

Article

Effects of Superabsorbent Polymer and Agroperlite on Soil Water Retention Under Controlled Evaporation Conditions

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Abstract

Soil moisture conservation is critical in arid and semi-arid agroecosystems, but open-top laboratory mass-loss tests quantify evaporation dynamics rather than field water-holding capacity. This study evaluated three laboratory experiments with dark chestnut soil (Haplic Kastanozem) and Ordinary Chernozem (Haplic Chernozem) represented by local light-, medium-, and heavy-loam classes. Experiment 1 compared an untreated control, SAP-P (100 mesh powder; 0.20% of dry-soil mass), agroperlite (5.0%), and their composite over a standardized 7-day interval. A randomized-block analysis across six soil-texture combinations detected a significant treatment effect ($F_{3,15} = 12.90$, $p < 0.001$). Fisher’s LSD separated the control from all amended treatments, while the three amendments did not differ from one another. Experiment 2 evaluated five SAP doses over a common 12-day interval. Dose responses were non-monotonic and were not significant for SAP-P, SAP-B, or SAP-G in the primary ANOVA ($p = 0.155$, 0.983 , and 0.471 , respectively); therefore, no statistically supported optimum dose was inferred. Experiment 3 found no significant particle-form effect in either light loam ($p = 0.148$) or heavy loam ($p = 0.536$). The results support a general reduction in short-term evaporation loss by the amendments in Experiment 1, but they do not identify a superior amendment, optimum SAP dose, or superior SAP particle form. Field validation is required before agricultural recommendations are made.

Keywords: superabsorbent polymer; agroperlite; evaporation; laboratory water loss; soil texture; Northern Kazakhstan



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1. Introduction

In the steppe zone of Northern Kazakhstan, soil moisture deficit is a primary limiting factor for crop yield and represents a major agronomic constraint. Recent agroclimatic studies demonstrate pronounced spatial heterogeneity in heat and moisture availability, with aridization intensifying along a north-south gradient [1–3]. Consequently, growing-season moisture availability serves as a key criterion for agroclimatic zoning and assessing the sustainability of rainfed agriculture in this region.

Under conditions of increasing climate variability, technologies that regulate the local soil water regime are becoming essential as they increase available moisture in the root zone without substantially raising irrigation requirements. One promising approach is the application of superabsorbent polymers (SAPs), which absorb large quantities of water, retain it within the polymer network structure, and release it gradually as the surrounding water potential declines [4–7]. A global meta-analysis of over 1500 observations reported that SAP application increases crop yields by 12.8% and water use efficiency by 17.2% on average, demonstrating their potential under water-scarce conditions [7]. However, the effectiveness of SAPs depends on multiple factors, including soil texture, polymer chemistry, application method, and particle morphology [8].

At the hydrophysical level, SAPs increase the water-holding capacity of the soil-polymer system by creating additional water reservoirs within the pore space. Consequently, SAP application improves the soil water retention curve, decreases evaporation rates, and increases soil resistance to drying [5,8,9]. Increasing the SAP dosage enhances moisture retention, but this relationship is nonlinear. Beyond a specific threshold, the water retention effect stabilizes [7]. Furthermore, particle morphology significantly influences water retention dynamics. Fine particles possess a larger specific surface area and facilitate rapid swelling, whereas larger spherical granules function as localized water reservoirs, providing prolonged moisture release [8]. Although these hydrophysical mechanisms are well-documented, their interactive effects in specific regional soils remain poorly understood.

In addition to synthetic polymers, recent studies have increasingly investigated the application of mineral porous materials such as agropelite. Owing to its porous structure, perlite retains significant volumes of water, and its combination with SAPs forms composite systems with enhanced water-retention properties [10]. However, most existing studies have examined SAPs and perlite separately or in limited soil types, and their combined effects on water retention remain poorly understood, particularly in the chernozem and dark chestnut soils of Northern Kazakhstan. Furthermore, the literature emphasizes the need to optimize application rates to achieve maximum agronomic effectiveness while minimizing excessive polymer accumulation [11,12]. Moreover, the influence of SAP particle morphology (e.g., powder, beads, granules) on water retention has received less attention than dosage effects, despite its potential to affect swelling kinetics and spatial distribution in the soil matrix.

For Ordinary Chernozem and dark chestnut soils in Northern Kazakhstan, systematic comparisons of SAP, agropelite, and their composite are limited, and dose- and particle-form responses have not been tested within a unified gravimetric framework. The objective of this study was to quantify short-term evaporation loss from open-top laboratory vessels amended with SAP-P, agropelite, and SAP-P + agropelite across two soil types and three local texture classes, and to evaluate SAP dose and particle-form effects over standardized observation periods. Three hypotheses were tested: H1, amendment treatment affects cumulative and mean daily water loss across soil-texture blocks; H2, SAP dose affects 12-day water loss within each SAP form; and H3, SAP particle form affects 12-day water loss in light- and heavy-loam soils. These hypotheses were evaluated using omnibus ANOVA, Fisher's LSD only after a significant omnibus test, and nonparametric sensitivity analyses.

2. Materials and Methods

2.1. Soil Materials and Open-Top Laboratory Setup

The soils originated from the steppe zone of Northern Kazakhstan, which extends approximately from 48° to 55° N and from 60° to 79° E. The region has a strongly continental climate. Annual precipitation generally declines from about 320–340 mm in the north to

250–300 mm in the central zone and approximately 200 mm in the south; May–August precipitation ranges from about 160–170 mm in the north to 60–80 mm in the south [1]. This pronounced moisture gradient makes evaporation control and short-term soil–water conservation agronomically important.

Two regionally widespread soils were studied: dark chestnut soil (Haplic Kastanozem) and Ordinary Chernozem (Haplic Chernozem). Each soil was represented by the local Kachinsky textural classes light loam, medium loam, and heavy loam. Particle-size classification was performed by the Kachinsky sedimentation (pipette) method [13]. The local class names are retained throughout the manuscript and are not treated as direct equivalents of USDA textural classes.

Soils were air-dried, cleared of visible plant residues and coarse inclusions, and passed through a 2 mm sieve. A 100 g dry-soil portion was used per container. Each treatment was originally established in five containers. The containers had impermeable bottoms and no drainage holes, but their tops remained open throughout drying. Thus, the response variable was gravimetric water loss from an open-top, no-drainage laboratory system. It should not be interpreted as direct measurement of field capacity, capillary water retention, or plant-available water.

An equal nominal quantity of water was added within each experiment. Because the soils differed in texture and pore structure, treatment comparisons were made within soil-texture blocks, and absolute losses among texture classes were not interpreted as direct measurements of intrinsic field water retention.

Humus content was determined by the Tyurin method in the Simakov modification [14], soil reaction by the potentiometric method [15], and bulk density by the core method [16]. Field capacity and wilting point were not used as response variables; the analysis was based on gravimetric water-balance measurements (Table 1).

Table 1. Initial physicochemical properties of the soils and local texture classes.

Soil Type	Local Texture Class	Humus, %	pH (H ₂ O)	Bulk Density, g cm ^{−3}
Dark chestnut	Light loam	2.4–2.8	7.3–7.6	1.28–1.32
Dark chestnut	Medium loam	2.8–3.2	7.4–7.7	1.30–1.34
Dark chestnut	Heavy loam	3.0–3.5	7.5–7.8	1.32–1.36
Ordinary Chernozem	Light loam	4.5–5.2	6.8–7.2	1.18–1.24
Ordinary Chernozem	Medium loam	5.0–5.8	6.9–7.3	1.20–1.26
Ordinary Chernozem	Heavy loam	5.5–6.2	7.0–7.4	1.22–1.28

Note: Texture classes are reported according to the Kachinsky sedimentation (pipette) method and should be interpreted within that classification system.

2.2. Water-Retaining Materials and Nomenclature

The synthetic amendment was a cross-linked potassium polyacrylate superabsorbent polymer (SAP) was obtained from Henan Materials Co., Ltd. (Zhengzhou, China). Three size-defined forms were used consistently throughout the study: SAP-P, powder (100 mesh; approximately 0.15 mm); SAP-B, spherical beads (2.0–2.5 mm); and SAP-G, coarse granules (5–10 mesh; approximately 2.0–4.0 mm). Agroperlite was used as a porous mineral amendment supplied by Henan Materials Co., Ltd.

Agroperlite consisted of irregular, porous expanded-mineral particles and was applied as received. The untreated control is described as an experimental treatment in Section 2.3 rather than as a material in Table 2.

Table 2. Characteristics and standardized abbreviations of the amendments.

Abbreviation	Material/Form	Nominal Particle Size	Recorded pH/Absorption	Role in Experiments
SAP-P	Potassium-polyacrylate powder	100 mesh (~0.15 mm)	8.1/450 g g ⁻¹	Fine SAP fraction; used in Experiment 1
SAP-B	Potassium-polyacrylate beads	2.0–2.5 mm	8.1/450 g g ⁻¹	Intermediate spherical fraction
SAP-G	Potassium-polyacrylate granules	5–10 mesh (~2.0–4.0 mm)	8.1/450 g g ⁻¹	Coarse granular fraction
P	Expanded agroperlite; irregular porous mineral particles	Commercial fraction used as received	Porous expanded mineral	Structure-modifying mineral amendment

2.3. Experimental Design and Standardized Observation Windows

The three experiments were conducted as independent laboratory runs with separate hydration and drying periods. Consequently, their untreated controls represent experiment-specific baselines and were analyzed only within the corresponding experimental design.

Experiment 1 compared four treatments within each of six soil-type × texture blocks: untreated control; SAP-P at 0.20% of dry-soil mass; agroperlite at 5.0%; and SAP-P + agroperlite at the same component rates. Amendments were thoroughly mixed with soil. Samples were wetted using the common within-experiment procedure and allowed to hydrate for 12–24 h. A common endpoint of 7 elapsed days (eight weighing dates) was used for every block, and all endpoint losses were recalculated from the daily weighing series.

Experiment 2 evaluated 0, 0.05, 0.10, 0.20, and 0.30 g SAP per 100 g dry soil for SAP-P, SAP-B, and SAP-G. The analysis covered 10–22 February 2026, corresponding to 12 elapsed days. A quadratic optimum was not imposed because the observed responses did not show the monotonic decrease followed by a biologically interpretable plateau required for such inference.

Experiment 3 compared the untreated control with SAP-P, SAP-B, and SAP-G in light- and heavy-loam dark chestnut soil over 16–28 February 2026 (12 elapsed days).

2.4. Weighing-Lysimetry Water-Balance Calculations

The open-top vessels were treated as small laboratory weighing lysimeters. Because the vessels had impermeable bottoms, no drainage, and no plants, the decrease in system mass over each observation interval was attributed to water loss by evaporation.

Cumulative water loss at time t was calculated as $L_t = M_0 - M_t$, where M_0 is system mass after hydration and M_t is system mass at time t .

Interval water-loss rate was $v_i = (M_i - 1 - M_i)/(t_i - t_{i-1})$, where i denotes the observation interval, M_i is the system mass at the end of interval i , and t_i is the corresponding elapsed time and mean daily water loss was L_t/T , where T is elapsed time in days.

Control-relative change was calculated as $100 \times (L_{\text{treatment}} - L_{\text{control}})/L_{\text{control}}$. Negative values indicate lower evaporation loss than the corresponding control, whereas positive values indicate greater evaporation loss.

2.5. Statistical Analysis

Daily gravimetric observations were converted to interval water-loss rates and organized by treatment and elapsed-time block. Experiment 1 used the six soil-type $\times$ texture combinations as blocks. Experiments 2 and 3 used 12 daily equivalent intervals to assess the consistency of treatment trajectories. In the SAP-B and SAP-G series of Experiment 2, one weighing interval spanned two elapsed days (13–15 February); the observed mass difference was divided by two and the resulting average daily rate was assigned to each of the two elapsed-day blocks. This alignment affected only the temporal analysis and not the observed 12-day endpoint loss. Block standard errors (SE) in Experiment 1 were calculated across the six soil-texture blocks. Temporal SEs in Experiments 2 and 3 describe day-to-day variation among the 12 daily equivalent interval rates.

Experiment 1 was analyzed as a randomized complete block design with treatment as a fixed effect and the six soil-type $\times$ texture combinations as blocks. Experiments 2 and 3 were evaluated as repeated-block series with elapsed day as the blocking factor. Fisher's least significant difference (LSD) was applied at $\alpha = 0.05$ only after a significant omnibus ANOVA. For Experiment 1, Duncan's multiple range test was calculated only as a secondary robustness check to determine whether an alternative mean-separation procedure produced the same grouping; because it agreed fully with Fisher's LSD, only Fisher LSD letters are presented. No mean-separation test was performed or reported when the primary omnibus ANOVA was non-significant.

Friedman tests were used as nonparametric sensitivity analyses. ANOVA was treated as the primary inferential analysis. When ANOVA and Friedman tests produced inconsistent outcomes, no treatment-specific post hoc inference was made. Analyses were performed in Python 3.13.5 using SciPy 1.17.0 and statsmodels 0.14.6.

3. Results

3.1. Experiment 1: Sap-P, Agroperlite, and Composite Treatments

All three amendments descriptively reduced 7-day endpoint water loss relative to the control in each soil-texture block (Table 3). The lowest endpoint was associated with SAP-P in the light- and medium-loam blocks, whereas agroperlite or the composite had the lowest endpoint in the heavy-loam blocks. These within-block rankings are descriptive and should not be read as separate significance tests for each soil.

Table 3. Seven-day total water loss in Experiment 1 (g per 100 g dry soil).

Soil Type	Texture	Control	SAP-P	Agroperlite	SAP-P + Agroperlite
Dark chestnut	Light loam	21.02	19.53	19.90	19.84
Dark chestnut	Medium loam	20.64	19.37	19.57	19.40
Dark chestnut	Heavy loam	19.47	19.10	18.85	18.36
Ordinary Chernozem	Light loam	19.41	18.71	19.32	18.83
Ordinary Chernozem	Medium loam	19.32	18.51	19.01	18.56
Ordinary Chernozem	Heavy loam	19.24	18.26	17.38	17.40

Note: Values are treatment endpoint means calculated over the standardized 7-day interval.

The treatment effect was significant in the randomized-block ANOVA ($F_{3,15} = 12.90$, $p = 0.00020$). Fisher's $LSD_{0.05}$ was 0.42 g and separated the untreated control from the three amended treatments, while SAP-P, agropperlite, and the composite did not differ from one another (Table 4). Duncan's test was used only as a robustness check and produced the same grouping. The Friedman sensitivity test was also significant ($\chi^2_3 = 12.20$, $p = 0.0067$; Kendall's $W = 0.678$).

Table 4. Experiment 1 treatment means, block standard errors, and mean-separation groups.

Treatment	Mean Total Loss, g	Block SE, g	Control-Relative Change, %	Fisher LSD Group
Control	19.85	0.32	0.00	a
SAP-P	18.91	0.20	−4.72	b
Agropperlite	19.01	0.36	−4.26	b
SAP-P + agropperlite	18.73	0.35	−5.63	b

Note: Means followed by the same letter are not significantly different according to Fisher's LSD at $\alpha = 0.05$. A Duncan robustness check yielded the same grouping. SE, standard error calculated across the six soil-type $\times$ texture blocks.

Treatment means and texture-specific control-relative changes are summarized in Figure 1. The most negative changes occurred in heavy-loam Ordinary Chernozem under agropperlite (−9.66%) and SAP-P + agropperlite (−9.56%), whereas the smallest absolute change occurred for agropperlite in light-loam Ordinary Chernozem (−0.48%).

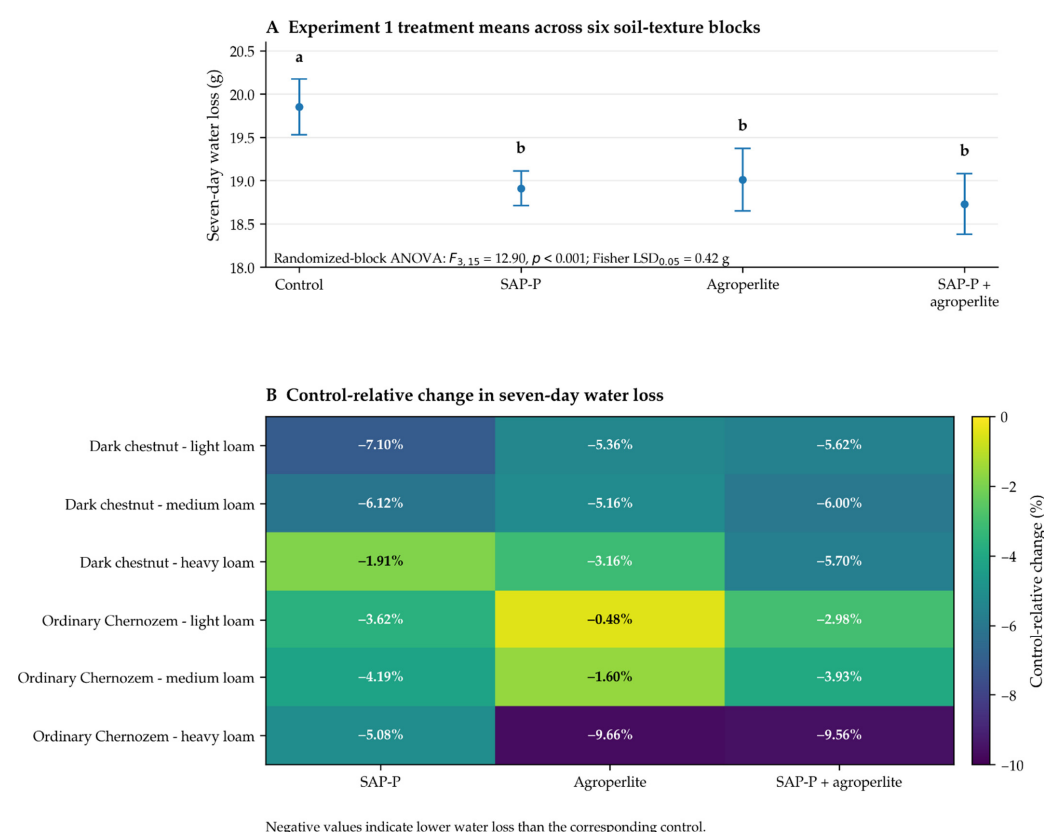
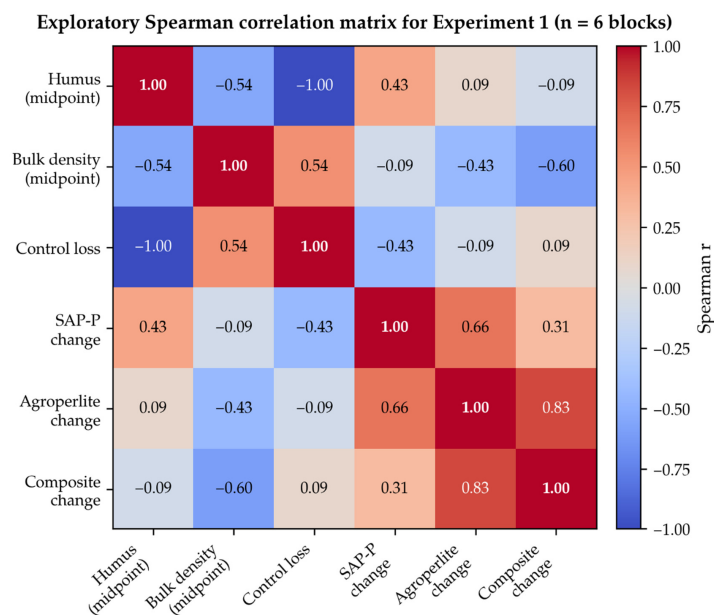


Figure 1. Experiment 1 treatment response. (A) Seven-day treatment means across six soil-texture blocks; points show means and error bars show block standard errors. Different letters indicate significant differences according to Fisher's LSD at $\alpha = 0.05$; Duncan's test produced the same grouping as a secondary robustness check. (B) Control-relative change in seven-day water loss for each amendment within each block. Negative values indicate lower loss than the corresponding control.

The Spearman matrix was examined only as an exploratory description (Figure 2). The control-relative changes under agroperlite and the composite had $r_s = 0.83$ (nominal $p = 0.042$), but the analysis was based on only six soil-texture blocks. Accordingly, no coefficient was used as confirmatory evidence or to support causal or treatment-specific conclusions.



Coefficients are exploratory because only six soil-texture blocks were available; no confirmatory inference is implied.

Figure 2. Exploratory Spearman correlation matrix for Experiment 1 based on six soil-texture blocks (n = 6). Humus and bulk-density midpoints were calculated from the ranges reported in Table 1. Owing to the limited sample size, the coefficients and nominal p -values are descriptive and should not be treated as confirmatory evidence.

The cumulative trajectories showed progressive separation of the untreated control from the amended treatments over the seven-day interval, with the clearest late-stage separation in dark chestnut soil and heavy-textured Ordinary Chernozem (Figure 3).

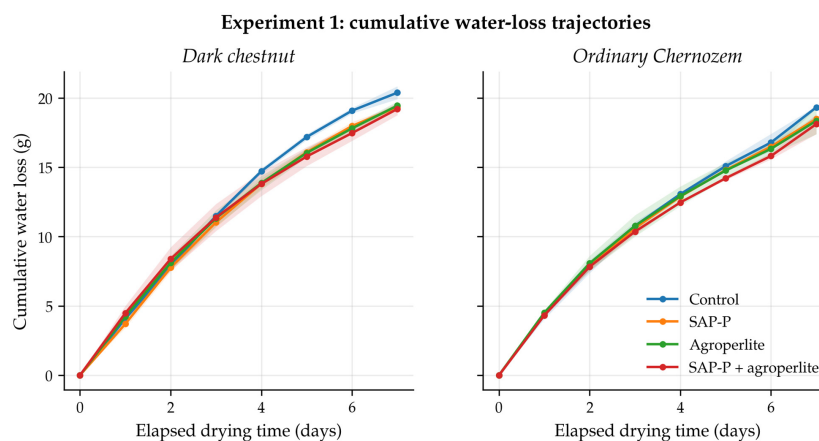


Figure 3. Experiment 1 cumulative water-loss trajectories for dark chestnut soil and Ordinary Chernozem. For dark chestnut soil, curves are means across the three local texture classes; for Ordinary Chernozem, curves are means across the two texture classes for which complete daily weighing series were available (light and heavy loam). Shaded bands represent standard errors across the corresponding texture classes. The trajectories are presented descriptively; inferential treatment comparisons are reported in Tables 3 and 4.

3.2. Experiment 2: Dose Responses of Three Sap Forms

Standardization to the common 12-day window changed the interpretation of the dose experiment. None of the three SAP forms showed a monotonic decline in endpoint water loss with increasing dose (Tables 5 and 6). Descriptively, the lowest endpoint occurred at 0.30 g for SAP-P, 0.05 g for SAP-B, and 0.10 g for SAP-G. Because these minima occurred at different rates and the primary ANOVA detected no dose effect, an “optimal” dose was not estimated.

Table 5. Experiment 2 endpoint losses, temporal standard errors, and control-relative changes.

SAP Form	Dose, g 100 g ^{−1}	12-Day Loss, g	Mean Daily Loss ± Temporal SE, g d ^{−1}	Control- Relative Change, %
SAP-P	0.00	15.91	1.326 ± 0.310	0.00
SAP-P	0.05	16.17	1.347 ± 0.346	+1.61
SAP-P	0.10	16.62	1.385 ± 0.294	+4.45
SAP-P	0.20	17.37	1.448 ± 0.338	+9.19
SAP-P	0.30	15.12	1.260 ± 0.235	−4.97
SAP-B	0.00	15.58	1.298 ± 0.598	0.00
SAP-B	0.05	14.13	1.178 ± 0.311	−9.27
SAP-B	0.10	14.92	1.243 ± 0.301	−4.22
SAP-B	0.20	15.90	1.325 ± 0.283	+2.07
SAP-B	0.30	16.50	1.375 ± 0.304	+5.91
SAP-G	0.00	15.34	1.279 ± 0.266	0.00
SAP-G	0.05	15.48	1.290 ± 0.252	+0.87
SAP-G	0.10	15.14	1.261 ± 0.235	−1.34
SAP-G	0.20	15.74	1.312 ± 0.261	+2.59
SAP-G	0.30	15.30	1.275 ± 0.266	−0.25

Note: Endpoint loss is the observed 12-day mass difference. Mean daily loss equals endpoint loss divided by 12; temporal SE describes variation among the 12 daily equivalent interval rates. SE, standard error. Negative control-relative changes indicate lower evaporation loss than the corresponding zero-dose control, whereas positive values indicate greater evaporation loss.

Table 6. Experiment 2 primary ANOVA and nonparametric sensitivity tests for mean daily loss.

SAP Form	ANOVA F _{4,44}	ANOVA <i>p</i>	Friedman χ ₄ ²	Friedman <i>p</i>	Kendall W
SAP-P	1.76	0.155	12.87	0.0119	0.268
SAP-B	0.10	0.983	13.27	0.0100	0.277
SAP-G	0.90	0.471	6.13	0.189	0.128

Note: ANOVA used elapsed day as the blocking factor. ANOVA, analysis of variance; W, Kendall’s coefficient of concordance. Friedman tests were used only as nonparametric sensitivity analyses; no pairwise post hoc inference was made when the primary ANOVA was non-significant.

The primary ANOVA did not detect a significant dose effect for SAP-P, SAP-B, or SAP-G. The Friedman sensitivity tests were significant for SAP-P and SAP-B, but the disagreement between the primary and sensitivity analyses was not considered robust evidence of dose-specific differences. Therefore, no pairwise post hoc conclusions were drawn (Figure 4).

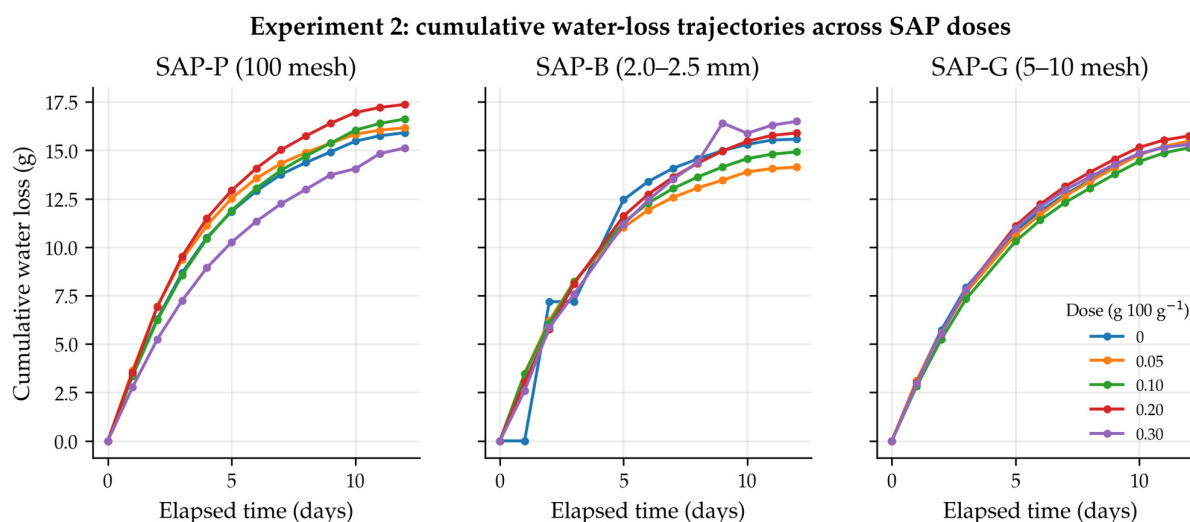


Figure 4. Experiment 2 cumulative water-loss trajectories over 12 days for SAP-P, SAP-B, and SAP-G at five application rates. The trajectories are shown descriptively; primary and sensitivity test results are reported in Table 6.

3.3. Experiment 3: Particle Form in Light and Heavy Loams

In light loam, all three size-defined SAP forms had lower 12-day endpoint losses than the control, with descriptive control-relative changes of -8.01% to -8.66% . In heavy loam, SAP-B and SAP-G produced small negative changes (-1.23% and -1.72%), whereas SAP-P produced a positive change ($+4.53\%$), indicating greater loss than the control (Table 7). The primary omnibus tests were non-significant, and the results do not support a universal advantage of the finest fraction.

Table 7. Experiment 3 endpoint losses, temporal standard errors, and control-relative changes.

Texture	Treatment	12-Day Loss, g	Mean Daily Loss $\pm$ Temporal SE, g d ⁻¹	Control-Relative Change, %
Light loam	Control	25.28	2.107 $\pm$ 0.431	0.00
Light loam	SAP-P	23.09	1.924 $\pm$ 0.364	-8.66
Light loam	SAP-B	23.25	1.938 $\pm$ 0.334	-8.01
Light loam	SAP-G	23.18	1.932 $\pm$ 0.330	-8.30
Heavy loam	Control	23.97	1.998 $\pm$ 0.449	0.00
Heavy loam	SAP-P	25.06	2.088 $\pm$ 0.414	$+4.53$
Heavy loam	SAP-B	23.68	1.973 $\pm$ 0.360	-1.23
Heavy loam	SAP-G	23.56	1.963 $\pm$ 0.351	-1.72

Note: Endpoint loss is the observed 12-day mass difference. Mean daily loss equals endpoint loss divided by 12; temporal SE describes variation among the 12 daily interval rates. SE, standard error. Negative control-relative changes indicate lower evaporation loss than the corresponding control, whereas positive values indicate greater evaporation loss. The primary ANOVA and Friedman sensitivity tests were non-significant for both light- and heavy-loam soils (Table 8).

Table 8. Experiment 3 primary ANOVA and nonparametric sensitivity tests for mean daily loss.

Texture	ANOVA $F_{3,33}$	ANOVA p	Friedman χ^2_3	Friedman p	Kendall W
Light loam	1.90	0.148	2.70	0.440	0.075
Heavy loam	0.74	0.536	3.80	0.284	0.106

Note: ANOVA used elapsed day as the blocking factor. ANOVA, analysis of variance; W, Kendall's coefficient of concordance. No post hoc mean separation was performed because the omnibus tests were non-significant.

The descriptive cumulative curves differed between textures: all three harmonized SAP forms remained below the control in light loam, whereas the SAP-P trajectory approached and then exceeded the control in heavy loam (Figure 5). These patterns are descriptive and do not constitute evidence of a significant texture $\times$ particle-form interaction.

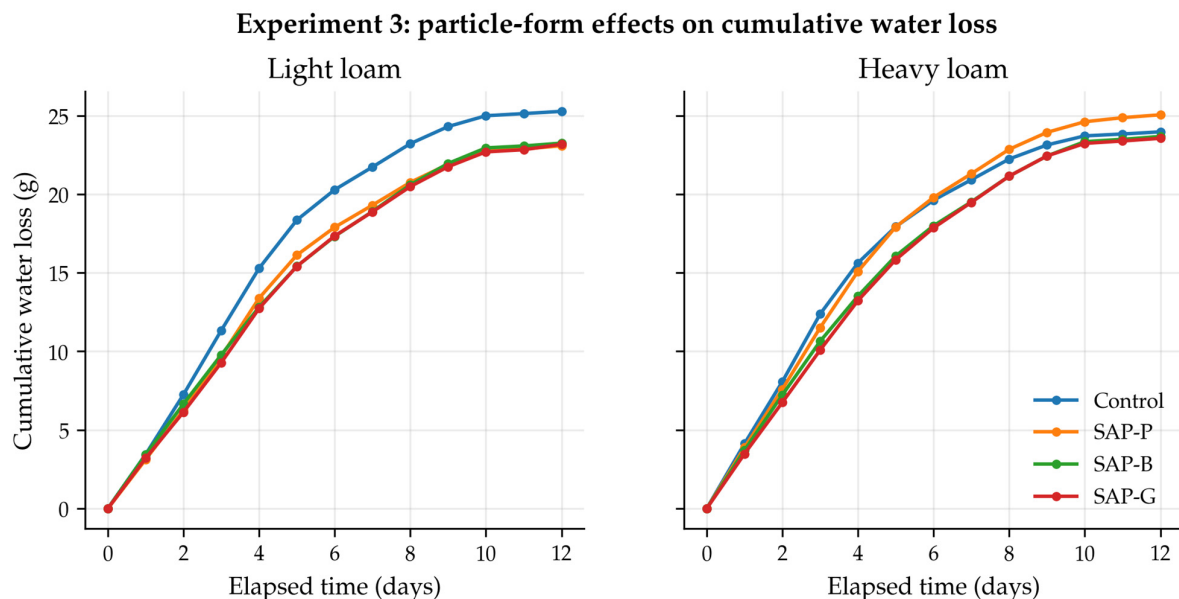


Figure 5. Experiment 3 cumulative water-loss trajectories for the untreated control and three harmonized SAP forms in light- and heavy-loam dark chestnut soil.

4. Discussion

Experiment 1 demonstrated a significant overall amendment effect, but SAP-P, agrop-erlite, and SAP-P + agrop-erlite did not differ significantly from one another. Descriptive rankings suggested that SAP-P tended to produce relatively low evaporation losses in some light- and medium-loam blocks, whereas agrop-erlite or the composite ranked favorably in some heavy-loam blocks. These within-texture contrasts were not tested as separate significant effects and should be regarded as hypotheses for further study rather than demonstrated texture-specific responses.

Previous studies suggest that polymer swelling, specific surface area, spatial distribution, and pore-space confinement can influence soil-SAP behavior [17–21]. These mechanisms may offer possible explanations for the descriptive rankings observed here, but the present experiment did not measure swelling, pore connectivity, or water-potential distributions directly. They therefore cannot be treated as confirmed explanations of treatment performance.

Agrop-erlite is known to modify pore structure and aeration in soil or substrate mix-tures [22,23], and a composite may combine mineral structural effects with polymeric water storage. However, the absence of significant differences among the three amendments in Experiment 1 precludes attributing the observed heavy-loam rankings to a confirmed material-specific mechanism.

The heatmap summarizes descriptive control-relative changes, while the correlation matrix is exploratory only. Agrop-erlite and the composite had a Spearman coefficient of $r_s = 0.83$ across the six blocks, but this estimate is highly uncertain at $n = 6$ and does not establish a shared mechanism or causal relationship.

The cumulative trajectories also indicate that treatment differences accumulated gradually during drying rather than arising from a single anomalous interval. By contrast, the

crossing trajectories in Experiments 2 and 3 explain why endpoint minima did not translate into stable dose or particle-form rankings.

Experiment 2 did not show a statistically significant or consistently monotonic dose response for any SAP form. SAP performance is known to depend jointly on concentration, ionic environment, wetting–drying history, swelling confinement, and soil pore geometry [19–21,24,25]. The present response pattern therefore supports evaluating application rate as a soil- and formulation-specific factor rather than inferring a quadratic optimum.

Experiment 3 likewise did not demonstrate a general particle-form effect. SAP-P was descriptively favorable in light loam but not in heavy loam, whereas the omnibus tests were non-significant in both textures. The mechanisms proposed for fine particles—rapid swelling, greater surface area, and more uniform spatial distribution—remain plausible [19,25], but their expression may depend on texture-related constraints [17,21].

The experimental design defines the scope of inference. Open-top vessels with impermeable bottoms isolated gravimetric loss dominated by evaporation and did not reproduce drainage, root uptake, or field redistribution. Equal nominal water addition did not impose an identical initial matric potential across contrasting textures, and the three experiments were independent runs with experiment-specific controls. Consequently, the results describe comparative laboratory evaporation dynamics within each experimental design.

Field validation should therefore include drainage, natural temperature and precipitation variability, plant uptake, repeated wetting–drying cycles, and long-term assessment of SAP stability and environmental safety. Such validation is essential before translating the laboratory response into application recommendations [17–21,24,25].

5. Conclusions

The study quantified short-term evaporation loss from open-top laboratory vessels containing dark chestnut soil and Ordinary Chernozem of contrasting local texture classes. In Experiment 1, treatment significantly affected 7-day water loss across six soil-type $\times$ texture blocks ($F_{3,15} = 12.90$, $p < 0.001$). Fisher's LSD separated the untreated control from all amended treatments, while SAP-P, agropperlite, and SAP-P + agropperlite did not differ from one another. Experiment 2 showed no significant primary ANOVA dose effect for SAP-P, SAP-B, or SAP-G, and Experiment 3 showed no significant particle-form effect in either light or heavy loam. Thus, the data support a general amendment effect under the conditions of Experiment 1 but do not identify a superior amendment, universal optimum dose, or generally superior SAP particle form.

Under the tested open-top, no-drainage laboratory conditions, SAP-P, agropperlite, and SAP-P + agropperlite reduced short-term evaporation loss relative to the untreated control in Experiment 1, but the three amendments were not significantly different from one another. Effects of SAP dose and particle form were not significant in the primary analyses. Replicated field experiments incorporating drainage, plant water uptake, natural weather variability, repeated wetting–drying cycles, and long-term environmental safety assessment are required before these amendments, application rates, or formulations can be recommended for agricultural practice.

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