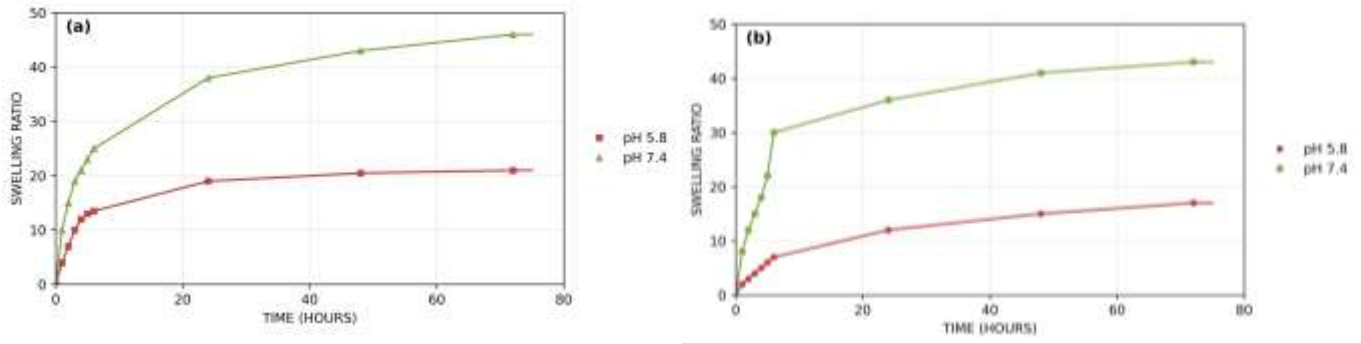

Figure 5. Swelling ratio dynamics of the SAP/hydrogel material in soil samples at pH 5.8 and pH 7.4 (as supplied/redrawn).

Discussion

Localized subsurface placement of a commercial cross-linked polyacrylamide superabsorbent polymer (SAP) redistributed soil water storage toward the effective root zone. Relative to the control, the reported decrease in moisture in the surface layer (0–20 cm) concurrent with an increase in the 20–40 cm layer implies lower near-surface evaporative losses and greater retention at depths that sustain crop transpiration during short dry spells. This pattern is consistent with SAP mechanisms described in reviews and experimental studies, where swelling and gel formation increase soil water retention (often increasing field capacity and reducing drainage losses) and buffer moisture fluctuations around the root zone (Krasnopeeva et al., 2022; Rajanna et al., 2022; Omar and Alsharaeh, 2024; Kishor et al., 2024). The concurrent increase in root-zone moisture reserves further supports the interpretation that the principal benefit of SAP in this system is stabilization of plant-available water between irrigation events (Palma et al., 2024; Rajanna et al., 2024). In early foundational work, Hüttermann et al. (1999) similarly demonstrated that hydrogel addition can prolong plant survival under drought stress, supporting the general concept of hydrogels as moisture buffers in root environments.

Application depth and dose should be treated as coupled design variables. Although deeper placement can protect retained water from direct evaporation, excessive depth may reduce SAP–root contact and therefore limit plant access to retained water. The absence of a clearly proportional additional response at 40 cm placement and/or 60 kg ha^{-1} in this single-season trial is plausibly explained by diminishing marginal accessibility of stored water, even if total water retention in the profile increases. Field evidence from cereal systems indicates that coupling SAP placement with agronomic practices that enhance rooting into the treated zone can be more effective than simply increasing application rate (Rajanna et al., 2022, 2024). In the present context, 30 kg ha^{-1} at 20 cm likely optimized the overlap between the SAP-treated band and active wheat roots while maintaining a practical application intensity, consistent with Kazakhstan steppe field results reported by Manabaev et al. (2026a,b).

Soil chemical conditions can further modulate polyacrylamide-based SAP performance. Increased ionic strength and divalent cations can suppress swelling and alter water-release kinetics through charge screening and ionic cross-bridging within the polymer network; consequently, SAP benefits may be attenuated under saline, sodic, or Ca/Mg-rich conditions and under repeated wet–dry cycles typical of steppe irrigation management (Krasnopeeva et al., 2022; Palma et al., 2024). Consistent with this, Dorraji et al. (2010) reported that hydrogel responses can be constrained by soil salinity, and Saha et al. (2020) quantified the interactive control of polymer × soil texture on plant-available water and irrigation frequency. Moreover, SAP effects can evolve with aging and water quality; Banedjschafie and Durner (2015) showed that water retention properties of SAP-amended sandy soil were affected by aging and water quality. Complementary evidence that cross-linked polyacrylamides can alter soil hydraulic behavior (water retention and conductivity), particularly in sandy matrices, has also been documented in classic soil physics work (Bhardwaj et al., 2007).

From an operational standpoint, the combination of SAP banding with slitter-based subsurface placement is notable because soil-physical changes translate into management gains. The reported reduction in irrigation frequency (two events to one) and fewer mechanical operations indicate potential improvements in water productivity and labor/energy efficiency. Comparable improvements in water productivity and/or soil water distribution have been documented for SAP use across diverse cropping systems, including drip-irrigated horticultural crops (Kishor et al., 2024), vineyards under water-management constraints (Frioni et al., 2024), and deficit-irrigated saffron production where SAP improved water productivity and product quality (Ahmadian et al., 2024). Collectively, these studies support the premise that SAPs can be integrated into irrigation management as buffering amendments, but that the magnitude of benefit is contingent on placement strategy, irrigation regime, and crop rooting behavior (Rajanna et al., 2024; Palma et al., 2024).

Several limitations should be acknowledged. The experiment was implemented at a single site and season, and the SAP was described by commercial specification without in-study characterization (e.g., swelling capacity under site-specific ionic strength, particle size distribution, stability under repeated wet–dry cycles, and potential interactions with fertilizer bands). In addition, cross-linked polyacrylamide SAPs are not designed to biodegrade rapidly; therefore, polymer persistence and potential environmental trade-offs (including long-term accumulation and interactions with soil biota) require explicit assessment alongside agronomic benefits (Krasnopeeva et al., 2022; Omar and Alsharaeh, 2024; Abdelgelil et al., 2025). Future multi-year trials should quantify yield stability and water productivity, monitor soil physical structure and nutrient dynamics, and incorporate cost–benefit analysis under farm-scale operations, thereby defining conditions under which SAP placement delivers robust and economically justified performance improvements (Rajanna et al., 2024; Palma et al., 2024).

Conclusion

Localized subsurface placement of a commercially available cross-linked polyacrylamide superabsorbent polymer (SAP) under irrigated wheat conditions in Eastern Kazakhstan altered the vertical distribution of soil water by decreasing moisture in the 0–20 cm layer while increasing moisture in the 20–40 cm layer, thereby improving root-zone water storage. This redistribution was accompanied by a practical reduction in seasonal irrigation requirement, with irrigation frequency decreasing from two events to one and total applied irrigation declining from 1,800 to 900 m^3 ha^{-1}. Across the tested SAP rate–depth combinations, placement at 20 cm with a moderate rate (30 kg ha^{-1}) provided the most favorable balance between water-regime improvement and application intensity, whereas higher rate and/or deeper placement did not yield clearly proportional additional benefit under the study conditions. Overall, these findings support targeted subsurface SAP placement as a potentially effective water-saving management option for irrigated cereal systems in the region. However, broader recommendations require multi-year and multi-site validation to quantify yield stability, soil physical responses, and the persistence and agronomic efficiency of SAP under farm-scale practice.

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