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TEMPERATURE LIMITATIONS IN THE USE OF HYDROGELS ON LEPTOSOLS IN A SEMI-ARID REGION OF BRAZIL

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Abstract

Due to their high-water retention capacity, hydrogels are considered promising soil conditioners to improve soil plant available water content in semi-arid environments; however, little is known about how soil temperature affects the functionality of hydrogels. In this study, the effect of soil temperature on physical attributes of soil amended with a Acrylamide-*co*-Potassium Acrylate hydrogel was evaluated. A laboratory experiment was installed in a scheme (4x4) x 4 - four soil temperatures (30, 45, 65 and 105 °C), four exposure times (40, 70, 100, and 130 days) with four repetitions. The test soil was a Leptsol with sandy loam texture and of the hydrogel was applied at a dose of 0.1% w w^{-1}. Soil moisture at field capacity (θ_{FC}) and permanent wilting point (θ_{WP}), plant available water (AW), bulk density (BD), and soil porosity were evaluated. The resulting data was subjected to two-way analysis of variance. The hydrogel increased the θ_{FC} of the soil, from 0.14 to

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0.19 m^3 m^{-3} at 45°C and 56 days. At 40 days, a minimum θ_{WP} (0.05 m^3 m^{-3}) was observed at 92 °C. In general, θ_{FC} increased, while the θ_{WP} decreased, providing improved soil water storage. Plant available water was up to three times higher in soil with hydrogel across a temperature range of 30-105 °C. In all treatments irrespective of temperature and exposure time, the soil BD and porosity were improved in comparison to the un-amended control. This constitutes an advantage in the use of the hydrogel as a soil conditioner. Even with the interaction of abiotic factors acting on the hydrogel, there are beneficial effects on the water storage capacity, soil BD, and soil porosity.

Keywords: Superabsorbent hydrogel. Leptsol. Physical soil properties. Water storage.

1 Introduction

Drylands, which include arid and semi-arid ecosystems, cover 41% of the earth's surface, play an important role in the global ecosystem, and are home to more than two billion people (Hoover et al., 2020). Arid and semi-arid environments are distinctive in terms of landforms, soil, fauna, flora, and water balance. Water scarcity and high-intensity, low-frequency rainfall are characteristic of these regions (Santos et al., 2016).

The predicted global expansion of arid and semi-arid lands will increase the population affected by water scarcity and land degradation (Feng and Fu, 2013). To feed an increasing global population, it is necessary to take advantage of drylands and use their natural resources sustainably (Thombare et al., 2018). Severe water scarcity is becoming common in many arid and semi-arid regions of the world (Mohammadinezhad and Ahmadvand, 2020), with water management being one of the biggest challenges for these regions (Abobatta, 2018).

The combination of anthropic pressure and aridity led to extreme degradation of large areas of Caatinga a native xeric shrubland of the Brazilian semi-arid region, giving rise to so-called ‘desertification hotspots’. Thus, means of preserving biodiversity and developing strategies to

reclaim and restore these areas are urgent (Silva et al., 2014). Additionally, soil degradation implies a reduction or loss of its productive potential. Consequently, it is necessary to find alternatives to maintain/improve agricultural production and promote recovery of degraded areas. The use of hydrogels, to facilitate habitat restoration as well as support agricultural production in semi-arid regions is essential in order to ensure natural and agro-ecosystem functionality.

Hydrogels increase water use efficiency where irrigation water is limited (Bakass et al., 2002), and have been used in dry regions to increase the soil's capacity to absorb and retain water (Zain et al., 2018), improve crop growth (Yang et al., 2018) and restoration of degraded lands (Hüttermann et al., 2009). The positive effects of hydrogels have also been related to increased soil porosity, providing better oxygenation to plant roots (Ullah et al., 2015) and reduced soil BD (Hou et al., 2018).

Considering the characteristics of arid and semi-arid regions, it is necessary to understand how high temperatures affect the efficacy of hydrogels when applied to soil. Studies have indicated that increasing temperature compromises the functionality of agricultural hydrogels, highlighting a reduction of up to 60% of the water retention capacity in soil amended with hydrogel at temperatures up to 35 °C (Andry et al., 2009). The absorption of water by hydrogels (Acrylamide-co-Potassium Acrylates) decreased (from 37 to 97%) with increasing temperature from 20 to 65 °C (Nascimento et al., 2021).

In arid and semi-arid regions of the world, including the Brazilian semi-arid region, soil temperature values ranging from 25 to 60 °C have been recorded (Correia et al., 2012; Gao et al., 2007; Reyes et al., 2016; Wu et al., 2017; Xiao et al., 2016). Inappropriate management practices (e.g. deforestation) are commonly adopted in semi-arid regions, leaving the soil exposed to the effects of temperature, as solar radiation incident is direct to the soil surface (Scharenbroch and Bockheim, 2007; Souto et al., 2005). Thus, it is important to know the extent to which soil temperature negatively affects the functionality of hydrogels for agricultural use and habitat restoration.

This research critically evaluated the impact of thermal stress and exposure time, on the efficacy of a commercial hydrogel to improve water storage capacity, soil BD, and soil porosity. The study focused on soils and environmental conditions indicative of Brazilian semi-arid regions but the results are applicable in a global context.

2 Material and methods

2.1 Experimental site and soil used

The study was carried out from January to June 2018 through an experiment installed and conducted at the Soil Physics laboratory of the Federal University of Ceará, located at the Campus do Pici (Fortaleza, CE, Brazil). The soil used in the experiment was a Leptsol with a sandy loam texture, collected at the Vale do Curu Experimental Farm (Pentecoste, CE) (Latitude: 3º45'S; Longitude: 39º15'W). A bulk randomly selected composite sample of the topsoil layer (0-0.2 m) was collected from areas with visible signs of degradation (absence of vegetation, erosion processes, signs of fire use, and compaction). The bulk sample was subsequently air-dried, ground, to pass a < 2 mm sieve and homogenised prior to physical and chemical characterization (Table 1).

In the granulometric analysis, the 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 and Bauder, 1986). The soil BD was determined by the beaker method (Almeida et al., 2017) and particle density according to Blake and Hartge (1986).

Soil porosity was obtained from the bulk density and particle density of the soil (Flint and Flint, 2002) according to equation 1:

$$\alpha = \left(1 - \frac{\rho_s}{\rho_p}\right) \qquad (1)$$

α - porosity ($m^3\ m^{-3}$), ρ_p and ρ_s - particle density and bulk density ($kg\ m^{-3}$), respectively.

For chemical characterization of the soil, the following analyzes were performed: pH, was measured in H_2O (1: 2.5) by potentiometry; potential acidity (H + Al), was extracted on 5g of soil with calcium acetate buffered at pH 7.0 and determined by titration (Teixeira et al., 2017); Ca^{2+} and Mg^{2+}, were extracted with 1M KCl solution (Teixeira et al., 2017) and determined by atomic absorption spectrometry; exchangeable aluminum (Al^{3+}), was extracted with 1M KCl solution and determined by titration following the method of Teixeira et al. (2017). Sodium (Na^{+}) and potassium (K^{+}) were extracted with Mehlich 1 Solution and determined by flame photometry (Teixeira et al., 2017). Total organic carbon (TOC) was determined by wet oxidation (Yeomans and Bremner, 1988). The cation exchange capacity (CEC), the sum of bases (SB), base saturation (V%), aluminium saturation (m%), and sodium saturation percentage (PST) were calculated following Teixeira et al. (2017).

2.2 Characterization of the hydrogel

The hydrogel used was a commercial product (Forth Gel®), characterized on the manufacturer's label as a copolymer of acrylamide and potassium acrylate. To further refine the characterization of the product, elemental analysis, X-ray fluorescence spectrometry (FRX), particle size, and residual acrylamide content of the hydrogel were undertaken.

Elementary analysis of carbon (C), hydrogen (H) and nitrogen (N) was performed using a Carlo Erba EA 1108 microanalyzer; the C/N ratio was obtained by the ratio between C and N; the elemental composition of the acrylate was determined by X-ray fluorescence spectrometry (FRX) using X-ray fluorescence spectrometer, model ZSXMini II (Rigaku); the particle size fraction was determined using 24 mesh (0.710 mm), 35 mesh (0.425 mm) and 48 mesh (0.300 mm) sieves and residual acrylamide content determined by high-performance liquid chromatography (HPLC) in a chromatograph model LC-20AD from Shimadzu, coupled to the diode array detector model SPD-M20A, at a wavelength of 197 nm (Table 2) following Nascimento et al. (2021).

Infrared spectroscopy (FTIR) and X-ray diffraction were also performed for the characterization of the hydrogel. Infrared absorption spectroscopy (FTIR) was performed on FT equipment IR-8500 (Shimadzu), operating in the 400-4000 cm^{-1} range; X-ray diffraction was performed using an XPert Pro MPD diffractometer (Panalytical), with Cu-Kα radiation, varying 2θ from 5 to 70º (Figure 1). To determine the swelling curve, 30 mg of the of the hydrogel with particle size between 24 and 35 mesh were weighed in a 30 mL filter crucible (Nº 0 porosity) previously moistened. This set was completely submerged in distilled water as addition of salts in the swelling solution reduces the water holding capacity of the hydrogel (Andry et al., 2009). The set (crucible + gel) was removed at intervals of time (2, 4, 6, 8, 10, 12, 15, 30, 45, 60, 90, 120, 180, 240 minutes), the outer wall of the crucible was the dry and the system weighed. The procedure was performed in triplicate. Swelling was calculated following the procedure adopted by (Guilherme et al., 2015; Magalhães et al., 2013; Zhao et al., 2019), using equation 2:

$$S = \frac{Wt - W0}{W0} \quad (2)$$

W0 represents the mass (g) of the hydrogel dried at 65 °C and Wt is the mass (g) of the hydrogel expanded at time t. This resulted in the hydrogel swelling curve in distilled water (0.003 dS m^{-1}) (Figure 2).

2.3 Experimental design and treatments

The experimental design was entirely randomized, in split plot system (4x4) x 4, with two factors (soil temperature and exposure time), each with 4 levels. The dose of hydrogel used was 0.1% (w w^{-1}), determined experimentally to result in no visible structural alteration in the soil confined to a 100 cm^3 cylinder following a wetting and drying cycle.

The treatments were as follows: I) temperatures (T1 = 30 °C; T2 = 45°C; T3 = 65 °C and T4 = 105 °C); II) exposure times (40, 70, 100 and 130 days). The treatments were evaluated with four replications, totalling 64 experimental units. Each experimental unit consisted of a stainless-steel

cylinder with dimensions of 5 x 5 cm (100 cm^3) filled with homogenized soil with hydrogel at a dose of 0.1% w w^{-1}, sealed with tissue at the bottom.

2.4 Experiment installation, conduction, and evaluations

The sealed stainless-steel cylinders of known mass (experimental units) were placed in plastic trays. Each experimental unit was filled with soil homogenized with the dry hydrogel (without separation of particle size fractions) and, later, they were hydrated by capillarity. Each sample consisting of a stainless-steel cylinder filled with soil + hydrogel was saturated for 24 hours and, after saturation, showed an initial density of 1.15 g cm^{-3}.

Subsequently, the samples were placed in an oven with air circulation and subjected to temperatures (T1= 30 °C; T2= 45 °C; T3= 65 °C and T4= 105 °C). At the end of each exposure period (40, 70, 100, and 130 days), the samples were analyzed for soil moisture at field capacity (θ_{FC}) and permanent wilting point (θ_{WP}), plant available water (AW), soil BD and soil porosity.

The field capacity (θ_{FC}) was determined in deformed samples, after equilibrium at a tension of 10 kPa, using the gravimetric method in a Haines funnel (Klute, 1986). Soil moisture at permanent wilting point (θ_{WP}) was determined in deformed samples, using a gravimetric method in a Richards extractor after equilibrium at a tension of 1500 kPa (Klute, 1986). Plant available water (AW) was calculated as the difference between θ_{WP} and θ_{WP}.

The samples were taken to an oven at 105 ºC until constant mass was attained. Bulk density (BD) was determined using equation 3:

$$BD = \frac{Ms}{Vs} \qquad (3)$$

BD (g cm^{-3}) = Density of the soil; Ms (g)= Mass of dry soil; Vs (cm^{-3}) = Total soil volume.

Soil porosity was determined from the soil bulk density and particle density, according to equation 1.

The homogeneity of variance and the normality of the residuals were tested before conducting the analysis of variance (Two-way ANOVA), with level of significance of 99% ($p < 0.01$). When the

interaction between factors and/or each isolated factor was significant, linear regressions were performed. All statistical analyzes were performed using SAS 9.3 ("SAS 9.3 free Software," 2011).

3 Results and discussion

With the F test of analysis of variance (ANOVA), a significant interaction was found for all sources of variation: θ_{FC}, θ_{WP}, AW, BD, and porosity.

3.1 Field capacity (θ_{FC})

At 40 days, the relationship between θ_{FC} and soil temperature is represented by a decreasing linear function, so that there is a decrease in θ_{FC} of 0.0004 $m^3\ m^{-3}$ for each 1 °C increase in soil temperature (Figure 3a). For 70 and 100 days, the model to which the experimental data fitted was quadratic; at 70 and 100 days maximum values of θ_{FC} were 0.17 and 0.15 $m^3\ m^{-3}$ respectively (Figure 3a). Andry et al., (2009) observed that the water retention efficiency of a hydrophilic hydrogel applied to a sandy soil decreased by up to 60% when the temperature increased from 15 to 35 °C. In the present study, higher tolerance of the hydrogel to temperatures was observed, with a reduction of up to 15% in water retention in θ_{FC} (in 10 kPa) with temperature increases from 30 to 105 °C. Minimal effects of temperature up to 40 °C have already been reported in hydrophilic agricultural hydrogels immersed in saline solutions (Molloy et al., 2000). However, the absorption of water by PAM hydrogels (Acrylamide-co-Potassium Acrylates) decreased with increasing temperature from 20 to 65 °C in saline solutions (Nascimento et al., 2021).

The term "polymeric network" refers to cross-linking, which prevents the dissolution of hydrophilic polymeric chains from the hydrogel to the aqueous phase (Hennink and Nostrum, 2012). N, N′-methylene- (bis) -acrylamide (BAA) the water-soluble cross-linking agent most commonly used in the production of superabsorbent hydrogels (Wu et al., 2001). The water retention capacity is related

to the degree of cross-linking of the hydrogel (Dorkoosh et al., 2000) creating contrasting rates of three-dimensional expansion and porous structures (Ahmed, 2015).

At 30 °C, the minimum value of θ_{FC} was ~0.14 $m^3 m^{-3}$ at 105 days (Figure 3b). At 45 °C, the experimental data best fitted a cubic model and the maximum value for θ_{FC}, was 0.19 $m^3 m^{-3}$, following 56 days of exposure (Figure 3b). At 65 °C, a decreasing linear function is observed, with daily reductions in θ_{FC} of 0.0002 $m^3 m^{-3}$ (Figure 3b).

It is important to highlight that hydrogel addition increased the baseline value of θ_{FC} of the test soil (0.14 $m^3 m^{-3}$) by up to 37%, at a soil temperature of 45 °Cover the shorter exposure times reaching a maximum value of 0.19 $m^3 m^{-3}$ (Figure 3a, Table 1). These results confirm that hydrogel addition can improve water storage in the soil and supports the observation of Mandal et al. (2015) but that efficacy is limited to <100 days. This corroborates that findings of Savi et al. (2014) who observed a significant loss of water retention capacity in a hydrogel (cross-linked polyacrylic acid-potassium salt) amended substrate after 150 days. In the present study, there was a decline in water-holding capacity in the soil with hydrogel after *circa* 100 days especially at higher temperatures.

The increase in the θ_{FC} of the hydrogel treated soils did not affect the free porosity of water (or aeration), which was 30% at maximum θ_{FC}. It is recognised that there is a restriction in the development of plants when the volume of pores with air in the soil is < 0.1 cm^3 of air per cm^3 of soil, that is, porosity free of water less than 10% (Grable and Siemer, 1968).

3.2 Permanent wilting point (θ_{WP})

Just as there was a change in the water retention efficiency from 100 days (greater reduction of θ_{FC} - Figure 3a), at 100 days a change in retention efficiency at 1500 kPa was also observed (maximum point θ_{WP} (0.08 $m^3 m^{-3}$) at 91 °C (Figure 4a). This reduction in θ_{FC} and increase in θ_{WP} implies a reduction in the water available to plants. This θ_{WP} value (0.10 m^3 m^{-3}) is close to the soil condition

associated with the untreated control (Table 1, Figure 4a), indicating a change in the hydrogel's water retention capacity with the combination of higher values of the temperature x time.

At 40 days, the lowest θ_{WP} (0.05 $m^3\ m^{-3}$) was observed at 92 °C (Figure 4a). This combination of time and temperature resulted in an increase in the range of water available to plants. At 70 days, the response was obtained in the form of a decreasing linear function, with a reduction of 0.0001 $m^3\ m^{-3}$ in θ_{WP} per °C increased, and at 130 days the experimental data fitted a cubic model (Figure 4a). At 65 and 105 °C, the adjustment models were again cubic, with maximum θ_{WP} of 0.084 and 0.08 $m^3\ m^{-3}$ at 107 and 110 days, respectively (Figure 4b). This increase in θ_{WP} leads to a reduction in the water supply for the plants.

When the samples were subjected to 1500 kPa, across the range of temperature and exposure times investigated, 82-90% of the water absorbed by the soil + hydrogel mixture was released, indicating that a significant portion of the water is not strongly retained, which would make it unavailable to plants. This corroborates the findings of Fonteno and Bilderback (1993) who observed that with the addition of a PAM hydrogel to sandy substrates 95% of the water retained in the hydrogel/soil substrate, at tensions below 1500 kPa, was available to plants.

It is interesting to note that the time taken for soil samples amended with the hydrogel to reach equilibrium at the tension of 1500 kPa was longer than the unamended control. An increase in the number of days to reach θ_{WP} has been previously reported in cultivation systems amended with hydrogels (Abedi koupai et al., 2008). The θ_{WP} of sand without added hydrogel was achieved between 2 and 3 days, compared to 6-7 days and 9-10 days for a sand treated with a potassium acrylate hydrogel of applied at 1.0 and 2.0 g kg^{-1} respectively (Abedi koupai et al., 2008; Baasiri et al., 1986).

Considering the range of temperatures and time periods evaluated in this study, the addition of hydrogel to the test soil causes the θ_{WP} to shift below that of the unamended control (Figure 4). This

effect, in combination with the increase in soil moisture at θ_{FC} (Figure 3) is an advantage, as it offers significantly more AW to plants.

3.3 Available water (AW)

Hydrogels, when applied to the soil, can improve the water supply to plants due to the increase in the soil's capacity to store water (Wolter et al., 2002). In this study, at 40 days, the maximum AW value was 0.12 $m^3\ m^{-3}$ at 87 °C (Figure 5a) – significantly higher than that observed for the unamended soil (0.04 $m^3\ m^{-3}$ - Figure 5a, Table 1). At 100 days, a decreasing linear function was observed in the AW, with a reduction of 0.0002 $m^3\ m^{-3}$ per 1 °C increase in temperature (Figure 5a). The AW to plants (between 10 and 100 kPa) for all soil types without hydrogel was lower compared to samples with hydrogel (Narjary et al., 2012). Water retention in the soil, between 10 and 1500 kPa (corresponding to plant AW), increased with increasing levels of sodium acrylate polymers (Varennes et al., 1997).

At 45 °C, the maximum AW value was 0.13 $m^3\ m^{-3}$ at 58 days (Figure 5b). Even under increasing temperature and exposure times, the soil with hydrogel showed greater AW for longer as compared with the unamended control (Figure 5). Agaba et al., (2011) observed that the application of an acrylamide polymer (0.4% w w^{-1}) to soil of sand texture in which *Agrostis stolonifera* was cultivated, resulted in a higher AW value for a longer time (enough water was retained by the hydrogel and was available for growth of the grass over the 69 days growth period) as compared with an unamended control, reducing the frequency of irrigation (limited irrigation to only once up to the time of harvesting the *Agrostis stolonifera*). Similarly, Koupai et al., (2008) stated that the application of hydrogels to sandy soils can result in a significant reduction in the frequency of irrigation required which is an important issue in arid and semi-arid regions of the world in order to improve water use efficiency.

In the current study, the AW was higher, across all exposure times, than that initially observed in the unamended soil even at temperatures above 60 °C, and a gradual release of part of the AW could be expected with changes in the soil temperature. The increase in AW in the hydrogel amended treatments is explained by the addition of the PAM hydrophilic functional groups to the soil. Therefore, the greater capacity of the test soil to retain water across the range of temperatures and exposure times tested is attributed to the polymeric structure of the hydrogel which contain the hydrophilic functional group's acrylamide and potassium acrylate which, are capable of creating hydrogen bridges with soil water (Abedi koupai et al., 2008; Marandi and Reza, 2008).

In the current study, up to a three-fold increase in plant AW was verified after addition of 0.1% w w^{-1} of the commercial hydrogel to the sandy-loam soil evaluated. Similar findings were observed by Varennes et al. (1997) when adding 0.2% (w w^{-1}) of sodium polyacrylate hydrogels to a sandy soil. The AW content increased 2.2 and 3.2 times in a loamy and sandy soil, respectively, with the application of 0.8% w w^{-1} (Abedi koupai et al., 2008). A hydrogel dose of 0.2% w w^{-1}increased the soil moisture by 40% in a sandy clay loam soil, compared to an unamended treatment, and also increased the AW by 125% (Abedi koupai et al., 2008).

Considering an area of 1 ha and a homogeneous soil layer of 0.2 m, the water storage in the Leptsol sandy loam used in this study without hydrogel would be 80 m^3 ha^{-1}. In the condition of maximum AW associated with hydrogel addition, the test soil water storage would be 260 m^3 ha^{-1}, representing an increase of 180 m^3 ha^{-1}. These values show that the tested commercial hydrogel has excellent potential to contribute to water management in soils in arid and semi-arid regions and constitute a major strategy for increasing water use efficiency, habitat restoration and plant production in drylands.

3.4 Bulk density and Porosity

Concerning soil BD, at 40 and 70 days, linear increases in BD in increments of 0.0009 and 0.0016 g

cm^{-3}, were observed following a unitary increase in temperature (°C), respectively. For 100 and 130 days, maximum values of soil BD of 1.42 and 1.32 g cm^{-3} were observed at 97 and 64 °C, respectively (Figure 6a).

With the addition of the studied hydrogel, the soil BD increased significantly by 12% (considering conditions of maximum exposure time and temperature). However, even in these conditions, BD was lower than the unamended soil (1.49 g cm^{-3} - Table 1). Soil BD decreases with the application of superabsorbent hydrogel because the product promotes the formation of macropores in the soil (Baasiri et al., 1986; Bai et al., 2010; Hou et al., 2018).

The observed increase in BD with increase in temperature, indicates that temperature changes the efficiency of the hydrogel, causing a reduction in the improvement of physical properties. Hydrogels can absorb and lose water in a reversible way, as related to intrinsic factors of the external environment, such as temperature, which in turn can contribute to the collapse or phase change of the hydrogel (Ahmed, 2015). With the collapse of the hydrogel, there is a rearrangement of particles or aggregates, so that spaces previously occupied by the hydrated hydrogel suffer volume reduction and, therefore, the density of the soil is increased. At a critical temperature, the elasticity of the hydrogel reaches zero and the hydrogel becomes infinitely compressible (Molloy et al., 2000). At a constant temperature of 37 °C, it has been reported that a PAM hydrogel can change its physical properties, becoming softened when wet and brittle when dry (Smith et al., 1996).

Regarding soil porosity, at 40 and 70 days, a decreasing linear relationship was observed with 1 °C increase in temperature, resulting in a decrease in porosity of 0.0339 and 0.0591 $m^3\ m^{-3}$, respectively (Figure 6b). For 100 and 130 days, minimum values of soil porosity (46 and 49%) occurred at temperatures of 96 and 74 °C, respectively (Figure 6b). In the experimental conditions of temperatures and exposure time, the porosity of the soil increased as compared with the unamended soil (PT = 44% - Figure 6b, Table 1). The soil porosity decreased with increasing temperature, with a decrease of up to 10% when the temperature is raised from 30 to 105 °C (Figure 6b).

In the semi-arid region of China, it was observed that soil BD decreased with the addition of a potassium polyacrylate hydrogel, resulting in improved total soil porosity due to macropore formation (Hou et al., 2018). The wetting and drying cycles promote loosening of the soil structure and increased aeration because during the expansion of the hydrogel there is a detachment of the soil mass and an increase in its total porosity (Paluszek, 2011).

In all the evaluated treatments, soil BD and porosity were improved in comparison to the unamended soil (Figure 6), which constitutes an advantage in the use of the hydrogel as a soil conditioner. The results of this study confirm that the presence of the hydrogel reduces soil BD and increases soil porosity across the range of soil temperatures and exposure times investigated. This has the potential to have a beneficial impact on oxygenation of plant roots (Ullah et al., 2015). After adding hydrogel to the soil, even under thermal stress, total porosity and θ_{FC} increased, while the θ_{WP} decreased, providing a significant improvement in plant AW.

4 Conclusions

This research demonstrates that under extreme abiotic stress, that the hydrogel tested across all temperatures and exposure times evaluated, improves the water storage capacity, soil BD, and soil porosity. The tested hydrogel has very high potential to contribute to water management in soils in arid and semi-arid regions.

The addition of the hydrogel increased the value of θ_{FC} of the soil by up to 37%. However, and critically, the increase in the θ_{FC} of the test soil caused by the addition of the hydrogel did not affect the free porosity of water. Considering the range of temperatures and time periods evaluated, the addition of hydrogel to the soil resulted in a significant shift (up to 60%) in the θ_{WP} to below that of the unamended control. This effect, associated with the increase in soil moisture at θ_{FC} is an advantage, as it offers significantly more AW to plants.

An increase of up to 3 times in AW was verified after addition of 0.1% w w^{-1} of the commercial hydrogel to the sandy-loam soil evaluated. Considering a condition of maximum water storage with the incorporated of the hydrogel to a depth of 0.2m, the soil water storage would increase by up to 180 m^3 ha^{-1}. This demonstrates that the hydrogel tested has a high potential to contribute to improved water management in soils in arid and semi-arid regions and can be used as a strategy for increasing water use efficiency and plant production.

The BD and porosity of the soil were improved in comparison to the unamended soil, which is also an advantage in the use of this hydrogel as a soil conditioner.

The temperatures investigated in this study that replicate Brazilian semi-arid environments and exposure times lead to a progressive loss of hydrogel efficacy (reduction in the absorption capacity). Thus, there is a potential benefit for crops with a short growth cycle (horticulture). Future research should be based on improving the characteristics of hydrogels and their efficacy over extended exposure times and in adverse conditions typical of arid and semi-arid environments.

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