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Hydric stress index of sunflower irrigated with water replacement fractions and magnetically altered water

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INFO

Keywords
Helianthus annuus L.
water stress
magnetic field

ABSTRACT

The objective was to evaluate the water sensitivity of sunflower (Helianthus annuus L.) using the crop water stress index (WSI) and leaf area (AF), when subjected to soil water variation and using normal and magnetized water in irrigation. The experiment was conducted in pots with cv BRS 323 grown in red latosol. The design was randomized blocks (DBC) in a 4 x 2 x 4 factorial scheme with 4 replications, with 4 water replacement fractions (100, 75, 50, 25% - RH); 2 types of irrigation water (normal and magnetized) and 4 evaluation periods (20, 40, 60 and 80 days after emergence - DAE). The magnetization occurred through the Sylocimol magnetizer constantly deposited in a different reservoir and the RHs were administered with the fractions of the crop's real evapotranspiration (ETrc) obtained by the water balance. In calculating the WSI, the air temperature was measured using a maximum and minimum thermometer and the leaf temperature was measured using a digital infrared thermometer. FA was calculated indirectly after measuring leaf lengths. Magnetized water reduced AF and increased WSI. Greater plant hydration reduced WSI, regardless of the type of water. The highest WSI occurred at HRs of 25% and 50% at 68 and 84 DAE, respectively. The maximum leaf area predicted under magnetized water irrigation corresponds to a water replacement fraction of 127.5%, which lies beyond the experimental range tested, reflecting a theoretical optimum limited by water quality.

RESUMO

Palavras-chaves
Helianthus annuus L.
estresse hídrico
campo magnético

Índice de estresse hídrico do girassol irrigado com frações de reposição hídrica e água alterada magneticamente

Objetivou-se avaliar a sensibilidade hídrica do girassol (Helianthus annuus L.) mediante o índice de estresse hídrico da cultura (WSI) e a área foliar (AF), quando submetido à variação da água no solo e utilizando água normal e magnetizada nas irrigações. O experimento foi conduzido em vasos com a cv BRS 323 cultivada em latossolo vermelho. O delineamento foi o de blocos ao acaso (DBC) em esquema fatorial 4 x 2 x 4 com 4 repetições, sendo 4 frações de reposição hídrica (100, 75, 50, 25% - RH); 2 tipos de água de irrigação (normal e magnetizada) e 4 épocas de avaliação (20, 40, 60 e 80 dias após a emergência - DAE). A magnetização ocorreu por meio do magnetizador Sylocimol depositado constantemente em reservatório distinto e as RH's foram ministradas com os fracionamentos da evapotranspiração real da cultura (ETrc) obtida pelo balanço hídrico. No cálculo do WSI, mensurou-se a temperatura do ar por um termômetro de máxima e de mínima e a temperatura foliar por um termômetro digital infravermelho. A AF foi calculada indiretamente após medição dos comprimentos das folhas. A água magnetizada reduziu a AF e aumentou o WSI. Uma maior hidratação das plantas reduziu o WSI, independentemente do tipo de água. A área foliar máxima prevista sob irrigação com água magnetizada corresponde a uma fração de reposição hídrica de 127,5%, o que está além da faixa experimental testada, refletindo um ótimo teórico limitado pela qualidade da água.

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INTRODUCTION

Sunflower (*Helianthus annuus* L.) is a crop of significant economic value due to its versatility of use, particularly its exploitation for the production of oil and grains in Brazil and in different regions of the world (Zarian et al. 2019; Embrapa, 2022; Oliveira et al. 2021). This crop is considered tolerant to heat and water stress, when compared to other cultivated species. However, it is also sensitive to variations in soil water levels, since the productive potential of genotypes depends on management practices that favor their full development, such as the quantity and quality of water used in partial and/or total irrigation management (Amaral et al. 2020; Embrapa, 2022).

The modernization of irrigation techniques in view of different water demands and crop contour conditions has contributed to the development and optimization of technologies that aim to improve plant development, which helps to mitigate the harmful effects of hydric deficit or excess (Lopes and Lima 2015, Pizetta et al. 2023).

The use of the water stress index (WSI) and water magnetization used in irrigation has gained prominence in recent studies for promoting better management of water used in crops, improving water use efficiency in agriculture (Generoso et al. 2017, Turco et al. 2022). The WSI reports the effects of reducing water available to the plant with the consequent increase in leaf temperature and reduction in plant transpiration, and can be used to characterize the tolerance of a crop to stress caused by water deficiency (Embrapa, 2022; Carvalho et al. 2022).

The magnetic field imposed on irrigation water is a technology that does not remove or add any substance to the water, but causes changes in its physical-chemical parameters resulting from the organization of clusters, changes in pH and electrical conductivity, among others, (Selin et al. 2019; Dastorani et al. 2022), which provides changes in the availability of water and its nutrients, influencing the physiological processes of plants (Alderfasi et al. 2016; Mahmoud et al. 2019).

In the literature, results are reported that prove the improvement in growth, yield, response to saline stress, water stress and efficiency in water use in sunflower crops, when irrigated with magnetized water, to be cited (Nahyra et al. 1991; Zarian et al. 2019; Mahmoud et al. 2019; Dastorani et al. 2022). However, more research is possible involving cultivar diversity, water regimes and water quality, for example (Mendes et al. 2020), expanding the horizon of understanding of the sunflower's response to abiotic factors.

Due to the lack of further studies in the literature on the interaction of these factors, the aim was to evaluate the sensitivity of sunflower, through WSI, when consulted to the variation in water availability in the soil, using normal water and magnetized water in water replacements.

MATERIAL AND METHODS

The experiment was conducted in a protected environment located on the premises of the Federal Institute of Northern Minas Gerais - Campus Arinos, at coordinates 15º55’12.75’’ S and 46º8’5.57’’ W, at an altitude of 525.0 m. The region has an Aw climate (tropical with dry winters and rainy summers) according to the Kopper-Geiger classification.

The plant material used was sunflower (*Helianthus annuus* L.) cv BRS 323, grown in plastic pots with a capacity of 25 dm³, whose filter element, below the cultivation soil, was composed of a 1 cm layer of gravel No. 1, a shading screen and above it 24 dm³ of experimental soil. The sampling plan consisted of a randomized block design (DBC), assembled in a 4 x 2 x 4 factorial scheme, with four replications, with factor A consisting of 4 water replacement fractions (100, 75, 50, 25% - RH); factor B: 2 types of irrigation water (normal supply water and magnetized water) and factor C: (4 evaluation times, being at 20, 40, 60 and 80 days after emergence - DAE.

The lysimeters were completed with a Dystroferric Red Latosol (LVD) composed of 3.0% organic matter (tanned cattle manure) and particles in aqueous form in the same place of the experiment and sent to the Nativa agricultural Laboratory - Formosa (GO) for textural classification, organic material, pH in water, P, K, Ca, Mg, Al, H+Al, S, CTC and V whose values are shown in Table 1.

Table 01 - Textural class and physical and chemical characteristics of the soil

pH	P	K	Ca	Mg	H	Al	SB	CTC	V	Sand	Silt	Clay
$CaCl_2$	(mg dm^{-3})		------------- cmolc dm^{-3} --------------						%	----- g kg^{-1}-----		
4.5	8.24	180	2.43	0.94	4.50	0.02	3.67	8.20	44.8	404	215	381

P, K e Na extracted with HCl 0,05 mol L^{-1} + H_2SO_4 0,0125 mol L^{-1}; Ca, Mg e Al extracted with KCl 1 mol L^{-1} pH 7,0. Source: Nativa agricultural Laboratory, Formosa-GO

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To increase the base saturation to 80%, liming was done with dolomitic limestone filler and then the soil was kept incubated for 40 days with moisture close to field capacity.

The NPK sources used for fertilization were simple superphosphate, potassium chloride and urea, and the quantities were determined by chemical analysis of the soil and the recommendations proposed by Novais et al. (2011) for cultivation in pots. Fertilization with urea was divided and applied in three stages: 35% at the foundation/planting stage, 35% at the growth stage and 30% at the formation and maturation of achenes.

Planting was done manually with ten seeds per pot and thinned after verifying 80% emergence leaving only one plant per pot.

The crop's irrigation was done manually and daily, determining the actual crop evapotranspiration (ETr) from the water balance of water in the soil inside 4 extra pots (drainage lysimeters) whose methodology was used in previous works (Verssiani et al. 2021, Mendes et al. 2020). The irrigation consisted of adding a known volume of water to the lysimeter until the gravitational stop water movement. After the drainage stopped, the average volume was obtained by the difference between the applied volume (VA) and the drained volume (VD), resulting in the retained volume (VR). The average retained volume of the 4 lysimeters represented 100% of the water replacement and was fractionated into 75%, 50% and 25% of the Etr.

The magnetization of the water used in the experiment was performed using a Sylocimol Rural magnetizer; model Rural 3000, manufactured by Timol Indústria [9]. This magnetizer was deposited and maintained in a tank separate from the normal water tank during the crop cycle.

To evaluate the thermal stress of the crop, the Crop Water Stress Index (WSI) used by Carvalho et al. (2022) viewed in Eq. 1, whose index consists of assessing the damage caused by the low availability of water transported in the cultivars, mainly by the xylem and other physiological means.

$$WSI = \frac{(Tc - Tar)}{(Tc - Tar)UBL} - \frac{(Tc - Tar)LBL}{(Tc - Tar)LBL}$$

Where: WSI is Crop water stress index (varieties between 0 and 1); Tc is canopy temperature (°C); Tar is air temperature (°C); LBL is lower baseline (°C); UBL = upper baseline (°C).

To supply Equation 1, the air temperature (Tar) (ºC) was measured using a maximum and minimum thermometer installed at a representative point of the experiment's boundary conditions, and the leaf temperature was measured using a digital infrared thermometer, model TD-965 from the manufacturer Digimess. The lower baseline (LBL) and upper baseline (LBL) were determined by the lowest and highest air temperatures measured throughout the crop cycle, respectively.

The leaf temperature measurements always occur between 8:00 am and 10:00 am in the leaves of the middle third of each plant (Figure 1a). The leaf area (LA) was calculated using Eq. 2 proposed by Maldaner et al. (2009).

$$AF = 1{,}7582L^{1{,}7067}$$

Where: AF is the leaf area (cm²) and L is the widht of the leaf (cm).

The electrical conductivity (Figure 1b) and pH (Figure 1c) of the water used to irrigate also monitored.

(a) (b) (c)

Figure 01 - Measurements of leaf temperature (a), electrical conductivity (b) and pH (c) of irrigation water. Source: Authors (2024)

The data were subjected to analysis of variance using Sisvar v.5.8 software and when significant at the 5% probability level, multiple linear regression was used for quantitative variables and mean test

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for qualitative variables (Tukey $p<0.05$). The figures and tables were created using Excel® (MS) software.

RESULTS AND DISCUSSION

According to the analysis of variance in Table 2, there is an effect of the treatments on the isolated factors RH and period, as well as the interaction between the factors water type (A) and RH, and also RH and period (E). The discussion of the results was based on the unfolding of the interactions for the water stress index and leaf area, correlating when possible.

Table 02 - Analysis of variance for the variables water stress index (WSI) and leaf area (LA) in irrigated sunflower

Source of variation	**Mean squares**		
	GL	**WSI**	**Leaf area**
Block	3.00	0.02*	153110.17^{ns}
Water (A)	1.00	0.00^{ns}	1233722.02^{ns}
Water replacement (RH)	3.00	0.05**	84768635.19**
Period (E)	3.00	1.20**	183918005.37**
A x RH	3.00	0.02*	1304024.78*
A x E	3.00	0.00^{ns}	316778.39^{ns}
RH x E	9.00	0.02**	9993142.32**
A x RH x E	9.00	0.00^{ns}	301950.84^{ns}
Residue	93.00	0.00	382791.54
CV (%)		13.24	14.93

**, * - Significant at the 1% and 5% level, respectively. ^{ns} - Not significant. GL – Degree of freedom. CV (%) – coefficient of variation

In the unfolding of the interactions of the type of water within each RH significance was observed only at 75% of RH for the WSI (Table 3) and 50 and 75% for the AF (Table 4).

Table 03 - Unfolding of the interaction of the type of water within 75% water irrigation, for the crop water stress index variable

Irrigation water type	**Crop water stress index variable**
Normal	0.59 b
Magnetized	0.66 a

Different letters in the column are different at the 5% probability level.

Table 04 - Unfolding of the interaction of the type of irrigation water within the water replacements of 50 and 75%, for the leaf area variable

Irrigation water type	**Water replacement (%)**	
	50	**75**
Normal	4039.73a	5570.23a
Magnetized	3550.70b	4988.88b

Different letters in the column are different at the 5% probability level.

Based on the averages obtained, there was an increase of 11.86% in the WSI of sunflower when magnetized water was used in relation to normal water (Table 3). In the AF, it was seen that the use of magnetized water resulted in approximate reductions of 12.10% and 10.44% when 50 and 70% RH were used, respectively. This result is probably due to the increase in the electrical conductivity of the water (ECw) induced by the magnetic field in the irrigation water.

ECw is one of the parameters used to classify water according to salinity hazard and, although the types of water used in the study are in category C1 (low salinity water), it was observed that the 11.49% increase in ECw of magnetized water (166.52 µS cm^{-1}) compared to normal water (147.39 µS cm^{-1}) was sufficient to increase WSI and reduce AF during the sunflower cycle, which shows that this cultivar is sensitive to this level of ECw.

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Although both types of water used belong to category C1 (low salinity, ECw < 250 µS cm⁻¹), this classification is only indicative of general agronomic risk and does not eliminate differences within the low-salinity range itself. In the present study, the 11.49% increase in the electrical conductivity of magnetized water (from 147.39 to 166.52 µS cm^{-1}) altered the osmotic potential of the soil solution and, consequently, the water absorption gradient by the roots. This small variation, although not sufficient to reclassify the water into another salinity category, was physiologically significant for the sunflower cultivar BRS 323, which exhibited an increase in the water stress index (WSI) and a reduction in leaf area (AF).

Previous studies (e.g., Azevedo et al., 2018; Gheyi et al., 2016) have highlighted that even slight increases in salinity - especially in cultivars with moderate sensitivity - can reduce the osmotic potential of soil water and affect plant water uptake and transpiration. Thus, the observed effect does not result from excessive salinity, but from the physiological sensitivity of the crop to the increased osmotic pressure of magnetized water, which also undergoes physicochemical changes (such as cluster structure, ionic mobility, and pH) capable of modifying its interaction with the soil and the root system.

In the present study, the ECw of the soil solution was not calculated; however, it is known that water from the hydric replacement is made available via the substrate and ECw is one of the determining parameters in the quality of irrigation water, significantly influencing the potential for soil salinization (Gheyi et al. 2016), which may have occurred for RH's of 50 and 75%. Despite not measuring the soil solution ECw, the consistent monitoring of irrigation water conductivity and the clear physiological responses observed in WSI and AF provide strong indirect evidence that the slight increase in ECw of magnetized water influenced plant–soil interactions. In the unfolding of the interaction of RH within each type of irrigation water, it was observed that the adjusted mathematical models were linear for the WSI (Figure 2a) and quadratic for the AF (Figure 2b), which is similar for both types of water used in the experiment. The greater water supply to the soil increased plant hydration in the study and decreased the WSI. More hydrated plants have greater leaf water potential and higher transpiration rates that help to cool and reduce leaf temperature (Mendes et al. 2018). However, when used magnetized water, the maximum AF would only be obtained at a RH of 127.5% (5845.0 cm²), that is, outside the water range imposed in the study. This value was estimated from the vertex of the second-degree regression equation adjusted between AF and RH (Figure 2b), where the derived maximum point represents the theoretical optimum water replacement. Such behavior indicates that the magnetic treatment reduced the plant's ability to reach its potential leaf expansion within the tested RH range, suggesting that water quality limited the physiological performance of the cultivar.

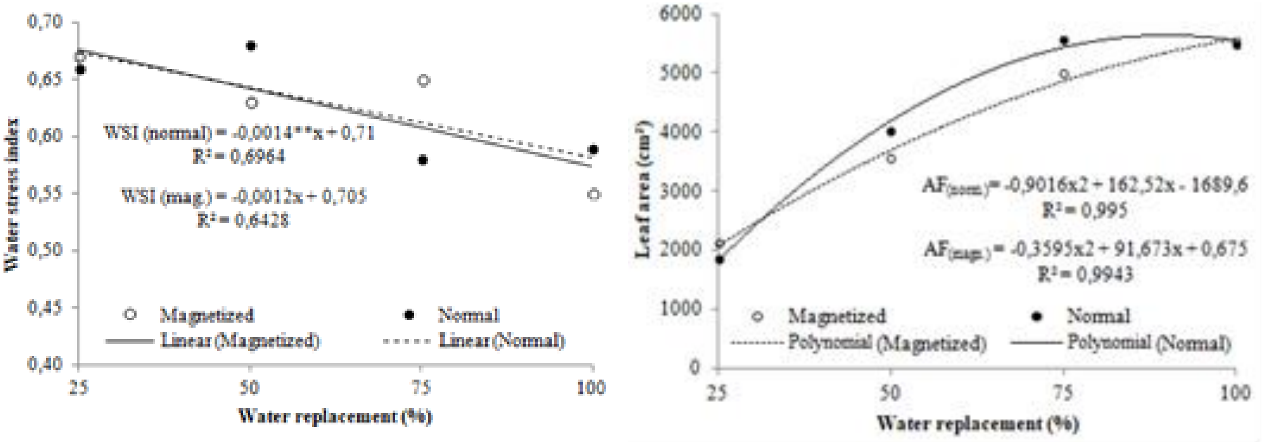

Figure 02 - Unfolding of the interaction of water replacement within each irrigation water type, for the variables WSI(a) and leaf area (b)

This is a typical condition of low water availability for plants due to its quality, since, even with 100% RH, it is clear that the imposed magnetic field prevented the sunflower from obtaining maximum AF in the trained RH range. According to Azevedo et al. (2018), in conditions of increased salinity, there is an increase in osmotic pressure, where plants do not provide sufficient suction forces to meet their water needs. When normal water is used in irrigation, maximum AF occurs at a RH of 90.13% (5634.25 cm²), that is, this cultivar does not require 100% of ETr to express its greatest

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growth potential in AF.

In the unfolding of the RH interaction within each period, there was significance only for 40 and 80 DAE (Figure 3a), with linear relationships in the WSI. The linear coefficients of the lines clearly show a greater sensitivity of the WSI with the variation of soil water for 80 DAE.

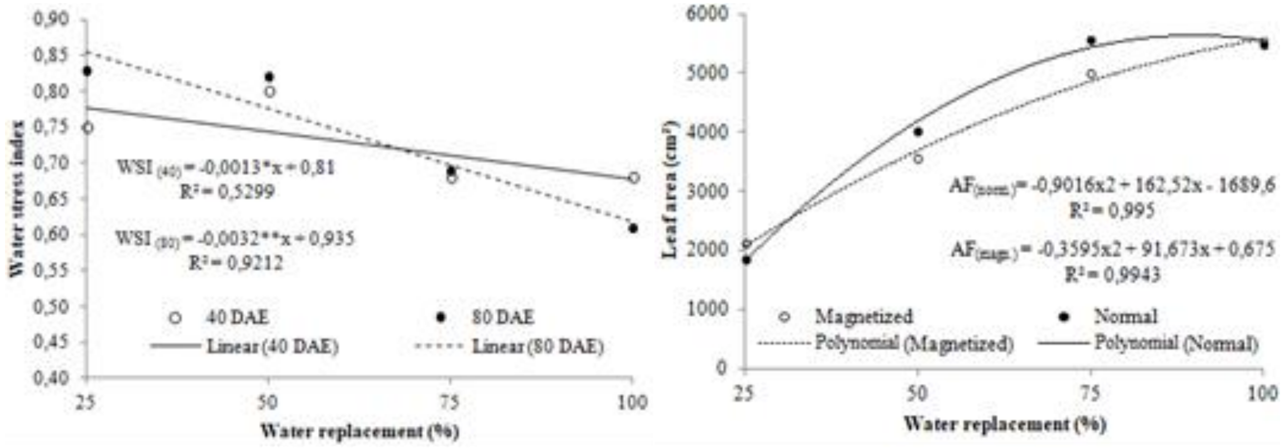

Figure 03 - Unfolding of the interaction of water substitution within each evaluation period, for the variables WSI (a) and leaf area (b)

At 40 and 80 DAE, the sunflower was in the R1 and R8/R9 stages, respectively. At the R1 stage, the sunflower has a floral bud with a star-shaped bract formation, while at R8 to R9 the development and physiological maturation of the achenes occurs (Castiglioni et al. 1997). Therefore, in the latter, the crop is in greater metabolic activity and more susceptible to variations in soil water, which explains the greater information on the line at this time. Corroborating this result, Hussain et al. (2018) explains that the effects of water stress on the sunflower do not depend on the development stage, but are most critical for exposure to high soil water content, germination, anthesis and achene filling, which can cause a reduction of up to 50% in its production.

Analyzing the unfolding of the interaction of RH within each period, for AF variable, the variance analyzes showed significance only for 40, 60 and 80 DAE (Figure 3b). The RH treatments were imposed from 12 DAE after accounting for more than 80% of emergence which explains the non-significance found for 20 DAE.

At 40 DAE the adjusted model was linear, and was increase of 68.99 cm² of AF (angular coefficient of the line) was observed for each 1% increase in RH, with a maximum of 8,166.9 cm² when using 100% RH. During this period the sunflower was in transition between the V-24 and R1 stages, characterized by the end of true leaf formation, with a sequence of expansion and increase in leaf area and appearance of inflorescence (flower bud). The increase in AF is an expansion process that depends on turgor pressure, that is, it is responsive to the greater water supply available.

At 60 and 80 DAE the sunflower produced the largest leaf areas with water replacement of approximately 89%. The increases were 7689.13 cm² (stage R6 – final concentration) and 6027.68 cm² (stage R9 – physiological maturity), respectively. At 60 days the sunflower requires greater photosynthetic activity than at 80 days. The leaf area is the part of the sunflower most favored by the adequate transport of available water and represents the assimilatory apparatus for the production of photosynthesis (Maia Júnior et al. 2016; Lopes and Lima 2015). After flowering, the reduction in water availability severely affected the leaves and the reduction of the photosynthetic apparatus resulted in the translocation via phloem of photo assimilates to the grains, altering the source and sink relationship (Hussain et al. 2018).

In Figure 4 it is possible to verify adjustments of second-order polynomials in the WSI. The adjusted curves show maximum WSI values of 0.83 (25% of RH at 68 DAE), 0.85 (50% at 84 DAE), 0.66 (75% of RH at 53 DAE) and 0.80 (100% of RH at 65 DAE). In summary, the greatest thermal stresses in the BRS 323 cultivar occurred when 25% and 50% of RH were applied.

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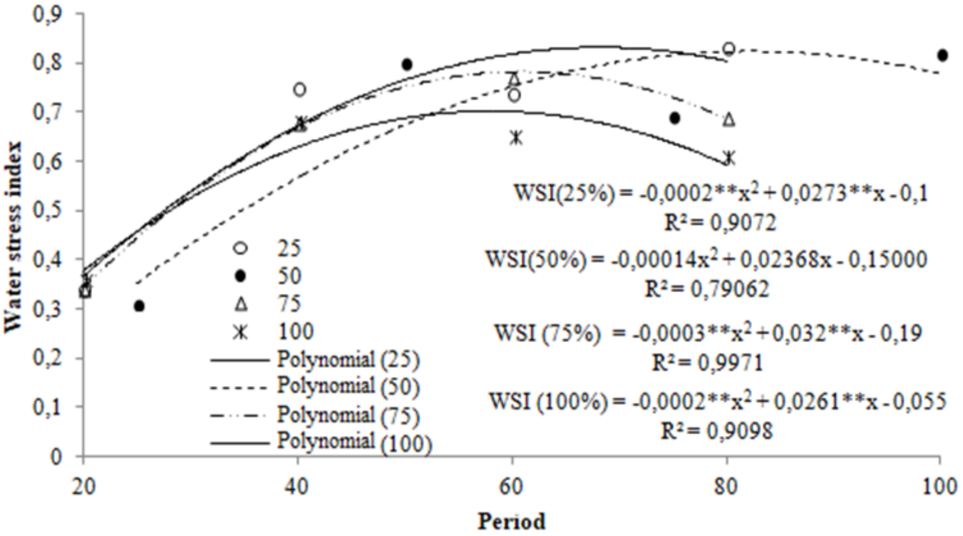

Figure 04 - Unfolding of the interaction of the evaluation period within each water replacement for the WSI variables

A second-order polynomial equation is also observed in Figure 5, in the unfolding of the interaction of the period within each RH, for the AF variable.

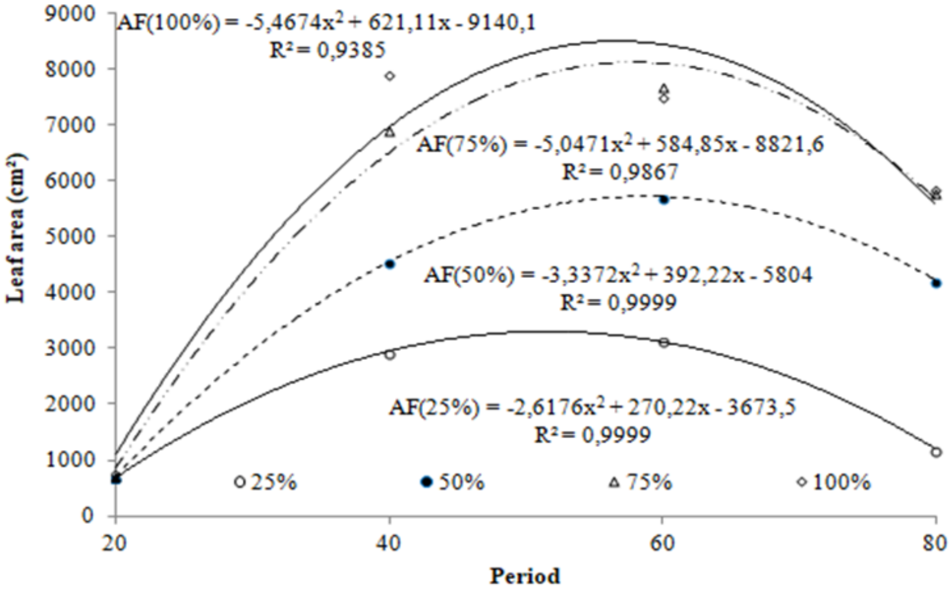

Figure 05 - Unfolding of the interaction of the period within each water replacement for the leaf area variable

According to the models, larger AF is observed in the R6 stages (final flowering) at 52, 59 and 58 DAE, respectively for 25% (3300.84 cm²), 50% (5720.37 cm²) and 75% (8121.27 cm²). This result shows that the largest leaf areas and their responses to water replacement precede the first phase of achene development (stage R7) aiming at a higher photosynthetic rate for translocation of photoassimilates to the reproductive organs. This statement corroborates the results described in the analysis in Figure 3b.

It is important to emphasize that any plant species only supports the AF that it can maintain and is dependent on the water availability of water in the soil, because, as the leaves grow, their capacity to produce photoassimilates increases until they reach maturity, which consists of their final growth, a phase in which photosynthetic rates then begin to decrease (Taiz and Zeiger 2016). In addition, the photoassimilates in each leaf vary according to the development of the plant, therefore, new leaves are initially considered as drains and only irreversibly transform into drains when they reach about 1/3 to ½ of their final size (Lopes and Lima 2015).

It is observed that the interaction between water availability, RH and period affect the sunflower in different ways, through the expression of the WSI and AF values seen in Figures 4 and 5. For Lopes and Lima (2015), the variation in the water regime of a plant affects its development and growth in a multifaceted way, modifying several characteristics such as anatomy, morphology, biochemistry and physiology. cell growth, as is the case of AF, consists of the physiological process most sensitive to the variation in water availability and this intrinsically affects the WSI, since transpiration is a process that the plant also uses to reduce thermal stress (cooling) preventing possible effects resulting from the increase in temperature (Castiglioni et al. 1997; Gomes et al. 2021; Silva et al. 2021).

Despite the consistency and robustness of the results obtained, this study acknowledges certain methodological limitations inherent to the experimental design. The electrical conductivity of the soil solution (ECw_soil) was not directly measured, which prevents a precise quantification of the osmotic effect magnitude associated with magnetized water. Consequently, the inferences regarding the relationship between ECw and the plants physiological responses are based on indirect estimations derived from the irrigation water, thereby constraining the quantitative interpretation of the ionic processes involved. It is therefore recommended that future studies perform direct measurements of soil solution ECw to enhance the understanding of the electrochemical and hydric dynamics within the soil–plant system under different water quality conditions.

CONCLUSIONS

Irrigation with magnetized water resulted in a reduction in leaf area and a consequent increase in the sunflower's water stress index, to the detriment of the use of normal water.

The crop's water stress index reduces linearly with the increase in soil water, regardless of the type of water used, as a result of better plant hydration.

The greatest water stresses in the BRS 323 cultivar occurred when 25% and 50% water replacement were applied at 68 and 84 DAE, respectively.

The theoretical maximum leaf area under magnetized water corresponds to a 127.5% water replacement, exceeding the range tested experimentally. This prediction is based on model calculations and was not directly observed.The magnetization of irrigation water increases water stress in sunflower, requiring higher than standard replenishment levels; thus, monitoring its electrical conductivity is essential to optimize irrigation and prevent physiological losses, and further field studies are needed to validate the agronomic viability of these practices.

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