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Comparison in characteristics between synthetic and natural superabsorbent polymers and their effects on some chemical properties of calcareous soil

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Abstract

This study investigated the characteristics and impacts of natural and synthetic superabsorbent polymers (SAPs) on selected chemical properties of calcareous soil. In salt and NPK solutions, the swelling behavior, cationic affinity, soluble and exchangeable potassium forms, and cation exchange capacity of both SAPs were measured. Using a variety of extraction techniques, the pH and electrical conductivity of soil and soil–SAP systems were assessed. The results showed that the free-swelling capacity of the synthetic SAP was significantly higher than that of the natural SAP, and it swelled more rapidly, reaching near saturation in 16 minutes compared with 80 minutes for the natural SAP. As electrolyte concentration increased, both SAPs showed reduced swelling. Both SAPs stored similar amounts of extractable potassium, but their release and retention processes differed and showed weak exchange for Na (≈16%), moderate affinity for Ca (≈80%) and Mg (≈59%), and extremely high exchange for Fe, Mn, Zn, and Cu (>98%). The pH values of both SAPs were identical, while the natural SAP showed an increase in EC values. EC increased as the SAP percentage increased. The natural SAP had significantly higher CEC and EC in soil–gel systems than the synthetic SAP.

Keywords: Natural SAP, synthetic SAP, calcareous soil, chemical properties, NPK, salts

Introduction

Recent estimates suggest that global food demand will require a 40% increase over the next two decades in the yields of major crops, despite only a 10% expansion in cultivated land (Godfray *et al*., 2010). Consequently, improving crop yield per unit area is essential to meet future food requirements. Under these global conditions, it is necessary not only to increase productivity but also to use limited resources more efficiently, particularly fertile land and water (Spiertz, 2012).

Making the best use of this precious resource is extremely important, as agriculture depends on water and provides food. In this context, Wood and Johnson (1991) stated that the use of superabsorbent polymers (SAPs) as soil conditioners could improve yield per unit area. Additionally, Wu *et al*. (2008) demonstrated that the water and nutrient storage characteristics of SAPs can help conserve limited resources. This may be one of the factors contributing to the growing interest in SAPs in agriculture, together with the emerging water scarcity problem and the need for water conservation and efficient use.

Hydrophilic, slightly crosslinked superabsorbent polymers (SAPs) can absorb large amounts of water owing to their functional groups and osmotic pressure. Dodangeh *et al*. (2024) and Raza (2025) reported increasing interest in hybrid and sustainable polymers for agricultural use, particularly for improved water retention, salinity tolerance, and environmental safety. Although they generally have lower water uptake and weaker mechanical properties, natural SAPs derived from biopolymers (starch, cellulose, and chitosan) are strongly preferred because of their biodegradability and environmentally friendly nature. However, as reported by Muhammad *et al*. (2024), synthetic (acrylic-based) SAPs have high mechanical strength and swelling capacity but low biological degradability, which continues to drive the development of environmentally safe SAPs.

By enhancing water and nutrient retention, both natural and synthetic polymers significantly alter the chemical properties of soil. Olad *et al*. (2018) and Yang *et al*. (2020)

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observed that, in addition to increasing soil organic matter and microbial activity, natural polysaccharide-based SAPs improve soil buffering capacity, reduce salinity, increase cation exchange capacity (CEC), and restrict nutrient leaching through ion exchange pathways and biodegradable functional groups.

Superabsorbent polymers (SAPs), both natural and synthetic, have been shown to enhance soil water retention and physical characteristics; however, the effectiveness of SAPs varies based on soil conditions and polymer composition. While natural biopolymer-based SAPs provide the benefits of biodegradability and enhanced environmental sustainability, synthetic polyacrylate-based SAPs typically show higher swelling capacity, nutrient retention, cation exchange capacity (CEC), and nutrient use efficiency (NUE) (Malik *et al*., 2022; Adjuik *et al*., 2022; Ali *et al*., 2023; Negim *et al*., 2024). Both kinds of SAPs improve soil porosity, aggregation, structure, and water-holding capacity, which encourages root development and boosts plant performance, especially in situations where water is scarce. However, the soil environment has a significant impact on SAP effectiveness. According to earlier research, dissolved salts reduce SAP swelling. Multivalent cations, like Ca^{2+} and Fe^{3+}, cause larger reductions than monovalent ions because they create more cross-links within the polymer network, which results in structural collapse and decreased water absorption (Liu *et al*., 2020; Batara *et al*., 2025; Jagota *et al*., 2025). Although these reactions are well known, the majority of earlier research has mostly concentrated on crop reactions, water retention, and swelling behavior in distilled water, saline solutions, or non-calcareous soils; relatively little attention has been paid to how the physicochemical traits of various commercial SAPs affect soil chemical properties in calcareous soils (Venkatachalam & Kaliappa, 2023; Wang & Zhu, 2025). Studies carried out in other soil types cannot directly infer SAP performance since calcareous soils are characterized by high pH, rich $CaCO_3$, and higher Ca^{2+} concentrations (FAO, 2022; Brownrigg *et al*., 2022; Sheikh-Abdullah *et al*., 2023). This study's main novelty is its evaluation of SAP performance in calcareous soil conditions using an integrated assessment of swelling behavior, potassium release, cation exchange capacity, pH, electrical conductivity, and soil chemical properties. It also compares extraction techniques, showing their impact on the measurements of electrical conductivity and the evaluation of SAP-induced alterations (Muhammad *et al*., 2024; Buchmann *et al*., 2025). Additionally, this study shows that the analytical method itself affects the interpretation of SAP-induced changes in soil chemistry, particularly electrical conductivity, an aspect that has received little attention in prior SAP research, by contrasting saturated paste and filtrate extraction methods (Rhoades, 1996; Corwin & Scudiero, 2020). Together, these results offer fresh mechanistic understanding of SAP–soil interactions in alkaline calcareous soils and show that choosing the right commercial SAPs for calcareous agricultural systems should take into account both the SAP's overall physicochemical effects on the soil and its capacity to absorb water (Yang *et al*., 2024; Zhu *et al*., 2024).

Materials and Methods

Soil preparation

Soil samples were taken from fields at the University of Duhok, College of Agricultural Engineering Sciences, in the Kurdistan Region, Iraq. The samples were air-dried, ground, and passed through a 2 mm sieve to evaluate the effects of superabsorbent polymers (SAPs) on soil physical and chemical properties, including the assessment of specific physicochemical characteristics of the SAPs, both alone and in mixtures with soils, Table (1) shows the routine analysis for the soil under study.

Table 1: Physical and chemical properties of the soil under study

Property	Unit	Value
pH		7.8
EC	$dS\ m^{-1}$	0.20
Available N	$mg\ L^{-1}$	52.2
Available P		5.9
Soluble K		0.32
Ca		**1.05**
Mg	$mmol\ L^{-1}$	0.40
Cl		0.50
HCO_3		1.9
CO_3		Trace
O.M	$g\ kg^{-1}$	15
CEC	$cmol_c\ kg^{-1}$	42.5
Clay		574
Sand	$g\ kg^{-1}$	196
Silt		230
Soil texture	Clay	

Superabsorbent polymers (SAPs)

Both natural and synthetic superabsorbent polymers (SAPs) were used in this investigation. Polyter® (France), a naturally occurring SAP, is a biodegradable cellulose-based hydrogel that creates tiny water reservoirs in the soil. By releasing nutrients gradually, it improves plant growth, soil

Table 2: Properties of the superabsorbent polymers under study

Property	Natural SAP (Polyter)	Synthetic SAP (AQUASORB)
Composition	Cellulose-based hydrogel	Cross-linked potassium polyacrylate hydrogel
Functional groups	Mainly hydroxyl (–OH) groups, ether (C–O–C) and alcohol (C–O)	Carboxylate ($–COO^-$), carboxylic acid (–COOH), and amide (–CONH–) groups.
Particle size	0.315–3.0 mm	0.3–1.0 mm
Initial ion/nutrient content	Contains incorporated NPK nutrients	Contains potassium (K^+) as the counter-ion; no added NPK fertilizer
Biodegradability	Biodegradable in soil (about 2–3 years)	Not readily biodegradable

moisture, and nutrient availability. AQUASORB® (SNF SAS, France), a synthetic SAP, is a polyacrylamide-based hydrogel with a high capacity to absorb water. It enhances soil moisture and plant growth, releases water and nutrients gradually, is chemically stable, and is not biodegradable (Table 2).

Water absorption characteristics of the SAP

Free swelling capacity (FSC)

A dry weight (W1) for a sample of SAPs was obtained, and then the sample was submerged in distilled water to initiate the swelling process. The steps were repeated three times, and the wet weight (W2) was recorded.

Swelling velocity

Swelling velocity is the rate at which SAPs reach their maximum absorption. The SAPs were weighed into teabags, and each teabag was submerged in a beaker of distilled water. The teabags were removed at different intervals (i.e. 10 s, 30 s, 1, 4, 8, 16, 32, 64, and 80 min); the average swelling behavior of both SAPs was determined by replicating the experiments three times.

Swelling capacity vs. ions concentration

To assess the impact of ion concentrations on natural and synthetic SAP absorption, varying concentrations (i.e., 0, 100, 400, 800, 1200, 1600, and 2000 mg L^{-1}) of NaCl, $CaCl_2$, $FeCl_3$, and commercial NPK were used. The SAPs were weighed into teabags, then submerged in different solutions for one hour, then reweighed after eliminating the excess water; the average swelling capacity in saline and fertilized conditions was calculated.

Cationic interaction parameters

Determination of the Soluble-K fraction

To remove soluble potassium, dry SAPs were submerged and stirred in distilled water, then filtered several times before analysis. The residual gels were then used to extract exchangeable potassium for analysis.

Determination of the exchangeable-K (from hydrated product)

Gel samples have been processed in the same way as in the previous procedure; 1 N ammonium acetate is used instead of distilled water for the extraction of exchangeable potassium from the polymer for additional measurement.

Soluble and exchangeable K fractions (from dry product)

To analyze available potassium, including soluble and exchangeable forms, dry SAP products were extracted directly with 1 N ammonium acetate. All procedures were carried out three times to estimate the mean quantity.

Cation exchange capacity (CEC)

The Rhodes procedure (1982) was used for measuring the cation exchange capacity (CEC) of SAPs. This involved saturating the SAPs with Na, removing excess Na with ethanol, displacing the adsorbed Na with ammonium acetate, and then estimating the extracted sodium.

Cationic affinity (selectivity) of SAPs

Exchange of preferred cations by the SAPs

SAPs were immersed in a 0.5 meq L^{-1} salt solution containing multivalent ions (Ca^{2+}, Mg^{2+}, Zn^{2+}, Cu^{2+}, Mn^{2+}, and Fe^{3+}), then shaken, filtered, and rinsed with 50% ethanol to remove the supernatant solution containing non-exchangeable cations.

Extraction of the exchanged cations from the SAPs

Exchanged cations in the previous step were desorbed from the SAPs by submerging the material in 1 N ammonium acetate; this process was repeated three times to ensure complete extraction, and the filtrates accumulated for analysis.

Effects of SAPs on basic soil properties

pH of SAPs

A given weight of SAPs was hydrated to maximum swelling with distilled water to produce SAP gels; the procedure was replicated three times, and the pH was recorded.

pH of soils and soil-gel systems

Air-dried, sieved soil was suspended at a 1:10 soil–water ratio with and without SAPs (0.3% and 0.6% w/w). The procedure was triplicated, and soil pH was recorded for both soil and soil–gel treatments

Electric conductivity of SAPs

The same procedure used for estimating SAPs' pH was applied for SAPs' EC; each treatment was replicated three times and EC was determined.

Electric conductivity of soils and soil-gel systems

Air-dried, sieved soil was suspended in distilled water (1:10), shaken, and EC was determined in the saturated and filtered soil solution. All measurements were taken in duplicate, and the procedure was repeated for soils treated with 0.3% and 0.6% SAPs.

Cation exchange capacity (CEC) of soils and soil-gel systems

Rhodes's (1982) method was used to measure soil cation exchange capacity (CEC) in soil with SAPs. The procedure involved saturating the soil with sodium acetate, removing any surplus with ethanol, replacing it with 1 N ammonium acetate, and measuring the extracted sodium concentration to determine total CEC.

Data analysis and Statistics

The statistical program Minitab (Version 16) was used to evaluate the experimental data. Three independent replicates (n = 3) of each treatment were used in the factorial arrangement of the completely randomized design (CRD) experiment. Treatment effects were assessed using analysis of variance (ANOVA), and treatment means were compared at the 5% probability level ($p \leq 0.05$) using Tukey's honestly significant difference (HSD) test. The results were displayed as the mean ± standard deviation (SD).

Results and Discussions

Free swelling capacity of SAPs

The free swelling capacity of synthetic SAPs was significantly higher (432.3 g g^{-1}) than that of natural SAPs (344.1 g g^{-1}) ($p < 0.05$) (Table 3). This increase may be attributed to the stronger osmotic pressure and higher density of ionic functional groups in synthetic networks (Zohuriaan-Mehr & Kabiri, 2008). In contrast, natural SAPs have a lower charge density and more rigid biopolymers, which reduces swelling but ensures environmental friendliness and biodegradability (Guilherme *et al*., 2015; Chen *et al*., 2025).

Swelling velocity

Swelling velocity showed that SAP type, swelling time, and their combination had a significant impact ($p < 0.05$) on water absorption (Table 4). Natural SAPs expanded steadily for almost 80 minutes, whereas synthetic SAPs swelled more rapidly, approaching saturation within 16 minutes. A controlled hydration response was observed, with a constant increase in absorption over time. These interdependent effects demonstrate how crosslinking density and polymer structure govern swelling efficiency and rate (Olad *et al*., 2018; Sroka & Sroka, 2024).

Natural SAP swelled gradually to 360 g g^{-1} over 80 minutes, whereas synthetic SAP swelled significantly faster, reaching close to its maximum absorption in 16 minutes (Figure 1). This reflects structural differences: natural SAPs are more heterogeneous and exhibit slower diffusion, while synthetic networks contain dense hydrophilic groups and well-connected pores that accelerate water intake. As a result, natural SAP reaches a comparable or slightly lower capacity more slowly, whereas synthetic SAP attains equilibrium rapidly. According to recent research, swelling kinetics and water uptake rates are strongly influenced by SAP type, content, and particle structure (Malik *et al*., 2023; Xu *et al*., 2025).

Swelling capacity vs. salt concentration

NaCl Salt

SAP type, NaCl concentration, and their interaction significantly affected swelling behavior ($p< 0.05$), as presented in Table (5). The consistently superior performance of synthetic SAPs over natural ones confirms their stronger hydrophilic properties and more coherent network structure. For both materials, increasing NaCl concentration significantly decreased swelling because of ionic buffering and diminished osmotic pressure. Regarding the combined effect, synthetic SAPs maintained greater expansion under

Table 3: Evaluation of the Free Swelling Capacity of Natural and Synthetic SAPs

SAP Type	Free Swelling Capacity (FCS) ± SD (g g^{-1})
Natural SAP	344.1**a** ±23.3
Synthetic SAP	432.3**b** ±26.0

Means designated with dissimilar letter are significantly different ($p < 0.05$), mean ± SD (standard deviation) (n = 3).

Table 4: Swelling velocity of both Natural and Synthetic super absorbent polymers (SAPs)

SAP types	Time duration (min.)									Effect of SAP types
	10 Sec.	30 Sec.	1 Min.	4 Min.	8 Min.	16 Min.	32 Min.	64 Min.	80 Min.	
Natural SAP	38.4**g** ±1.87	42.7**g** ±1.74	43.7**g** ±1.40	82.8**fg** ±9.29	115.2**f** ±14.56	196.4**e** ±28.30	248.5**d** ±26.30	308.7**bc** ±25.90	354.4**ab** ±7.87	**159.0b**
Synthetic SAP	101.3f ±8.63	170.9**e** ±12.32	193.7**e** ±34.70	265.3**cd** ±4.42	336.4**b** ±14.52	392.8**a** ±3.78	390.4a ±2.40	400.5**a** ±1.56	398.5**a** ±5.86	**294.4a**
Effect of Time Duration	**69.8f**	**106.8e**	**118.7e**	**174.1d**	**225.8c**	**294.6b**	**319.5b**	**354.6a**	**376.5a**	

Means designated with dissimilar letter are significantly different ($p < 0.05$), mean ± SD (n = 3).

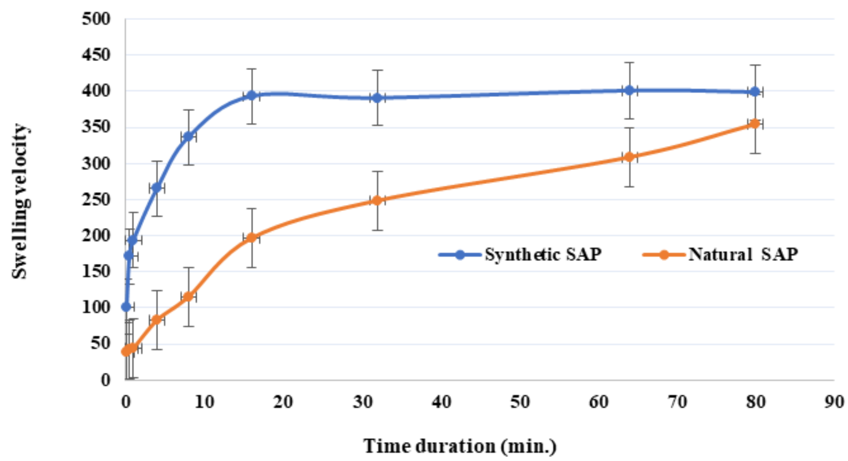

Figure 1: Swelling velocity of natural vs synthetic super absorbent polymers (SAPs)

salinity stress, whereas natural SAPs were more sensitive to NaCl salt. Similar findings were reported by Zohuriaan-Mehr & Kabiri (2008) and Mahon *et al.* (2020), who showed that polymer composition affects the ability of SAPs to withstand salt.

$CaCl_2$ Salt

The results shown in Table (6) revealed that free swelling capacity was significantly influenced by SAP type, $CaCl_2$ level, and their interaction ($p < 0.05$). Compared with natural SAPs, synthetic SAPs initially exhibited greater expansion, but above 400 mg L^{-1}, natural SAPs showed greater swelling than synthetic SAPs. Overall, increasing $CaCl_2$ significantly reduced swelling in both materials because of structural breakdown and ionic bridging caused by Ca^{2+}; the substantial interaction demonstrated that natural SAPs are more sensitive to divalent ions. These results are consistent with previous studies highlighting the predominant suppressive effect of divalent cations on SAP swelling (Sultana *et al.*, 2018; Trivedi and Chourasia, 2023).

$FeCl_3$ Salt

In accordance with Table (7), free swelling capacity was significantly affected by SAP type, $FeCl_3$ level, and their interaction ($p < 0.05$). Initially, swelling was slightly greater in synthetic SAPs than in natural ones; however, from 400 ppm and above, natural SAPs swelled more than synthetic ones. The swelling of both SAP types decreased substantially as $FeCl_3$ increased. Through ionic crosslinking and network breakdown, Fe^{3+} significantly reduced SAP swelling, diminishing water uptake from >300–400 g g^{-1} to <10 g g^{-1} above 1200 mg L^{-1}. In agreement with the substantial restricting effects of trivalent cations documented in recent studies, the degree of suppression varies among SAP types, confirming differences in ion sensitivity and binding potential (Ulfin *et al.*, 2024; Sroka & Sroka, 2024).

Table 5: Free swelling capacity (%) of both natural and synthetic what? under different concentrations of NaCl salt

SAP type	NaCl Salt Solution (mg L^{-1})							Effect of SAP
	0	100	400	800	1200	1600	2000	
Natural SAP	310.7**b** ±25.5	213.5**b** ±9.55	123.0**d** ±9.34	95.2**de** ±1.301	77.9**e** ±5.69	71.5**ef** ±2.42	40.5**f** ±4.14	**133.2b**
Synthetic SAP	402.1**a** ±2.20	309.0**b** ±2.21	182.4**c** ±3.32	128.6**d** ±2.78	105.2**de** ±0.736	83.2**e** ±32.8	81.5**e** ±1.266	**184.6a**
Effect of NaCl	**356.4a**	**261.2b**	**152.7c**	**111.9d**	**91.5de**	**61.8f**	**76.5ef**	

Means designated with dissimilar letter are significantly different ($p < 0.05$), mean ± SD (n = 3).

Table 6: Free swelling capacity (%) of both Natural and synthetic what? under different concentrations of $CaCl_2$ salt

SAP type	$CaCl_2$ Salt Solutions (mg L^{-1})							Effect of SAP
	0	100	400	800	1200	1600	2000	
Natural SAP	312.6**b** ±25.3	253.1**c** ±7.49	151.2**d** ±1.32	56.4**e** ±2.53	33.5**ef** ±1.110	29.5**ef** ±4.33	2.6**f** ±0.1469	**119.8b**
Synthetic SAP	404.5**a** ±1.58	272.1**c** ±33.5	153.8**d** ±18.1	44.1**e** ±0.400	32.5**ef** ±0.411	25.9**ef** ±1.85	2.1**f** ±0.204	**133.6a**
Effect of $CaCl_2$	**358.6a**	**262.6b**	**152.5c**	**50.2d**	**33.0d**	**27.7d**	**2.4e**	

Means designated with dissimilar letter are significantly different ($p < 0.05$), mean ± SD (n = 3).

Table 7: Free swelling capacity (%) of both Natural and synthetic what? under different concentrations of $FeCl_3$ salt

SAP type	$FeCl_3$ Salt Solution (mg L^{-1})							Effect of SAP
	0	100	400	800	1200	1600	2000	
Natural SAP	308.7**b** ±25.9	134.4**d** ±3.38	22.9**e** ±4.34	13.2**e** ±3.69	10.4**e** ±0.460	6.1**e** ±0.488	6.0**e** ±0.289	**71.7b**
Synthetic SAP	400.5**a** ±1.56	160.3**c** ±8.73	6.8**e** ±0.0271	5.2**e** ±1.087	6.2**e** ±0.638	7.1**e** ±1.000	4.5**e** ±0.181	**84.4a**
Effect of $FeCl_3$	**354.6a**	**147.4b**	**14.9c**	**9.2c**	**8.3c**	**6.6c**	**5.3c**	

Means designated with dissimilar letter are significantly different ($p < 0.05$), mean ± SD (n = 3).

Table 8: Free swelling capacity (%) of both Natural and synthetic SAPs under different concentrations of NPK

SAP types	NPK Solutions (mg L^{-1})							Effect of SAP
	0	100	400	800	1200	1600	2000	
Natural SAP	314.5**b** ±26.3	274.5**c** ±10.02	168.6d ±8.99	118.5**ef** ±5.57	106.2**fg** ±1.93	96.4**fg** ±0.765	92.8g ±1.000	**167.4b**
Synthetic SAP	406.9**a** ±2.22	288.9**c** ±3.77	189.0**d** ±1.73	135.8**f** ±3.01	116.0**efg** ±4.23	100.9**fg** ±2.99	97.5**fg** ±0.435	**190.7a**
Effect of NPK	**360.7a**	**281.7b**	**178.8c**	**127.1d**	**111.1e**	**98.7ef**	**95.2f**	

Means designated with dissimilar letter are significantly different ($p < 0.05$), mean ± SD (n = 3).

NPK fertilizer

SAP type, NPK rate, and their interaction significantly affected free swelling capacity ($p < 0.05$), as Table (8) shows. With NPK treatment, synthetic SAPs maintained a higher mean swelling than natural SAPs, indicating a more stable structure. Rather than a sudden network disruption, swelling decreased gradually for both SAPs as NPK levels increased, indicating significant ionic protection. In terms of interaction trends, natural SAPs changed more consistently, while synthetic SAPs maintained greater swelling at all concentrations. Recent studies have documented similar nutrient-induced variation in SAP swelling (Dingley *et al.*, 2024).

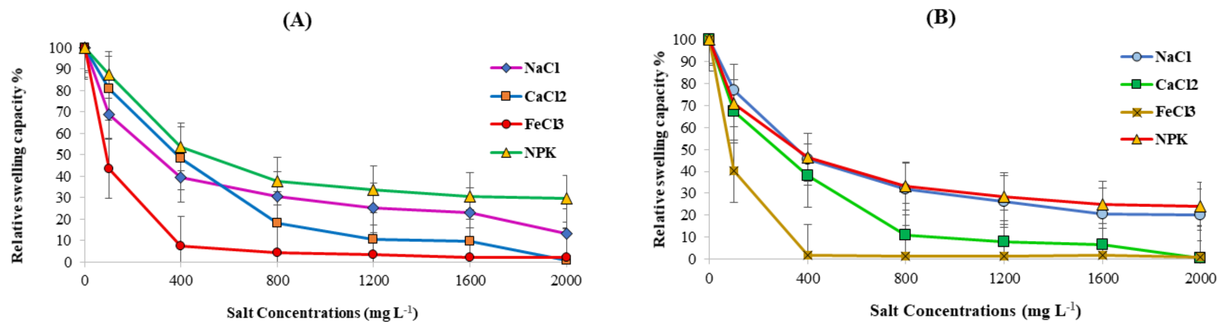

Figure 2: Relative swelling capacity (%) of natural (A) and synthetic (B) SAPs under increasing NaCl, $CaCl_2$, $FeCl_3$, and NPK concentrations

Table 9: Potassium fractions (ppm SI units pl.) in natural and synthetic superabsorbent polymers (SAPs)

SAP Type	Soluble K	SD	Exchangeable K	SD	Soluble & Exchangeable K	SD
	from swollen SAPs				from Dry SAPs	
Natural SAP	16.953**a**	±0.523	26.36**b**	±2.61	43.79**a**	±2.07
Synthetic SAP	6.497**b**	±0.523	34.728**a**	±0.523	46.377**a**	±0.518

Means designated with dissimilar letter are significantly different ($p < 0.05$), mean ± SD (n = 3)

Table 10. Residual exchangeable cations as indicators of cation selectivity in natural and synthetic SAPs

Cation	Natural SAP		Synthetic SAP	
	Exchange %	±SD	Exchange %	±SD
Ca	80.00**b**	±5.000	80.00**b**	±5.0000
Mg	58.85**c**	±4.120	58.85**c**	±0.0410
Na	15.57**d**	±2.400	15.57**d**	±0.0009
Cu	98.78**a**	±0.160	99.16**a**	±12.350
Zn	98.92**a**	±0.115	99.03**a**	±0.0008
Fe	99.96**a**	±0.007	99.97**a**	±2.4000
Mn	99.54**a**	±0.114	99.71**a**	±0.0135

Means designated with dissimilar letter are significantly different ($p < 0.05$). within each column by Tukey´s HSD test, mean ± SD (n = 3)

Table 11: pH values of natural and synthetic SAPs determined in distilled water and 0.01 M $CaCl_2$.

SAP type	Solution		Effect of SAP
	pH (Distilled water)	pH ($CaCl_2$ 0.01 M)	
Natural SAP	6.81**a** ±0.353	5.72**b** ±0.325	**6.27a**
Synthetic SAP	6.68**a** ±0.0265	5.90**b** ±0.0153	**6.29a**
Effect of Solution	**6.75a**	**5.81b**	

Means Designated with dissimilar letter are significantly different ($P < 0.05$), mean ± SD (n = 3)

Relative swelling capacity (%)

Figure (2) showed that as electrolyte concentration increased, both superabsorbent polymers exhibited reduced swelling, although their sensitivity differed. Salts markedly diminished the expansion of the natural SAP, particularly in the presence of multivalent ions. Ionic charge was confirmed that ionic charge plays a part in polymer contraction, with $FeCl_3$, $CaCl_2$ and NaCl causing the strongest suppression. Swelling in NPK solution also decreased, albeit less markedly, suggesting that mixed ions are less harmful. Owing to its enhanced hydration capacity and more robust network, the synthetic SAP retained higher swelling. Recent research on salt-responsive hydrogels supports these observations (Sultana *et al*., 2018).

Cationic interaction parameters

Determination of soluble and exchangeable potassium fractions

Different cation affinity trends between natural and synthetic SAPs are shown in Table (9). Natural SAPs had significantly higher soluble potassium (K) in the swollen state, which accelerated nutrient availability even though the extractable potassium (K)concentration was comparable. These variations indicate that although both SAPs may store similar amounts of extractable K, their release and retention processes differ. According to recent research, biopolymer-based SAPs promote rapid nutrient release, while synthetic polyacrylate SAPs have a greater capacity for cation exchange and longer K retention (Olad *et al*., 2018; Malik *et al*., 2022).

Cationic affinity

Both synthetic and natural SAPs showed a comparable pattern of cation selectivity (Table 10), with weak exchange for Na (≈16%), moderate affinity for Ca (≈80%) and Mg (≈59%), and extremely high exchange for multivalent and transition metals (Fe, Mn, Zn, Cu; >98%). This mechanism is largely determined by the hydration shell and charge of the cation, which promote strong ionic bonding of multivalent ions to $–COO^-$ groups. The fact that both SAPs responded in the same way indicates that the chemistry of the polymer, rather than material origin, controls ion exchange (Stocker *et al*., 2022). Recent research on SAP–soil systems has consistently shown preferential retention of di- and trivalent cations over monovalent ions, as well as limited Na affinity because of its large hydrated radius (Guilherme *et al*., 2015; Zohuriaan-Mehr & Kabiri, 2008). The strong affinity of the evaluated SAPs for micronutrient cations (Fe, Mn, Zn, and Cu) has important implications for calcareous soils. In such soils, the considerable affinity of the examined SAPs for these micronutrient cations has significant consequences. While improved retention would reduce micronutrient loss, excessive adsorption might temporarily restrict their availability for plant uptake, potentially exacerbating the deficiencies typical of high-pH calcareous soils. Consequently, these interactions should be considered when choosing SAPs and micronutrient fertilization strategies. The long-term bioavailability of adsorbed micronutrients requires field research (Skiba *et al*., 2015; Lentz & Ippolito, 2021; Drozd *et al*., 2024).

Effects of SAPs on basic soil properties

pH of SAPs

Table (11) shows that the pH values of natural and synthesized SAPs were identical in all extraction media, ranging from slightly acidic to almost neutral. Ionic strength effects, ionic shielding, and hydrogen ion displacement within the polymer network caused the pH to drop in 0.01 M $CaCl_2$. Because both polymers maintained similar buffering capacity and chemical integrity, these findings suggest that solution chemistry, rather than SAP type, predominantly controls pH response (Yang *et al*., 2024).

pH of soils and soil-gel systems

Soil pH remained within a narrow alkaline range irrespective of SAP levels, which is in agreement with the study's overall results and indicates that application rate did not substantially alter soil buffering capacity (Table 12). This supports our broader conclusion that SAP amendments produced little change in the soil's chemical balance.

This trend indicates intrinsic differences in the ionic characteristics, polymer composition, and exchange interactions of the soil–gel system. Taken together, these findings support the hypothesis that SAP effects on soil reaction under alkaline conditions are determined primarily by material characteristics rather than dosage, which is consistent with known polymer–soil interaction processes (Bai *et al*., 2010; Li *et al*., 2014).

Ionic-based analysis is more sensitive to SAP–soil mixtures than distilled water, as shown by the considerable decrease in soil pH in 0.01 M $CaCl_2$ for both natural and synthetic SAPs with increasing dosage (Table 13). This decrease results from the exchange of H^+ with Ca^{2+}, which increases the activity of hydrogen ions. The effect of synthetic SAP is linked to the exchange of polyacrylate cations, while natural SAP exhibited buffering behavior rather than a real decrease in soil acidity, perhaps due to the presence of organic functional groups (Malik *et al*., 2022).

Determination and effects on soil electrical conductivity (EC)

Electrical conductivity of SAPs

There were statistically significant differences in electrical conductivity (EC) between extraction media and SAP types (Table 14). Both saturated and filtrate extracts of the natural SAP showed increased EC, most likely as a result of soluble ions from its organic form. The lower EC of the synthetic polymer reflects its chemically defined, inert structure. For both SAPs, filtrate EC was higher than saturated EC, indicating enhanced ion mobilization during filtration. These findings are consistent with recent research on bio-based versus synthetic polymers (Fu *et al*., 2022; Sroka & Sroka, 2024), which shows that the extraction medium affects ionic release, while SAP type determines total conductivity.

Electrical conductivity of soils and soil-gel systems

SAP type, application rate, and their combination had a significant influence on soil electrical conductivity (EC) (Table 15). In both saturated and filtrate extracts, natural SAP constantly exhibited higher EC than synthetic SAP, indicating stronger mobilization of soluble ions from its organic and mineral components. EC gradually increased as SAP rate increased, suggesting enhanced ion exchange and dissolution of easily soluble ions. Moreover, in all treatments, filtrate extracts showed higher EC than saturated extracts, suggesting that filtration promotes greater ion mobility than equilibrium saturation. These results are in line with studies demonstrating the combined regulation of SAP composition, dosage, and extraction method on soil EC responses (Yang *et al*., 2020; Spiteri and Sacco, 2024).

Cation exchange capacity (CEC)

Cation exchange capacity (CEC) of SAPs

The two types of SAP had significantly different cation exchange capacities (CECs); natural SAP had a higher CEC than synthetic SAP (1.84 and 1.76 meq·100 g^{-1}, respectively; ($p < 0.05$; Table (16), suggesting a stronger intrinsic capacity for holding cations. The extremely low standard deviations confirm high measurement precision and reliability. These variations support trends reported in other studies, which show that SAP chemical composition and functional groups significantly influence ion exchange behavior (Xu *et al*., 2025; Wang *et al*., 2025).

Table 12: Soil pH values amended with natural and synthetic SAPs (0.0, 0.3, and 0.6%) measured in distilled water

SAP type	SAP %			Effect of SAP
	0.0	0.3	0.6	
Natural SAP	8.30**abc** ± 0.0208	8.27**bc** ± 0.0265	8.23**c** ± 0.0115	**8.27b**
Synthetic SAP	8.34**ab** ± 0.0208	8.36**ab** ± 0.0513	8.36**a** ± 0.0462	**8.35a**
Effect of SAP %	**8.32a**	**8.31a**	**8.30a**	

Means designated with dissimilar letter are significantly different ($p < 0.05$), mean ± SD (n = 3)

Table 13: Soil pH values amended with natural and synthetic SAPs (0.0, 0.3, and 0.6%) measured in 0.01 M $CaCl_2$

SAP type	SAP %			Effect of SAP
	0.0	0.3	0.6	
Natural SAP	**7.54a** ±0.0666	**7.42b** ±0.0513	**7.35b** ±0.0416	**7.43a**
Synthetic SAP	**7.54a** ±0.0252	**7.44ab** ±0.0153	**7.38b** ±0.0351	**7.45a**
Effect of SAP %	**7.54a**	**7.43b**	**7.37b**	

Means designated with dissimilar letter are significantly different ($p < 0.05$), mean ± SD (n = 3)

Table 14: Electrical conductivity values of natural and synthetic SAPs (µS cm^{-1})

SAP types	Media		Effect of SAP
	Saturated	Filtrate	
Natural SAP	22.43**a** ±1.447	25.97**a** ±1.85	**24.20a**
Synthetic SAP	12.34**c** ±1.132	16.90**b** ±1.92	**14.62b**
Effect of Media	**17.39b**	**21.44a**	

Means Designated with dissimilar letter are significantly different ($P < 0.05$). within each column by Tukey´s HSD test, mean ± SD (n = 3)

Table 15: Effect of applying natural and synthetic SAPs at rates (0.0, 0.3, and 0.6%) on soil electrical conductivity (µS cm^{-1})

SAP type	SAPs % (Saturated)			Effect of SAP
	0.0	0.3	0.6	
Natural SAP	94.97**d** ±1.595	126.77**b** ±3.10	153.67**a** ±4.86	**125.13a**
Synthetic SAP	97.10**d** ±0.608	111.93**c** ±1.88	125.03**b** ±2.12	**111.36b**
Effect of SAP %	**96.03c**	**119.35b**	**139.35a**	
SAP types	**SAPs % (Filtrate)**			**Effect of SAP**
	0.0	**0.3**	**0.6**	
Natural SAP	113.77**d** ±0.252	143.53**bc** ±1.59	169.60**a** ±5.31	**142.30a**
Synthetic SAP	114.27**d** ±1.16	130.53**c** ±4.47	154.13**b** ±10.66	**132.98b**
Effect of SAP %	**114.02c**	**137.03b**	**161.87a**	

Means designated with dissimilar letter are significantly different ($p < 0.05$), mean ± SD (n = 3)

Table 16: Cation exchange capacity (CEC) of natural and synthetic SAPs

SAP Type	CEC (meq·100 g^{-1})	SD
Natural SAP	1.84**a**	± 0.0063
Synthetic SAP	1.76**b**	± 0.0061

Means designated with dissimilar letter are significantly different ($p < 0.05$), mean ± SD (n = 3)

Table 17: Cation exchange capacity (CEC) of control and SAP-amended soils

Condition	CEC (meq·100 g^{-1})	SD
Soil (Control)	42.54**a**	± 1.92
Soil with Nat. SAP	44.12**a**	± 0.07
Soil with Syn. SAP	44.01**a**	± 1.92

Means designated with dissimilar letter are significantly different ($p < 0.05$), mean ± SD (n = 3), Nat. = natural Syn.= Synthetic

Cation exchange capacity (CEC) of soil and soil-gel systems

The CEC values of the control, natural SAP, and synthetic SAP soils were statistically comparable (Table 17). However, the slight increase observed with natural SAP suggests a minor improvement in cation-binding capacity. This pattern is in line with previous research indicating that SAPs do not significantly increase soil CEC, but instead primarily affect soil water retention and ion mobility within the soil solution (Xu *et al*., 2025; Malik *et al*., 2023).

Conclusions

This study showed that the soil ionic environment, polymer composition, and analytical technique all affect how effectively superabsorbent polymers (SAPs) function in calcareous soils. The important role of ionic charge and cationic affinity in regulating polymer behavior was confirmed by the reduced swelling of both natural and synthetic SAPs with increasing ionic strength, particularly in the presence of multivalent cations. Although these swelling trends are well established, this study offers a comprehensive evaluation of commercially available SAPs under calcareous soil conditions by relating swelling characteristics to potassium release, cation exchange capacity, electrical conductivity, pH, and soil chemical properties. The findings also showed that, while soil pH was only marginally affected because of the buffering capacity of calcareous soils, electrical conductivity and potassium fractions were influenced by SAP type, application rate, and extraction technique. These results show that evaluating SAP performance should take into account its impact on soil chemical characteristics, in addition to water absorption capability. Therefore, water-retention efficiency and physicochemical compatibility with the soil environment should be considered when choosing SAPs for calcareous soils. Overall, this study offers useful guidance for selecting suitable commercial SAPs to enhance nutrient dynamics and water management in calcareous agricultural soils.

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