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Can the physical-hydraulic properties of degraded soil be improved using polymers?

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Abstract

For a degraded soil it is assumed that improvements in key physical-hydraulic properties occur at an optimum superabsorbent polymer (SAP) application rate, following repeated wetting and drying cycles. A column experiment was carried out in a shade house (Ceará State, Brazil), following a completely randomized design, in a 6×4 factorial scheme in which six SAP application rates (0—control, 0.15, 0.30, 0.60, 1.20, and 2.40 g kg^{-1}) were incorporated into a sandy loam soil and subjected to four numbers of wetting and drying cycles (one, three, six, and nine cycles), with three replications. Soil bulk density, total porosity, macroporosity and microporosity, degree of flocculation, plant available water, and pore distribution by size were evaluated. After six wetting and drying cycles, the highest SAP rate reduced soil bulk density by 4%–9% compared to the control. At an SAP application rate of 1.2 g kg^{-1} the degree of flocculation increased by 25%, mainly after six wet and drying cycles. From the rate of 0.15 g kg^{-1} SAP onward, there was a 20% reduction in macroporosity and a 28% increase in microporosity, increasing total porosity, particularly after six cycles. SAP rates ranging from 0.15 to 0.6 g kg^{-1} increased available water by 12%–33%, while the highest polymer rate increased available water by 40%–50% compared to the control. This increase in soil available water is of strategic importance for water use efficiency, crop yields, and restoration activities in degraded dryland sandy soils.

Plain Language Summary

Dry lands have damaged soils with very little water to grow food. Hydrogels are materials that can hold water in the soil to help plants grow. But we need to know if the water stays just in the hydrogel or if the hydrogel helps the soil itself hold more

Abbreviations: ASL, above sea level; DF, degree of flocculation; Macro, macroporosity; Micro, microporosity; PVC, polyvinyl chloride; SAP, superabsorbent polymer; SWRC, soil water retention curve; TP, total porosity; W/D, wetting and drying; WA, water availability; WDC, water-dispersible clay.

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water over time as it gets wet and dries. In our study, we found that the hydrogel improves the soil pores and increases the amount of water available for plants.

1 | INTRODUCTION

The revegetation of degraded areas in drylands is a challenge due to water scarcity and demands innovative alternatives to improve water availability (WA) to plants (Asmelash & Rannestad, 2024; Stapleton et al., 2024). Superabsorbent polymers (SAPs) are considered strategic to improve plant WA in the soil (Adjuik et al., 2022; Womack et al., 2022; Zheng et al., 2023). SAPs are defined as cross-linked polymer networks, natural or synthetic, and are classified as copolymers when they consist of more than one monomer, such as acrylamide and potassium acrylate (Singh et al., 2016; Thakur & Thakur, 2015). These polymers are degraded over time, including the residual acrylamide, indicating their safety for application in agricultural soils (do Nascimento et al., 2021).

The beneficial effects of SAPs in soil are multifaceted and vary in magnitude depending on factors related to soil attributes, polymer properties and characteristics, application rates and mode of application, as well as the number of wetting and drying (W/D) cycles that the polymer undergoes following its application to the soil (do Nascimento et al., 2021; Rabat et al., 2016; Ullah et al., 2015; Zheng et al., 2023). The contribution of SAPs to soil WA is due to their ability to absorb water from 400 to 1600 times their own weight (Ahmed, 2015; Guilherme et al., 2015; Ma et al., 2023; Suresh et al., 2018). On the other hand, the improvements in plant WA with SAP application may also occur due to other edaphic attributes associated with the polymer, such as increased soil structural stability, soil total porosity (TP), and proportion of aeration pores, as well as a reduction in soil bulk density (Abdelghafar et al., 2024; Albalasmeh et al., 2022; Hussien et al., 2012; Leciejewski, 2009; do Nascimento et al., 2018).

Despite these reported benefits, studies diverge regarding the extent and persistence of structural improvements across different soil textures (Abdelghafar et al., 2024; Buchmann et al., 2015; Hussien et al., 2012; Ji et al., 2022). SAP does not alter the structure of sandy soil but reduces the bulk density as well as the hydraulic conductivity of clay soil (Abdelghafar et al., 2024). The reduction in bulk density due to SAP application is associated with the increase in TP and may be attributed to the displacement and rearrangement of soil particles around the SAP particles, while the decrease in soil hydraulic conductivity may be attributed to the hydrophilic properties of the polymer (Abdelghafar et al., 2024; Hussien et al., 2012).

The application of SAP can influence soil structure in response to W/D cycles, with changes observed after 2 and 3 W/D cycles for sandy and clay soils, respectively (Buchmann et al., 2015; Ji et al., 2022). In the clay soil, the positive effect was attributed to increased cementation, which prevented the breakdown of macroaggregates during the cycles (Ji et al., 2022). For sandy soil, the effect was attributed to the W/D cycles regarding that SAP expansion when wet and contraction when dry can bring the soil particles closer together, favoring aggregation and the generation of a stable porous network (Nascimento, Simmons et al., 2021; do Nascimento et al., 2018).

There is uncertainty as to whether the structural benefits in sandy soils persist after numerous W/D cycles (Buchmann et al., 2015). The increase in available water up to 6 months after SAP application suggests that the polymer's effects on soil structure may persist even after numerous W/D cycles in sandy soil (Banedjschafie & Durner, 2015). However, abiotic conditions such as temperature and salt concentration can compromise the expansion and contraction of SAPs (Nascimento, Simmons et al., 2021; C. D. V. do Nascimento et al., 2021). Thus, W/D cycles may be insignificant in terms of their influence on soil aggregation and physical-hydraulic properties in response to the application of acrylamide and potassium acrylate copolymer-based SAPs. In this way, SAP performance as soil conditioners is not always convergent regarding benefits to soil physical-hydraulic properties (Louf et al., 2021; Shainberg et al., 2011).

This study was carried out to test the hypothesis that there is an interaction between copolymer application rates and the number of W/D cycles, improving the physical-hydraulic properties that have a beneficial effect on soil functionality and ecosystem services provision of a degraded sandy soil. The objective of this study was to evaluate the effect of the addition of commercially available SAP copolymer rates on the physical attributes of a degraded sandy Acrisol submitted to repeated W/D cycles.

2 | MATERIALS AND METHODS

2.1 | Experimental site and soil

The experiment was carried out in a shade house (average temperature of 31°C), located in Fortaleza (Ceará, Brazil), at the geographic coordinates of 3°44'26.22" S and

TABLE 1 Physicochemical characterization of the Acrisol used in the study, with determination of soil particle size distribution, pH values, Ca, Mg, Na, and K contents, as well as calculations of cation exchange capacity (CEC), base saturation (V%), and exchangeable sodium percentage (ESP).

Variables	Value
Exchange complex	
pH (H ₂ O)	5.9
Ca ²⁺ (cmol _c kg ⁻¹)	1.7
Mg ²⁺ (cmol _c kg ⁻¹)	0.6
Na ⁺ (cmol _c kg ⁻¹)	0.2
K ⁺ (cmol _c kg ⁻¹)	0.3
CEC (cmol _c kg ⁻¹)	3.2
V (%)	88.0
ESP (%)	6.3
Soil particle size distribution	
Coarse sand (%)	45.0
Fine sand (%)	28.0
Silt (%)	8.0
Clay (%)	19.0
Textural classification	Sandy loam

38°34'30.63" W at 26 m above sea level (ASL). The local climate is defined as tropical hot subhumid, with annual rainfall of 1338 mm and an average temperature between 26°C and 28°C (IPECE, 2017). The soil used was from the AB and BA soil horizons of an ARGISSOLO VERMELHO-AMARELO Eutrófico (dos Santos et al., 2018), which corresponds to an Acrisol (IUSS Working Group WRB, 2022), collected in Quixadá (CE, Brazil, coordinates of 5°00'13.75" S and 38°59'50.75" W at 189 ASL, Table 1). In the soil characterization, pH was measured in H₂O (1: 2.5) by potentiometry; Ca²⁺ and Mg²⁺ were extracted with 1 M KCl solution (Teixeira, 2017) and determined by atomic absorption spectrometry (Thermo Scientific ICE 3000 series); and sodium (Na⁺) and potassium (K⁺) were extracted with Mehlich 1 solution and determined by flame photometry (Teixeira, 2017). Cation exchange capacity (CEC), base saturation (V%), and exchangeable sodium percentage were calculated following Teixeira (2017). Clay was quantified by the pipette method, sand by wet sieving, and silt by the difference between the initial mass of the sample and the masses of clay and sand (Gee & Or, 2002).

The climate in the site of soil collection is hot tropical semi-arid, with annual rainfall of 838.1 mm and an average temperature between 26°C and 28°C (IPECE, 2017). The soil used was degraded and characterized by the absence of vegetation cover due to overgrazing, low input of organic residues due to lack of vegetation, and the occurrence of inter-rill and rill erosion in the study area.

Core Ideas

- Superabsorbent polymer improves soil physical-hydraulic properties.
- Superabsorbent polymer (2.4 g kg⁻¹, six wetting and drying cycles) decreases soil bulk density by 4%–9%.
- Superabsorbent polymer (2.4 g kg⁻¹) increases soil water availability by up to 50%.

2.2 | Experimental design and treatments

A randomized experimental design was used in a factorial scheme (6 × 4) × three replications, totaling 72 experimental units. Each experimental unit, in which soil mixed with treatments was added, consisted of a set composed of a polyvinyl chloride (PVC) column of 0.15 m external diameter and height of 0.15 m and a stainless-steel ring of 0.07 external diameter and height of 0.05 m (Figure 1).

In the first treatment factor, six application rates of commercially available SAP were evaluated (0.0—control, 0.15, 0.30, 0.60, 1.20, and 2.40 g kg⁻¹ of soil (w/w)), corresponding to 0, 0.93, 1.86, 3.72, and 7.44 Mg ha⁻¹ of soil. The highest application rate (2.4 g kg⁻¹) corresponds to the recommended value per perennial planting hole by the manufacturer of the SAP used. In the second treatment factor, four numbers of W/D cycles of the soil to which the SAP was added (1, 3, 6, and 9 W/D cycles) were evaluated.

The SAP used was a granular copolymer of acrylamide and potassium acrylate (CoAm + AcK), with granular size ranging from 0.7 to 3.2 mm. The SAP is hydrophilic and forms a hydrogel when wetted (Nascimento, Mota et al., 2021). It consists of 39.7% carbon, 6.7% hydrogen, and 15.0% nitrogen quantified by means of an elemental analyzer (Nascimento, Mota et al., 2021). Potassium acrylate monomers showed 99% potassium and 0.8% sulfur, obtained by X-ray fluorescence spectrometry (Nascimento, Mota et al., 2021).

2.3 | Experiment description

A rubber ring was used to fix a porous cotton fabric to the bottom of each PVC column to retain soil particles and enable the columns to be filled with soil (Figure 1). The SAP at the desired application rates was thoroughly mixed with approximately 2.7 kg of soil, an amount adjusted to ensure filling of the PVC column up to a height of 0.10 m. The aim was to achieve a soil bulk density of 1.55 g cm⁻³, which is a typical value for a sandy loam texture class (Zeri et al., 2018). When

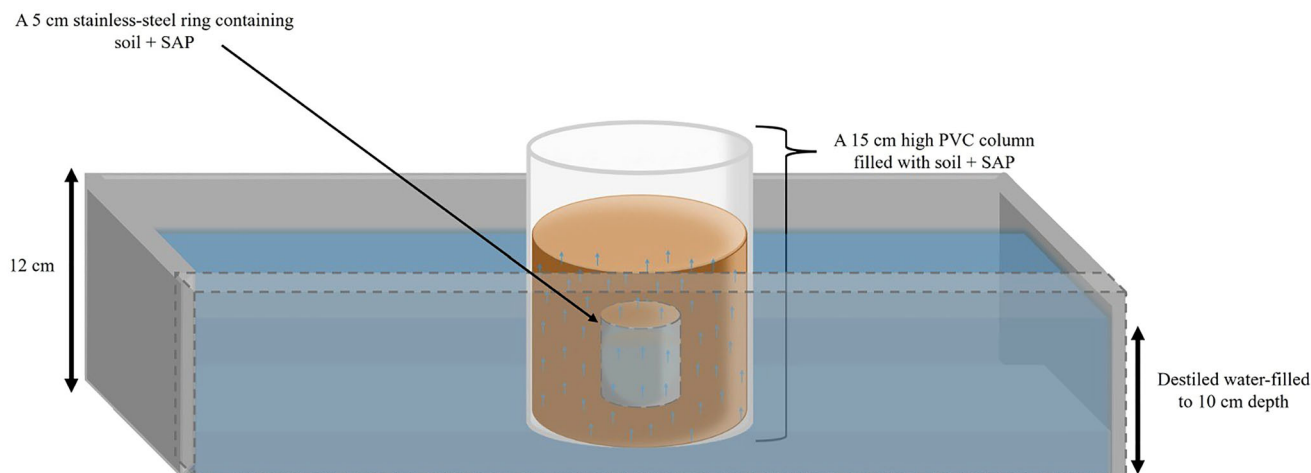


FIGURE 1 Experimental unit consisting of a set of polyvinyl chloride (PVC) (polyvinyl chloride) columns (0.15 m external diameter, 0.15 m height) and a stainless-steel ring (0.07 m external diameter, 0.07 m 0.05 m height), filled with soil containing superabsorbent polymer (SAP) rates and placed in a tray containing distilled water for application of wetting and drying (W/D) cycles.

0.025 m of the PVC column height was filled with homogenized material (soil + SAP), the stainless-steel ring (0.07 m external diameter, 0.05 m height) was positioned in the center of the PVC column, and the remaining soil + SAP was added, ensuring the complete filling of the stainless-steel ring. All layers were carefully added and compacted with manual pressure to ensure homogeneity throughout the PVC column up to a depth of 0.10 m (Figure 1). The 0.05 m at the top of the PVC columns was not filled to avoid extravasation of the homogenized material (soil + SAP) due to SAP expansion during W/D cycles.

Each set of PVC column and stainless-steel ring containing soil and SAP was subjected to W/D cycles. The wetting was carried out by adding distilled water to plastic trays inside which the experimental units were located, providing slow wetting of the soil by capillarity. The soil was wet by capillary rise, up to the superficial portion of the set PVC columns + stainless-steel rings placed on trays containing distilled water (Figure 1). Four days of wetting the excess water in the trays was discarded, and the treatments were put to air drying until constant weight was reached, which took approximately 15 days. Subsequently, the experimental units were returned to the plastic trays for an additional W/D cycle as appropriate.

2.4 | Performance metrics

For each treatment soil physical attributes were analyzed at the end of each W/D cycle. In disturbed samples particle density was determined by the volumetric flask method (Blake & Hartge, 1986b). The metal rings were carefully removed from the PVC columns and oven-dried at 105°C until a constant mass was achieved to determine the bulk density (Blake & Hartge, 1986a). With the data of particle and soil densities,

the total porosity was calculated from Equation (1) (Danielson & Sutherland, 1986).

$$TP = (1 - BD/PD) \quad (1)$$

where TP is the total porosity ($\text{cm}^3 \text{ cm}^{-3}$) and BD and soil particle density are, respectively, bulk and particle densities (g cm^{-3}).

Soil particle size and water-dispersible clay (WDC) were determined on disturbed samples with non-preserved structure (Gee & Or, 2002). In the method to determine soil particle size sodium hydroxide (NaOH) 1 mol L⁻¹ was used for the chemical dispersion of particles. Sand content was determined by sieving, and clay content by the pipette method. Silt content was calculated by difference, considering the initial soil sample minus the sum of sand and clay. The WDC was determined using the same procedure as for particle size analysis, differing by the absence of chemical dispersant and the exclusion of the sand and silt fractions. With the values of total clay and WDC, the degree of flocculation (DF) was calculated, according to Equation (2) (Donagema et al., 2011).

$$DF(\%) = \left(\frac{TC - WDC}{TC} \right) \times 100 \quad (2)$$

The soil water retention curves (SWRCs) were initially intended to be obtained using stainless-steel rings. However, due to the excessive delay in moisture stabilization of the samples—particularly at higher SAP rates and at higher tension points—it was decided to obtain the curve using part of the samples removed from the stainless-steel ring after the treatments. These samples were placed in rubber rings (0.01 m height and 0.06 m internal diameter) with a water-permeable fabric at the base to prevent the loss of soil particles and SAP (Richards & Weaver, 1944) (Figure 2).

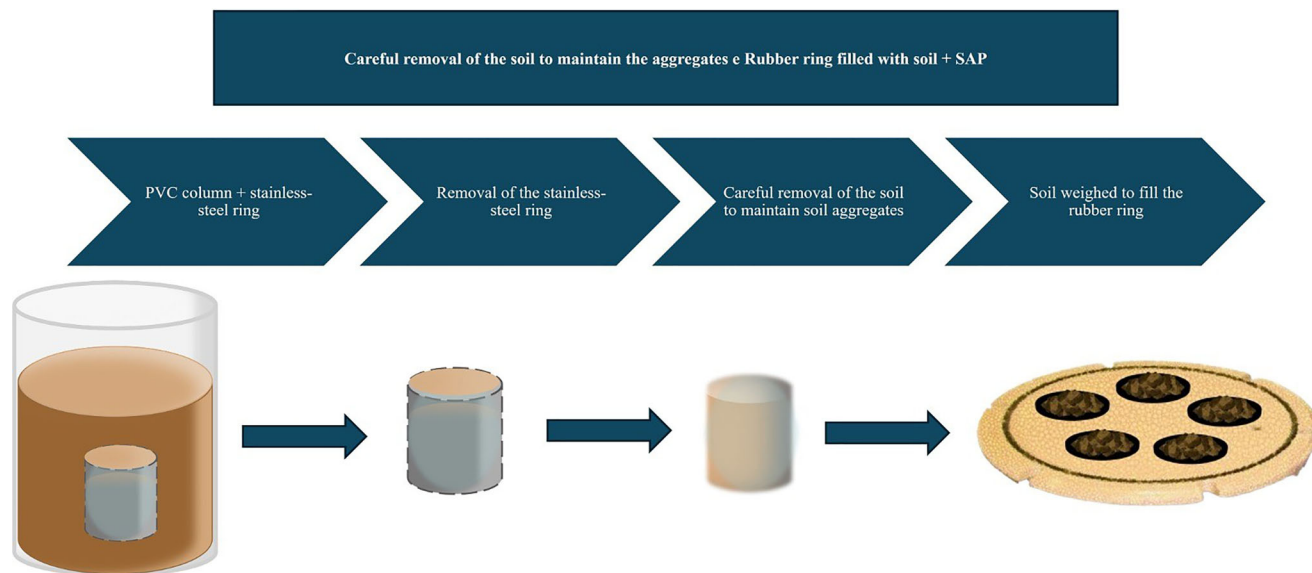


FIGURE 2 Steps involved in removing soil samples from cylinders with different rates of superabsorbent polymer (SAP) after wetting and drying (W/D) cycles, to obtain water retention curves. PVC, polyvinyl chloride.

Although removal from the stainless-steel ring disturbed the samples, the aggregates formed in response to the treatments were maintained. For the low-tension points (0, 2, 6, and 10 kPa), the Haines funnel method was employed (Haines, 1930). Points corresponding to 33, 500, and 1500 kPa were determined using a porous Richards plate extractor (Klute, 1986). Once the soil water content values were obtained for all tension points, the data were fitted to a mathematical model based on Equation (3) (van Genuchten, 1980).

$$\theta = \theta_r + \frac{\theta_s - \theta_r}{[1 + (\alpha |\varphi_m|)^n]^m} \quad (3)$$

where θ corresponds to the water content ($\text{cm}^3 \text{cm}^{-3}$), θ_r and θ_s are, respectively, the residual water and saturation contents ($\text{cm}^3 \text{cm}^{-3}$), φ_m is the matric soil water potential (kPa), α and φ_m scaler, m and n are model fit parameters related to the shape of the curve.

The data were adjusted with the aid of the 5.0 Trial Version of the Table Curve 2D program (Table Curve 2D, 2014), with variables θ_s and θ_r fixed, respectively, to soil water contents corresponding to saturation and a tension of 1500 kPa. The adjustment of the parameters α , m , and n was based on the Newton–Raphson interactive method, with no dependence of the parameter m on n (Dourado-Neto et al., 2000). From the parameters of the van Genuchten equation, the pore distribution by size was calculated using the equation proposed by Van Genuchten–Mualem (Equation 4) as a function of hydraulic load $C(h)$ (de Jong van Lier, 2020).

$$C(h) = \frac{d\theta}{dh} = (\theta_s - \theta_r) (n-1) \alpha^n |h|^{n-1} [1 + (\alpha |h|)^n]^{\frac{1}{n}-2} \quad (4)$$

The microporosity (Micro) was considered equal to the volumetric water content in equilibrium with a tension of 6 kPa, applied using the Haines funnel (Danielson & Sutherland, 1986). This tension value is related to the emptying of pores with a diameter $\geq 50 \mu\text{m}$ (macropores). Thus, the volume of water remaining after equilibrium at 6 kPa equates to the micropore volume, allowing macroporosity (Macro) to be calculated by subtracting Micro from the TP.

The available water (AW) was calculated by determining the difference in water content after equilibrium at 33 and 1500 kPa, corresponding to the water content at the field capacity and at the permanent wilting point ($\theta_{cc} - \theta_{pmp}$), respectively.

2.5 | Statistical analysis

Normality and homogeneity tests were performed for BD, DF, TP, Macro, Micro, and AW data. It was found that the data referring to AW did not present a normal distribution, so that these data were transformed to $\sqrt{(x + 0.5)}$, according to the results of the Box-Cox test (Box & Cox, 1964). Using SISVAR software version 5.6 (Ferreira, 2011), analysis of variance was performed. Tukey's test at 5% probability was used to compare means of the qualitative treatment factor (W/D cycles), and regression analysis was undertaken for the quantitative treatment factor (SAP application rate).

3 | RESULTS

There was a significant interaction between both treatment factors ($p < 0.01$) for BD, DF, and TP (Table 2). Macro,

TABLE 2 Summary of statistical significance of variance and regression analysis for soil bulk density (BD), degree of flocculation (DF), total porosity (TP), macroporosity (Macro), microporosity (Micro), and available water (AW) in response to superabsorbent polymers (SAP) application rates (*R*) and number of wetting (*W*) and drying (*D*) cycles (*C*).

Variation source	BD <i>F</i> values	DF	TP	Macro	Micro	AW
Rates	12.986**	3.959**	7.815**	4.763**	7.949**	25.067**
Cycles	10.100**	32.534**	13.261**	0.341ns	0.995ns	1.778ns
R × C	11.306**	10.368**	10.491**	1.893ns	1.290ns	1.148ns
CV (%)	4.13	7.23	3.25	12.94	19.28	17.49
Regression equations and <i>R</i> -squared						
1 cycle	$y = -0.0227x + 1.1843$ $R^2 = 0.90$ ns	$y = 4.9932x^2 - 27.803x + 76.514$ $R^2 = 0.97$ **	$y = -0.0041x^2 + 0.0213x + 0.5721$ $R^2 = 0.59$ **	$y = 0.0007x^2 - 0.0359x + 0.3619$ $R^2 = 0.99$ **	$y = -0.0018x^2 + 0.0401x + 0.1829$ $R^2 = 0.95$ **	$y = 0.0257x + 0.0566$ $R^2 = 0.90$ **
3 cycles	$y = -0.0404x + 1.198$ $R^2 = 0.86$ **	$y = 4.7268x + 65.252$ $R^2 = 0.78$ **	$y = -0.003x^2 + 0.0193x + 0.5405$ $R^2 = 0.56$ **	$y = 0.0417x^2 - 0.119x + 0.3706$ $R^2 = 0.65$ **	$y = -0.0457x^2 + 0.1448x + 0.1613$ $R^2 = 0.75$ **	$y = 0.0156x + 0.0616$ $R^2 = 0.97$ **
6 cycles	$y = -0.0335x + 1.1243$ $R^2 = 0.70$ *	$y = 3.7504x + 74.885$ $R^2 = 0.48$ *	$y = -0.0041x^2 + 0.021x + 0.5721$ $R^2 = 0.59$ **	$y = -0.0315x^2 + 0.025x + 0.3703$ $R^2 = 0.99$ **	$y = 0.0276x^2 - 0.0039x + 0.1994$ $R^2 = 0.99$ **	$y = 0.0239x + 0.0571$ $R^2 = 0.90$ **
9 cycles	$y = -0.045x + 1.1566$ $R^2 = 0.05$ **	$y = 5.632x^2 - 15.983x + 74.003$ $R^2 = 0.53$ *	$y = 0.0136x^2 - 0.0152x + 0.5627$ $R^2 = 0.08$ **	$y = 0.0072x^2 - 0.0316x + 0.3586$ $R^2 = 0.08$ **	$y = 0.0138x^2 + 0.069x + 0.2177$ $R^2 = 0.69$ **	$y = 0.0189x + 0.0684$ $R^2 = 0.72$ **

Abbreviations: CV, coefficient of variation; ns, non-significant.

* and ** denote significant difference at 1% level and 5% level.

Micro, and available water differed significantly ($p < 0.01$) only in response to SAP application rates (Table 2). Linear equations best represented the responses between BD and SAP application rates for the W/D cycles evaluated (one, three, six, and nine cycles), with no significant difference observed for the single W/D cycle (Table 2). The other physical-hydraulic properties evaluated were better represented by quadratic equations, with significant differences after all W/D cycles (Table 2).

With nine W/D cycles, the control resulted in significantly lower bulk density—BD (0.89 g cm^{-3}). At the 0.15 g kg^{-1} SAP treatment, significantly lower soil BD values (1.10 – 1.19 g cm^{-3}) were observed in response to 1, 3, and 6 W/D cycles in comparison with nine cycles that resulted in significantly higher soil BD (1.42 g kg^{-1} , Figure 3A).

The DF (Figure 3B) in the control without SAP was significantly higher in response to 1 and 9 W/D cycles (77% and 78%, respectively), while three and six cycles resulted in significantly lower degrees of flocculation (66% and 73%, respectively). At the 0.30 g kg^{-1} SAP treatment, the DF was significantly higher (81%) with 6 W/D cycles, while one, three, and nine cycles resulted in lower DF (64%–68%). At the 0.60 g kg^{-1} SAP treatment, the DF was significantly higher (79%) with 6 W/D cycles (79%, respectively), while one, three, and nine cycles resulted in significantly lower DF values (65%–70%). The 1.2 g kg^{-1} SAP treatment resulted in DF significantly higher with 3 and 6 W/D cycles (74% and 76%,

respectively), while 1 W/D cycle resulted in significantly lower DF (49%). Finally, the higher DF (84%) was observed in response to 2.4 g kg^{-1} SAP treatment and 6 W/D cycles. In contrast, the lowest ($p < 0.05$) DF (39%) was observed when samples were subjected to a single W/D cycle across 2.4 g kg^{-1} SAP application rate (Figure 3B).

Macro decreased from 0.38 to $0.30 \text{ cm}^3 \text{ cm}^{-3}$ with SAP application. This reduction began to occur at the rate of 0.15 g kg^{-1} SAP and was more pronounced at 2.4 g kg^{-1} (Figure 3C). Conversely, Micro increased from 0.20 to $0.28 \text{ cm}^3 \text{ cm}^{-3}$ with SAP application, with the increase observed from 0.6 g kg^{-1} SAP onward and being most pronounced at 2.4 g kg^{-1} (Figure 3D). Although no significant response to the number of W/D cycles was detected, the reduction in Macro at 0.15 g kg^{-1} SAP was more marked after nine cycles, whereas the increase in Micro at 2.4 g kg^{-1} SAP was more pronounced after six W/D cycles (Figure 3C,D).

TP ranged from 0.54 to $0.65 \text{ cm}^3 \text{ cm}^{-3}$, with the highest value observed in the control treatment in response to nine W/D cycles (Figure 3E). At the rate of 0.15 g kg^{-1} SAP, a significant difference was observed among W/D cycles, with the highest TP ($0.59 \text{ cm}^3 \text{ cm}^{-3}$) recorded after six cycles. The WA did not differ in response to W/D cycles, but 2.4 g kg^{-1} SAP treatment resulted in higher amount of available water ($0.12 \text{ cm}^3 \text{ cm}^{-3}$) in relation to the other rates of the polymer that led to WA between 0.056 and $0.089 \text{ cm}^3 \text{ cm}^{-3}$ (Figure 3F).

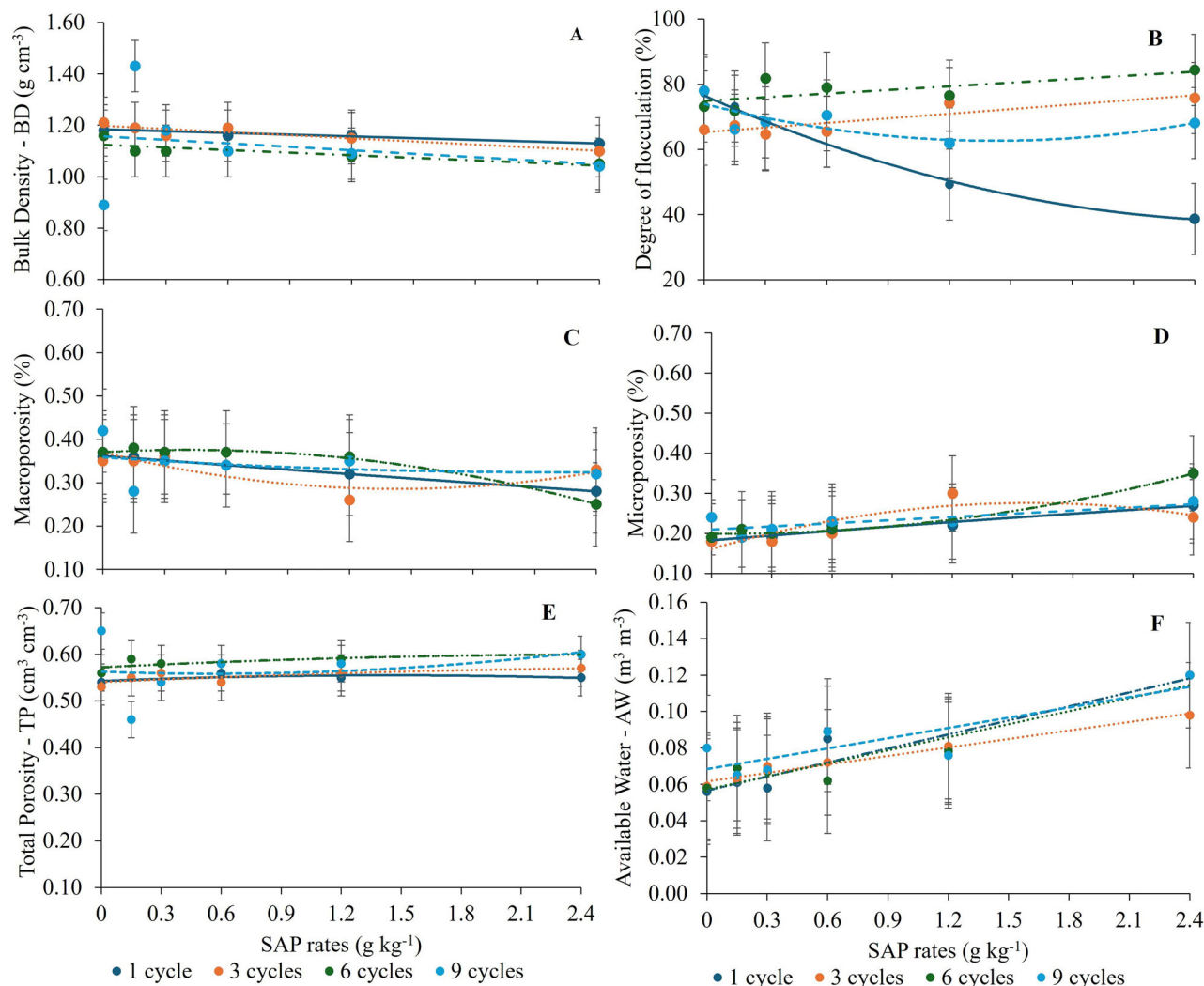


FIGURE 3 Soil bulk density (A), degree of flocculation (B), macroporosity (C), microporosity (D), total porosity (E), and available water content (F) of soil subjected to increasing superabsorbent polymer (SAP) application rates (g kg^{-1}) and number of wetting (W) and drying (D) cycles.

When analyzing TP in relation to the SWRC, it is observed that TP ranges from 0.54 to $0.65 \text{ cm}^3 \text{ cm}^{-3}$, with these values being higher than those recorded at saturation moisture ($0.36\text{--}0.61 \text{ cm}^3 \text{ cm}^{-3}$). In both cases, the highest values were associated with the highest SAP dose and/or the greatest number of W/D cycles (Figures 3E and 4). Moreover, the most pronounced discrepancy between TP and saturated water content occurred at the lowest measured values. In the soil water characteristic curves, the reduction in moisture is less pronounced for 2.4 g kg^{-1} SAP treatment subjected to one, six, and nine W/D cycles (Figure 4A,C,D). With one W/D cycle, the 2.4 g kg^{-1} SAP treatment resulted in a moisture content 23% higher than that observed for the absence of the polymer (control) in soil saturation (Figure 4A). At the 6 and 10 kPa tensions, the highest SAP rate (2.4 g kg^{-1}) resulted in about 34% more soil moisture (Figure 4A).

The 2.4 g kg^{-1} SAP treatment was associated with a significant 33% increase in soil water content as compared to the

untreated control at saturation (0 kPa). The 1.2 g kg^{-1} SAP treatment at 6, 10, 33, 500, and 1000 kPa tension was associated with significant 38%, 44%, 47%, 44%, and 55% increases in soil water content as compared with the untreated control (Figure 4B).

After six W/D cycles, the 2.4 g kg^{-1} SAP treatment was associated with significant 45%, 52%, 59%, 60%, and 59% increases in soil water content at 6, 10, 33, 500, and 1500 kPa as compared with the untreated control, respectively (Figure 4C). After nine W/D cycles, at soil saturation (0 kPa), the 2.4 g kg^{-1} SAP treatment was associated with a significant 49% increase in soil water content compared to the 0.15 g kg^{-1} SAP treatment (Figure 4D). At 10 kPa, the 2.4 g kg^{-1} SAP treatment was also associated with a significant 18% increase in soil water content as compared with the untreated control (Figure 4D).

In the pore size distribution curves (Figure 5A–D), the treatments with SAP in one and three W/D cycles, except for

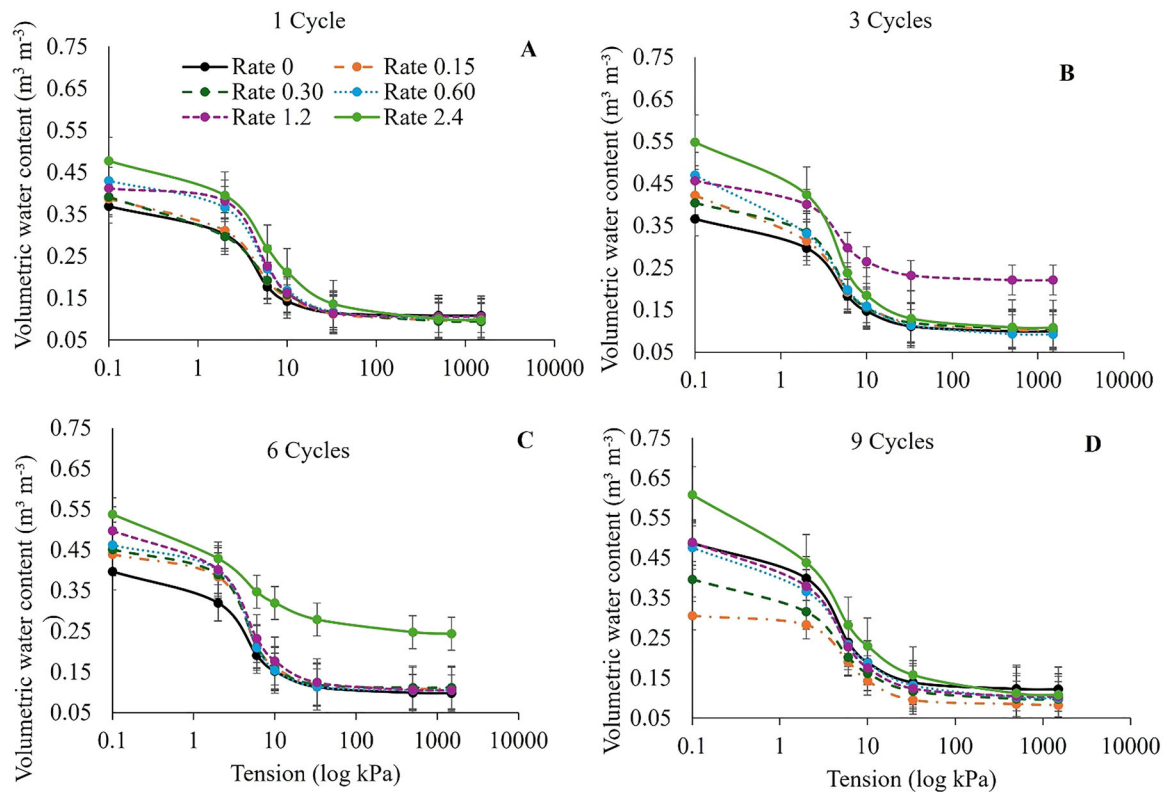


FIGURE 4 Effect of superabsorbent polymer (SAP) application rate on soil water retention curves as affected by 1 (A), 3 (B), 6 (C), and 9 (D) wetting and drying (W/D) cycles.

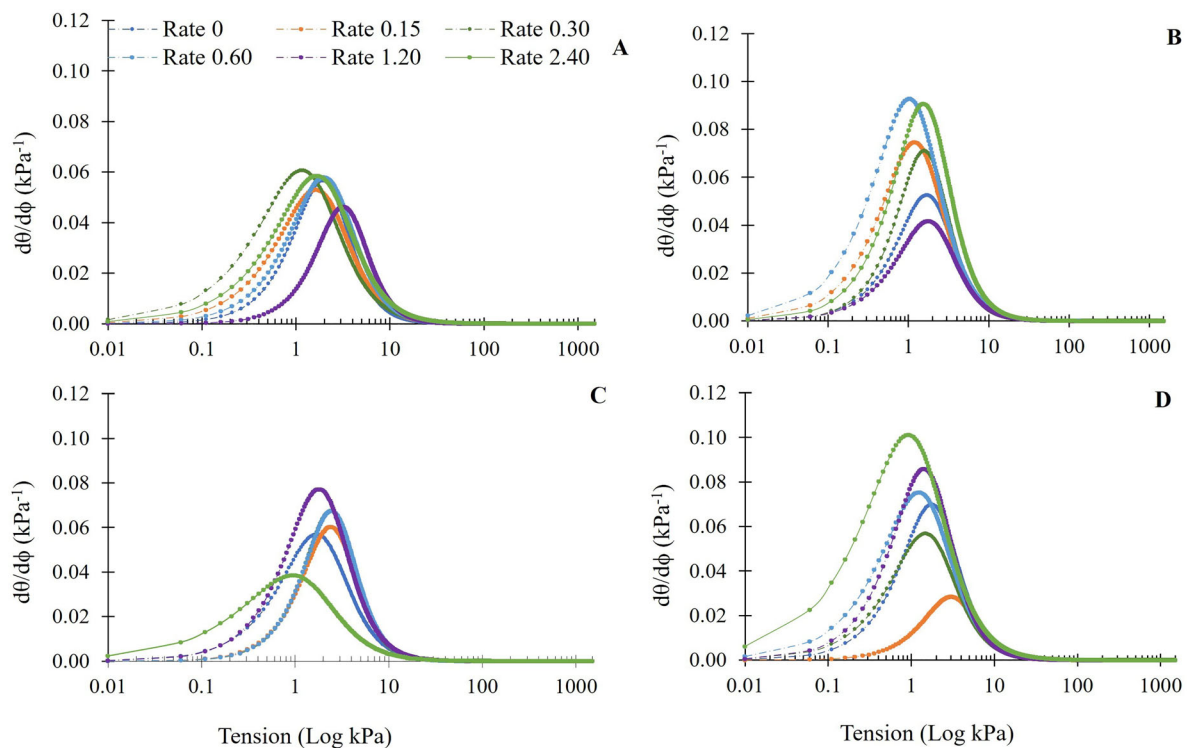


FIGURE 5 Effect of superabsorbent polymer (SAP) application rate on pore distribution curves by size following 1 (A), 3 (B), 6 (C) and 9 (D) wetting (W), and drying (D) cycles.

the 1.2 g kg^{-1} dose, favored an increase in porosity, especially in the volume of structural pores with larger diameters (at tensions lower than 1 kPa). These are interaggregate pores that, when emptied of water, promote the internal drainage of excess water in the soil, as well as gas and heat exchange between the soil and the atmosphere. When assessing pore size distribution after the soil was subjected to six W/D cycles, it is noteworthy that the application of SAP at the 2.4 g kg^{-1} dose likely caused the collapse of part of the larger pore volume, resulting in a reorganization of the porous structure compared to the other treatments. For the condition in which nine W/D cycles were applied, SAP at the 2.4 g kg^{-1} dose stood out for significantly contributing to the increase in total soil porosity, with a marked effect on the formation of larger-diameter pores, that is, structural pores. A similar but less intense effect was observed when SAP was applied at doses of 0.6 and 1.2 g kg^{-1} . The other treatments, particularly SAP at the 0.15 g kg^{-1} dose, reduced TP compared to the control.

Overall, after three W/D cycles, only the rate of 0.3 g kg^{-1} SAP treatment did not contribute to the increase in the volume of larger pores (pores $\geq 200 \mu\text{m}$, Figure 5B). After six W/D cycles, the 2.4 g kg^{-1} , notably, followed by the rate of 1.2 g kg^{-1} SAP treatment, resulted in significant increases in the volume of large pores (pores $\geq 200 \mu\text{m}$) as compared to the untreated control (Figure 5C). With nine W/D cycles, the 2.4 g kg^{-1} SAP treatment was associated with a significantly larger volume of pores (again, pores $\geq 200 \mu\text{m}$) as compared with all other treatments (Figure 5D). In contrast, a significant reduction in Macro was observed for the 0.15 g kg^{-1} SAP treatment (Figure 5D).

4 | DISCUSSION

The reduction in soil BD in response to SAP was observed in studies in which the effects were more significant for polymer rates between 2 and 3 g kg^{-1} of soil (Abdelghafar et al., 2024; Hussien et al., 2012). The rate 3 g kg^{-1} of SAP, whose composition was not identified, when compared to the absence of the polymer, caused a negligible 0.03 g cm^{-3} reduction in the BD of sandy soil (Abdelghafar et al., 2024). In the current study, the reduction in soil BD of the sandy soil with rates of SAP (acrylamide and potassium acrylate copolymer) ranged from 0.05 to 0.39 g cm^{-3} . The effect of SAP reducing soil BD is more dependent on the texture and salinity of the soil than on the type of SAP in terms of its swelling capacity (Hussien et al., 2012). The reduction in soil BD with the application of SAP is more significant in sandy soils, such as the one used in this study (Abdelghafar et al., 2024; Hussien et al., 2012). This can be attributed to the smaller particle size and higher electrical charge of clay soils, which promote particle bonding and the formation of aggregates, unlike sandy soils. Furthermore, clay soils typically contain more organic mat-

ter than sandy soils, further enhancing aggregation (Kumari & Mohan, 2021).

The SAP effect on decreasing soil BD is explained by the rearrangement of soil particles that are close to the polymer particles that expand when hydrated (Abdelghafar et al., 2024). This justifies why the W/D cycles applied in this study also influenced soil BD, as they represented multiple hydration/dehydration, which caused the rearrangement of soil particles to form aggregates.

Lower soil BD values with SAP rates and W/D cycles were associated with an increase in the DF, mainly from the first three W/D cycles. Flocculation is considered the first step toward soil aggregation and occurs through cationic bridging with clay particles and soil organic carbon, promoted by bivalent cations, such as Ca^{2+} and Mg^{2+} (Bronick & Lal, 2005). The application of a negatively charged SAP favors the formation of these bonds, as demonstrated by the application of a sodium polyacrylate-based SAP, which promoted bonding between the polymer and soil colloids, explaining not only the flocculation, but also the cementation that favored the formation of water-stable aggregates in a soil with 30.4% clay content (Ji et al., 2022).

In this study, the SAP was a copolymer of acrylamide and potassium acrylate, which contains hydrophilic groups and carboxylic groups whose negative electrical charges contribute to cation bridging with soil colloids to provide aggregation (Ji et al., 2022). However, sandy soils have limited exchange sites associated with clay particles and organic colloids (da Costa et al., 2020), which makes it difficult to bond with the negative charges associated with the functional groups of the SAP. Therefore, it is understood that the effects of SAP contributing to the aggregation of sandy soils should be more effective in the presence of fine sand or clay particles that are associated with the soil CEC.

The highest SAP rate (2.4 g kg^{-1}) provided a 21% decrease in the number of pores larger than $50 \mu\text{m}$ in relation to the absence of the polymer (Figure 3C). The application of a polyacrylate SAP at a rate of 4 g kg^{-1} in a sandy loam soil decreased pores in the range of >276 to $<828 \mu\text{m}$ (Womack et al., 2022). However, SAP also influences the morphology and architecture of the pore network, increasing the proportion of pores oriented in the same direction, which may contribute to macropore formation (Womack et al., 2022). In the present study, in all combinations of treatments, Macro was $>0.1 \text{ cm}^3 \text{ cm}^{-3}$, a value considered as minimum to guarantee the efficiency of air flow in the soil (Grable & Siemer, 1968). As for micropores ($<50 \mu\text{m}$), there was a tendency for these to increase in samples that received SAP from the rate of 0.6 g kg^{-1} onward, being more pronounced at 2.4 g kg^{-1} , with a marked effect observed after six W/D cycles (Figure 3D).

Particularly at the lowest SAP doses and the lowest number of W/D cycles, TP was not fully filled with water at saturation moisture content, resulting in a more pronounced discrepancy

between TP and saturated water content, likely due to limitations in pore size distribution. With the increase in SAP application rates and the number of W/D cycles, a reorganization of the pore space occurred, promoting greater filling of the TP at the saturation point (Figure 4). Changes in soil BD, reflecting an increase in TP, influenced the water characteristic curves and, consequently, the plant WA. The same type of SAP evaluated in this study, when applied to sandy soil at a rate of 2 g kg^{-1} and subjected to irrigation with brackish water, resulted in plant WA of $0.63 \text{ cm}^3 \text{ cm}^{-3}$ up to a tension of 2 kPa (Martins Melo et al., 2023). This value is higher than the WA of $0.41 \text{ cm}^3 \text{ cm}^{-3}$ observed in this study for an SAP rate of 2.4 g kg^{-1} up to a tension of 2 kPa, but the fact stands out that both in this and in the Martins Melo et al. (2023) study, SAP increased plant WA as compared to the untreated control.

The less pronounced decrease in soil moisture with increasing tensions in SAP at a rate of 2.4 g kg^{-1} is associated with a greater proportion of micropores, which reflect lower soil hydraulic conductivity. A reduction in the hydraulic conductivity of sandy soil was observed in studies in which potassium polyacrylate-based SAPs and other unspecified SAPs were evaluated at rates of 3.3 and 3.0 g kg^{-1} (Abdelghafar et al., 2024; Albalasmeh et al., 2022). Lower rates of SAP ($0.4\text{--}0.7 \text{ g kg}^{-1}$) increased the hydraulic conductivity of the sandy soil, but higher rates ($3.0\text{--}3.3 \text{ g kg}^{-1}$) reduced the hydraulic conductivity due to a more expressive increase in polymer volume, promoting the aggregation of soil particles to a degree that alters macropore structure, connectivity, and intrapore space, which, in turn, affect hydraulic conductivity (Abdelghafar et al., 2024; Albalasmeh et al., 2022). In this context, it is emphasized that the application rate of SAP must be carefully controlled to avoid compromising soil hydraulic conductivity, thereby ensuring it does not negatively impact plant development.

SAP rates increased plant WA by 50% as compared with the absence of the polymer. This corroborates the findings of other studies in which polyacrylamide and potassium acrylate SAP were applied to the soil in rates reaching up to 3.3 g kg^{-1} (Albalasmeh et al., 2022; Martins Melo et al., 2023). As there was no isolated effect of the number of W/D cycles on plant WA, it is assumed that the abiotic conditions to which the polymer was subjected when applied to the soil (e.g., soil salinity, temperature) did not compromise the functionality of the SAP. Irrigation with brackish water (electrical conductivity $>1.0 \text{ dS m}^{-1}$) and high temperatures compromises water retention by SAPs (Nascimento, Mota et al., 2021; Martins Melo et al., 2023).

There is an interaction between SAP rates and W/D cycles, so that the highest rate of the polymer (2.4 g kg^{-1}) leads to lower soil BD, and rates from 1.2 g kg^{-1} subjected to three W/D cycles favor structural attributes, to the point that SAP application results in greater plant AW.

5 | CONCLUSION

The application of SAP significantly enhances the physical and hydrological properties of degraded sandy soils, even under successive W/D cycles. At a rate as low as 0.15 g kg^{-1} , and particularly after six W/D cycles, TP increased, accompanied by a reduction in Macro and a corresponding increase in Micro. In terms of soil functionality, the application rate of 2.4 g kg^{-1} yielded the most pronounced effect, resulting in up to a 50% increase in plant-available water compared with the control. This marked improvement in water-holding capacity not only enhances water-use efficiency but also strengthens drought resilience, thereby directly supporting the ecosystem service of water regulation. Altogether, this approach represents a robust and sustainable strategy for rehabilitating degraded sandy soils.

AUTHOR CONTRIBUTIONS

Mirian Cristina Gomes Costa: Conceptualization; data curation; formal analysis; funding acquisition; investigation; methodology; project administration; supervision; visualization; writing—original draft; writing—review and editing. **Gustavo Henrique da Silva Albuquerque:** Conceptualization; data curation; formal analysis; investigation; methodology; validation; visualization; writing—original draft. **Francisca Gleiciane da Silva:** Methodology; visualization; writing—review and editing. **Robert William Simmons:** Conceptualization; formal analysis; visualization; writing—original draft; writing—review and editing. **Carlos Tadeu dos Santos Dias:** Formal analysis; visualization; writing—original draft; writing—review and editing. **José Lucas Martins Melo:** Methodology; visualization; writing—review and editing. **Jaedson Cláudio Anunciato Mota:** Conceptualization; formal analysis; methodology; visualization; writing—original draft; writing—review and editing.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

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