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Article

Use of hydrogels in the cultivation of ornamental sunflower irrigated with brackish water

Uso de hidrogéis no cultivo de girassol ornamental irrigado com água salobra

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Abstract
Saline stress affects the growth and development of crops worldwide. The use of hydrogels can alleviate the deleterious effects of salts on plants. Thus, the objective was to evaluate the use of hydrogels on the growth and biomass accumulation of sunflowers irrigated with brackish water. The experiment was conducted in a protected environment belonging to the Federal Institute of Education, Science, and Technology of Ceará – IFCE/Sobral Campus, located in the municipality of Sobral, Ceará State, Brazil. The experimental design was randomized blocks, in a factorial scheme (3 × 3), with one factor consisting of three levels of electrical conductivity of irrigation water (0.3, 1.0, and 2.0 dS m^{-1}) and the second referring to the use of hydrogels: without the presence of hydrogel, synthetic hydrogel, and alternative hydrogel (acrylate-acrylamide polymer matrix incorporated with kaolin). Increased electrical conductivity of the irrigation water reduces the leaf growth rate, abundance, and biomass accumulation of ornamental sunflowers. The use of hydrogels does not attenuate the deleterious effects of salinity on plant height growth rate, or stem, root, and total dry mass accumulation under 2.0 dS m^{-1} irrigation. Conversely, synthetic hydrogel regarding stem diameter growth rate and both hydrogels regarding root growth partially reduce salt impacts, allowing greater expansion in stem diameter and root system length of ornamental sunflower. The use of the alternative hydrogel increases the outer capitulum diameter of ornamental sunflower, demonstrating superior performance compared to the synthetic hydrogel for this floral structure.
Keywords: Protected cultivation, floriculture, *Helianthus annuus* L., hydroabsorbent polymer, salinity.

Resumo
O estresse salino afeta o crescimento e o desenvolvimento de culturas agrícolas em todo o mundo. O uso de hidrogéis pode amenizar os efeitos deletérios dos sais nas plantas. Assim, o objetivo foi avaliar o uso de hidrogéis no crescimento e no acúmulo de biomassa de girassóis irrigados com água salobra. O experimento foi conduzido em ambiente protegido, pertencente ao Instituto Federal de Educação, Ciência e Tecnologia do Ceará – IFCE/Campus Sobral, localizado no município de Sobral, estado do Ceará, Brasil. O delineamento experimental foi em blocos casualizados, em esquema fatorial (3 × 3), sendo um fator composto por três níveis de condutividade elétrica da água de irrigação (0,3, 1,0, e 2,0 dS m^{-1}) e o segundo referente ao uso de hidrogéis: sem a presença do hidrogel, hidrogel sintético e hidrogel alternativo (matriz polimérica de acrilato-acrilamida incorporada com caulim). O aumento da condutividade elétrica da água de irrigação reduz a taxa de crescimento foliar, o florescimento e o acúmulo de biomassa no girassol ornamental. O uso de hidrogéis não atenua os efeitos deletérios da salinidade sobre a taxa de crescimento em altura de planta, acúmulo de massa seca do caule, da raiz e total sob irrigação com condutividade elétrica de 2 dS m^{-1}. Por outro lado, o hidrogel sintético na taxa de crescimento do diâmetro do caule e ambos os hidrogéis no crescimento radicular reduzem parcialmente os impactos dos sais, permitindo maior expansão em diâmetro do caule e comprimento do sistema radicular do girassol ornamental. O uso do hidrogel alternativo incrementa o diâmetro externo do capítulo do girassol ornamental, apresentando desempenho superior ao hidrogel sintético nessa estrutura floral.
Palavras-chave: Cultivo protegido, floricultura, *Helianthus annuus* L., polímero hidroabsorvente, salinidade.

Introduction

The ornamental sunflower is a species of great aesthetic value that, in recent years, has been highlighted in the cultivation of ornamental species as a cut and pot plant (Moura et al., 2022). Its commercial relevance is driven by a short production cycle, which enables year-round cultivation, particularly in greenhouses. Furthermore, it is a drought-tolerant crop; however, flower production and quality can be affected by water salinity (Guimarães et al., 2021; Liu et al., 2024).

Salinity is one of the main abiotic stresses that significantly limit crop growth and production worldwide (Kaura et al., 2023), causing physiological dysfunctions and damage to plant morphology, which can lead to serious lesions that, in the case of ornamentals, depreciate their economic value (Ji et al., 2022).

As most ornamental plant species are not halophytes (Toscano et al., 2023; Soliman et al., 2024), it is crucial to adopt water management practices that allow the use of lower quality water for irrigation, such as brackish water, in the cultivation of these species, especially in regions with arid and semi-arid climates that have poor rainfall distribution (Soliman et al., 2024).

One strategy that allows for the use of brackish water in semi-arid regions would be the use of hydrogels. In agriculture, these polymers are preferred due to their ability to retain and release water in the soil (Nascimento et al., 2021; Das et al., 2025). Studies demonstrate that hydrogels can improve soil solution properties, thereby mitigating salinity and promoting plant growth and productivity (Tefera et al., 2022; Sousa et al., 2022; Moreira et al., 2024).

However, there is a debate regarding the efficiency and biodegradability of these polymers. Although synthetic hydrogels exhibit high water absorption capacity, they have limitations in saline environments and undergo slow degradation, raising environmental concerns. In contrast, hybrid hydrogels emerge as a promising alternative; their physically and chemically modified composition enables ion adsorption and reduces environmental impact (Adjuik et al., 2023; Maksimova et al., 2023; Rahimi Mamaghani et al., 2025).

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Depending on their composition, hybrid hydrogels can absorb Na^+ ions from the soil solution onto their surface. This mechanism mitigates damage to root cell membranes and reduces ionic toxicity, enabling plant growth even under salt stress (Zvulunov et al., 2019; Wang et al., 2025). In ornamental crops such as sunflowers, even though hydrogels show similar efficiencies when irrigated with saline water, the hybrid hydrogel offers an alternative for maintaining the aesthetic quality of the flowers.

Given this context, the use of water-retentive polymers can mitigate the deleterious effects of salt stress and improve the morphological responses of ornamental sunflower crops irrigated with brackish water. Thus, the objective was to evaluate the use of hydrogels on the growth and biomass accumulation of sunflowers irrigated with brackish water.

Material and Methods

The experiment was conducted from June to September 2023, in a protected environment (agricultural screen), at the Federal Institute of Education, Science, and Technology of Ceará – IFCE/Sobral Campus, located in the municipality of Sobral, Ceará State, Brazil, at 03° 40' 59''S latitude, 40° 20' 28'' W longitude, and 70 m altitude. The city has a hot semi-arid tropical climate, with historical rainfall records of 821.6 mm/year, average temperatures between 26 and 28 °C (Santos and Caracristi, 2022), and an evapotranspiration index of 1951.1 mm.

The meteorological data referring to temperature and relative humidity, obtained during the experimental period, are shown in Fig. 1A and B.

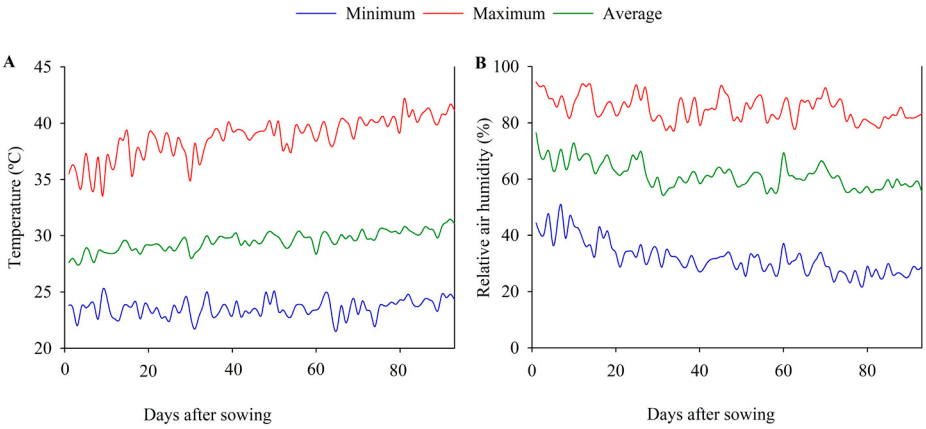

Fig 1. Average values of temperature (A) and relative humidity (B) during the experimental period.

The experimental design was randomized blocks, in a 3 × 3 factorial scheme, with five replicates, the first factor being the application of three electrical conductivities of irrigation water (0.3, 1.0, 2.0 dS m^{-1}), and the second factor was cultivation without hydrogel (WH), synthetic hydrogel (SH), and alternative hydrogel (AH) (acrylate-acrylamide polymer matrix incorporated with kaolin) (Fig. 2).

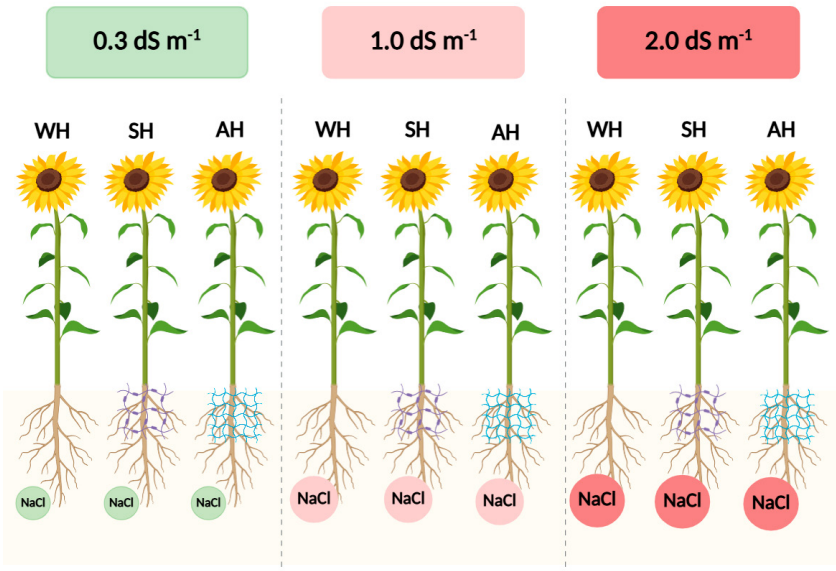

Fig 2. Graphical summary of the treatments used in the experiment. (WH: without hydrogel; SH: synthetic hydrogel; AH: alternative hydrogel). The NaCl symbols represent the increasing levels of irrigation water electrical conductivity, while the hydrogel symbols illustrate their respective polymer types. Both symbols are only schematic representations.

The AH used in this study is a hybrid (organic-inorganic) composite synthesized from an acrylate-acrylamide polymer matrix incorporating kaolin (10%), a clay composed of hydrated aluminum silicates. The synthesis was carried out using potassium acrylate and acrylamide as monomers, potassium persulfate (KPS) as the initiator, and N, N'-methylenebisacrylamide (MBA) as the cross-linking agent.

The pots, with a volumetric capacity of 1.2 L, were filled with a 1 cm layer of gravel, and a TNT fabric was placed on top of the gravel to aid drainage. They were then filled with 1 L of poagem substrate, which is a type of clay used in ceramic construction. The chemical composition of poagem can be seen in Table 1.

Table 1. Chemical and physical attributes of the substrate used before treatment application.

Chemical characteristics											
OM	**Ca^{2+}**	**K^+**	**Mg^{2+}**	**Na^+**	**SB**	**P**	**CEC**	**(V**	**PES)**	**ECse**	**pH**
(%)	---------- ($cmol_c \cdot kg^{-1}$) -------					($mg \cdot kg^{-1}$)	($cmol_c \cdot kg^{-1}$)	(%)		($dS\ m^{-1}$)	water
0.2	3.3	0.102	1.4	0.22	5.02	101.77	5.02	100	4.33	0.82	7.7

OM - Organic matter; SB - Sum of bases; CEC - Cation exchange capacity; V - Base saturation; PES - Percentage of exchangeable sodium; ECse - Electrical conductivity of soil saturation extract; pH - hydrogen potential

Two seeds of the 'Anão-de-Jardim' cultivar were sown at a depth of 2 cm. Seven days after sowing (DAS), once the plant stand was established, thinning was performed, leaving only one plant per pot.

The saline solutions used in the study were prepared using water supplied by the Serviço Autônomo de Água e Esgoto (SAEE; ECw = 0.3 dS m^{-1}; control). To achieve electrical conductivity levels of 1.0 and 2.0 dS m^{-1}, NaCl was added based on the relationship between ECw and salt concentration ($mmol_c\ L^{-1}$ = EC × 10), as described by Richards (1954). The solutions were stored in 250 L reservoirs. Water samples were collected daily to measure ECw using a digital conductivity meter (CD-820, Instrutherm), ensuring the accuracy and adjustment of the treatments throughout the experiment.

Until 20 DAS, the water used for irrigation came from the SAEE in Sobral, with an ECw of 0.3 dS m^{-1}. After this period, the pots were irrigated manually according to the pre-established treatments. The volume of water applied daily per pot was quantified using drainage microlisimeters, and a plastic container was placed under each pot to quantify the excess drained water. The salinity of the leaching fraction was monitored daily throughout the experiment. The calculation used to quantify the volume used per plant was determined according to Eq. 1.

Where:

$$Vu = Vp - Vd \quad (1)$$

Vu - volume used per plant (mL day^{-1});

Vp - volume placed per pot (mL day^{-1}); and,

Vd - average volume drained per pot (mL day^{-1}).

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Next, the calculation was made for the daily response volume, with 20% of the consumption forecast, so that the excess placed could be drained (Eq. 2).

Where:

$$Vr = 1.2 \text{ x } Vu \quad (2)$$

Vr - daily response volume (mL day^{-1}).

At 21 DAS, SH and AH were applied; these had been previously hydrated by soaking 0.6 g of each dry substance in 200 mL of water for one hour. To place the hydrogel near the root zone without damaging the root system or exposing the polymer to direct sunlight, a 2 cm layer of soil was removed from the surface of each pot. The hydrogel was applied manually and evenly, then covered with the removed soil layer.

Fertilization was performed at 15 DAS according to Castro and Oliveira (2005), with a foundation of 60 mg of nitrogen (N), 70 mg of phosphorus (P), and 200 mg of potassium (K), in the form of urea, simple superphosphate (P_2O_5), and potassium, respectively.

To meet the crop's nutritional requirements, a nutrient solution was applied alongside the irrigation at 45, 55, 65, and 75 DAS. Each treatment received 2 mL of a micronutrient stock solution, formulated according to the methodology of Castellane and Araújo (1995), supplying 0.88 mg of Mn, 0.10 mg of Cu, 0.96 mg of B, and 0.10 mg of Mo per application. Additionally, 2 mL of a urea stock solution (500 mg of N), 4 mL of an iron-EDTA solution (20 mg of Fe), and 2 mL of a monobasic phosphate solution (120 mg of P) were applied. The stock solutions were diluted in a volume of water corresponding to the irrigation level of each treatment, ensuring that the same quantity of

The assessment of the initiated growth variables was carried out at 27 and 34 DAS. Plant height (PH) was measured using a tape measure from the plant base (0.5 cm above the surface) to the insertion of the capitulum. Stem diameter (SD) was measured with a digital caliper at approximately 5 cm above the substrate surface, and the number of leaves (NL) was counted manually from the base to the apex, considering only fully expanded leaves. Next, the methodology described by Benincasa (2003) was adopted to determine the absolute growth rates for plant height (AGRPH), stem diameter (AGRST), and growth rate in number of leaves (AGRNL): The equations used to determine these rates were (Eq. 3, 4, and 5):

$$\text{AGRPH} = \frac{(Ph2 - Ph1)}{(t2 - t1)} \quad (3)$$

$$\text{AGRST} = \frac{(Sd2 - Sd1)}{(t2 - t1)} \quad (4)$$

$$\text{AGRNL} = \frac{(Nl2 - Nl1)}{(t2 - t1)} \quad (5)$$

Where: AGRPH - Absolute growth rate in height in $cm.day^{-1}$; Ph1 and Ph2 are the plant heights (cm) at times 1 and 2, respectively; AGRST - Absolute growth rate in stem diameter, in $mm.day^{-1}$; Sd1 and Sd2 are stem diameters (cm) at times 1 and 2, respectively; AGRNL - growth rate in number of leaves; Nl1 and Nl2 are the number of leaves at times 1 and 2, respectively.

At 90 DAS, the roots were separated from the aerial parts of the plants and washed in running water to remove any adhering residues. Root growth (RG) was then measured using a ruler graduated in centimeters. Flower opening (FO) was determined through daily observations, counting the days from sowing to the full opening of the flower head. The number of days to flower head emergence (FHE) was obtained by counting the days from sowing to the emergence of the first flower bud. The number of petals (NP) was obtained by visual counting at the time of complete capitulum opening.

The plants were cut flush with the substrate surface and separated into stem+leaves, roots, and capitulum. After the material was separated, it was placed in kraft paper bags according to each treatment and placed in a forced-air circulation oven at 65 °C for drying to constant weight (approximately 72 hours). After drying, the material was weighed using an analytical balance graduated in grams (g). The total dry mass (TDM) was calculated from the data obtained after weighing and the sum of the dry masses of the different parts of the plant.

At the end of the experiment (90 DAS), the internal diameter of the capitulum (IDC) was measured at the ends that form viable seed-producing flowers, and the external diameter of the capitulum (EDC) was measured from one end of the sterile, colored flowers to the other end of these flowers, both measured with a ruler graduated in cm.

The obtained results were subjected to the Shapiro-Wilk normality test, Bartlett's test for homogeneity of variance, and the Durbin-Watson test for error independence. The data met the assumptions for analysis of variance, and no data transformation was required. Subsequently, the data were subjected to analysis of variance using the F test. When significant results were found, the data were subjected to Tukey's test at a 5% significance level ($p < 0.05$). All analyses were performed using the AgroR package in R software (R Core Team, 2021).

Results

The growth rates in plant height, stem diameter, and root growth of the ornamental sunflower crop were significantly influenced by the interaction between the electrical conductivity of the irrigation water and the different types of hydrogels. On the other hand, the growth rate of the number of leaves showed a significant effect only from the electrical conductivity of irrigation water, without influence from the types of hydrogels.

Analysis of the comparison of means test for the growth rate in height of ornamental sunflowers (Fig. 3A) showed that plants irrigated with low salinity water (0.3 dS m^{-1}) and treated with synthetic hydrogel showed significantly higher growth (1.70 cm day^{-1}) than those irrigated with water with an ECw of 1.0 dS m^{-1}, except for plants treated with alternative hydrogel. In addition, these plants were statistically superior to plants irrigated with water at an ECw of 2.0 dS m^{-1}, regardless of the presence of hydrogel. When comparing plants treated with synthetic hydrogel to those irrigated with increasing levels of salinity and receiving this type of hydrogel, a difference of 23.53% and 37.65% was observed in plants irrigated with 1 and 2 dS m^{-1}, respectively, compared with 0.3 dS m^{-1}, demonstrating the negative effect of salinity on the growth of ornamental sunflower plants.

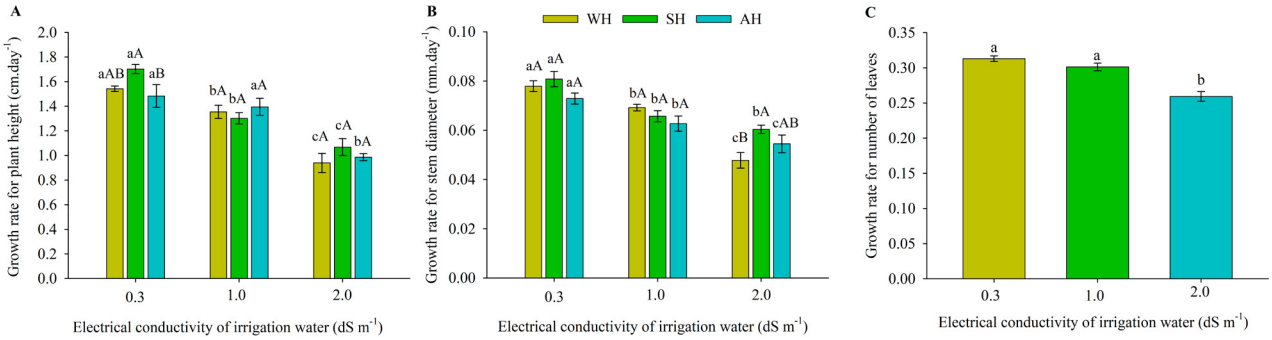

Fig 3. Absolute growth rate in height (A) and stem diameter (B) of ornamental sunflower plants as a function of different electrical conductivities of irrigation water and types of hydrogels, and growth rate in the number of leaves of ornamental sunflower leaves as a function of different electrical conductivities of irrigation water (C). Averages followed by the same lowercase letter compare hydrogel treatments within each salinity level, and uppercase letters compare salinity levels within each hydrogel treatment by Tukey's test ($p < 0.05$). Columns followed by the same letter do not differ by Tukey's test ($p < 0.05$). Vertical bars represent standard error (n = 5). WH: without hydrogel; SH: synthetic hydrogel; and AH: alternative hydrogel.

Analysis of the growth rate in stem diameter of ornamental sunflowers (Fig. 3B) revealed that plants irrigated with low-salinity water (0.3 dS m^{-1}), regardless of the presence of hydrogel, showed statistically superior growth compared to those subjected to higher levels of salts in the irrigation water. Like the AGRPH results, plants treated with synthetic hydrogel and irrigated with low-salinity water achieved the highest mean stem growth value (0.080 mm day^{-1}). Although the stem diameter growth rate decreased under irrigation with ECw of 2.0 dS m^{-1}, synthetic hydrogel partially attenuated the deleterious effects of salinity, resulting in an average growth of 0.060 mm day^{-1}, statistically similar to that of plants irrigated with ECw of 1.0 dS m^{-1}. Furthermore, when comparing this value with the highest average growth observed (obtained in plants irrigated with low salinity and treated with synthetic hydrogel), a 25% reduction was found.

Regarding the growth rate of the number of leaves of ornamental sunflowers as a function of the electrical conductivity levels of the irrigation water (Fig. 3C), it was found that plants subjected to higher salinity (2.0 dS m^{-1}) had a growth rate of 0.25 leaves, statistically differing from those irrigated with water of lower salinity (0.3 and 1.0 dS m^{-1}). This result represents a reduction of 19.25% and 16.67%, respectively, which can be attributed to the increase in the amount of salts in the irrigation water.

The mean comparison test (Fig. 4B) confirmed the patterns observed previously, showing that sunflower plants irrigated with ECw 0.3 and 1.0 dS m^{-1} and treated with SH had the highest mean root growth values, with 26.40 cm and 25.30 cm, respectively, differing statistically from the other treatments. Under the highest salinity level (2.0 dS m^{-1}), a decrease of 52.27% and 53.41% in root growth was observed for the SH and AH treatments, respectively, calculated in relation to the maximum growth achieved by the SH hydrogel treatment at 0.3 dS m^{-1} (26.40 cm). Nevertheless, plants treated with either hydrogel (SH or AH) under 2.0 dS m^{-1} still maintained statistically superior root growth compared to plants that did not receive hydrogel. The visual differences in root density and root growth across these treatments are illustratively presented in Fig. 4A.

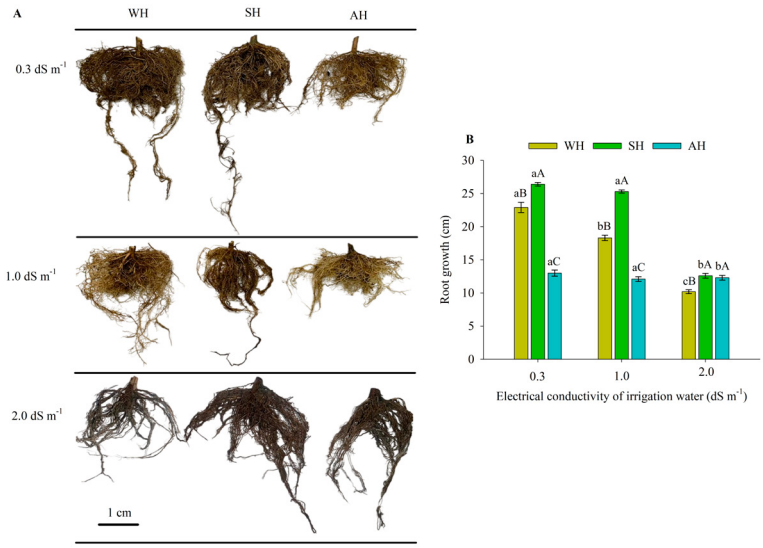

Fig 4. Roots (A) and root growth (B) of ornamental sunflowers as a function of different electrical conductivities of irrigation water and hydrogel types. Averages followed by the same lowercase letter compare hydrogel treatments within each salinity level, and uppercase letters compare salinity levels within each hydrogel treatment by Tukey's test ($p < 0.05$). WH: without hydrogel; SH: synthetic hydrogel; and AH: alternative hydrogel. Vertical bars represent standard error (n = 5).

The analysis of variance of the productive aspects of ornamental sunflowers showed that the electrical conductivity of the irrigation water had a significant effect on all variables analyzed, except for capitulum emission. On the other hand, the different types of hydrogels, as well as the interaction between the factors, did not have a significant influence on the results.

The opening of ornamental sunflower flowers, depending on the different levels of electrical conductivity of the irrigation water (Fig. 5A), shows that plants subjected to higher salinity (2.0 dS m^{-1}) flowered at 81 days. This value differed statistically from plants irrigated with water of lower salinity (0.3 dS m^{-1}), which reached flower opening on average at 85 days, representing a reduction of 4.94%. However, plants irrigated with water of higher salinity (2.0 dS m^{-1}) did not differ significantly from those irrigated with ECw of 1.0 dS m^{-1}, which flowered in 84 days.

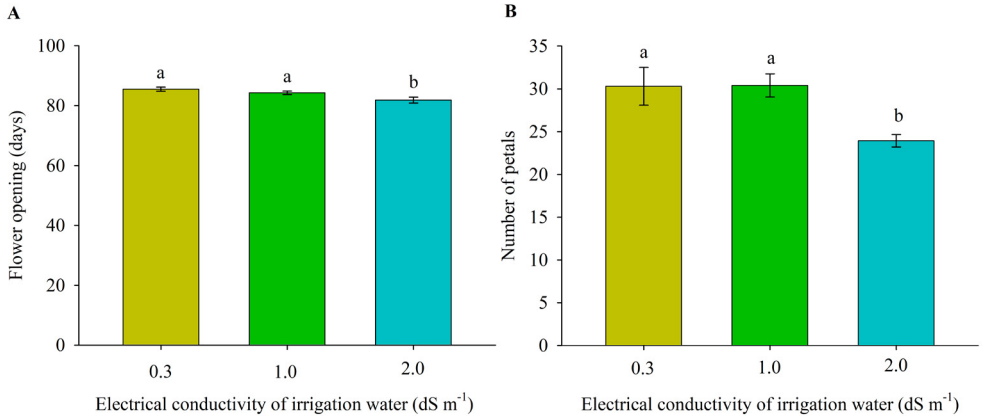

Fig 5. Flower opening (A) and number of petals of sunflowers irrigated with different electrical conductivities of irrigation water. Columns followed by the same letter do not differ by Tukey's test ($p < 0.05$). Vertical bars represent standard error (n = 5).

Although irrigation with higher electrical conductivity reduced the time for flower opening (Fig. 5A), it was observed that these flowers had fewer petals (Fig. 5B), with an average of 23 petals. This value differed statistically from plants irrigated with ECw of 0.3 and 1.0 dS m^{-1}, representing a reduction of 21.28% and 20.92%, respectively.

As previously described, there was no significant interaction effect between the factors regarding the inner and outer diameters of the sunflower capitulum. However, Fig. 6A shows the sunflower capitulum at the end of the cycle following the application of the treatments.

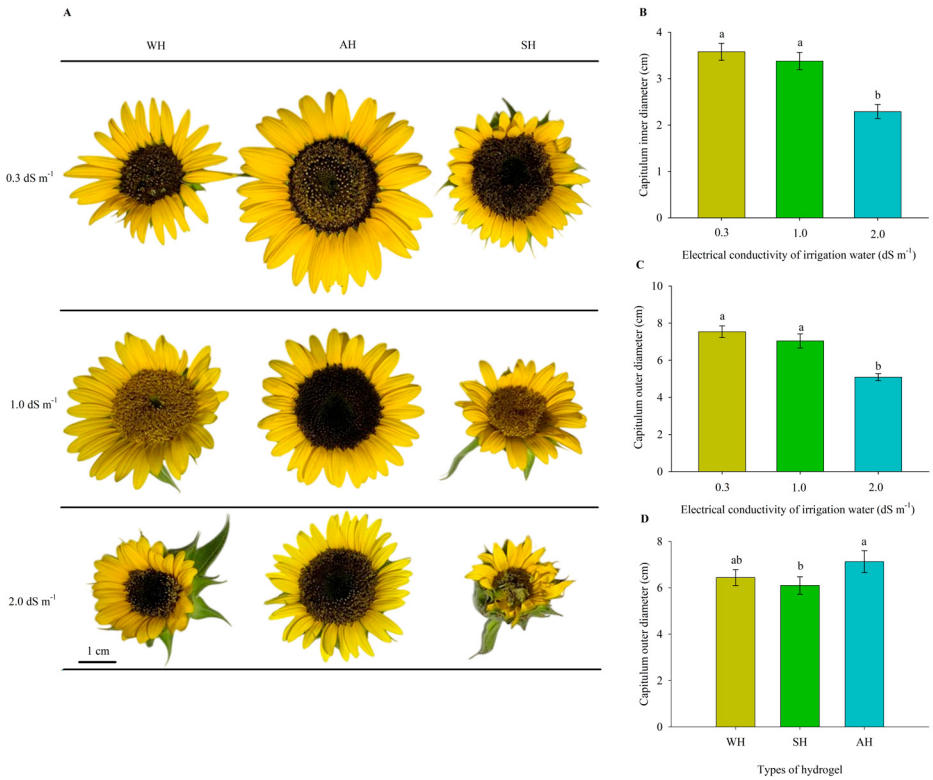

Fig 6. Sunflower capitulum (A), internal (B) and external (C) diameter of ornamental as a function of different electrical conductivities of irrigation water, and external diameter of capitulum sunflower as a function of hydrogel types (D). Columns followed by the same letter do not differ by Tukey's test ($p < 0.05$). Vertical bars represent standard error (n = 5).

The analyses of the internal and external diameters of the floral head (Fig. 6B and C) corroborate the previous observations, showing that increasing the electrical conductivity of irrigation water significantly reduces these dimensions. Plants irrigated with water of higher salinity (2.0 dS m^{-1}) showed significant reductions compared to those irrigated with lower ECw (0.3 dS m^{-1}). Specifically, the internal diameter decreased by 36.03%, while the external diameter decreased by 32.49%, highlighting the negative impact of salt stress.

Regarding the external diameter of ornamental sunflower flowers as a function of hydrogel types (Fig. 6D), it was observed that plants receiving AH had the highest mean values (7.13 cm), differing statistically from those receiving SH (6.10 cm). However, there was no statistical difference in relation to WH-grown plants (6.44 cm).

The variables dry mass of the stem, root, and total dry mass of the ornamental sunflower were significantly influenced by the interaction between the electrical conductivity of the irrigation water and the different types of hydrogel. In contrast, the dry mass of the flower was affected only by the electrical conductivity of the irrigation water (Fig. 7).

The comparison test of means for flower dry weight as a function of irrigation water electrical conductivity (Fig. 7A) indicated that plants irrigated with low-salinity water (0.3 dS m^{-1}) had higher flower dry weight (2.94 g), statistically differing from those irrigated with conductivities of 1.0 and 2.0 dS m^{-1}. This difference resulted in a reduction of 35.71% and 55.10%, respectively, when compared to plants irrigated with water of lower salt concentration (0.3 dS m^{-1}).

The analysis of stem dry mass (Fig. 7B), considering the interaction between the evaluated factors, revealed that plants irrigated with water with lower salt concentration (0.3 and 1.0 dS m^{-1}) and that did not receive hydrogel differed statistically from those irrigated with water with higher salt concentration (2.0 dS m^{-1}) without the application of hydrogel. In addition, among the plants irrigated with the highest electrical conductivity of water (2.0 dS m^{-1}), those that received hydrogel presented numerically higher values (5.60 and 5.45 g) compared to those that did not receive it (4.80 g), with an increase of 14.29% and 11.93%, respectively.

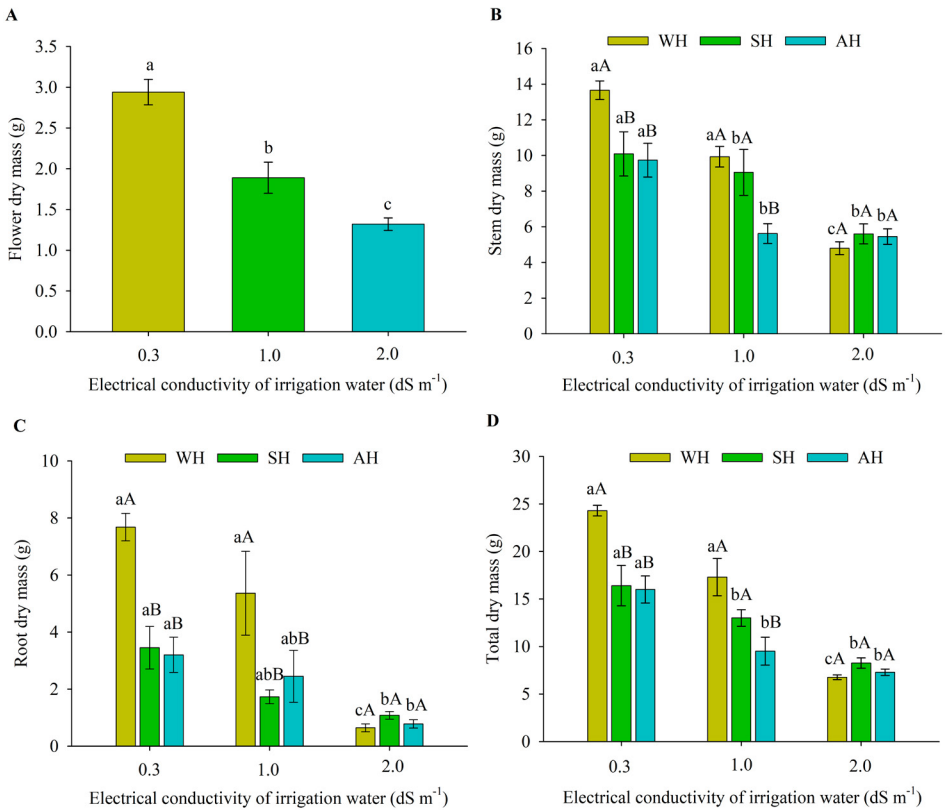

Fig 7. Dry mass of ornamental sunflower flowers as a function of different electrical conductivities of irrigation water (A) and dry mass of the stem (B), root (C), and total (D) of ornamental sunflower plants irrigated with different electrical conductivities of irrigation water and types of hydrogels. Columns followed by the same letter do not differ by Tukey's test ($p < 0.05$). Averages followed by the same lowercase letter compare hydrogel treatments within each salinity level, and uppercase letters compare salinity levels within each hydrogel treatment by Tukey's test ($p < 0.05$). WH: without hydrogel; SH: synthetic hydrogel; and AH: alternative hydrogel. Vertical bars represent standard error (n = 5).

The analysis of the dry mass of the roots of sunflower plants (Fig. 7C), considering the interaction between the evaluated factors, shows that plants irrigated with water of lower salinity (0.3 and 1.0 dS m^{-1}) and that did not receive hydrogel had higher root biomass, with mean values of 7.67 g and 5.36 g, respectively. These results differed statistically from both the plants that received hydrogel under the same electrical conductivity conditions and those that did not receive hydrogel and were irrigated with water with higher salinity (2.0 dS m^{-1}). The plants subjected to the latter condition had a considerably lower root dry mass (0.64 g), representing a reduction of 91.44% and 88.06% compared to the highest mean values obtained at an electrical conductivity of 0.3 dS m^{-1}.

The results obtained for the dry mass of the stem and root (Fig. 7B and C) directly reflected the total dry mass of the ornamental sunflower (Fig. 7D). It was observed that plants that did not receive hydrogel and were irrigated with water of lower salinity (0.3 and 1.0 dS m^{-1}) differed statistically from those irrigated with 2.0 dS m^{-1} without hydrogel. In addition, plants without hydrogel subjected to higher water electrical conductivity had a significantly lower average total dry mass (6.76 g) compared to the other experimental conditions. Still, regarding the plants irrigated with water of higher salt concentration and without hydrogel, there was a reduction of 72.12% and 61.01% in relation to the highest values obtained with hydrogel, respectively.

Principal component analysis (PCA) revealed that the first two components together explain 80.7% of the total data variability (Fig. 8).

The resulting biplot shows the formation of distinct groupings among variables, reflecting response patterns associated with the application of

treatments. It was observed that the first group is composed of the variables internal and external diameter of the capitulum and flower opening, which were predominantly associated with treatment 0.3_AH. A second group, formed by the variables number of petals, growth rate in height, capitulum opening, growth rate in number of leaves, and dry mass of leaves, had no direct association with a specific treatment. The third group, composed of stem diameter growth rate, root dry mass, total dry mass, stem dry mass, and root growth, was more strongly related to treatments 1.0_WH, 1.0_SH, and 0.3_SH.

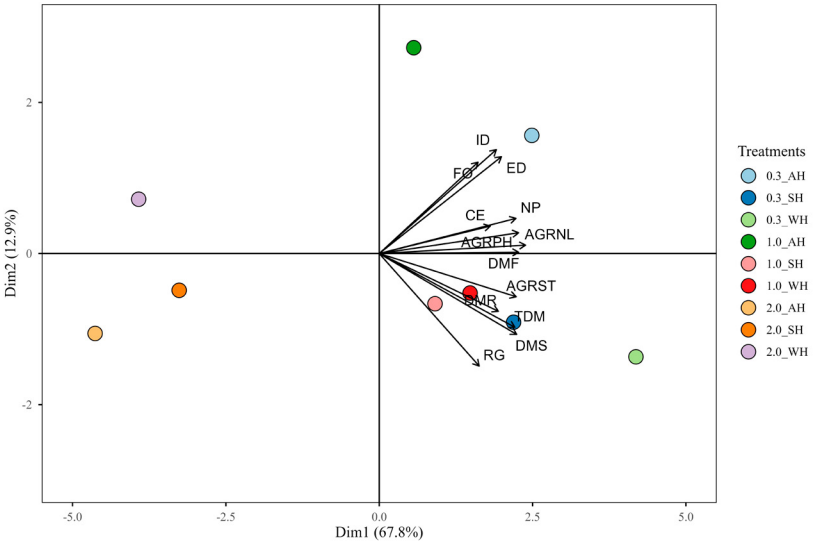

Fig 8. Principal component analysis (PCA) in ornamental sunflower plants as a function of different types of hydrogels irrigated with brackish water. The direction and length of the arrows indicate how each characteristic contributes to the first two components of the PCA. Aligned vectors indicate a strong positive relationship between the two characteristics. Vectors at right and opposite angles indicate no relationship and/or a negative correlation, respectively. Treatments: 0.3, 1.0, and 2.0 dS m^{-1} (irrigation water electrical conductivity); WH (without hydrogel), SH (synthetic hydrogel), and AH (alternative hydrogel).

Discussion

In particular, most floral and ornamental crops are classified as glycophytes, i.e., species that are sensitive to the accumulation of salts in the growing environment. These plants have a salinity tolerance limit, above which several negative effects can be observed, especially in aesthetic aspects, which are decisive for their commercial value, such as the ornamental sunflower (Toscano et al., 2023). Consequently, it is necessary to explore management strategies, such as the application of different hydrogels, to assess whether these polymers can mitigate salt-induced stress in sunflower production.

The results obtained in this study revealed a significant reduction in all growth variables evaluated in ornamental sunflower cultivation. A decrease in growth rate in height, stem diameter, number of leaves, and root growth was observed, especially in plants irrigated with high salt concentrations (2.0 dS m^{-1}) and without the presence of hydrogel.

The adverse effects of salinity on plant growth generally occur in two distinct phases. The first is related to the reduction in the water absorption capacity of plants, caused by an increase in the osmotic potential of the soil. This condition hinders water uptake by the roots, compromises the plant's water relations, and reduces cell turgor, which is essential for cell expansion. In the second phase, known as the ionic phase, there is an excessive accumulation of ions, mainly sodium (Na^+) and chlorine (Cl^-), in plant tissues. This accumulation can be toxic and is directly associated with the induction of leaf senescence (Ji et al., 2022). Thus, the impacts of salinity on sunflower growth will have visual impacts on market value. The results found in the present study are in accordance with Lei et al. (2020), who found that increased salinity significantly reduced sunflower crop growth.

However, the use of hydrogel, both in its alternative and synthetic forms, contributed to partially mitigating the deleterious effects of salinity on different aspects of ornamental sunflower growth in our present study. The alternative hydrogel, for example, promoted better performance in the height growth rate of plants irrigated with water with an electrical conductivity of 1.0 dS m^{-1}. The synthetic hydrogel, on the other hand, had a positive effect on the growth rate of stem diameter under irrigation with an ECw of 2.0 dS m^{-1}. In addition, both types of hydrogels had positive effects in mitigating root growth reduction under high salinity conditions (2.0 dS m^{-1}). These quantitative responses are visually consistent with the root growth shown in Fig. 4A, where plants treated with hydrogels maintained root systems even under salt stress.

According to Nascimento et al. (2021), the increase in salt concentration in the solution reduces the hydrogel's ability to absorb water molecules, compromising its main function, which is water retention. However, the results obtained in this study suggest that, despite the high salinity, the water retainers still played a positive role in the growth and especially in the root architecture of sunflower plants. Possibly, the hydrogels adhered to the substrate particles, forming microenvironments more favorable to moisture retention and nutrient availability (Navroski et al., 2015). In addition, the presence of hydrogel may have stimulated the plant to increase the length of the root system to a region with a lower concentration of NaCl to sustain plant growth (Singh et al., 2024).

The positive effects of water-retaining polymers have also been reported in other ornamental species, although responses vary depending on cultivation conditions and the dosages used. Abdel-Magied et al. (2025) observed that the addition of 25% hydrogel to the culture medium during the micropropagation of *Russelia equisetiformis Schltdl. & Cham*. reduced damage caused by salt stress, promoting improvements in plant growth parameters. These results indicate that, although a 25% hydrogel concentration reduced the deleterious effects of salts on *Russelia equisetiformis Schltdl. & Cham*. under in vitro conditions, this dosage would likely be insufficient for cultivation in soil or substrate, as carried out in our study. On the other hand, Sousa et al. (2022), when studying *Tagetes patula L.* seedlings, found that the greatest root growth occurred in the absence of hydrogel (0 g L^{-1}), followed by the application of 1 g L^{-1} of the polymer, both irrigated with low salinity water (ECw 0.5 dS m^{-1}), with average root lengths of 3.96 and 3.68 cm. These results differ from those found in the present study, given that the greatest mean root lengths were observed when synthetic hydrogel was used with low-salinity water.

The increase in salt concentration in the soil can directly interfere with the transition from the vegetative to the reproductive state of plants, reflected in many cases in the anticipation or delay of flower opening (anthesis), an important aspect in ornamental species. (García-Caparros and Lao, 2018). This process is regulated both by endogenous factors, such as the presence of florigen, and by exogenous factors, such as photoperiod

and environmental conditions, including salinity (Guzman and Marques, 2023). Thus, the results obtained in this study indicate that salinity promoted the anticipation of anthesis in ornamental sunflowers (Fig. 5A), suggesting that the plant's metabolism did not follow photoperiodic signals alone, but activated acclimatization mechanisms aimed at survival under adverse environmental conditions.

In tomato cultivation, Ghanem et al. (2009) observed that anthesis was significantly delayed in plants treated with 150 mM NaCl, with the first anthesis recorded at 18 days, while in plants grown without salt stress, this event occurred at 16 days. This delay was attributed to floral abortion induced by saline conditions at different stages of application. In contrast, Soliman et al. (2024) reported that increasing salinity to 2000 ppm promoted an increase in the number of flowers in *Calendula officinalis*. This result was interpreted as an adaptive strategy of the plant, which accelerates the flowering process as a survival mechanism under adverse conditions.

Although the increase in the electrical conductivity of irrigation water promoted the anticipation of anthesis in ornamental sunflowers, salt stress reduced the number of petals (Fig. 5B), inducing morphological changes in the flowers. This negative effect was also evident in the reduction of the internal and external diameters of the floral capitulum (Fig. 6B and 6C). Saline stress triggers osmotic, ionic, and oxidative effects that compromise cell division and floral differentiation, in addition to affecting fragmoplast formation and the structural organization of plant cells, directly impacting the cytoskeleton (Baranova and Gulevich, 2021). These effects, taken together, result in morphological deformations (Guzman and Marques, 2023), which, as demonstrated in this study, compromise the growth and floral structure of the plant. Guimarães et al. (2021) found that increasing the electrical conductivity of irrigation water reduced the number of petals and the internal and external diameter of ornamental sunflower crops.

Regarding the differences observed in external diameter based on the hydrogel type, it was found that ornamental sunflower plants grown with AH hydrogel exhibited higher values than the other plants, although they did not differ from those grown without the water-retaining agent. This result can be attributed to the type of material used to produce the hydrogel. The AH hydrogel material consists of an acrylate-acrylamide polymer matrix incorporating kaolin. This is presumably explained by physical interactions, specifically hydrogen bonding between the hydroxyl groups on the kaolin surface and the carboxylate groups of the potassium acrylate units, as well as the amide groups of the acrylamide segments along the polymer chains (Ma et al. 2016; Moreira et al., 2020; Rahimi Mamaghani et al., 2025). These interactions can form a stable network and contribute to soil water availability, which in turn, can be absorbed by the plant. Consequently, cell elongation was stimulated, resulting in the greater external diameters observed.

The increase in the electrical conductivity of irrigation water reduced the accumulation of dry matter in ornamental sunflower plants, regardless of the presence of hydrogel. In salinity-sensitive plants such as sunflowers, the inability to regulate the influx of ions, mainly Na^+ and Cl^-, impairs photosynthetic activity and overall metabolism, leading to growth inhibition and, consequently, reduced dry matter production (Sousa et al., 2023). Similar results were obtained in sunflower (Han et al., 2022) and *Calendula officinalis L* (Azizi et al., 2021) cultures. It should be noted in the present study that sunflower plants grown without the presence of sunflower had higher dry matter in the stem and root at ECw 0.3 and 1.0 dS m^{-1}, consequently higher total dry matter.

The superior plant biomass performance observed in the absence of hydrogel can be attributed to changes in soil physical properties caused by the water-retaining agent. The swelling of the hydrogel altered the substrate's porosity and macropore structure. Consequently, this impaired soil hydraulic conductivity, water movement, and water availability to the plants (Albalasmeh et al., 2022). Supporting this, Sousa et al. (2022) noted that while hydrogel can increase water retention in the substrate, it may also reduce aeration in the root zone.

On the other hand, the reduction in biomass of plants irrigated with saline water (2.0 dS m^{-1}) is due to decreased water absorption by the hydrogel under saline irrigation, a result of the soluble salts presents in the brackish water. Water absorption by the polymer matrix occurs via osmotic pressure gradients between the hydrogel network and the external solution (Costa et al., 2022). However, continuous irrigation with brackish water can induce anion-anion electrostatic repulsion, thereby altering the osmotic equilibrium between the external solution and the polymer matrix. It is presumed that this process diminished the hydrogel's water-holding capacity and reduced the availability of stored water for plant uptake, thereby affecting sunflower biomass (Maksimova et al., 2023; Wang et al., 2025).

However, despite the reduction in sunflower dry matter associated with increased irrigation water electrical conductivity, at an ECw of 2.0 dS m^{-1}, the presence of SH and AH hydrogels partially mitigated the deleterious effects of salinity compared to plants grown without the polymer at the highest salinity level used in this study. This effect can be attributed to the hydrogel's ability to dilute the overall electrical conductivity of the soil solution, thereby minimizing ionic stress and promoting biomass production under these conditions (Tefera et al., 2022).

These results corroborate those found by Sousa et al. (2022), who found that even with irrigation at 6.0 dS m^{-1}, the water-retaining polymer led to an increase in total dry mass compared to treatments without the polymer, indicating a possible mitigating effect on the damage caused by water salinity. On the other hand, Costa et al. (2022) found that the application of 0.07% (w/w) hydrogel composed of potassium acrylate, acrylamide, and mineral in sandy soil did not reduce the salts in the leachate or their availability in the soil and favored the initial development of corn crops irrigated with saline water.

In the multivariate analysis using biplot (Fig. 8), used to identify the treatment that performed best (combination of irrigation water salinity and hydrogel type) for ornamental sunflowers, it was found that the first group comprising internal diameter, external diameter, and floral opening was associated with treatment 0.3_AH. According to Haq et al. (2023), principal component analysis (PCA) is a statistical tool that allows the evaluation of the effect of treatments on the crop studied, while revealing the interrelationships between the characteristics of interest.

In contrast, the third group was associated with variables related to sunflower growth, modulated by the presence or absence of hydrogel and by the levels of salts in the irrigation water. The results suggest that ornamental sunflowers maintain their morphophysiological characteristics when grown below their salinity threshold (Maas et al., 1986), with a strong tendency for a positive response associated with the use of synthetic hydrogel.

Conclusions

Increased electrical conductivity of the irrigation water reduces the leaf growth rate, abundance, and biomass accumulation of ornamental sunflowers.

The use of hydrogels does not attenuate the deleterious effects of salinity on plant height growth rate, or stem, root, and total dry mass accumulation under 2.0 dS m^{-1} irrigation. Conversely, synthetic hydrogel regarding stem diameter growth rate and both hydrogels regarding root growth partially reduce salt impacts, allowing greater expansion in stem diameter and root system length of ornamental sunflower.

The use of the alternative hydrogel increases the outer capitulum diameter of ornamental sunflower, demonstrating superior performance compared to the synthetic hydrogel for this floral structure.

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Author Contribution

GMS: Investigation, Formal Analysis, Data Curation, Software, Writing – Original Draft, Writing – Review & Editing. **FLLS:** Investigation, Data Curation. **JDRA:** Investigation, Data Curation. **JTMS**: Investigation, Software, Writing – Review & Editing. **TVAV:** Conceptualization, Investigation, Methodology, Project Administration, Funding Acquisition. **LGPN:** Conceptualization, Investigation, Methodology, Project Administration, Funding Acquisition. **FHAR:** Methodology, Resources. **GGS:** Supervision, Writing – Review & Editing, Validation.

Conflict of Interest

The authors declare that there is no conflict of interest.

Data Availability Statement

Data will be made available upon request to the authors.

Declaration of generative AI and AI-assisted technologies in the writing process

The authors declare that the use of AI and AI-assisted technologies was not applied in the writing process.

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