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Superabsorbent Polymers as a Tool for Sustainable Water Management in Semi-Arid Agriculture: A Case Study from the Upper Cheliff Plain, Algeria

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Abstract: Water scarcity presents a significant challenge to agriculture in Mediterranean regions, where semi-arid climates, irregular rainfall, and increasing water demand threaten crop productivity. Superabsorbent polymers (SAPs), or hydrogels, offer a promising solution by enhancing soil water retention and improving irrigation efficiency. This study evaluates the effect of potassium polyacrylate hydrogel on soil properties in Algeria's Upper Cheliff plain, a semi-arid area experiencing declining rainfall and rising temperatures. A randomized block experiment was conducted to assess five hydrogel application rates (0 to 4 g per plant^{-1}) under drip irrigation. Key soil parameters-moisture content, pH, temperature, and electrical conductivity (EC)-were monitored throughout the duration of the experiment. Results indicated that moderate hydrogel doses (1.75 to 2 g per plant^{-1}) significantly increased soil water retention (up to 34.9%, compared to 27.93% in control plots). These doses also caused slight reductions in soil pH and helped stabilize soil temperature. Conversely, higher application rates yielded diminishing benefits and led to increased EC levels, suggesting a potential risk of soil salinity. Statistical analysis confirmed that treatment effects were significant ($p<0.05$), with the most favourable outcomes observed at moderate application levels. These findings underscore the potential of SAPs to mitigate water stress in Mediterranean agriculture. However, precise dosing is essential to maximize water savings while minimizing the risk of soil salinity. While this study focuses on soil responses to hydrogel application, future research will include data on tomato growth performance.

Key words: Superabsorbent polymers (SAPs), Soil water retention, Semi-arid agriculture, Irrigation efficiency, Sustainable water management, Cheliff Plain (Algeria).

Water scarcity has become one of the most pressing challenges for global agriculture, particularly in Mediterranean regions characterized by semi-arid climates, irregular rainfall patterns, and increasing pressure on limited water resources

(AbdAllah *et al.*, 2021; Bouderbala, 2020; Hennia *et al.*, 2024; Kouider *et al.*, 2018; Merouchi *et al.*, 2024). Agriculture currently consumes more than 70% of the world's freshwater supply, a figure expected to rise significantly due to the projected 50% increase in global food demand by 2050 (Abobatta, 2018; Bouderbala, 2021; Suresh *et al.*, 2018). In such a context, optimizing water use in agriculture is not only necessary for sustaining crop productivity but also critical for preserving freshwater resources and ensuring long-term food security (Bauli *et al.*, 2021; Bouderbala *et al.*, 2014). Traditional irrigation techniques, often inefficient and poorly adapted to the climatic variability of Mediterranean environments, exacerbate water losses through evaporation, deep percolation, and surface runoff (Saha *et al.*, 2020). Consequently, there is an urgent need for innovative and sustainable solutions that enhance water retention in the soil and improve the efficiency of irrigation systems (AbdAllah *et al.*, 2021; Belouchrani *et al.*, 2021).

Among emerging technologies, superabsorbent polymers (SAPs)-also known as hydrogels-have shown great potential as soil conditioners capable of transforming water management in agriculture (Bai *et al.*, 2013; Suresh *et al.*, 2018). These cross-linked hydrophilic materials can absorb and retain hundreds to over a thousand times their weight in water, gradually releasing it in response to plant demand (Ai *et al.*, 2021; Kouider *et al.*, 2018). By improving the water-holding capacity of the root zone, SAPs help crops maintain optimal hydration during dry spells, reduce irrigation frequency by up to 50%, and minimize water loss through deep infiltration and evaporation(AbdAllah *et al.*, 2021).

Initially developed in the 1980s from synthetic acrylates, SAPs have since evolved toward more sustainable, biodegradable formulations based on cellulose, lignocellulose, or protein derivatives-aligning with circular economy and environmental safety goals (Kalhapure *et al.*, 2016). Research has demonstrated that SAPs not only enhance soil structure, aeration, and nutrient retention, but also contribute to higher crop yields under drought stress, as observed in crops like tomato (AbdAllah *et al.*, 2021; Suresh *et al.*, 2018).

Despite these advantages, the scalability and long-term environmental implications of SAPs, particularly those derived from non-renewable sources, remain areas of active investigation. Nevertheless, their ability to enhance water-use efficiency and soil resilience makes SAPs a promising tool in the face of climate change and increasing agricultural demands. This study investigates the effectiveness of superabsorbent polymers (SAPs) in improving soil water retention and optimizing irrigation practices under semi-arid Mediterranean conditions, with a focus on their potential to enhance sustainable water management in agriculture.

Materials and Methods

The study was conducted in the agricultural Upper Cheliff plain, located approximately 120 Km southwest of Algiers. This region lies between 36°10′ and 36°20′ N latitude and 2°00′ and 2°25′ E longitude, and covers a total utilized agricultural area of 181,676 hectares (DSA, 2021). The plain is bounded by the Zaccar Massif to the north, the Ouarsenis Range to the south, Djebel Gountas (Djendel Threshold) to the east, and the Doui Massif to the west (Bouderbala, 2019). The experimental field was carried out at the University of Djilali Bounaama, Khemis Miliana, located within the Upper Cheliff plain. The precise geographical coordinates of the experimental site are 36°15′20.04″N latitude and 2°14′25.98″E longitude (Fig. 1).

The Cheliff plain, located in northern Algeria, experiences significant climatic constraints typical of Mediterranean regions. These conditions negatively impact agricultural productivity, particularly for water-demanding crops like tomato. Historical climate data reveal a decline in annual rainfall from 490 mm (1965-1980) to 406 mm (1980-2022), accompanied by a temperature increase from an average of 16.5°C to 18.5°C over the same periods (Kelkouli *et al.*, 2024). The soils of the area are classified as heavy clay-silty-loam. Clay content in these soils increased with depth (from 40.85% in 0-20 cm to 51.1% in 40-60 cm), Concurrently, fine silt content decreases from 30.5% to 24%, and coarse silt remains relatively stable between 18.2% and 20.75%. but, the fraction of fine sand dropped from 6.8% to 1.2%, suggesting lower drainage capacity in deeper horizons. The analysis of soil across three depth intervals (0-20 cm, 20-40 cm, and 40-60 cm) revealed notable

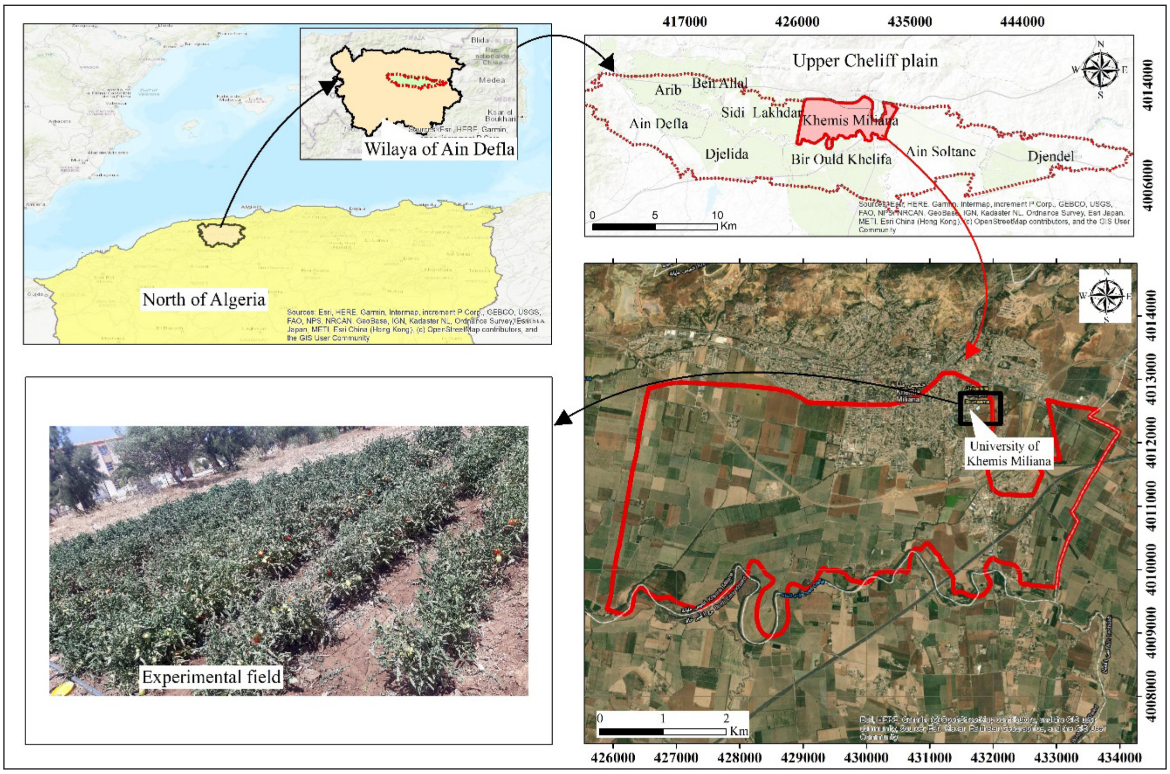

Fig. 1. Location of the Upper Cheliff plain and the Experimental field.

variations in physico-chemical properties. The pH values across all depths, ranged between 8.34 to 8.83 but electrical conductivity (EC), decreased with depth (127.4 µS cm^{-1} at the 0-20 to 85 µS cm^{-1} (40-60 cm). The soils had sufficient calcium and magnesium throughout the profile. Magnesium content increased with depth and reached to 109.35 mg kg^{-1} at the deepest layer (40-60 cm). Potassium levels also increased significantly with depth, rising from 9 mg kg^{-1} in the topsoil to 33.5 mg kg^{-1}. Total nitrogen content is highest at the surface (9 mg kg^{-1}), progressively decreasing to 0.55 mg $kg^{-1}$with depth, reflecting organic matter stratification and microbial activity concentrated near the surface. The amount of organic carbon and concentration of ammonium, nitrate and nitrite were maximum in the top 20 cm.

Physico-chemical analyses of the soil were carried out in the laboratory before planting, in order to characterize the properties of the studied soil and assess its basic fertility. Particle size distribution was determined according to the Robinson pipette method. All other parameters (pH, electrical conductivity, organic matter, total nitrogen, available phosphorus, exchangeable potassium, total and active limestone, calcium, magnesium) were analyzed following the protocols described in the reference work (Rodier, 2009).

Physico-chemical analyses of the irrigation water were carried out in the laboratory prior to the experiment, in order to evaluate its suitability for agricultural use. The measured parameters included pH (7.6), electrical conductivity (EC: 2,547 µS$\cdot$$cm^{-1}$), dissolved oxygen concentration (7.32 mg$\cdot$$L^{-1}$), as well as concentrations of calcium (232 mg$\cdot$$L^{-1}$), magnesium (94.8 mg$\cdot$$L^{-1}$), sodium (167 mg$\cdot$$L^{-1}$), chloride (391.2 mg$\cdot$$L^{-1}$), sulfate (450 mg$\cdot$$L^{-1}$), and bicarbonate (305 mg$\cdot$$L^{-1}$). All analyses were performed following the standard protocols (Rodier *et al.*, 2009). These values suggest that water quality is poor for irrigation purpose. The hydrogel used was potassium polyacrylate, a non-toxic, biodegradable polymer with a water retention capacity of 300 times its weight (Boutalbi and Seghir, 2021; Kouider *et al.*, 2018). It was applied to the soil in its swollen gel form before planting.

The experiment aimed to evaluate water consumption and assess the effectiveness and required quantity of superabsorbent polymer (hydrogel). Tomatoes, being the second most consumed vegetable globally (Nicola *et al.*,

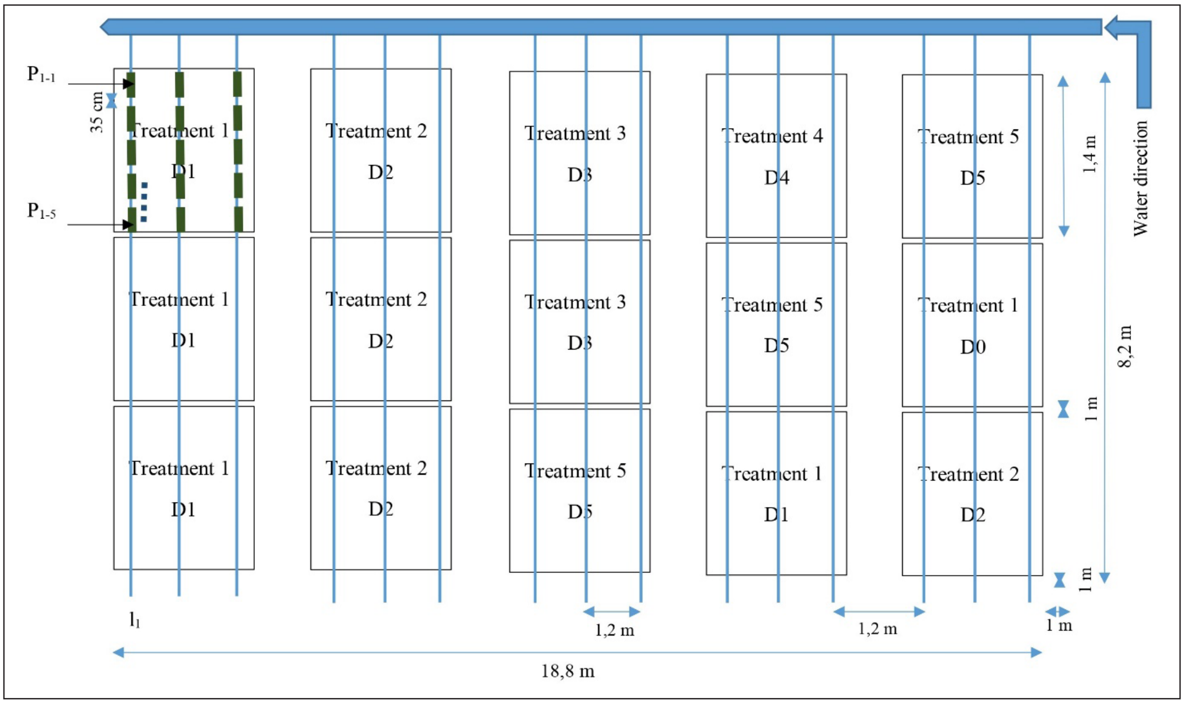

Fig. 2. Layout of experimental plot.

2009), were used as the test crop. Also, the tomato was chosen for its regional importance and high-water demand, particularly as it is cultivated during the dry season (April to August) in Algeria. Climatic data (rainfall, temperature, wind, evaporation, etc.) were obtained from a nearby station (ITGC Khemis Miliana, 2022).

The experiment was laid out in randomized block design over an 8.20 × 18 m plot. A total of 225 tomato plants (*Solanum lycopersicum* L.) were arranged in 15 rows, with 35 cm spacing between plants and 120 cm between rows. Drip irrigation system was installed, featuring drippers every 10 cm with a flow rate of 1.5 L h^{-1}, achieving 90% efficiency and uniformity. To evaluate the effect of hydrogels on soil conditioning, an experiment was conducted using five treatment groups: a control (D0) and four increasing doses of potassium polyacrylate hydrogel (Fig. 2) (D1 = 1g, D2 = 1.75g, D3 = 2g, D4 = 4g $plant^{-1}$). Throughout the experiment (planting to harvest), multiple parameters were monitored for soil moisture, temperature, pH, and electrical conductivity (EC) using *in-situ* device upto the depth of 10 cm. Additionally, soil measurements were taken weekly to assess temporal changes. Soil temperature was measured because it affects water availability and the effectiveness of superabsorbent polymers, which directly influence crop growth and development (Yang *et al*., 2020).

Data were analyzed using non-parametric methods due to violations of normality and homoscedasticity assumptions, which were assessed via Shapiro-Wilk and Levene's tests. Descriptive statistics were reported as means ± standard deviations (SD). The Kruskal-Wallis test was employed to identify significant differences between SAP dosage treatments for each parameter, and where significant differences were found ($p<0.05$), Dunn's post-hoc test with Bonferroni correction was applied for pairwise comparisons. All statistical analyses and visualizations, including boxplots, regression models, and heatmaps, were performed using Python (version 3.10) within the R ecosystem, utilizing libraries such as pandas, numpy, scipy, scikit-learn, seaborn, matplotlib, and scikit-posthocs.

Results and Discussion

Effect of superabsorbent polymer on soil water retention and physicochemical properties

The analysis of soil water content (W%) showed a clear improvement in water retention following the application of superabsorbent polymer (SAP), as illustrated in Fig. 3, and

Table 1. Descriptive Statistics (mean and SD) and Kruskal-Wallis H test of water content, pH, temperature (°C), electrical conductivity (µS cm-1) by SAP Dose

Polymer Dose	Mean				Std				Linear Fit			
	W	pH	T	EC	W	pH	T	EC	W	pH	T	EC
D0	27.93	7.43	28.51	217.72	17.22	0.75	1.73	287.28	30.15	7.47	27.92	227.18
D01	33.83	7.39	27.09	233.01	20.44	0.60	1.81	187.40	31.12	7.40	27.67	234.85
D02	31.56	7.47	27.46	250.67	20.95	0.46	1.86	268.08	32.10	7.34	27.42	242.52
D03	34.90	7.20	26.49	277.26	22.11	0.79	1.86	245.05	33.07	7.28	27.17	250.20
D04	32.26	7.21	27.56	233.96	19.44	0.75	2.11	181.85	34.04	7.21	26.92	257.87

Polymer Dose	Quadratic Fit				Kruskal Wallis Statistic H				Kruskal Wallis p-value			
	W	pH	T	EC	W	pH	T	EC	W	pH	T	EC
D0	28.51	7.43	28.44	211.71								
D01	31.94	7.42	27.41	242.59								
D02	33.74	7.37	26.90	257.99	12.51	22.19	33.08	18.51	0.014	0.0002	1E-06	0.001
D03	33.89	7.29	26.91	257.93								
D04	32.40	7.18	27.44	242.40								

tables 1 and 2. The average soil moisture content increased from 27.93% ± 17.22 in the control (D0) to a peak of 34.90% ± 22.11 at dose D03, followed by a slight decrease to 32.26% ± 19.44 at D04. This trend suggests the existence of an optimal SAP dose, beyond which benefits begin to plateau or decline. The trend could be explained by quadratic model which showed a bell-shaped response curve, with a maximum effect around D02-D03. Statistical analysis using the Kruskal-Wallis test ($H = 12.51$, $p = 0.014$) confirmed significant differences among treatments. Post-hoc analysis using Dunn's test revealed statistically significant differences between D0 and D01 ($p = 0.022$) and between D0 and D03 ($p = 0.041$), highlighting the efficacy of SAP at intermediate doses in enhancing soil water retention.

Soil pH values remained within a neutral to slightly alkaline range (7.20 to 7.47). The highest average pH was recorded in the control treatment (D0: 7.43 ± 0.75), while the lowest was observed at D03 (7.2 ± 0.8), indicating a slight acidification at higher SAP doses. The quadratic model again identified a minimum

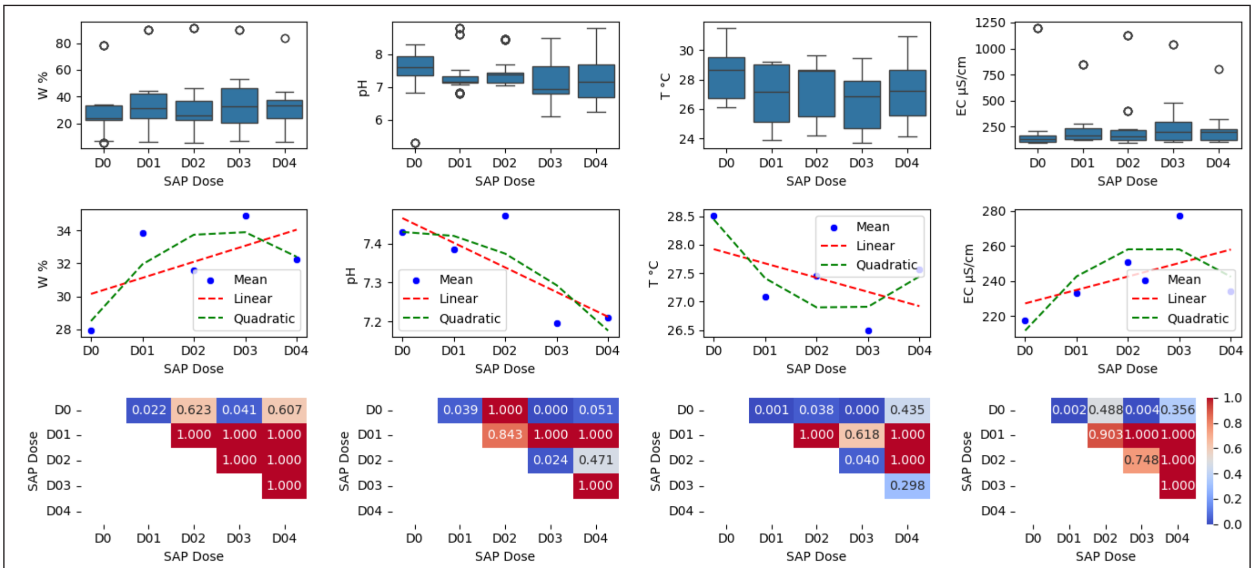

Fig. 3. Boxplots, regression models, and Dunn's post-hoc heatmaps for water content (W%), pH, temperature (T°C), and electrical conductivity (µS cm^{-1}) as affected by superabsorbent polymer dose. Each column represents one parameter (W, pH, T, or EC), showing the distribution, regression fit, and statistical significance of pairwise comparisons.

Table 2. Post-hoc Dunn's Test for Pairwise Comparison of SAP Doses

	Post-hoc Dunn (W)					Post-hoc Dunn (pH)				
	D0	D1	D2	D3	D4	D0	D1	D2	D3	D4
D0	1	0.022	0.623	0.041	0.607	1	0.039	1	0	0.051
D1	0.022	1	1	1	1	0.039	1	0.843	1	1
D2	0.623	1	1	1	1	1	0.843	1	0.024	0.471
D3	0.041	1	1	1	1	0	1	0.024	1	1
D4	0.607	1	1	1	1	0.051	1	0.471	1	1

	Post-hoc Dunn (T)					Post-hoc Dunn (EC)				
	D0	D1	D2	D3	D4	D0	D1	D2	D3	D4
D0	1	0.001	0.04	0	0.435	1	0.002	0.488	0.004	0.356
D1	0.001	1	1	0.618	1	0.002	1	0.903	1	1
D2	0.038	1	1	0.04	1	0.488	0.903	1	0.748	1
D3	4.52E-07	0.618	0.04	1	0.298	0.004	1	0.748	1	1
D4	0.435	1	1	0.298	1	0.356	1	1	1	1

near D03, indicating a non-linear response to SAP application. The Kruskal-Wallis test ($H = 22.19$, $p = 0.0002$) revealed statistically significant variation across treatments, and Dunn's test identified significant differences between D0 and D01 ($p = 0.039$), D0 and D03 ($p = 0.000$), and D02 and D03 ($p = 0.024$).

Soil temperature data suggest a moderating effect of SAP on thermal variation, with dose D03 showing the lowest recorded value (26.49 ± 1.86°C) compared to the control (28.51 ± 1.73°C). This indicates that SAP can act as a thermal buffer, particularly at intermediate application rates. The quadratic model revealed a temperature minimum around D02-D03, further supporting this interpretation. The Kruskal-Wallis test ($H = 33.078$, $p = 1.15\times10^{-6}$) confirmed highly significant differences among treatments, and Dunn's post-hoc test identified significant differences between D0 and D01 ($p = 0.001$), D0 and D02 ($p = 0.038$), and D0 and D03 ($p < 0.001$).

Electrical conductivity (EC) increased significantly with SAP application, peaking at D03 (277.26 ± 245.05 µS cm^{-1}) before decreasing at D04 (233.96 ± 181.85 µS cm^{-1}), indicating a saturation effect at higher doses. The quadratic model effectively captured this non-linear dynamic, identifying a peak response near D02-D03. The Kruskal-Wallis test ($H = 18.51$, $p = 0.001$) revealed statistically significant differences, supported by Dunn's test which confirmed significant differences between D0 and D01 ($p = 0.002$) and D0 and D03 ($p = 0.004$).

The findings from this study demonstrated that super absorbent polymer (SAP) application significantly improves soil water retention, moderates soil temperature, and influences soil pH and electrical conductivity under the semi-arid climatic conditions of the Cheliff plain in northern Algeria. These results are in line with multiple recent studies conducted across arid and semi-arid regions, reinforcing the utility of SAPs as effective soil conditioners for enhancing crop resilience to water stress.

The Cheliff region, characterized by declining rainfall and increasing temperatures (Kelkouli *et al.*, 2024), imposes substantial irrigation demands on crops like tomato. Under such conditions, the increase in average soil moisture from 27.93% in the untreated control to 34.90% at the optimal SAP dose (D03) is particularly significant. This bell-shaped response curve aligns with earlier work by Albalasmeh *et al*. (2022) in Jordan, who reported that hydrogel-treated soils exhibited up to 49% higher available water content, leading to improved water use efficiency and maize performance in semi-arid environments. Similarly, Abdelghafar *et al*. (2024), in Egypt, found that SAPs improved water retention and reduced hydraulic conductivity, facilitating better crop productivity under deficit irrigation conditions.

The observed thermal buffering effect of SAPs, with the lowest soil temperature recorded at the D03 dose (26.49°C), suggests a reduction in evaporative losses and improved soil microclimate. This is consistent with findings by Muhammad *et al*. (2025), who reviewed hydrogel applications across dryland agriculture systems and concluded that SAPs reduce soil surface temperatures and evaporation rates by up to 30%, thereby improving water conservation and plant-water relations.

Furthermore, the reduction in soil pH at higher SAP doses, although modest, may contribute to improved availability of certain elements in alkaline soils. The Cheliff soils were found to be moderately saline and highly alkaline, conditions that can hinder uptake of some ions. In this regard, Omar and Alsharaeh (2024), working in Saudi Arabia, designed high-performance hydrogels that not only enhanced water retention but also improved conservation in sandy soils. Their results underscore the dual role of SAPs in managing both water dynamics and soil conditions, especially in degraded or structurally weak soils. The increase in electrical conductivity (EC) observed in this study, peaking at moderate SAP doses, could be attributed to enhanced ion mobility in the soil matrix. However, this effect appeared to plateau or decline at higher application rates, indicating a saturation threshold. This pattern mirrors reports by Lahlimi *et al*. (2023), in Morocco, where SAPs improved the survival and growth of cork oak plantations in water-scarce regions, but over-application risked disrupting ionic balance.

In the local context, the moderate salinity and hardness of irrigation water, combined with the heavy clay-silty-loam soil texture, require tailored SAP application strategies. The SAP's capacity to reduce bulk density and enhance water retention is particularly advantageous in such soils, which are prone to compaction and poor infiltration. The current study's findings that soil moisture improved significantly with SAP application, without negatively impacting pH or promoting excessive salinity, validate SAP use as a feasible strategy for improving soil water dynamics in Mediterranean-like environments.

Overall, the combined climatic, soil, and water constraints in the Cheliff plain underscore the relevance of SAPs in addressing agricultural sustainability challenges in Algeria. When applied at optimal doses, SAPs can help buffer against erratic rainfall, reduce irrigation frequency, and support the productivity of high water-demand crops like tomato.

Conclusions

The application of superabsorbent polymers (SAPs) significantly influenced the soil's physicochemical properties, with clear agronomic implications. The data demonstrated a substantial improvement in soil water retention, reaching optimal levels at intermediate SAP doses (notably D02-D03), beyond which the benefits began to decline. Moreover, SAP application slightly reduced soil pH and contributed to thermal stabilization, providing a buffering effect that can be particularly advantageous under semi-arid climatic conditions. Electrical conductivity also followed a non-linear trend, increasing moderately with SAP application before plateauing, suggesting that while SAP can enhance soil ion retention, excessive doses may risk salinity buildup.

Statistical analyses (Kruskal-Wallis and Dunn's post-hoc tests) validated these observations by revealing significant differences between control and treated soils across water content, pH, temperature, and EC. The consistent bell-shaped responses observed across parameters highlight the importance of dose optimization to maximize benefits while minimizing potential negative effects.

In summary, these findings underscore the potential of SAPs as an effective soil amendment for improving water use efficiency and moderating soil conditions. However, their agronomic performance is dose-dependent, requiring careful calibration to achieve sustainable and efficient agricultural practices, particularly in water-stressed environments.

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