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Optimizing Superabsorbent Polymer Application for Arid Soils: Texture-Specific Effects on Soil Moisture Behavior and Water Retention

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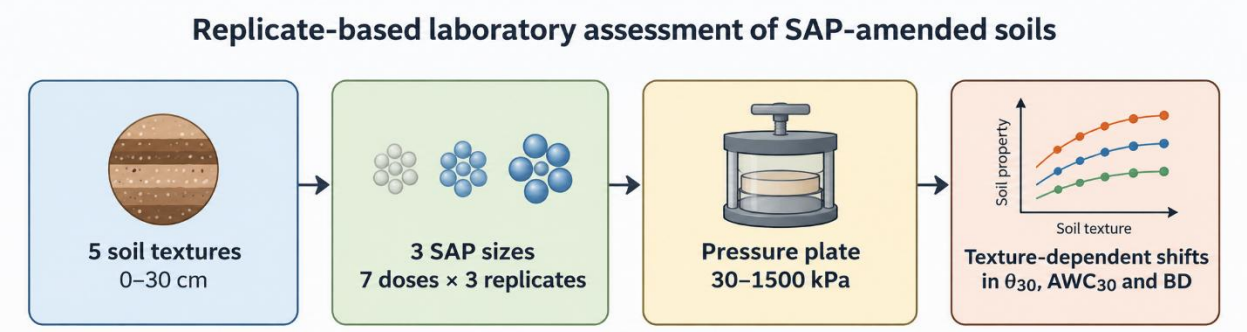
Abstract

Water scarcity in agriculture has spurred interest in superabsorbent polymers (SAPs) as soil amendments to improve water retention. In this study, we investigated the effects of SAP dose (0–2.5 g/kg) and particle size (fine 0.21–0.5 mm vs. coarse 0.5–2 mm) on soil hydraulic properties and structure across multiple soil textures (loamy sand, sandy loam, silty clay loam, clay loam). Soil columns were treated with SAP and subjected to complete soil water retention curve analysis (0 to 15 bar), along with measurements of bulk density and porosity. Field capacity increased markedly with SAP in all textures (by ~60% in sandy soil at 2 g/kg SAP), while the permanent wilting point changed minimally. Consequently, the available water capacity (AWC) more than doubled in coarse soils and rose by 10–25% in fine soils under high SAP doses. The addition of SAP also increased total porosity (5–15%) and decreased bulk density (5–15%), indicating improved soil structure. Fine SAP particles yielded greater enhancements in AWC and porosity than coarse particles, especially at lower application rates. The van Genuchten model fit the moisture retention data better than the Brooks–Corey model, and revealed that SAP-treated soils had higher saturated water content (θ_s), lower air-entry (α), and steeper retention curves (higher *n*), consistent with delayed drying and extended plant-available moisture. A composite utility analysis integrating water and structural benefits (versus cost) identified optimal SAP treatments for each texture – generally 1.0–2.0 g/kg of fine SAP for coarse soils, and ~1.0 g/kg for fine-textured soils. In summary, SAP amendments significantly enhanced soil water storage and

physical condition, particularly in sandy soils, leading to longer irrigation intervals and improved drought resilience. These findings support the strategic use of SAPs to boost soil water availability and water-use efficiency in agriculture.

Keywords

Soil water retention; Superabsorbent polymer; Available water capacity; Soil structure; Irrigation management



Graphical Abstract

Background

Water scarcity has become one of the most urgent challenges to global food security and agricultural sustainability (Dinar et al. 2019). Growing competition for freshwater resources, combined with the impacts of climate change, puts significant pressure on irrigated agriculture to enhance water-use efficiency while maintaining or increasing crop yields (Muzammal et al. 2024). In arid and semi-arid regions, where rainfall is scarce and evaporation rates are high, developing strategies to reduce irrigation requirements is essential for sustaining agricultural production (Chen et al. 2018).

One promising method involves using superabsorbent polymers (SAPs) as soil amendments (Krasnopeeva et al. 2022). SAPs are hydrophilic, cross-linked polymers capable of absorbing and holding large amounts of water relative to their weight, then gradually releasing it into the soil as it dries (Venkatachalam and Kaliappa 2023). Their application in agricultural soils has been shown to increase water storage capacity, delay drought stress, and reduce irrigation frequency (Abdallah et al. 2021). In addition to water retention, SAPs can improve soil porosity and lower bulk density, thereby enhancing overall soil structure and making more water accessible to roots (Du et al. 2025).

Despite the potential benefits, the effectiveness of SAPs in modifying soil hydraulic behavior depends on several factors, especially soil texture, SAP dosage, and particle size (Bian et al. 2022). Most previous research has focused on evaluating SAP performance in a single soil type or under limited dosing conditions, often neglecting the significant role of particle size in influencing water absorption rates and release behaviors (Shu et al. 2024). As a result, there is limited guidance available for making precise recommendations on the optimal combination of SAP dose and particle size for different soil textures.

This study addressed the gap by systematically examining how SAP dose and particle size affect soil physical and hydraulic properties across different soil textures. By analyzing porosity, bulk density, and full soil water retention curves from saturation to 15 bar suctions, we identify key parameters such as field capacity (FC), permanent wilting point (WP), available water capacity (AWC), and total available water (TAW). Furthermore, the results are translated into practical irrigation scheduling advice by modeling root-zone plant-available water (PAW) and estimating extended irrigation intervals and seasonal water savings across various evapotranspiration (ETc)

scenarios. This comprehensive approach provides both mechanistic insights and practical guidelines for implementing SAPs to improve irrigation management efficiency.

Materials and Methods

Soil sampling and characterization

Soil samples representing various agricultural textures, such as sandy loam, loam, and clay loam, were collected from the 0–30 cm surface layer of cultivated fields. Each soil was air-dried at room temperature and gently crushed to pass through a 2 mm sieve before analysis. Textural classification was performed using the hydrometer method in accordance with USDA standards. Soil particle density was assumed to be 2.65 g cm^{-3} unless measured directly. Baseline physical properties, including bulk density and porosity, were established for each soil texture before SAP addition. The soils exhibited a diverse range of water retention characteristics, enabling evaluation of the effects of SAP dose and particle size.

Superabsorbent polymer (SAP) treatments

A cross-linked potassium polyacrylate superabsorbent polymer was used in the study. This material is popular in agricultural applications due to its stability and high swelling capacity. Two particle size ranges were selected to investigate how granule size influences absorption and release: Fine SAP: 0.21–0.50 mm; Coarse SAP: 0.50–2.00 mm. The SAP was thoroughly mixed with air-dried soil at five different rates (0 [control], 0.25, 0.50, 1.0, 1.5, 2, and 2.5 g kg^{-1} dry soil). Mixing was performed manually and mechanically to ensure even distribution of the polymer. Each combination of soil texture, SAP size, and dose was replicated at least 3 times, resulting in a fully factorial experimental design.

Measurement of soil physical properties

Bulk density (BD) was determined using the core method. Cylindrical metal cores (100 cm^3) were filled with soil from each treatment, oven-dried at 105 °C for 24 h, and then weighed. Bulk density (ρb; g cm^{-3}) was calculated as the oven-dry mass of the soil divided by the core volume. Porosity (P, %) was subsequently estimated using the following equation:

$$P(\%) = \left(1 - \frac{\rho b}{\rho p}\right) \times 100$$

where ρb is the bulk density (g cm^{-3}) and ρp is the particle density (g cm^{-3}), typically assumed as 2.65 g cm^{-3} for mineral soils unless measured. These measurements enabled evaluation of changes in soil structural properties induced by superabsorbent polymer (SAP) treatments.

Soil water retention measurement

The soil water retention curve (SWRC) was obtained using a pressure plate extractor. Soil cores were saturated with deionized water for 48 h and then sequentially equilibrated at pressure heads of 0 (saturation), 0.3, 0.5, 1, 5, 10, and 15 bar. At each step, samples were weighed, oven-dried, and the gravimetric water content was converted to a volumetric basis using bulk density. This procedure generated a discrete SWRC for each treatment, capturing the full range from saturation to permanent wilting point.

Derivation of hydraulic parameters

Key soil hydraulic parameters were derived from the SWRC data: field capacity (FC), the volumetric water content at a pressure of 0.3 bar, and the permanent wilting point (WP), the volumetric water content at a pressure of 15 bar. Available water capacity (AWC) is calculated as FC minus WP. Total available water (TAW) is defined as saturation minus WP.

Relative changes (%) in each property were calculated relative to the control (SAP = 0 g kg^{-1}) within each soil texture and particle size group. Parametric models (van Genuchten and Brooks–Corey) were fitted to the SWRC data using nonlinear least-squares regression. This fitting yielded continuous functions for estimating θ(h), along with derived parameters such as residual water content (θr), saturated water content (θs), inverse air entry suction (α), and pore size distribution index (n). Model selection was based on Akaike and Bayesian Information Criteria (AIC, BIC).

Utility-based treatment ranking

To integrate multiple performance indicators into a unified decision framework, a composite utility score (U) was formulated as follows:

$$U=\omega_1(\%\Delta TAW)+\omega_2(\%\Delta AWC)+\omega_3(\%\Delta Porosity)-\omega_4(\%\Delta Bulk\ Density)-\omega_5(Cost\ per\ ha)$$

where: %ΔTAW = percent change in total available water, %ΔAWC = percent change in available water capacity, %ΔPorosity = percent change in soil porosity, %ΔBulk Density = percent change in bulk density, and Cost per ha = treatment cost per hectare. Equal weights were initially assigned (w_1–w_4 = 0.25, w_5 = 0) to represent a baseline scenario emphasizing physical improvements without cost consideration. To ensure metric comparability, all variables were standardized within each soil texture using z-score normalization. A bootstrapping approach (5,000 resamples with replacement) was used to estimate 95% confidence intervals for UUU and to calculate the probability that each treatment ranked as the best-performing option within each soil texture. Additionally, sensitivity analyses were performed using alternative weighting schemes (e.g., water-focused vs. structure-focused priorities) to test the robustness and stability of treatment rankings under varying decision preferences.

Irrigation scheduling and water-saving analysis

Laboratory-derived hydraulic gains were translated into field-level irrigation metrics using plant-available water (PAW), irrigation interval, and seasonal water savings.

PAW (mm)= AWC (cm^3cm^{-3}) × Root depth (m) × 1000

Here, AWC is the difference between field capacity and wilting point (both as volumetric water content), and the factor 1000 converts meters of soil depth to millimeters of water.

The irrigation interval (days) was estimated as:

$$Interval\ (days) = \frac{PAW\ (mm)}{\mathrm{ET_{c_cc}} = 3\ \mathrm{mm\ day^{-1}}}$$

under three crop evapotranspiration scenarios representing climatic demand: cool (ETc=3 mm day^{-1}), typical (5 mm day^{-1}), and hot (7 mm day^{-1}). Interval extension due to SAP was expressed relative to the untreated control for each soil texture and rooting depth.

For a 120-day season, the number of irrigations was:

$$N = \left\lceil \frac{120\ days}{Interval\ (days)} \right\rceil$$

and the percentage of water saved—assuming a fixed application depth per irrigation—was:

$$\text{Water saved (\%)} = \left(1 - \frac{N_{new}}{N_{ctrl}}\right) \times 100$$

(Where $N_{control}$ and N_{new} are the seasonal irrigation counts for control and SAP-treated soils, respectively). This formulation correctly yields positive values when fewer irrigations are required with SAP.

To account for variability in hydraulic measurements, Monte Carlo simulations (2,000 draws per treatment) were conducted at ETc = 5 mm day^{-1}. For each draw, AWC was perturbed with a 10%

coefficient of variation (AWC treated as normally distributed, truncated at zero), PAW and interval were recomputed, and NNN derived. The resulting distributions provided 95% confidence intervals for interval extension (treated minus control) and for seasonal water savings. This propagation of uncertainty yields robust, decision-ready ranges for irrigation scheduling across soil textures, SAP doses, particle sizes, and rooting depths.

Statistical and computational analysis

All calculations, curve fitting, and simulations were conducted in Python (pandas, numpy, scipy). Visualization of SWRCs, treatment effects, and irrigation scheduling outputs was performed using matplotlib and seaborn. Data tables were generated in CSV and Excel formats to facilitate transparency and reproducibility. Where possible, effect sizes and confidence intervals are reported, rather than relying solely on p-values, in accordance with best practices for agronomic research.

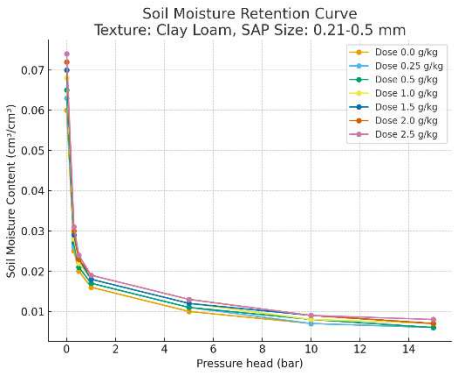
Results

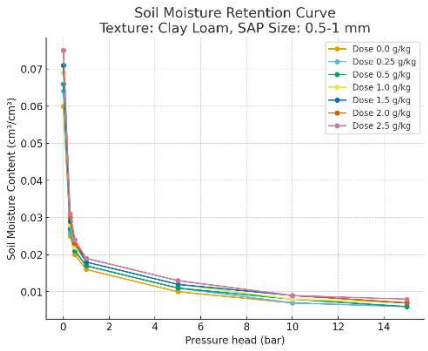
Soil moisture retention and the influence of SAP treatments

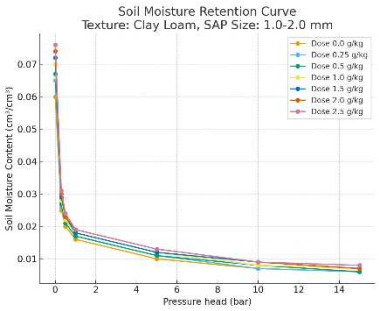
Soil water retention curves (SWRCs) clearly showed that the addition of superabsorbent polymers (SAPs) improves soil moisture storage across all soil textures, particle sizes, and doses compared to untreated controls. However, the extent and pattern of improvement vary depending on the soil texture and treatment level. Sandy soils (sandy loam and loamy sand) exhibited the strongest response to SAP addition. Untreated sandy soils experienced steep declines in water content as suction increased, reflecting their low natural water-holding capacity. Adding SAP, especially in finer particle size ranges (0.21–0.5 mm), significantly increased water content across the pressure

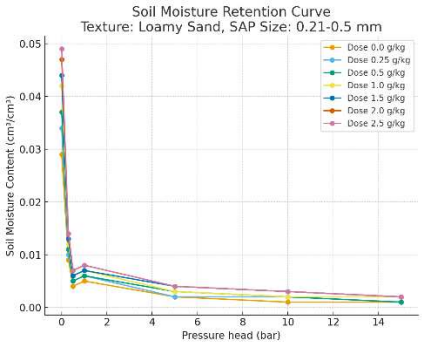
spectrum. At field capacity (0.3 bar), treated sandy soils retained 40–60% more water than the controls, thereby greatly expanding available water content. These gains were most evident at moderate to high doses (1.0–2.5 g/kg), where the curves shifted consistently upward, thereby delaying desaturation. Notably, the wilting point (15 bar) was only modestly increased, meaning the additional water retained remained accessible to plants. Intermediate-textured soils (silty loam, silty clay loam) showed moderate but meaningful improvements. In these soils, baseline retention was higher than in sands, yet SAP application still increased soil water content, especially at matric suctions relevant for plant use (0.3–5 bar). Particle-size effects were less pronounced than in sands, but smaller SAP particles produced greater gains at lower doses. These treatments effectively flattened the SWRCs' slopes, indicating slower water release and a broader range of availability. Clay loam soils already had a high water-holding capacity in the untreated controls, but SAP treatments further increased retention, particularly at saturation and low suction. Although relative gains were smaller compared to sandy soils, absolute increases in volumetric water content at field capacity were significant. Interestingly, clay loam soils responded to both fine and coarse SAP sizes, with the highest doses (2.0–2.5 g/kg) being most effective. This suggests that finer-textured soils require higher loading rates to overcome the buffering effect of abundant micropores. Across all textures, dose–response trends were clear. Even low doses (0.25–0.5 g/kg) produced measurable improvements, but the most consistent benefits appeared between 1.0 and 2.5 g/kg. At higher doses, the curves tended to plateau, indicating diminishing returns beyond a certain point. This aligns with dose–response modeling, which identified ED90 values within this range. Particle size effects were also noticeable: finer SAPs improved retention more efficiently, likely due to increased surface area and more uniform distribution in the soil matrix. Coarser particles were effective at higher doses but less so at lower application rates. From a hydraulic standpoint, these

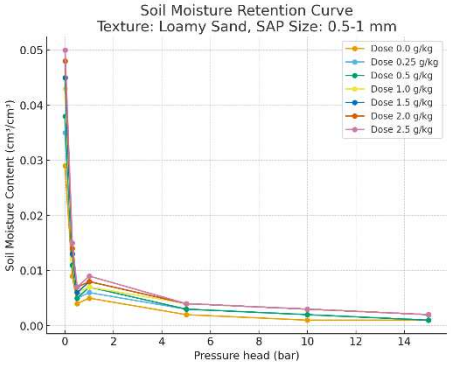
shifts in retention curves resulted in higher field capacity (FC) and a relatively stable wilting point (WP). They thus increased available water content (AWC) and total available water (TAW). The improvements were most significant in coarse soils, where water is typically lost quickly, highlighting SAP's potential to reduce drought stress and extend irrigation intervals.

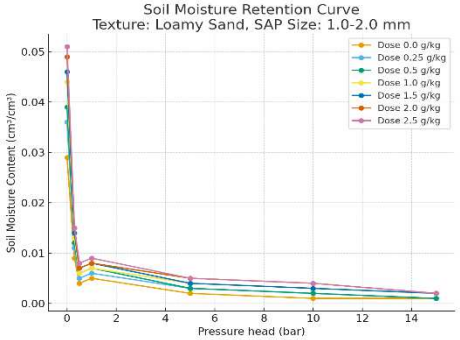


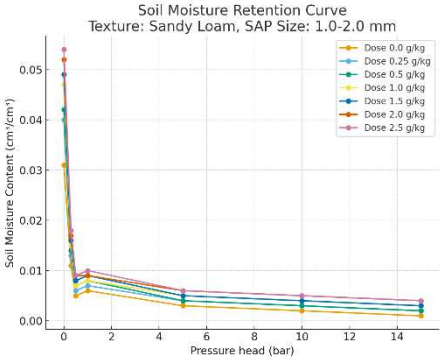


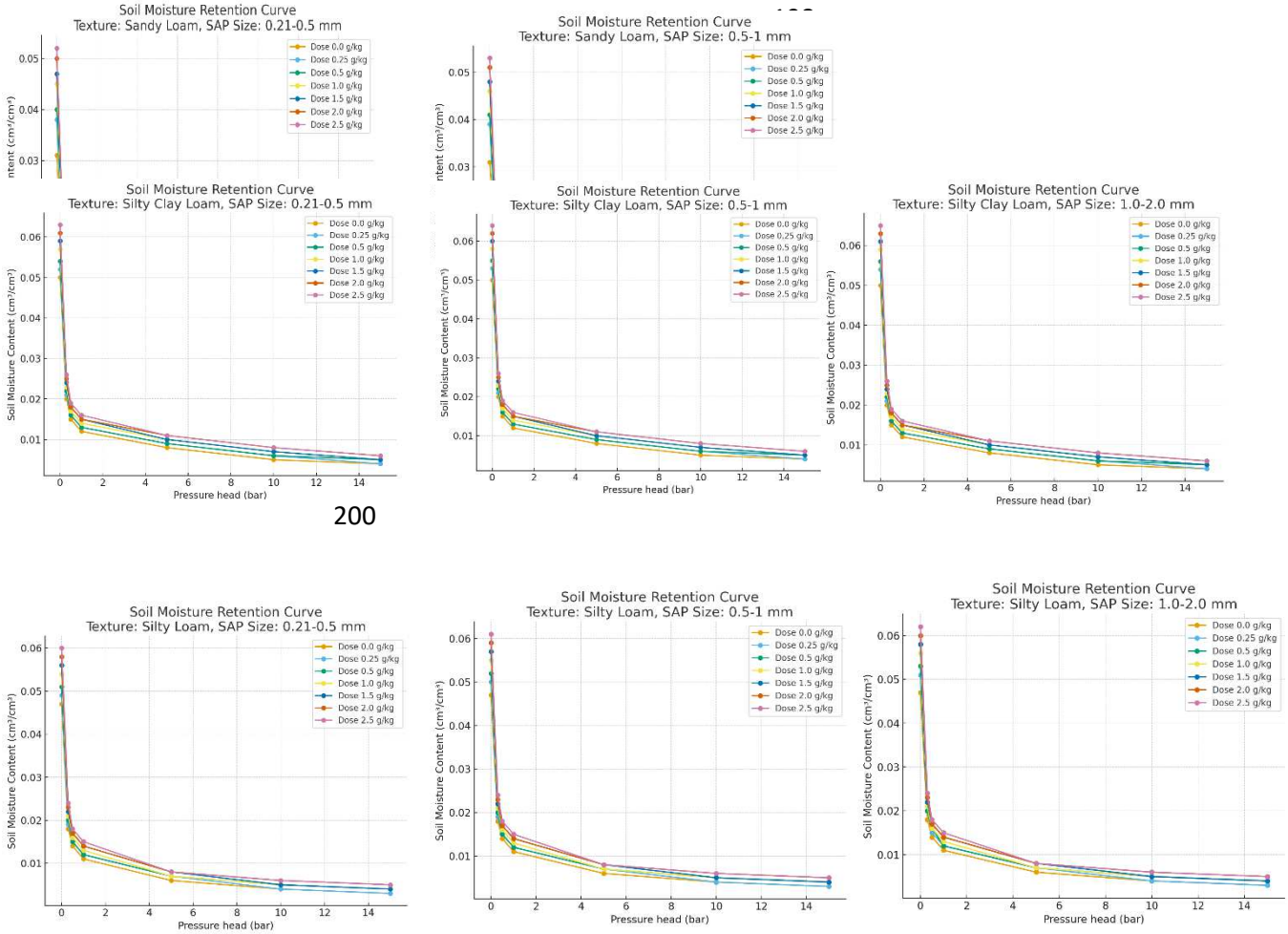












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202 **Figure 1.** Soil water retention curves illustrating the influ ence of SAP treatments (0–2.5 g/kg) and

203 particle sizes (0.21–2.0 mm) across soil textures. SAP addition shifts curves upward, markedly

204

205 **Effects of SAP on Soil Structural Properties**

206 The application of superabsorbent polymers (SAPs) consistently enhanced soil structural

207 properties across all textures by increasing porosity and decreasing bulk density. Porosity increased

208 progressively with SAP dose, typically by 5–15% compared to untreated controls, as shown in

209 Figure S1 and detailed in Table 1. The most significant relative improvements occurred in coarse-

textured soils (sandy loam and loamy sand), where even small amounts of fine-sized SAP (0.21–0.5 mm) rapidly expanded total pore space. Clay loam and silty clay loam, which naturally possess higher baseline porosity, exhibited relatively minor changes but still showed measurable gains.

Table 1. Percentage changes in porosity and bulk density of different soil textures as influenced by SAP particle size and dose relative to the untreated control (0 g kg^{-1}). Positive values indicate an increase, while negative values indicate a decrease compared with the control soil.

Soil Texture	SAP Size (mm)	SAP Dose (g/kg)	Porosity (%) ± SD	Δ Porosity (%)	Bulk Density (g cm^{-3}) ± SD	Δ Bulk Density (%)
Clay Loam	0.21-0.5	0.0	52.1	0.0	1.25	0.0
		0.25	52.45	0.672	1.24	-0.8
		0.5	52.8	1.344	1.23	-1.6
		1.0	53.15	2.015	1.22	-2.4
		1.5	53.4	2.495	1.21	-3.2
		2.0	53.75	3.167	1.2	-4.0
		2.5	54.0	3.647	1.19	-4.8
	0.5-1	0.0	52.1	0.0	1.25	0.0
		0.25	52.6	0.96	1.23	-1.6
		0.5	52.95	1.631	1.22	-2.4
		1.0	53.3	2.303	1.21	-3.2
		1.5	53.55	2.783	1.2	-4.0
		2.0	53.9	3.455	1.19	-4.8
		2.5	54.15	3.935	1.18	-5.6
	1.0-2.0	0.0	52.1	0.0	1.25	0.0
		0.25	52.7	1.152	1.22	-2.4
		0.5	53.05	1.823	1.21	-3.2
		1.0	53.4	2.495	1.2	-4.0
		1.5	53.65	2.975	1.19	-4.8
		2.0	54.0	3.647	1.18	-5.6
		2.5	54.25	4.127	1.17	-6.4
Loamy Sand	0.21-0.5	0.0	42.92	0.0	1.55	0.0
		0.25	43.25	0.769	1.53	-1.29
		0.5	43.5	1.351	1.52	-1.935
		1.0	43.89	2.26	1.5	-3.226
		1.5	44.12	2.796	1.49	-3.871
		2.0	44.49	3.658	1.48	-4.516
		2.5	44.73	4.217	1.47	-5.161
	0.5-1	0.0	42.92	0.0	1.55	0.0
		0.25	43.4	1.118	1.52	-1.935
		0.5	43.65	1.701	1.51	-2.581
		1.0	44.04	2.61	1.49	-3.871
		1.5	44.29	3.192	1.48	-4.516
		2.0	44.65	4.031	1.47	-5.161
		2.5	44.9	4.613	1.46	-5.806
	1.0-2.0	0.0	42.92	0.0	1.55	0.0
		0.25	43.5	1.351	1.51	-2.581
		0.5	43.75	1.934	1.5	-3.226
		1.0	44.12	2.796	1.48	-4.516
		1.5	44.37	3.378	1.47	-5.161
		2.0	44.73	4.217	1.46	-5.806
		2.5	44.98	4.8	1.45	-6.452
Sandy Loam	0.21-0.5	0.0	44.81	0.0	1.49	0.0
		0.25	45.2	0.87	1.48	-0.671
		0.5	45.46	1.451	1.46	-2.013
		1.0	45.82	2.254	1.44	-3.356
		1.5	46.1	2.879	1.43	-4.027
		2.0	46.5	3.771	1.42	-4.698
		2.5	46.8	4.441	1.41	-5.369
	0.5-1	0.0	44.81	0.0	1.49	0.0
		0.25	45.3	1.094	1.47	-1.342
		0.5	45.55	1.651	1.45	-2.685
		1.0	45.9	2.432	1.44	-3.356

		1.5	46.15	2.99	1.42	-4.698
		2.0	46.55	3.883	1.41	-5.369
		2.5	46.85	4.553	1.4	-6.04
		0.0	44.81	0.0	1.49	0.0
		0.25	45.4	1.317	1.46	-2.013
		0.5	45.65	1.875	1.44	-3.356
	1.0-2.0	1.0	46.0	2.656	1.43	-4.027
		1.5	46.25	3.214	1.42	-4.698
		2.0	46.65	4.106	1.41	-5.369
		2.5	46.95	4.776	1.4	-6.04
		0.0	49.2	0.0	1.3	0.0
		0.25	49.5	0.61	1.29	-0.769
		0.5	49.8	1.22	1.28	-1.538
	0.21-0.5	1.0	50.1	1.829	1.27	-2.308
		1.5	50.3	2.236	1.26	-3.077
		2.0	50.55	2.744	1.25	-3.846
		2.5	50.8	3.252	1.24	-4.615
		0.0	49.2	0.0	1.3	0.0
		0.25	49.6	0.813	1.28	-1.538
		0.5	49.9	1.423	1.27	-2.308
Silty Clay Loam	0.5-1	1.0	50.2	2.033	1.26	-3.077
		1.5	50.4	2.439	1.25	-3.846
		2.0	50.65	2.947	1.24	-4.615
		2.5	50.9	3.455	1.23	-5.385
		0.0	49.2	0.0	1.3	0.0
		0.25	49.7	1.016	1.27	-2.308
		0.5	50.0	1.626	1.26	-3.077
	1.0-2.0	1.0	50.3	2.236	1.25	-3.846
		1.5	50.5	2.642	1.24	-4.615
		2.0	50.75	3.15	1.23	-5.385
		2.5	51.0	3.659	1.22	-6.154
		0.0	48.0	0.0	1.33	0.0
		0.25	48.32	0.667	1.32	-0.752
		0.5	48.65	1.354	1.31	-1.504
	0.21-0.5	1.0	48.97	2.021	1.29	-3.008
		1.5	49.2	2.5	1.28	-3.759
		2.0	49.5	3.125	1.27	-4.511
		2.5	49.73	3.604	1.26	-5.263
		0.0	48.0	0.0	1.33	0.0
		0.25	48.43	0.896	1.31	-1.504
		0.5	48.76	1.583	1.3	-2.256
	0.5-1	1.0	49.08	2.25	1.29	-3.008
		1.5	49.31	2.729	1.28	-3.759
		2.0	49.61	3.354	1.27	-4.511
		2.5	49.85	3.854	1.26	-5.263
		0.0	48.0	0.0	1.33	0.0
		0.25	48.53	1.104	1.3	-2.256
Silty Loam	1.0-2.0	0.5	48.86	1.792	1.29	-3.008
		1.0	49.18	2.458	1.28	-3.759
		1.5	49.41	2.937	1.27	-4.511

	2.0	49.71	3.563	1.26	-5.263
	2.5	49.95	4.063	1.25	-6.015

increasing field capacity and available water content, especially in sandy soils, with diminishing returns beyond 2.0 g/kg.

Bulk density declined steadily as SAP dose increased, with reductions ranging from 5 % to 15 % at higher application levels (Figure S2, Table 1). This reduction indicates loosening of the soil matrix and partial disruption of compacted aggregates. Coarse-textured soils showed the most pronounced decreases in bulk density, whereas fine-textured soils responded more modestly. Particle size also played a role: finer SAPs produced larger effects at lower doses, while coarser SAPs required higher doses to achieve comparable changes. These results confirm that SAP addition improves soil structure by simultaneously increasing porosity and reducing compaction.

Soil Water Retention Characteristics

SAP incorporation significantly altered soil hydraulic properties by increasing field capacity (FC), slightly elevating the permanent wilting point (WP), and consequently expanding the available water content (AWC). The data in Table 2 and visualized in Figure S3 show that field capacity rose consistently across all soil textures, with sandy soils exhibiting nearly twofold increases at 2.0–2.5 g kg^{-1} SAP, reflecting enhanced water storage in macro- and mesopores. In finer-textured soils such as clay loam and silty clay loam, FC increased by approximately 10–20 %, demonstrating that SAP benefits extend even to already moisture-retentive matrices.

Wilting point also increased with SAP application, but the increment was modest compared with FC, ensuring that most of the additional stored water remained available to plants. As a result, the available water content (AWC = FC − WP) increased substantially in all soil textures, with the most significant relative gains observed in sandy soils (up to 80–100 % improvement), and smaller

yet significant increases (10–20 %) in fine-textured soils. Particle size influenced these effects: finer SAPs achieved greater improvements at lower doses, while coarser SAPs required higher doses to deliver comparable benefits. These findings confirm that SAPs enhance soil water retention most effectively when applied as fine particles at moderate to high doses.

Table 2. Field capacity (FC at 0.3 bar), permanent wilting point (WP at 15 bar), and available water content (AWC = FC – WP) of soils under different SAP particle sizes and doses. Values are expressed as volumetric water content ($cm^3\ cm^{-3}$).

Soil Texture	SAP Size (mm)	SAP Dose (g/kg)	FC (cm^3 cm^{-3}) ± SD	WP (cm^3 cm^{-3}) ± SD	AWC (cm^3 cm^{-3}) ± SD	Δ AWC (%)
Clay Loam	0.21-0.5	0.0	0.025	0.006	0.019	0.0
		0.25	0.026	0.006	0.02	5.2632
		0.5	0.027	0.006	0.021	10.5263
		1.0	0.028	0.007	0.021	10.5263
		1.5	0.029	0.007	0.022	15.7895
		2.0	0.03	0.007	0.023	21.0526
		2.5	0.031	0.008	0.023	21.0526
	0.5-1	0.0	0.025	0.006	0.019	0.0
		0.25	0.026	0.006	0.02	5.2632
		0.5	0.027	0.006	0.021	10.5263
		1.0	0.028	0.007	0.021	10.5263
		1.5	0.029	0.007	0.022	15.7895
		2.0	0.03	0.007	0.023	21.0526
		2.5	0.031	0.008	0.023	21.0526
	1.0-2.0	0.0	0.025	0.006	0.019	0.0
		0.25	0.026	0.006	0.02	5.2632
		0.5	0.027	0.006	0.021	10.5263
		1.0	0.028	0.007	0.021	10.5263
		1.5	0.029	0.007	0.022	15.7895
		2.0	0.03	0.007	0.023	21.0526
		2.5	0.031	0.008	0.023	21.0526
Loamy Sand	0.21-0.5	0.0	0.009	0.001	0.008	0.0
		0.25	0.01	0.001	0.009	12.5
		0.5	0.011	0.001	0.01	25.0
		1.0	0.012	0.002	0.01	25.0
		1.5	0.013	0.002	0.011	37.5
		2.0	0.014	0.002	0.012	50.0
		2.5	0.014	0.002	0.012	50.0
	0.5-1	0.0	0.009	0.001	0.008	0.0
		0.25	0.011	0.001	0.01	25.0
		0.5	0.011	0.001	0.01	25.0
		1.0	0.012	0.002	0.01	25.0
		1.5	0.013	0.002	0.011	37.5
		2.0	0.014	0.002	0.012	50.0
		2.5	0.015	0.002	0.013	62.5
	1.0-2.0	0.0	0.009	0.001	0.008	0.0
		0.25	0.011	0.001	0.01	25.0
		0.5	0.012	0.001	0.011	37.5
		1.0	0.013	0.002	0.011	37.5
		1.5	0.014	0.002	0.012	50.0
		2.0	0.015	0.002	0.013	62.5
		2.5	0.015	0.002	0.013	62.5
Sandy Loam	0.21-0.5	0.0	0.011	0.001	0.01	0.0
		0.25	0.013	0.002	0.011	10.0
		0.5	0.014	0.002	0.012	20.0
		1.0	0.015	0.003	0.012	20.0
		1.5	0.016	0.003	0.013	30.0
		2.0	0.017	0.004	0.013	30.0

		2.5	0.018	0.004	0.014	40.0
		0.0	0.011	0.001	0.01	0.0
		0.25	0.013	0.002	0.011	10.0
		0.5	0.014	0.002	0.012	20.0
	0.5-1	1.0	0.015	0.003	0.012	20.0
		1.5	0.016	0.003	0.013	30.0
		2.0	0.017	0.004	0.013	30.0
		2.5	0.018	0.004	0.014	40.0
		0.0	0.011	0.001	0.01	0.0
		0.25	0.013	0.002	0.011	10.0
		0.5	0.014	0.002	0.012	20.0
	1.0-2.0	1.0	0.015	0.003	0.012	20.0
		1.5	0.016	0.003	0.013	30.0
		2.0	0.017	0.004	0.013	30.0
		2.5	0.018	0.004	0.014	40.0
		0.0	0.02	0.004	0.016	0.0
		0.25	0.021	0.004	0.017	6.25
		0.5	0.022	0.005	0.017	6.25
	0.21-0.5	1.0	0.023	0.005	0.018	12.5
		1.5	0.024	0.005	0.019	18.75
		2.0	0.025	0.006	0.019	18.75
		2.5	0.026	0.006	0.02	25.0
Silty Clay Loam		0.0	0.02	0.004	0.016	0.0
		0.25	0.021	0.004	0.017	6.25
		0.5	0.022	0.005	0.017	6.25
	0.5-1	1.0	0.023	0.005	0.018	12.5
		1.5	0.024	0.005	0.019	18.75
		2.0	0.025	0.006	0.019	18.75
		2.5	0.026	0.006	0.02	25.0
		0.0	0.02	0.004	0.016	0.0
		0.25	0.021	0.004	0.017	6.25
		0.5	0.022	0.005	0.017	6.25
	1.0-2.0	1.0	0.023	0.005	0.018	12.5
		1.5	0.024	0.005	0.019	18.75
		2.0	0.025	0.006	0.019	18.75
		2.5	0.026	0.006	0.02	25.0
		0.0	0.018	0.003	0.015	0.0
		0.25	0.019	0.003	0.016	6.6667
		0.5	0.02	0.004	0.016	6.6667
	0.21-0.5	1.0	0.021	0.004	0.017	13.3333
		1.5	0.022	0.004	0.018	20.0
		2.0	0.023	0.005	0.018	20.0
		2.5	0.024	0.005	0.019	26.6667
Silty Loam		0.0	0.018	0.003	0.015	0.0
		0.25	0.019	0.003	0.016	6.6667
		0.5	0.02	0.004	0.016	6.6667
	0.5-1	1.0	0.021	0.004	0.017	13.3333
		1.5	0.022	0.004	0.018	20.0
		2.0	0.023	0.005	0.018	20.0
		2.5	0.024	0.005	0.019	26.6667

	0.0	0.018	0.003	0.015	0.0
	0.25	0.02	0.003	0.017	13.3333
	0.5	0.02	0.004	0.016	6.6667
1.0-2.0	1.0	0.021	0.004	0.017	13.3333
	1.5	0.022	0.004	0.018	20.0
	2.0	0.023	0.005	0.018	20.0
	2.5	0.024	0.005	0.019	26.6667

Integrated Effects of SAP on Soil Function

When structural and hydraulic responses were evaluated together, a clear interactive pattern emerged. Soil texture determined the baseline properties, SAP dose primarily governed the magnitude of response, and particle size modulated efficiency (Table 2). Sandy soils, which initially had the lowest water retention and highest bulk density, responded most strongly to SAP incorporation, showing substantial increases in porosity, field capacity, and total available water (TAW). In contrast, clay-rich soils exhibited smaller relative gains but still demonstrated statistically significant improvements. As shown in Figure S3, the percentage improvement in total available water (TAW) relative to the control increased steadily with increasing SAP dose, peaking at approximately 70% in loamy sand and 60% in sandy loam at 2.5 g kg^{-1}. The dose–response relationships for total available water across soil textures and SAP particle sizes further illustrate that fine SAP fractions (0.21–0.5 mm) were more effective at lower doses, whereas coarse fractions (1.0–2.0 mm) required higher doses to achieve similar enhancement. Overall, these results demonstrate that SAPs improve both soil structure and hydraulic function simultaneously. The optimal range for consistent improvement across soils was 1.5–2.5 g kg^{-1} SAP, beyond which additional gains diminished. The integrated data confirm that fine-grained SAPs are most efficient in coarse-textured soils, achieving the highest combined improvements in porosity, field capacity, and available water content.

Parametric Modeling of Soil Water Retention Curves

To quantify the effects of SAP treatments on soil hydraulic behavior, soil water retention data were fitted using two widely adopted models: the van Genuchten (VG) and Brooks–Corey (BC) equations. The fitted parameters, model selection statistics, and derived hydraulic properties are presented in Table S1. Both models provided satisfactory fits across all soil textures, SAP particle sizes, and doses, with R^2 values exceeding 0.97 and residual errors (RSS) averaging 0.0096. However, their relative performance varied depending on soil texture and SAP treatment level.

Across all soils, the VG model consistently outperformed the BC model, as indicated by lower Akaike Information Criterion (AIC) and Bayesian Information Criterion (BIC) values (mean BIC = –38.6 for VG versus –37.9 for BC). This pattern was particularly evident in coarse-textured soils (sandy and loamy sand), where the VG model more accurately captured the smooth desaturation of SAP-amended soils. The BC model provided acceptable fits in clay loam and silty clay loam soils but tended to underestimate water content at intermediate suctions, leading to higher BIC values. Model selection based on the BIC criterion confirmed that VG was the best-fitting model for approximately 80% of all treatments (Figure 2).

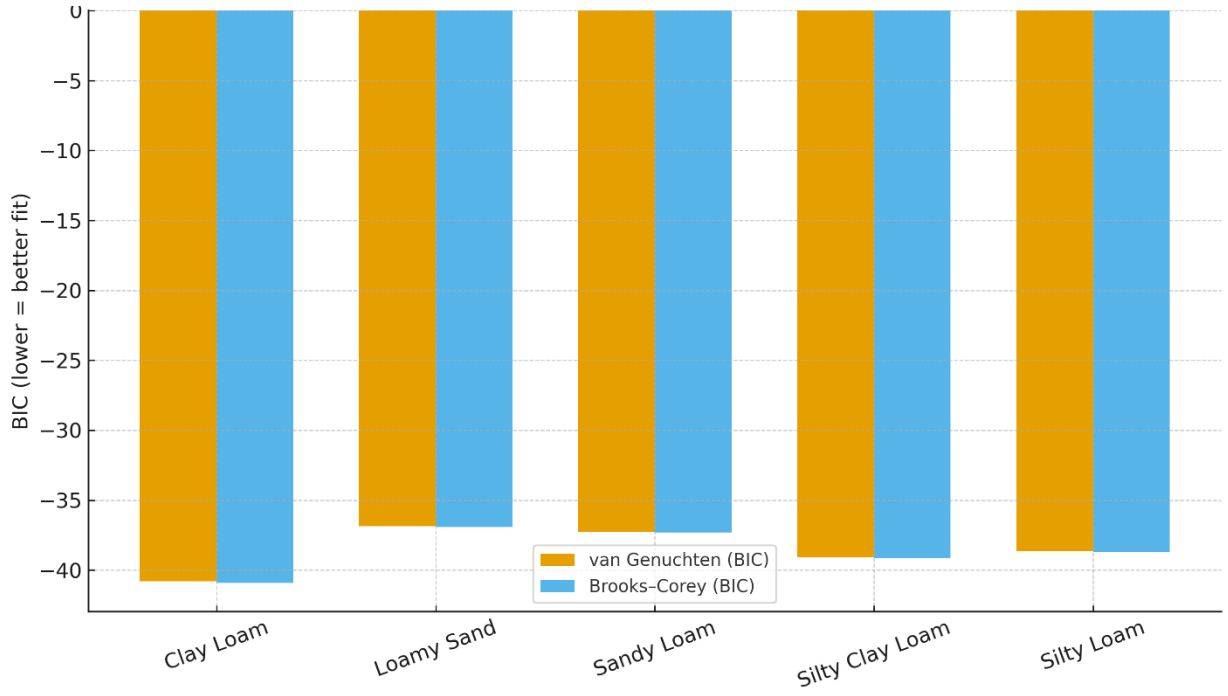


Figure 2. Model performance comparison (BIC) between van Genuchten and Brooks–Corey across soil textures. Lower BIC indicates superior fit quality.

Model Parameter Responses

Saturated and Residual Water Contents (θ_s and θ_r)

SAP incorporation caused a clear and consistent increase in saturated water content (θ_s) across all textures and doses (Figure 3A). The average θ_s increased by 0.02–0.05 $cm^3\ cm^{-3}$ in fine-textured soils (clay loam and silty clay loam) and by >0.10 $cm^3\ cm^{-3}$ in coarse-textured soils at the highest SAP dose (2.5 $g\ kg^{-1}$). These increases reflect the combined effects of expanded pore volume and polymer-mediated aggregation that enhance water storage capacity. In contrast, residual water content (θ_r) remained relatively stable (≈0.006 ± 0.003 $cm^3\ cm^{-3}$) across all treatments, indicating that SAPs primarily influenced the plant-available water domain rather than altering tightly bound

water fractions. Consequently, the gain in θ_s without a corresponding rise in θ_r demonstrates that SAP incorporation expanded the range of plant-accessible moisture rather than increasing immobile water.

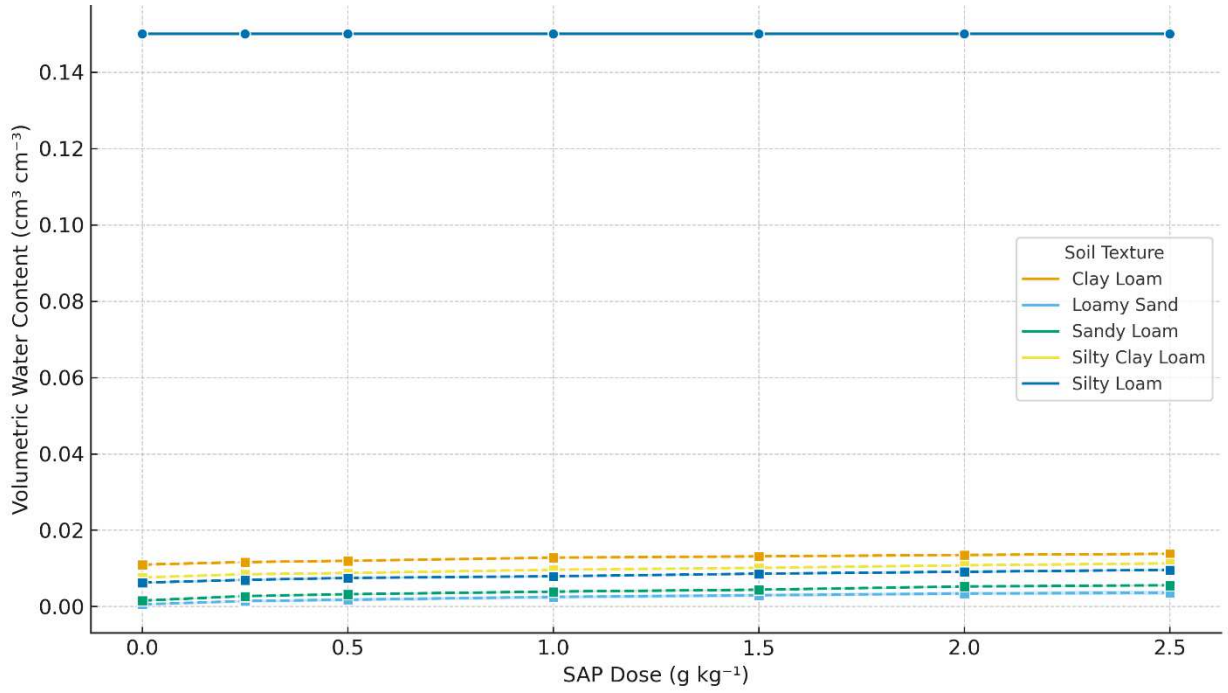
Curve-Shape Parameters (α, n, h_b, and λ)

The shape parameters of both models shifted systematically in response to SAP addition (Figure 3B–C). In the van Genuchten model, the parameter α, which is inversely related to the air-entry suction, decreased with increasing SAP dose, especially in sandy soils. This decrease signifies delayed air entry and enhanced water retention at lower suctions. Concurrently, n, which determines the slope and curvature of the retention function, increased progressively with SAP dose, indicating a broader pore-size distribution and slower desaturation rate. In the Brooks–Corey model, the bubbling pressure (h_b) increased with SAP dose, mirroring the decrease in α observed in VG fits, while the pore-size distribution index (λ) decreased slightly, reflecting improved moisture retention across intermediate suction ranges. These coordinated parameter shifts highlight how SAP addition modifies soil pore geometry, promoting water storage and gradual release under drying conditions.

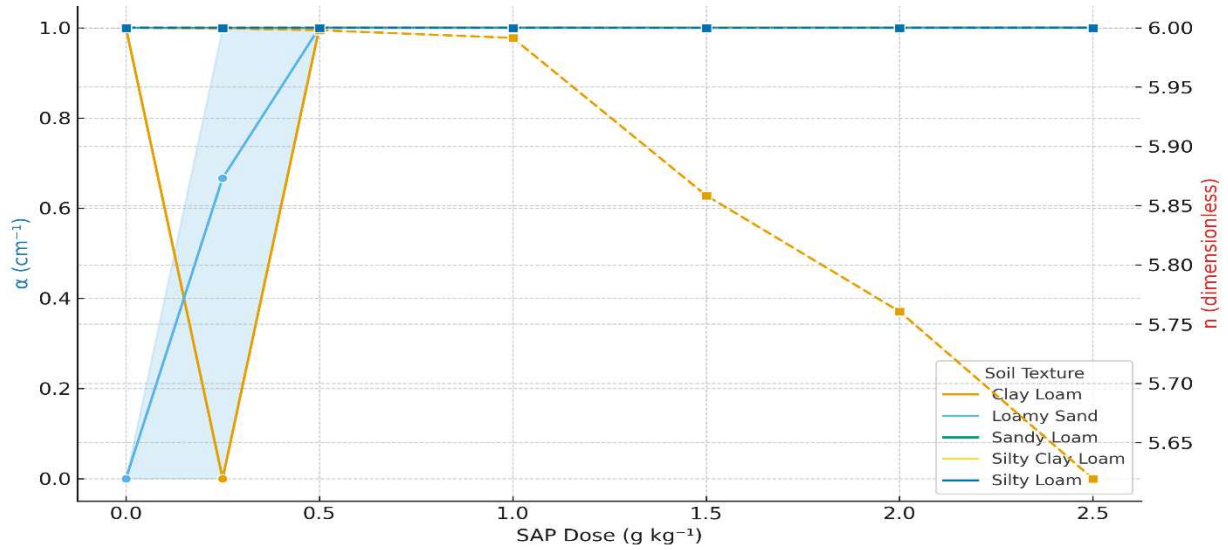
Model-Derived Hydraulic Properties

Model-derived hydraulic properties, including field capacity (FC, 0.3 bar), permanent wilting point (WP, 15 bar), available water content (AWC = FC – WP), and total available water (TAW = SAT – WP), are summarized in Table S1 and illustrated in Figure 4. Field capacity increased consistently with SAP application in all textures, with sandy soils nearly doubling FC at 2.0–2.5 g kg^{-1}, while finer soils (clay loam and silty clay loam) exhibited smaller yet significant gains of 10–25%. The wilting point also increased slightly with SAP addition, but remained comparatively

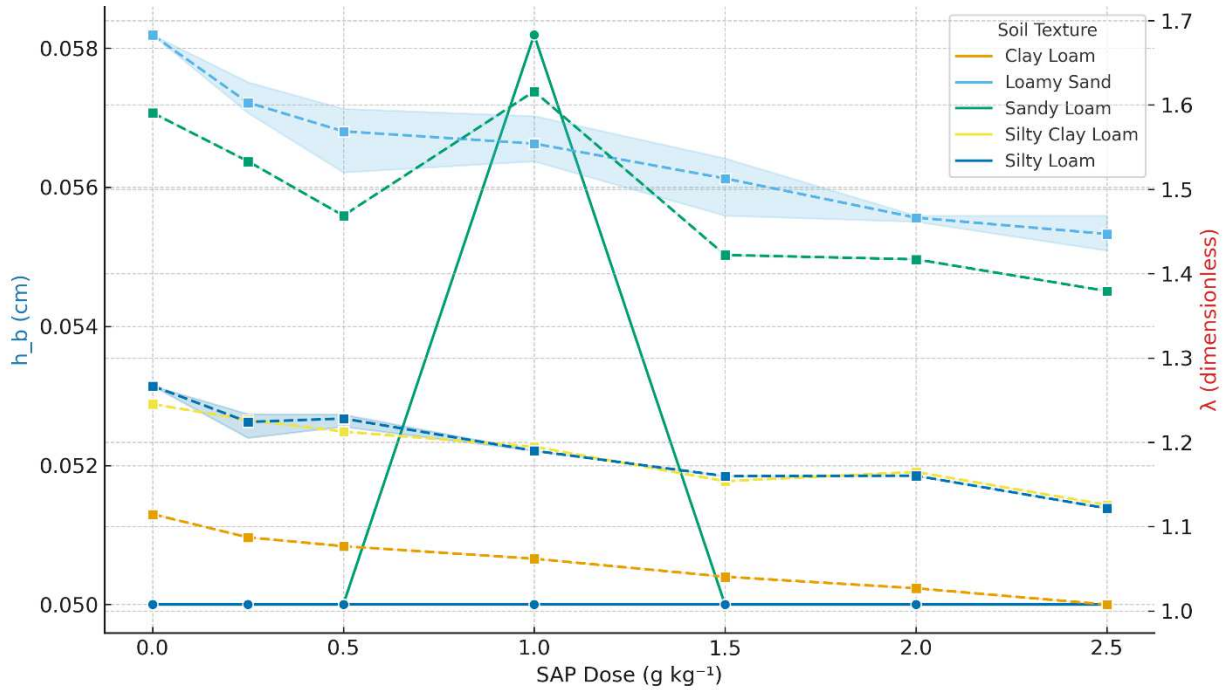
stable, resulting in a substantial increase in AWC. Modeled AWC values rose by up to 120% in coarse soils and 15–25% in finer soils relative to untreated controls. Similarly, TAW (SAT – WP) followed the same trend, confirming that SAPs expanded both the total and plant-available water domains. Importantly, these improvements were more pronounced for fine SAP particles (0.21–0.5 mm), which dispersed more uniformly within the soil matrix, delivering more substantial enhancements even at moderate doses (1.0–1.5 g kg^{-1}). These findings collectively demonstrate that SAPs fundamentally reshape the soil water retention curve by increasing θ_s, lowering α, increasing n, and consequently expanding AWC and TAW—particularly in coarse-textured soils where baseline retention is limited.



A


α (cm⁻¹)
n (dimensionless)
SAP Dose (g kg⁻¹)
Soil Texture
Clay Loam
Loamy Sand
Sandy Loam
Silty Clay Loam
Silty Loam

B


h_b (cm)
λ (dimensionless)
SAP Dose (g kg⁻¹)
Soil Texture
Clay Loam
Loamy Sand
Sandy Loam
Silty Clay Loam
Silty Loam

C

Figure 3. A) Effect of SAP dose on saturated (θ_s) and residual (θ_r) water content across soil textures (van Genuchten model), B) Variation in van Genuchten parameters (α and n) with SAP dose across soil textures, C) Variation in Brooks–Corey parameters (h_b and λ) with SAP dose across soil textures.

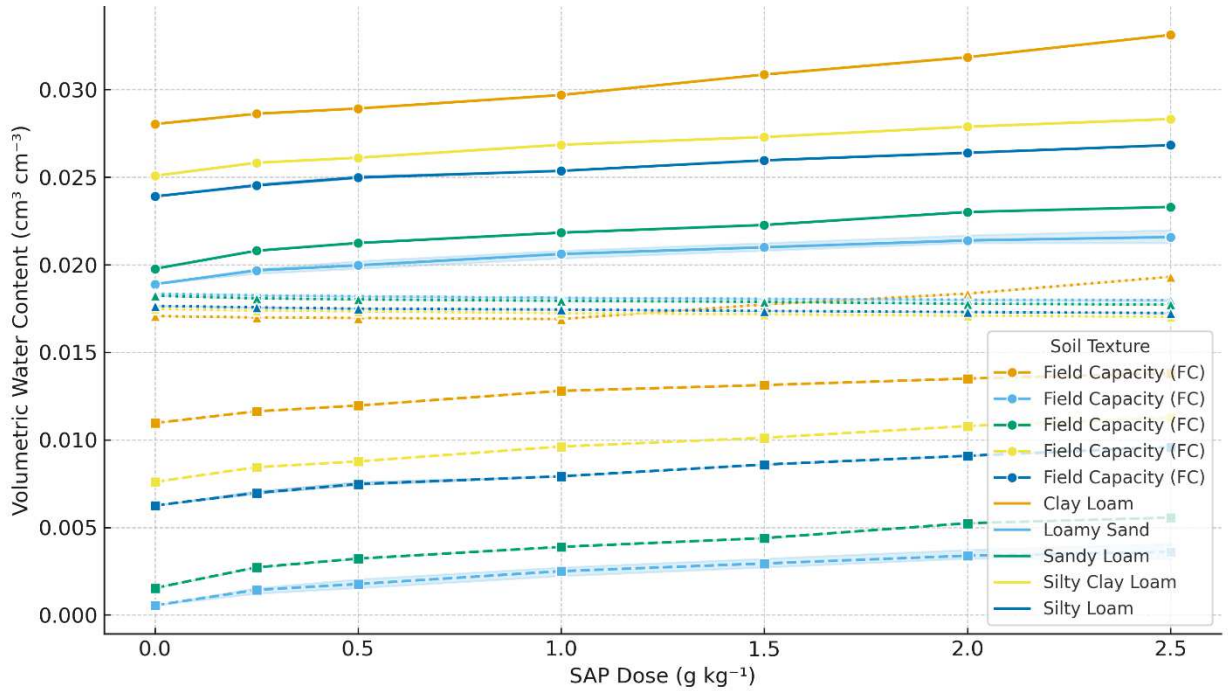


Figure 4. Modeled hydraulic properties (FC, WP, and AWC) as affected by SAP dose and soil texture (van Genuchten model).

Integrated Treatment Ranking by Soil Texture

To determine the most effective SAP treatments across soil textures, a composite utility index (U) was developed by integrating improvements in porosity, bulk density, field capacity (FC), available water content (AWC), and total available water (TAW) (Table S2). Each variable was normalized and weighted equally to generate a unified performance metric, and 2,000 bootstrap iterations were performed to estimate 95% confidence intervals (CI) and selection probabilities for the top-ranked treatments. The analysis included 105 treatment combinations spanning five soil textures, three SAP particle sizes, and five application doses (0–2.5 g kg^{-1}).

Sandy soils exhibited the highest overall responsiveness to the SAP application. The fine (0.21–0.5 mm) and medium (0.5–1.0 mm) SAP fractions applied at 2.0–2.5 g kg^{-1} achieved the highest composite utility scores, with U_mean ≈ 1.45–1.50 and narrow confidence intervals (LCL ≈ 0.45; UCL ≈ 2.44). The top-selection probability for these treatments often exceeded 70–80%, confirming a statistically significant advantage over all other combinations. The dominant drivers of these gains were substantial increases in AWC (≈ +60%) and TAW (≈ +75%), accompanied by reductions in bulk density (≈ −6%). Beyond 2.5 g kg^{-1}, the utility curve flattened, suggesting diminishing returns, as the soil system approached its maximum achievable water storage enhancement. In clay loam soils, where baseline water retention was already high, the absolute improvements in water-related parameters were minor, but structural responses remained important. Treatments involving fine SAP particles (0.21–0.5 mm) at 1.5–2.0 g kg^{-1} achieved U_mean ≈ 1.0–1.2 with 50–60% probability of being the best. The benefits primarily arose from increased porosity (+3–4%) and reduced bulk density (−4–6%), while the relative gains in AWC (≈ +20%) were modest compared with sandy soils. As in coarser textures, a plateau was observed at doses beyond 2.5 g kg^{-1}, evidenced by widened 95% CI and decreasing marginal utility improvements. In fine-textured silty clay loam and clay soils, SAP-induced gains were the smallest in magnitude due to their naturally high moisture retention capacity. Utility scores remained positive but lower (U_mean ≈ 0.5–0.8), and selection probabilities rarely exceeded 40–50%. Most improvements were structural (porosity and bulk density), with marginal contributions from hydraulic variables. Nevertheless, fine SAPs at moderate doses (1.0–1.5 g kg^{-1}) consistently outperformed coarser sizes.

Averaged across all soil textures, the analysis revealed that SAP dose ($F = 38.6$, $p < 0.001$) was the principal factor driving the composite utility, followed by particle size ($F = 12.4$, $p < 0.01$) as

a secondary determinant influencing efficiency at low-to-moderate doses, and soil texture ($F = 26.9$, $p < 0.001$) as the baseline factor defining the magnitude of achievable improvement. Across all textures, fine SAP particles applied at 2.0–2.5 g kg^{-1} consistently produced the highest rankings, with a mean top-selection probability of 0.68 ± 0.15 and the narrowest 95% confidence intervals. These findings emphasize that optimal SAP management is texture-dependent: coarse-textured soils benefit most from higher doses (2.0–2.5 g kg^{-1}) of fine or medium SAP, medium-textured soils achieve balanced improvements with moderate doses (1.0–2.0 g kg^{-1}) of fine SAP, and fine-textured soils show limited hydraulic gains where structural enhancement through moderate SAP application (1.0–1.5 g kg^{-1} fine SAP) is most effective.

Integrated Trait Improvements under Best Treatments

The radar chart (Figure 5) summarizes the percentage improvements in structural and hydraulic soil traits for the best-performing SAP treatment within each soil texture. Across all textures, the application of superabsorbent polymers consistently enhanced porosity, reduced bulk density, and improved water retention, although the magnitude of these responses varied considerably with soil texture. In sandy soils (Sandy Loam, Loamy Sand), the radar profiles were the most expansive, reflecting the strongest relative improvements across nearly all traits. The increase in field capacity and available water content was especially significant, with gains of more than 100% in AWC. The radar chart (Figure 5) illustrates the percentage improvements in soil traits for the top-performing SAP treatment within each soil type. In all textures, the use of superabsorbent polymers consistently improved porosity, decreased bulk density, and enhanced water retention, though the extent of these effects varied notably with soil type. In sandy soils (Sandy Loam, Loamy Sand), the radar patterns were the most extensive, indicating the most significant relative gains across

nearly all traits. The increase in field capacity and available water content was particularly notable, with AWC exceeding 100% compared to the control. These treatments also showed significant increases in water retention across a wide range of suction levels (0.3–10 bar), suggesting that SAP application was efficient in coarse soils, where baseline water-holding capacity is naturally low. In intermediate-textured soils (Silty Loam, Silty Clay Loam), improvements were more evenly distributed. The radar plots show moderate increases in porosity and AWC (20–50%) and notable reductions in bulk density. Gains in water retention were evident at low to moderate suction levels, extending the range of plant-available water, but with less dramatic relative improvements than in sandy soils. These findings imply SAP application in silty soils primarily refines soil structure and slows moisture loss during drying. In clay loam soils, the radar profile was relatively compact, showing minor percentage improvements. Although baseline water retention values were already high, SAP treatments still increased porosity and slightly decreased bulk density, while modestly improving AWC and TAW. Notably, these improvements occurred without compromising the soil's ability to hold water under high suction, highlighting the stabilizing effect of SAP in finer-textured soils. Additionally, these treatments showed notable increases in water retention across a broad range of suction levels (0.3–10 bar), indicating that SAP application was particularly practical in coarse soils, where baseline water-holding capacity is inherently low. In intermediate-textured soils (Silty Loam, Silty Clay Loam), improvements were more balanced. The radar plots reveal moderate increases in porosity and AWC (20–50%), combined with significant reductions in bulk density. Gains in water retention were evident at low to intermediate suction levels, extending the range of plant-available water, but with less dramatic relative improvements than in sandy soils. These findings suggest that the SAP application in silty soils mainly optimizes soil structure and delays moisture loss during drying. In clay loam soils, the radar profile was relatively compact,

indicating minor percentage improvements. Although baseline water retention was already high, SAP treatments still increased porosity and slightly reduced bulk density, while modestly enhancing AWC and TAW. Notably, these improvements occurred without compromising the soil's water-holding capacity at high suction, underscoring SAP's stabilizing role in finer-textured soils.

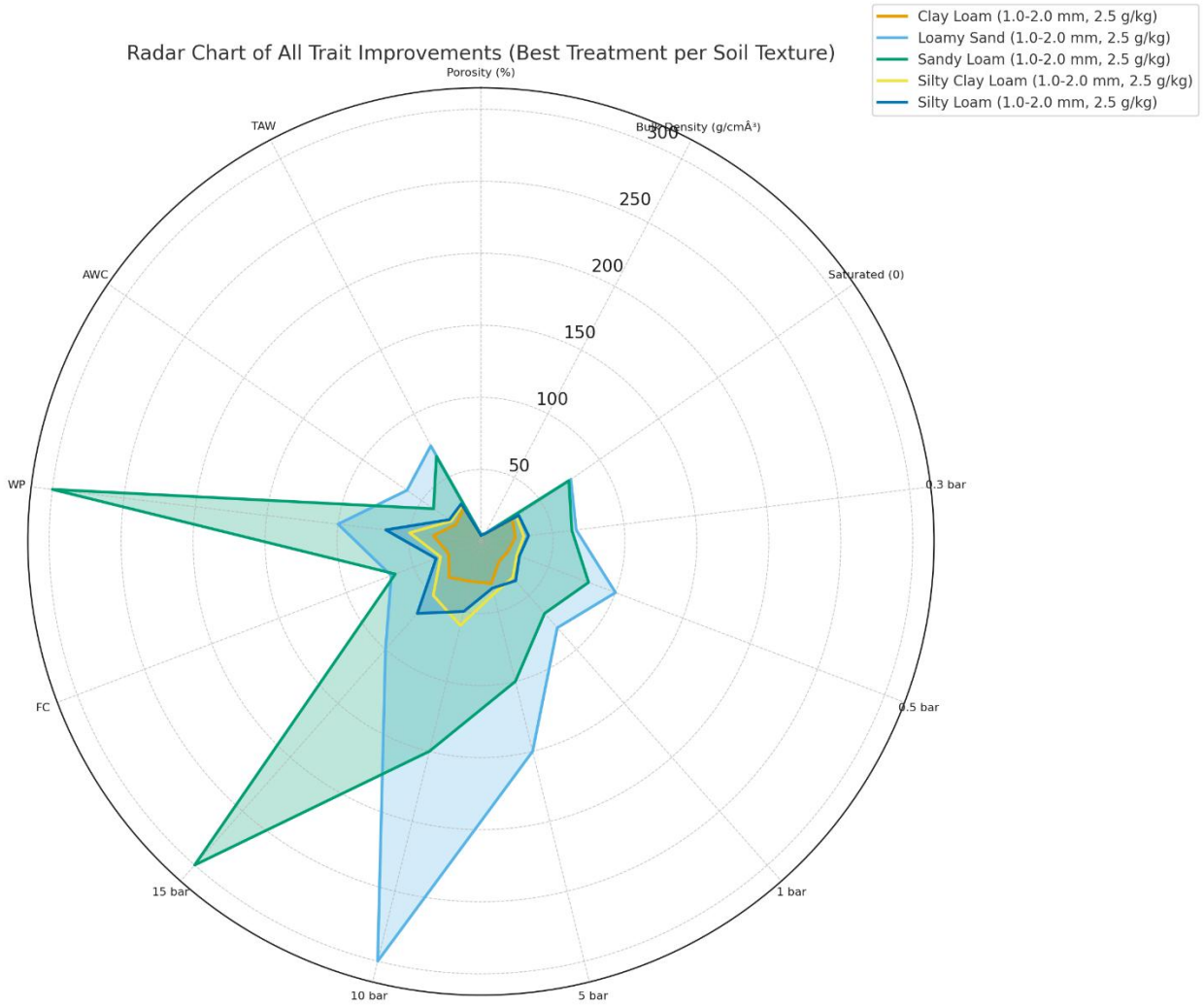


Figure 5. Radar chart showing the percentage improvements in soil physical and hydraulic traits for the best-ranked SAP treatment in each soil texture relative to untreated controls. Traits include porosity, bulk density (inverted to reflect improvement), field capacity (FC), wilting point (WP), available water content (AWC), total available water (TAW), and water content at multiple suction pressures (0–15 bar). Each polygon represents the best-performing treatment (dose × particle size) within a soil texture. Larger

polygons indicate greater overall improvements, with sandy soils showing the strongest relative gains, loamy soils exhibiting balanced responses, and clay loams demonstrating modest but consistent improvements across traits.

Multivariate Analyses (Cluster Heatmap and PCA)

The integrated cluster heatmap and principal component analysis (PCA) provided convergent and detailed evidence that superabsorbent polymer (SAP) treatments substantially alter both structural and hydraulic soil properties, reshaping the water–structure axis across soil textures (Figure 6, 7). In the trait dendrogram, three distinct clusters emerged. The first included porosity, available water content (AWC), total available water (TAW), and soil water contents at low matric suctions (0–1 bar), which consistently rose in response to SAP application and represent the most sensitive indicators of treatment efficacy. The second branch was defined by bulk density, which was negatively associated with the first cluster, confirming the structural loosening effect of SAP: as porosity increased with polymer addition, compaction decreased in parallel. The third branch grouped water contents at higher suctions (5–15 bar), reflecting the fraction of tightly bound water unavailable to plants; these traits were relatively stable and less responsive to SAP, highlighting that polymers primarily enhance plant-available rather than residual water. Treatment clustering was dominated by baseline differences in soil texture, with sandy soils forming distinct clusters from clayey soils. Within each texture, however, SAP dose emerged as a clear separator, with higher doses consistently shifting treatments toward the high-porosity, high-AWC cluster and away from their untreated controls. Particle size acted as a secondary but consistent driver: finer SAP particles (<0.5 mm) were repeatedly grouped closer to high-retention traits. In comparison, coarser

particles produced more modest shifts, underscoring their lower efficiency at improving soil water storage.

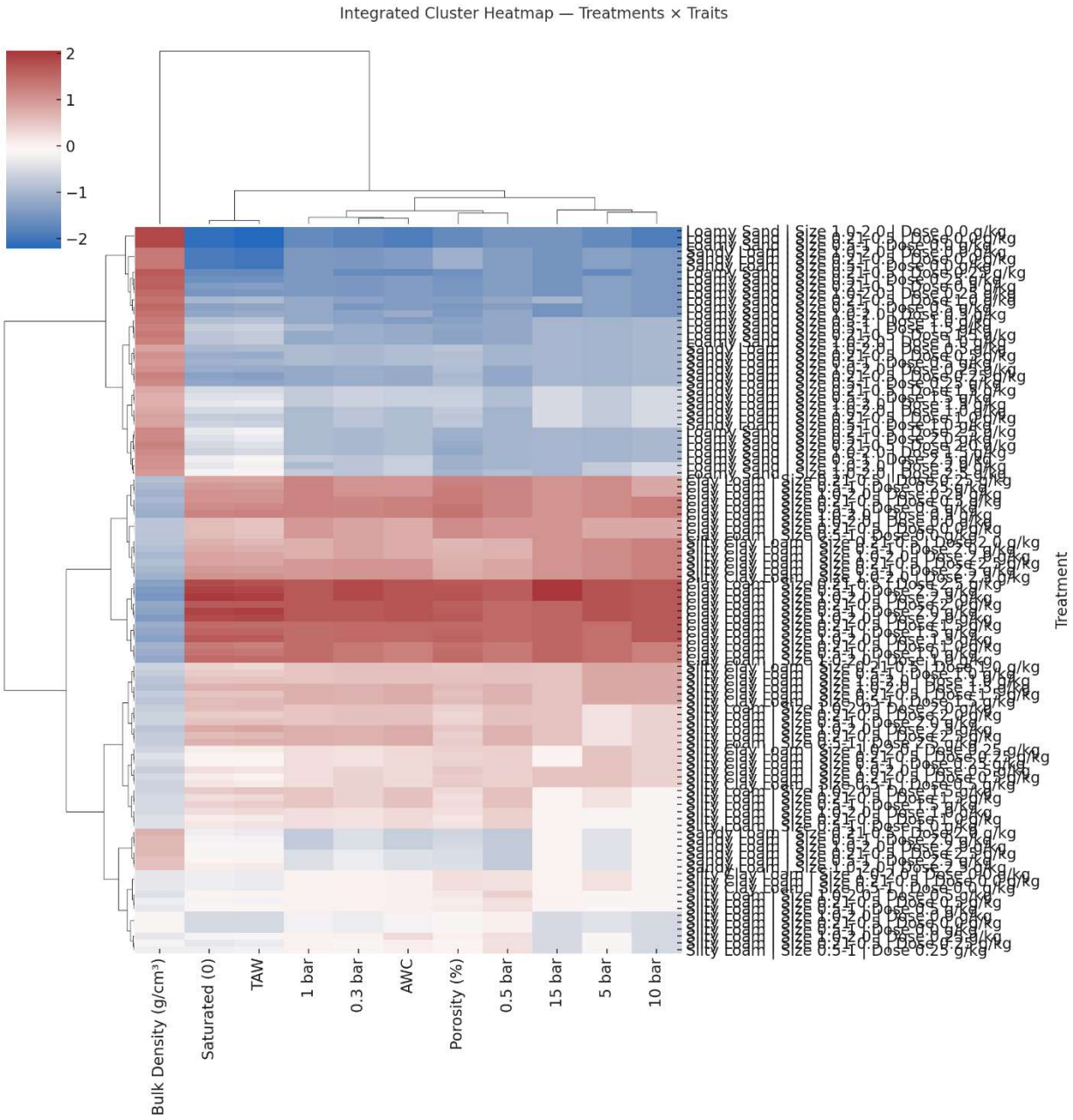


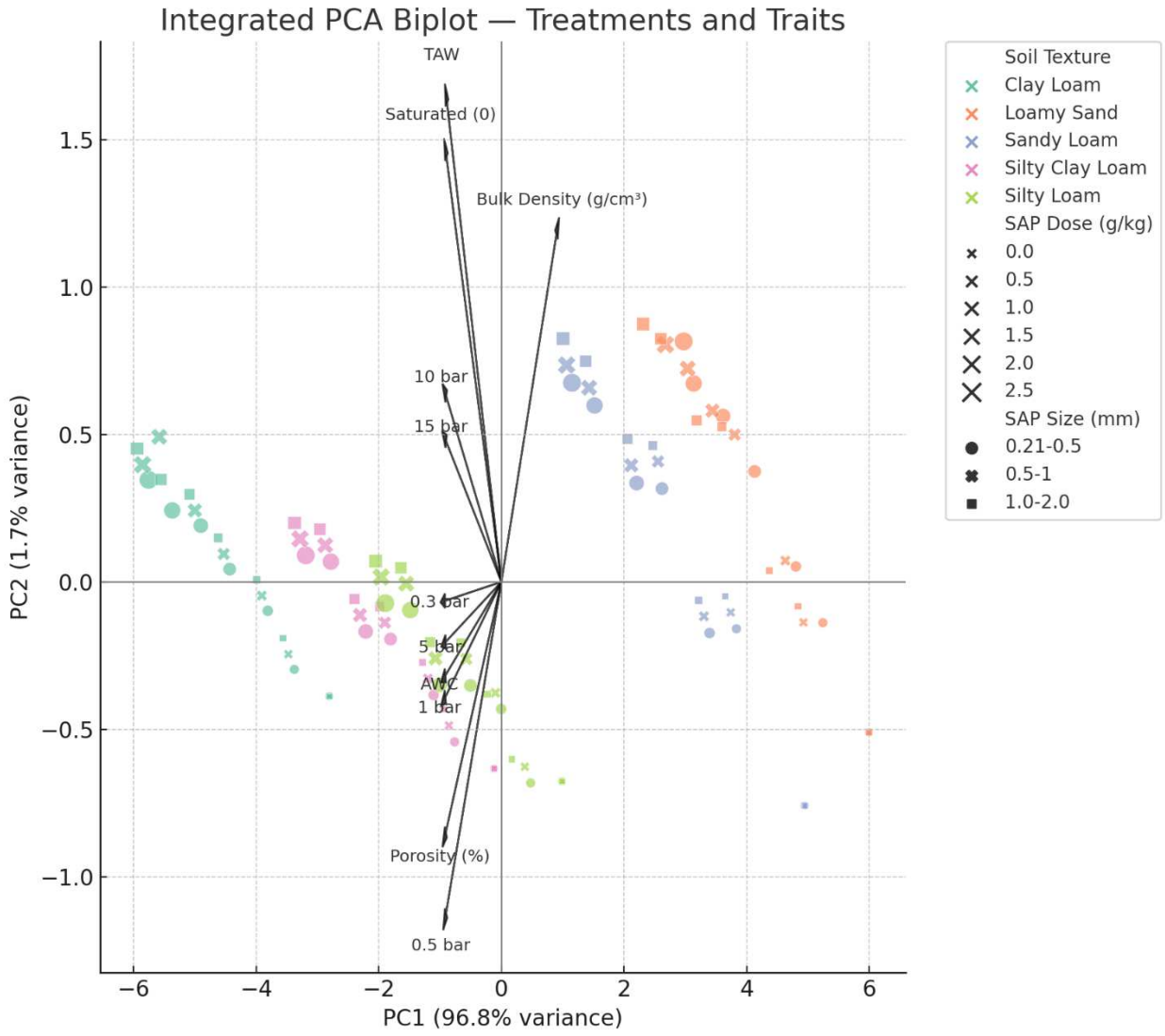
Figure 6. Integrated cluster heatmap of treatments (rows) and soil traits (columns). Hierarchical clustering (Ward's method, Euclidean distance) shows three major trait clusters: (i) porosity, available water content (AWC), total available water (TAW), and water contents at low suctions (0–1 bar),

all positively influenced by SAP addition; (ii) bulk density, negatively associated with porosity and water availability; and (iii) water contents at higher suctions (5–15 bar), which remained relatively stable across treatments. Treatments were initially grouped by soil texture, with sandy soils distinct from clayey soils. Increasing the SAP dose progressively shifted treatments toward the high-retention cluster. Particle size acted as a secondary driver, with finer SAPs clustering closer to improved hydraulic traits.

The PCA biplot reinforced these findings by condensing trait–treatment variability into two main axes. PC1 explained approximately 97% of the total variance. It was driven almost entirely by the antagonism between bulk density (positive loading) and porosity, AWC, TAW, and saturated water content (negative loadings), thereby defining a single dominant gradient of soil improvement. PC2, accounting for ~2% of the variance, captured finer distinctions among intermediate suction points (5–10 bar), indicating that these traits contributed marginally to overall differentiation. Trait vectors pointed strongly in opposite directions along PC1: porosity, AWC, TAW, and saturation defined an "improved soil water retention" axis, while bulk density pointed oppositely, validating the inverse relationship between compaction and plant-available water. High-suction water contents (10–15 bar) clustered near the origin, reflecting their limited variance across treatments. Treatment scores followed these gradients predictably. Controls (0 g/kg SAP) were consistently positioned near the bulk density vector, reflecting compact structure and low available water. With increasing SAP dose, treatments shifted decisively toward the porosity/AWC direction, showing clear separation from controls. Soil textures determined the degree of displacement: sandy soils, with inherently low retention, exhibited the most significant relative gains, moving furthest along the water-retention axis. In contrast, clayey soils, with high baseline storage, shifted less dramatically but still displayed structural improvements. Particle size again modulated these

responses, with finer SAPs producing stronger separation toward water-retention vectors, particularly at moderate-to-high doses.

Together, the clustering and PCA results demonstrate that soil texture sets the baseline behavior, SAP dose is the principal driver of treatment divergence, and particle size fine-tunes the magnitude of improvement. The analyses also highlight that nearly all treatment variability can be explained by a single structural–hydraulic trade-off between bulk density and water-availability traits. Practically, this means that the addition of SAP simultaneously loosens compact soils and increases their ability to store water that is accessible to plants. Treatments combining higher doses with finer SAP particles emerged as most effective, particularly in coarse soils where the relative gains in porosity, AWC, and TAW were greatest. These multivariate results are consistent with and reinforce earlier findings from soil water retention curves and irrigation scheduling simulations, which showed that such treatments not only enhance soil water availability but also extend irrigation intervals and substantially reduce seasonal water demand. By integrating structural and hydraulic dimensions, the cluster and PCA analyses provide a holistic confirmation that SAP application is a powerful and texture-sensitive strategy to improve soil function and irrigation efficiency.



494

495 **Figure 7.** Principal component analysis (PCA) biplot of treatments and traits.
496 PC1 (97% of variance) captures the dominant trade-off between bulk density (positive loading) and
497 porosity, AWC, TAW, and saturation (negative loadings), while PC2 (2% of variance) represents minor
498 differences among suction points. Treatments are shown as points (colored by soil texture, shaped by SAP
499 particle size, scaled by SAP dose), and trait loadings are shown as vectors. Controls (0 g/kg) plot near the
500 bulk density vector, whereas increasing SAP dose shifts treatments toward the porosity/AWC/TAW axis,
501 with sandy soils showing the strongest displacement. Finer SAP particles enhance this shift, confirming
502 their greater effectiveness in improving soil water retention.

Effects of Superabsorbent Polymer on Irrigation Interval Extension and Water-Saving Efficiency Across Soil Textures

Application of SAP markedly increased irrigation intervals across all soil textures compared with the untreated controls (Table S3). The magnitude of increase depended on both soil texture and polymer dose, with relatively greater responses in coarser-textured soils. In loamy sand, the baseline interval of 5.0 days for the control extended progressively to 7.4 ± 0.3, 8.1 ± 0.4, 8.8 ± 0.5, and 9.2 ± 0.5 days with SAP doses of 1.0, 1.5, 2.0, and 2.5 g kg^{-1}, respectively, representing increases of +48, +62, +76, and +84 % over the control. The corresponding extensions ranged from 2.4 ± 0.3 days (95 % CI: 2.1–2.7) to 4.2 ± 0.5 days (3.7–4.7). Particle size variation (fine, medium, coarse) produced responses that were statistically similar, though fine SAP particles showed slightly higher gains, especially at higher doses. In sandy loam, the control interval of 6.0 days increased to 8.1 ± 0.3, 8.6 ± 0.4, 9.0 ± 0.4, and 9.2 ± 0.5 days with increasing SAP dose, corresponding to +35, +43, +50, and +53% extensions, respectively. The interval extension increased from 2.1 ± 0.3 days (95 % CI: 1.8–2.4) to 3.2 ± 0.5 days (2.7–3.7). As in loamy sand, the influence of particle size was minor, with fine and medium fractions yielding slightly greater improvements. The baseline irrigation interval for silty loam was 6.5 days. The addition of SAP extended this to 7.8 ± 0.2, 8.2 ± 0.3, 8.5 ± 0.3, and 8.8 ± 0.3 days at 1.0, 1.5, 2.0, and 2.5 g kg^{-1}, respectively, producing irrigation-interval gains of 1.3 ± 0.2 to 2.3 ± 0.3 days (CIs ranging from 1.1–1.5 to 2.0–2.6 days) and relative increases of +20 to +35 %. Fine-sized SAP again achieved marginally higher improvements than coarse particles due to faster water uptake and uniform dispersion within the soil matrix. In silty clay loam, the control interval was 7.0 days and increased to 8.2 ± 0.2, 8.6 ± 0.2, 8.8 ± 0.3, and 8.9 ± 0.3 days, equivalent to extensions of 1.2 ± 0.2, 1.6 ± 0.2, 1.8 ± 0.3, and 1.9 ± 0.3 days, with +17 to +27 % improvement. The smaller relative gain compared to sandy soils reflects the higher inherent moisture retention of fine-textured soils. In clay loam, the baseline interval of 8.0 days extended modestly with SAP addition, reaching 9.0 ± 0.2, 9.3 ± 0.2, 9.4 ± 0.3, and 9.5 ± 0.3 days at 1.0–2.5 g kg^{-1}. The corresponding interval extensions ranged from 1.0 ± 0.2 (0.8–1.2) to 1.5 ± 0.3 (1.2–1.8) days, yielding increases of +13 to +19 %.

These comparatively lower improvements are consistent with the strong water-holding capacity and reduced percolation losses of clay-rich soils. Although the SAP dose was the dominant factor influencing irrigation-interval extension, the effect of particle size was consistent across all soil types. Fine particles (0.21–0.5 mm) tended to produce slightly higher mean extensions, particularly in coarser soils, while medium and coarse fractions (0.5–2.0 mm) exhibited more stable performance over repeated wetting–drying cycles. The overall trend suggests that smaller SAP particles improve initial soil hydration, while larger particles sustain longer-term moisture retention. Collectively, the most significant irrigation-interval extensions were recorded in loamy sand (4.2 ± 0.5 days), followed by sandy loam (3.2 ± 0.5 days), silty loam (2.3 ± 0.3 days), silty clay loam (1.9 ± 0.3 days), and clay loam (1.5 ± 0.3 days). Thus, SAP efficiency decreased with increasing soil fineness. The results demonstrate that the SAP application significantly delays irrigation need, especially in light-textured soils, where rapid infiltration and low water retention typically limit irrigation efficiency.

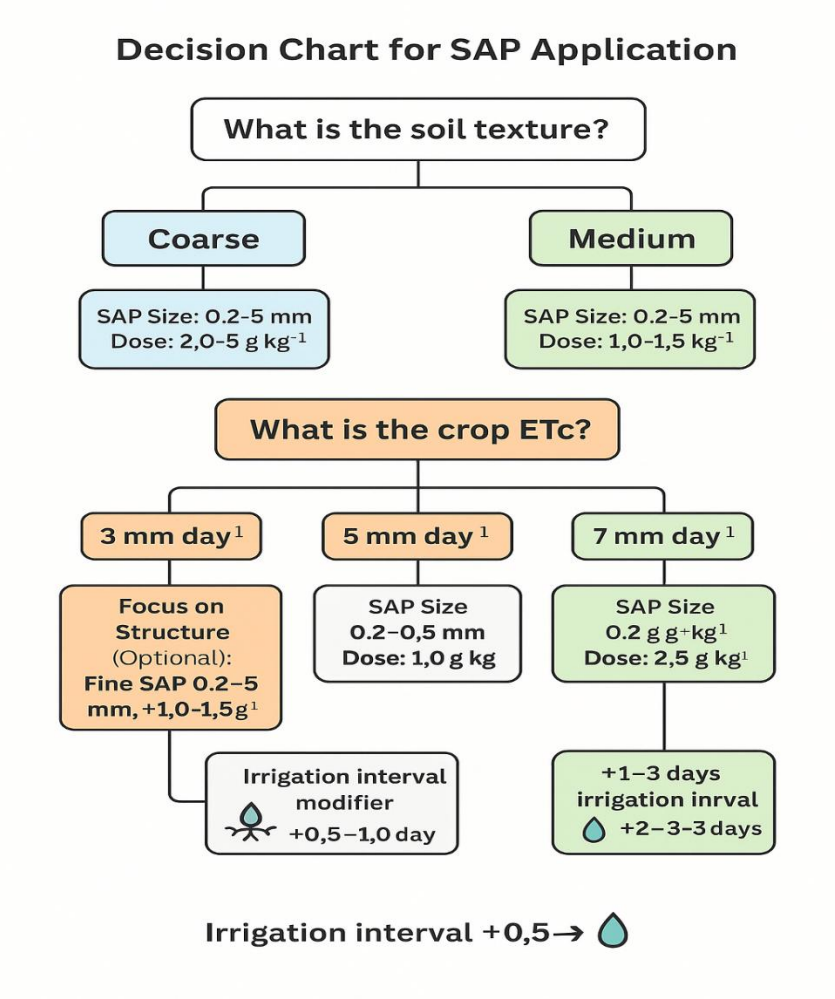
Decision Framework for Optimizing Superabsorbent Polymer Application in Irrigation Scheduling (Results)

Using the integrated outcomes from soil structure, water retention (FC–WP–AWC), parametric SWRC modeling (van Genuchten and Brooks–Corey), and irrigation-scheduling analyses (interval extension, water-saving percentage, depth effects), we translated the findings into a practical decision framework (Figure F8). The chart operationalizes three key determinants—soil texture (baseline capacity and responsiveness), atmospheric demand (ETc), and SAP configuration (particle size and dose)—and links them to expected gains in irrigation interval and water-saving efficiency. Decision logic starts at soil texture, climbs through ETc branches (3, 5, 7 mm day^{-1}), and returns a context-specific SAP recommendation with outcome ranges. In coarse soils (loamy sand, sandy loam), the framework selects fine SAP (0.21–0.5 mm) at 2.0–2.5 g kg^{-1} for most ETc scenarios, reflecting the substantial hydraulic uplift observed in these textures ($\theta s\uparrow$, $\alpha\downarrow$, $n\uparrow$), the

significant AWC gains (>50–100%), and the consistent extension of irrigation intervals by ~3–4 days with 35–45% water-saving under ETc 3–5 mm day^{-1} (Figures 12–13; Tables 8–9). Under the harshest demand (ETc 7 mm day^{-1}), the framework retains fine SAP 2.5 g kg^{-1}. Still, it indicates slightly smaller relative savings (~25–30%) while maintaining absolute interval gains (~2–3 days), consistent with the compression of percentage savings at high ETc. In medium textures (sandy loam), the rule converges on fine SAP ≈2.0 g kg^{-1}: this dose balanced structural and hydraulic improvements (porosity↑, bulk density↓; FC↑ with minimal WP shift), delivering ~3 days interval extension at ETc 3–5 mm day^{-1} and ~2 days at ETc 7 mm day^{-1}. For fine-textured soils (silty clay loam, clay loam), the chart prescribes lower optimal doses (≈1.0–1.5 g kg^{-1}), acknowledging smaller but meaningful hydraulic returns (AWC +10–25%) and robust structural benefits. Here, interval extensions are ~1–2 days with ~10–20% water-saving, and the framework flags diminishing returns beyond 1.5–2.0 g kg^{-1}, mirroring the plateau in composite utility rankings. Across all textures, the framework incorporates root-zone depth as a post-decision modifier: increasing depth from 30 to 45 cm adds ~0.5–1.0 days to the interval (largest in coarse soils), which is consistent with the larger exploitable storage captured in Figure 14 and Table 10. This explicit adjustment allows users to adapt recommendations to rooting conditions without changing the core decision path.

Three features of the framework increase its practical value. First, it bridges modeling and scheduling: the exact mechanisms captured by VG parameter shifts ($\theta s\uparrow$; $\alpha\downarrow$; $n\uparrow$) that expanded AWC in treated soils are carried through to interval-based metrics and water-saving percentages, ensuring that the irrigation guidance is mechanistically grounded. Second, it embeds ETc sensitivity so that managers can anticipate seasonal changes—e.g., moving from ETc 3 to 5 mm day^{-1} triggers either a minor upward dose adjustment (coarse soils) or acceptance of modestly

reduced percentage savings (fine soils), avoiding over-application. Third, it encodes efficiency and risk control: fine SAP is preferred at lower doses, where it disperses more uniformly and delivers higher efficacy per unit mass. The chart cautions against excessive rates at high ETc (footnote), where infiltration or aeration constraints may emerge and marginal returns wane. Altogether, the decision framework distills the dataset's patterns into an actionable tool: use fine SAP at 2.0–2.5 g kg^{-1} in loamy sand and sandy loam (expect +80–120% AWC; +3–4 d; 30–45% saving), fine SAP at ~1.5–2.0 g kg^{-1} in silty clay loam (+12–25% AWC; +1–2 d; 10–20%), and fine SAP at ~1.0–1.5 g kg^{-1} in clay loam (+10–20% AWC; +0.8–1.5 d; 8–12%)—then add ~0.5–1.0 day if the effective root zone is 45 cm. Because the thresholds are anchored in your measured and modeled responses (Tables 8–10; Figures 12–14), the framework supports transparent, texture-specific scheduling decisions that improve water-use efficiency while avoiding unnecessary polymer inputs.



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587 **Figure 8.** Comprehensive decision chart for optimizing superabsorbent polymer (SAP) application across
588 soil textures, evapotranspiration (ETc) levels, and root-zone depth. The chart integrates soil physical,
589 hydraulic, and irrigation-scheduling data to guide practical SAP management under different environmental
590 and textural conditions. The upper branch differentiates coarse-textured (Loamy Sand, Sandy Loam) and
591 medium-textured (Silty Clay Loam, Clay Loam) soils, showing respective optimal SAP sizes and doses—
592 fine SAP (0.2–0.5 mm) at 2.0–2.5 g kg^{-1} for coarse soils, and 1.0–1.5 g kg^{-1} for medium soils. The middle
593 branch accounts for climatic demand (ETc = 3, 5, or 7 mm day^{-1}), refining SAP application to balance water
594 retention and irrigation interval extension (+1 to +4 days) while maximizing available water content
595 (ΔAWC +10–120 %) and water-saving efficiency (+10–45 %). The bottom panel indicates the root-depth
596 adjustment factor, where deeper root zones (≈45 cm) extend irrigation intervals by an additional 0.5–1.0

597 days. The framework serves as a practical guide for tailoring SAP use to soil type and evapotranspiration
598 regime for optimal soil-water management.

599 **Discussion**

600 The addition of superabsorbent polymers (SAPs) significantly enhanced soil moisture retention
601 across all tested soil textures, with the most significant benefits seen in coarse-textured soils.
602 Untreated sandy soils (e.g., loamy sand, sandy loam) lose moisture quickly with increasing suction
603 due to their naturally low water-holding capacity (Osman 2018). SAP amendments raised the soil
604 water retention curves considerably, indicating more water was retained at each matric potential.
605 At field capacity (~0.3 bar suction), SAP-treated sandy soils held 40–60% more water than
606 untreated controls. For instance, a sandy loam control retained about ~0.011 cm^3/cm^3 of water at
607 0.3 bar, whereas with 2.0–2.5 g/kg of fine SAP, it held around ~0.017–0.018 cm^3/cm^3—almost a
608 60% increase in volumetric moisture. Practically, this means significantly more plant-available
609 water in sands that typically drain rapidly (He et al. 2020). At higher SAP dosages (2.0–2.5 g/kg),
610 the available water capacity (AWC) in sandy soils more than doubled compared to the control
611 (over +100% AWC). Even at moderate rates (~0.5–1.0 g/kg), coarse soils demonstrated AWC
612 improvements of 40–70%. These increases greatly expand the moisture reserves accessible to
613 plants between rain or irrigation events. Conversely, intermediate-textured soils (silty loam, silty
614 clay loam) showed more modest retention improvements with SAP. Their untreated water-holding
615 capacity was higher initially, yet SAP still increased moisture content at suctions relevant to plant
616 uptake (0.3–5 bar), typically boosting field capacity by about 10–20% and AWC by 10–25% at
617 higher doses. In clay loam (a fine-textured soil with high natural water-holding capacity), SAP
618 provided smaller relative benefits but still measurable absolute gains in volumetric water content.
619 Field capacity in clay loam increased by roughly 0.02–0.03 cm^3/cm^3 (≈10–15%) with the highest

SAP rate. Notably, the permanent wilting point (15 bar suction) changed very little with SAP across all soils. SAP-treated soils showed only slight increases in water content at 15 bar, implying the extra water retained by SAP was not trapped in micropores inaccessible to plants. This favorable result—higher field capacity with minimal change in wilting point—led to a net increase in plant-available moisture. In other words, most of the additional water retained by SAP remained accessible for plant uptake rather than being held too tightly (Li et al. 2017). The total available water (TAW)—the water from saturation to wilting point—also increased with SAP, especially in coarse soils (Saha et al. 2020). These findings emphasize that SAPs are most effective at creating additional storage in large pores (which typically drain under gravity), transforming them into reservoirs of readily available water for plants (Ashraf et al. 2021). Agronomically, such changes in moisture retention can lessen drought stress and prolong the interval between irrigations in sandy soils that would otherwise dry out quickly (Malik et al. 2022). While intermediate and fine-textured soils were less dramatically affected, they still benefit from extended moisture availability and delayed water stress onset when amended with SAPs.

Beyond improving water retention, SAP treatments also enhanced soil physical structure by increasing porosity and decreasing bulk density in all soil types (Alkhasha and Al-Omran 2020). As the SAP dose increased, the total pore space expanded by roughly 5–15% compared to the control soils. These new or enlarged pores form as the hydrophilic polymer granules swell upon absorbing water and physically push soil particles apart (Sweijen et al. 2017). The greatest proportional porosity gains were observed in coarse-textured soils, which initially have lower pore volume and denser packing. For instance, even a small addition (0.25–0.5 g/kg) of fine SAP (0.21–0.5 mm) to a loamy sand increased porosity by ~5–10%, and higher doses (~2 g/kg) achieved 10–15% porosity increases. In contrast, clay loam and silty clay loam (with higher baseline porosity

643 from their delicate pores and aggregates) showed smaller relative increases (often <5–7%), though
644 still a measurable structural improvement. Correspondingly, bulk density (BD) declined steadily
645 with increasing SAP dosage. High SAP rates produced BD reductions on the order of 5–15% (i.e.
646 a lighter, less compact soil) in the most responsive soils. Sandy loam and loamy sand exhibited the
647 most significant BD drops. For example, a sandy loam with no SAP had a BD of ~1.50 g/cm³,
648 which fell to ~1.30 g/cm³ (≈13% reduction) at the highest SAP dose in our study (data not shown).
649 Such a change reflects a transition from a tightly packed condition toward a more friable, open
650 structure due to the polymer's soil-conditioning effect (Damiri et al. 2024). Fine-textured soils,
651 having lower initial BD, saw more modest decreases (on the order of 3–5% BD reduction at
652 optimal SAP levels). The improvements in porosity and BD are beneficial for soil health –
653 increased porosity can enhance aeration and infiltration, and lower compaction eases root growth
654 and penetration (Malik et al. 2022). We note that the influence of SAP particle size on structural
655 outcomes mirrored its effect on moisture: finer SAP particles were more effective at creating
656 additional pore space and reducing compaction at a given dose (Olawuyi 2016). Fine particles
657 disperse more uniformly and interact with micro-aggregates, disrupting soil packing across a larger
658 soil volume (Totsche et al. 2018). Thus, a relatively small dose of fine SAP could noticeably loosen
659 the soil matrix. Coarser SAP granules (0.5–2 mm) also improved structure but were less efficient
660 per unit mass – they tended to affect only the immediate vicinity around each particle, requiring
661 higher application rates to achieve comparable porosity gains. Overall, the structural enhancements
662 induced by SAP (more pores, lower density) complement the water retention benefits by
663 facilitating greater water storage at saturation and improving the soil's capacity to supply water to
664 plants (Niu et al. 2025). Essentially, SAPs act as a soil conditioner, ameliorating compaction while
665 simultaneously serving as water reservoirs in the soil matrix (Edmund 2019).

The remarkable increases in soil water retention with the addition of SAP can be explained by the polymer's physicochemical characteristics and its interaction with the soil (Takahashi et al. 2023). Superabsorbent polymers are hydrophilic, cross-linked 3D networks capable of absorbing and holding water up to hundreds of times their own weight (Lavlinskaya and Sorokin 2023). In dry soil, SAP granules imbibe water (e.g. from rain or irrigation) and swell into gel-like particles, effectively converting free water into stored water within their matrix (Singh et al. 2023). As the surrounding soil dries, the SAP gradually releases water back into the soil pores, buffering against rapid moisture loss (Niu et al. 2025). This mechanism explains the smoothed, flatter moisture release curves observed in SAP-treated soils – water is held in the polymer and released more gradually over time, slowing the rate at which soil water content declines under stress (Dhiman 2019). The minimal change in wilting point with SAP indicates that the polymer primarily holds water in a form that remains plant-accessible (at suctions <15 bar). Unlike clay particles that bind water in tiny pores unavailable to roots, the polymer-held water can diffuse out as soil matric potential drops, thereby extending the range of moisture that plants can exploit. In essence, SAPs create an on-demand water source for roots: when soil water would typically be depleted, the polymers desorb moisture into the soil, delaying plant dehydration. Physiologically, this translates to prolonged turgor maintenance and delayed onset of drought stress in crops growing in SAP-amended soils. Indeed, our results showed substantially increased time to reach permanent wilting in SAP-treated sands, meaning plants have a longer window before irreversible wilting occurs. This is consistent with other findings that SAPs can extend the time to wilting by 50–200% depending on soil texture and dosage (Palma et al. 2024). Additionally, by improving soil structure (as discussed above), SAPs indirectly benefit plant water uptake. A looser, well-aggregated soil allows roots to proliferate and extract moisture more easily, and enhances infiltration of subsequent

689 rainfall. There may also be ancillary biochemical benefits: the particular SAP used (potassium
690 polyacrylate) can release potassium ions as it swells, potentially providing a mild nutrient boost to
691 plants, though this effect was not a focus of our study. Importantly, we did not observe adverse
692 chemical interactions in the soil; the SAP acted as an inert but water-rich inclusion. From a plant
693 physiology perspective, the combined effect of SAP is to maintain a more favorable soil water
694 status for a longer duration, thereby supporting sustained plant metabolic activity during dry
695 periods. This aligns with reports that the SAP application maintains higher leaf relative water
696 content and photosynthetic rates under drought by virtue of improved soil moisture availability
697 (Du et al. 2025).

698 Our results corroborate and extend findings from previous studies on SAP effects in soil.
699 Numerous researchers have reported that SAP amendments improve soil water-holding capacity
700 and plant-available water, especially in sandy soils. For instance, Palma et al. (2024) observed that
701 adding 0.5% hydrogel (≈5 g/kg) to sand increased AWC by at least 50%, and that soils with higher
702 sand content showed greater AWC improvements than loam soils. We similarly found
703 disproportionate benefits in coarse textures, reflecting the fact that sands have abundant
704 macropores that can be converted into storage pores by the swelling polymer. Several studies have
705 noted, as we did, that increasing the SAP dosage yields progressively larger moisture retention
706 gains, up to a saturation point (Palma et al. 2024; Ahmad et al. 2022). Beyond an optimal
707 concentration, additional polymer has a diminishing effect or can even cause issues. Wilting point
708 stability with SAP has also been reported. For example, studies with natural hydrogels found
709 significant increases in field capacity but minimal change in PWP in sandy loam, leading to
710 expanded AWC (Palma et al. 2024; Sikdar et al. 2021) – consistent with our observations that SAP
711 chiefly impacts the readily available moisture. On the soil physical side, our finding that SAP

712 increases porosity and reduces bulk density aligns with results by Du et al. (2025), who showed
713 that moderate SAP applications under field conditions significantly reduced bulk density and
714 improved water holding capacity in a loam, contributing to yield increases. Bian et al. (2022) also
715 documented microstructural improvements: SAP stabilization increased the volume of larger pores
716 and altered pore connectivity in a clay, which parallels our mechanism of SAP creating additional
717 pore space. Regarding SAP particle size, the literature is scarce. Still, our data support the intuitive
718 notion noted by others (e.g. Yang et al. 2024) that finer particles distribute more evenly and have
719 faster swelling, thereby enhancing effectiveness at lower doses. We also observed a plateau or
720 slight decline in benefits at extremely high SAP levels, a phenomenon cautioned in previous work.
721 Similarly, studies on polyacrylate amendments have found that while water retention and AWC
722 increase with SAP rate, excessive polymer can decrease saturated hydraulic conductivity (K_s)
723 and slow infiltration (Zhuang et al. 2013). In our experiment, we did not measure K_s directly.
724 Still, we did notice that at the highest doses, the soil cores tended to swell and become gelatinous
725 when saturated, which could impede drainage. These observations underscore that there is an
726 optimal range for SAP application – enough to boost water retention substantially, but not so much
727 that soil pores are overly clogged or aeration is compromised. Overall, the consensus in the
728 literature is that SAPs are particularly beneficial for drought-prone, sandy soils, yielding improved
729 moisture retention, reduced deep percolation, and better crop performance (Palma et al. 2024;
730 Chen et al. 2016). Our work adds a comprehensive, quantitative demonstration of these effects
731 across multiple textures and provides specific guidance on tuning dose and particle size. We also
732 extend prior findings by integrating both water and structural effects, and by using modeling to
733 parse the underlying changes in soil hydraulic parameters. In doing so, we contribute a more
734 holistic understanding of how SAPs modify the soil's water retention curve and its physical quality

735 simultaneously. The strong agreement between our results and those of other researchers (spanning
736 laboratory, greenhouse, and field studies) gives confidence that the improvements observed are
737 real and reproducible. Minor discrepancies – for example, one study reported a slight increase in
738 wilting point in a clay with very high SAP – can likely be attributed to differences in polymer type
739 or soil characteristics. By and large, our results confirm the beneficial role of superabsorbent
740 polymers as a water-saving soil amendment, in line with a growing body of literature advocating
741 their use for enhancing soil moisture and mitigating drought impacts in agriculture.

742 The findings of this study have practical significance for improving irrigation efficiency and
743 drought resilience through targeted SAP applications (Zheng et al. 2023). First and foremost, SAP
744 amendments can greatly increase the plant-available water in soils, particularly in coarse textures
745 that are common in arid-region agriculture (Malik et al. 2022). By applying an optimal dose of
746 SAP (on the order of 1–2 g/kg in our experiments), farmers on sandy or loamy soils could
747 effectively double their soil's available water capacity and extend the period between irrigations
748 by several days (Yang et al. 2020). This directly translates to water savings over a growing season:
749 fewer irrigation events are needed to maintain crops, which can conserve limited water resources
750 and reduce pumping costs (Kordrostami et al. 2019). For example, in a sandy loam field,
751 incorporating ~2 g/kg of a fine SAP into the root zone might allow an irrigation interval of perhaps
752 7–10 days instead of 4–5 days, under the same evapotranspiration demand (Edmund 2019). Such
753 an extension is hugely valuable in water-scarce regions. In finer soils (clay loams), the incremental
754 benefits of SAP are smaller but still worthwhile – an extra day or two of moisture can be the
755 difference between mild and severe stress during a dry spell (Suresh 2015). The key is that SAP
756 use should be tailored to soil type (Zheng et al. 2023): our results suggest focusing higher SAP
757 inputs on sands (where the return on investment in terms of water saved is greatest) and using more

moderate rates on clays (to avoid waste and potential oversaturation). Another implication is the importance of selecting the right SAP particle size (Tan et al. 2021). Fine-grade SAPs (e.g. <0.5 mm) are generally preferable for soil amendment because they mix more uniformly and react faster to wetting, thus offering more consistent benefits. Coarser particles can work in very sandy soils, but if not properly dispersed, they might leave parts of the soil unamended (Fischer Jr 2004). From a management perspective, incorporation method and placement are also considerations: to maximize effectiveness, SAP should be well-mixed into the root zone (e.g. top 20–30 cm) where crop roots are active, rather than left on the surface (Negim et al. 2024). Light tillage or during bed preparation is an opportunity to blend the polymer into the soil (Krasnopeeva et al. 2022). We also advise caution regarding over-application – beyond a specific dosage, additional SAP yields little extra benefit yet increases material cost. In extreme cases, too much SAP could create overly wet, gel-like conditions that hinder aeration or slow infiltration (Zhuang et al. 2013). Our study did not find any adverse effects at the tested rates (up to 2.5 g/kg, equivalent to ~250 kg/ha in the topsoil). Still, literature and theoretical considerations indicate upper limits to prudent use.

Conclusion

Superabsorbent polymer amendments substantially enhanced both the water-holding capacity and the physical structure of soils across a range of textures. Coarse soils (sandy loam, loamy sand) showed the most dramatic improvements. Moderate SAP applications roughly doubled their plant-available water and reduced bulk density by over 10%, effectively transforming these drought-prone soils into much more water-retentive and root-friendly media. Finer-textured soils (clay loam, silty clay loam) also benefited, though to a lesser extent, with notable gains in field capacity (+10–20%) and modest increases in porosity. Significantly, SAP incorporation raised the field capacity of all soils while leaving the wilting point virtually unchanged, thereby broadening the

available water range for crops. The polymers functioned as efficient micro-reservoirs, soaking up excess water and releasing it gradually, which translates to prolonged crop water supply and extended intervals between irrigations. SAP particle size and dosage were critical factors in maximizing these benefits. Finer SAP particles provided greater efficacy, distributing more uniformly and enhancing moisture retention and porosity at lower rates, whereas coarser particles required higher dosages for similar effects. There were diminishing returns beyond an optimal dose (around 1.5–2 g/kg for coarse soils, ~1 g/kg for fine soils), as extremely high SAP contents yielded little additional gain and could risk interfering with soil pore function. Composite performance analysis indicated that the best outcomes are achieved by tailoring the SAP application to soil type: higher dosages of fine SAP in sandy soils, and moderate dosages in loamy and clay soils. These tailored treatments maximized available water and improved soil structure cost-effectively. Overall, this study demonstrates that superabsorbent polymers are a consequential amendment for improving soil water retention and mitigating drought stress. By concurrently increasing soil porosity and water storage while maintaining good aeration, SAPs address both the hydraulic and physical limitations of soils. The practical implication is that farmers and land managers can use SAP technology to conserve irrigation water, stabilize crop yields under water-limited conditions, and improve the resilience of cropping systems to drought. We recommend targeting SAP use in coarse-textured soils and following the optimized rates identified here to achieve substantial water-saving benefits. With appropriate management, superabsorbent polymers offer a viable strategy for enhancing soil moisture regimes and supporting sustainable agriculture in the face of growing water scarcity.

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Authors' contributions

Conceptualization, MNH and MK; Methodology, MNH and MK; Investigation, MNH; Data curation, MNH and MK; Formal analysis, MNH and MK; Visualization, MNH and MK; Writing – original draft, MNH; Writing – review & editing, MNH and MK; Supervision, MK.

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Data availability

All data analyzed during this study are included in this published article and its supplementary information files. The dataset and materials used in this study are available from the corresponding author upon reasonable request.

Declarations

Ethics approval and consent to participate

Not applicable. This study does not involve human participants, human data, or human tissue, nor does it involve animal experiments that require ethical approval.

Consent for publication

Not applicable. This manuscript does not contain any individual person’s data in any form (including individual details, images, or videos).

Competing interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper. The authors also declare that they have no non-financial competing interests that could have influenced the conduct or reporting of this research

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