Ornamental Horticulture
ISSN 2447-536X | WWW.ORNAMENTALHORTICULTURE.COM.BR
SBFPO
Sociedade Brasileira de Floricultura e Plantas Ornamentais

ARTICLE

Quantifying the effect of soil water deficit on transpiration, growth, development, and quality of cut sunflower

Quantificando o efeito do déficit hídrico no solo na transpiração, desenvolvimento e qualidade de girassol de corte

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Abstract: Water deficit is a major abiotic factor limiting the growth, development, and yield of cut sunflowers (*Helianthus annuus* L.). The Fraction of Transpirable Soil Water (FTSW) is a reliable approach to assess plant responses to soil water deficit and determine stomatal closure thresholds. The objective in this study was to quantify the effects of soil water deficit on plant transpiration, growth, development, and quality of cut sunflower using the Fraction of Transpirable Soil Water (FTSW) approach. A pot experiment was conducted under controlled conditions with two treatments: no deficit and deficit, applied during the reproductive phase. The results showed that water deficit reduced stem length (96.9 cm to 87.5 cm), stem diameter (0.86 cm to 0.59 cm), and capitulum diameter (5.5 cm to 4.0 cm). Dry biomass of roots, stems, leaves, and capitulum were also negatively affected by water deficit, confirming the sensitivity of cut sunflower to soil water availability. The threshold FTSW for transpiration was estimated at 0.62, indicating the onset of stomatal closure. These findings agree with previous studies on gladiolus and chrysanthemum, reinforcing similarities in stomatal regulation among ornamental species. Efficient water management based on FTSW is essential to mitigate the negative effects of water deficit and maintain the commercial quality of cut sunflowers. The FTSW approach proved to be a valuable tool for sustainable management in ornamental horticulture and can be adapted for other species grown under water-limiting conditions.
Keywords: cut flowers, FTSW, fraction of transpirable soil water, stomatal control, water use efficiency.

Resumo: O déficit hídrico é um importante fator abiótico que limita o crescimento, o desenvolvimento e a produção de girassóis de corte (*Helianthus annuus* L.). A Fração de Água Transpirável do Solo (FATS) é uma ferramenta confiável para avaliar as respostas das plantas ao déficit hídrico do solo e determinar os limiares de fechamento estomático. O objetivo neste estudo foi quantificar o efeito do déficit hídrico no solo na transpiração, crescimento, desenvolvimento e qualidade de girassóis de corte usando a abordagem FATS. Um experimento em vaso foi conduzido sob condições controladas com dois tratamentos: sem déficit e déficit, aplicados durante a fase reprodutiva. Os resultados mostraram que o déficit hídrico reduziu o comprimento do caule (96,9 cm para 87,5 cm), o diâmetro do caule (0,86 cm para 0,59 cm) e o diâmetro do capítulo (5,5 cm para 4,0 cm). A biomassa seca de raízes, caules, folhas e capítulo também foi afetada negativamente pelo déficit hídrico, confirmando a sensibilidade do girassol de corte à disponibilidade de água no solo. O limite crítico de FATS para transpiração foi estimado em 0,62, indicando o início do fechamento estomático. Estes resultados concordam com estudos anteriores em gladíolo e crisântemo, reforçando similaridades na regulação estomática entre espécies ornamentais. O manejo eficiente da água com base na FATS é essencial para mitigar os efeitos negativos do déficit hídrico e manter a qualidade comercial dos girassóis cortados. O método da FATS provou ser uma ferramenta valiosa para o manejo sustentável na horticultura ornamental e pode ser adaptado para outras espécies cultivadas em condições de limitação de água.
Palavras-chave: controle estomático, eficiência no uso da água, FATS, flores de corte, fração de água transpirável do solo.

Introduction

Flower industry is one of the most dynamic sectors of Brazilian agribusiness, with an average annual growth of 10% over the last decade, reaching a revenue of 20 billion Brazilian reals in 2023 (Ibraflor, 2024). Among cut flower crops, sunflower (*Helianthus annuus* L.) stands out for its agronomic and aesthetic traits. Agronomic traits of cut sunflower include high planting density (32 plants m^{-2}), short annual cycle (50 to 70 days), easy cultivation in open field, low production costs, and adaptability and stability in different edaphoclimatic (Tomasi et al., 2024) while aesthetic traits are related to the beauty of its floral stems for use in bouquets and floral arrangements, with a vase life of 10 to 15 days (Beckmann-Cavalcante et al., 2024; Tomiozzo et al., 2024). Because of these traits, cut sunflower was introduced in the first semester of 2021 during the seventh phase of the Flowers for All Project, the largest inclusive floriculture extension project in Brazil (Streck and Uhlmann, 2021; Fonseca et al., 2024; Streck et al., 2024; Alves et al., 2025).

Low soil water content is the major abiotic factor causing crops yield loss worldwide (Jan et al., 2025). Water deficit has major impacts on growth and development of cut sunflower, affecting leaf area, root system, stems, and flowers. During periods of water stress, the plant redirects its photosynthetic products to mechanisms that ensure its survival. During water deficit, photosynthesis can be reduced, leading to a lower rate of carbon assimilation and, consequently, a slower growth rate (Souza et al. 2024; Tomiozzo et al., 2024). As a result, crop productivity is reduced when water is limited (Alberto et al., 2006). Under water deficit conditions, plants regulate stomatal conductance to minimize water loss, which directly affects photosynthetic efficiency and yield (Chen et al., 2023). Additionally, leaf area reduction is a common response to water stress, impacting plant growth and transpiration rates (Casadebaig et al., 2021). The mechanism by which plants perceive soil water deficit is a topic of debate in plant physiology. There are two main hypotheses to explain how plants perceive soil water deficit (Streck, 2004): (i) hydraulic signals originating in the leaves and (ii) chemical signals from the roots. During the 1970s and 1980s, the predominant view was that hydraulic signals in the leaves were responsible for stomatal closure in response to drought. However, in the second half of the 1980s and early 1990s, emphasis shifted to chemical signals, primarily abscisic acid (ABA), produced in the roots and transported to the leaves via the xylem. Both mechanisms may work together, depending on the plant species and environmental conditions (Streck, 2004). This reinforces the importance of stomatal control and leaf hydraulic networks in plant adaptation to

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water deficit, aligning with the observations of Luo et al. (2021) regarding the influence of the leaf hydraulic network on water distribution and the maintenance of water pressure under drought conditions.

Cut sunflower is highly sensitive to soil water deficit, and therefore irrigation is a critical management practice to ensure high-quality floral stems with good postharvest longevity (Souza et al., 2024). A mechanistic with practical application approach used to evaluate plant response to soil water deficit is the Fraction of Transpirable Soil Water (FTSW), which considers the soil water content range used by plants for transpiration, from field capacity (maximum transpiration) to a point where plant transpiration is reduced to 10% of the maximum (Sinclair and Ludlow, 1986). Previous studies have shown that FTSW is a reliable indicator for evaluating plant responses to water deficit in ornamental crops like chrysanthemum (Kelling et al., 2015) and gladiolus (Becker et al., 2021).

The transpiration vs. FTSW response curve ranges from 0 to 1, starting at 1 when soil water content is at field capacity and decreasing to zero when soil water content results in 10% of maximum transpiration. The point where the transpiration curve departs from 1 and begins to decline is associated with stomatal closure, known as critical or threshold FTSW (FTSWth). The transpiration vs. FTSW curve has been used to understand the responses of agricultural species to water deficit and to identify water deficit-tolerant genotypes within the same species, such as rice (Davatgar et al., 2009), beans (Pohlmann et al., 2023), soybean (Goergen et al., 2023), potato (Lago et al., 2012), and ornamental species like chrysanthemum (Kelling et al., 2015) and gladiolus (Becker et al., 2021). Furthermore, knowledge on the response of growth and development variables as a function of FTSW has practical applications in crop modeling (Tironi et al., 2017) and in scheduling irrigation (Lima et al., 2022). However, no studies using FTSW have been conducted in cut sunflowers, which constituted the rationale for this study. The objective in this study was to quantify the effects of soil water deficit on plant transpiration, growth, development, and quality of cut sunflower using the Fraction of Transpirable Soil Water (FTSW) approach.

Materials and methods

A pot experiment with the hybrid of cut sunflower Vincent’s Choice (Figure 1) was conducted between February and April 2024 in Jaguari, RS, Brazil (latitude: 29°48’ S; longitude: 54°69’ W). The experiment was conducted inside a plastic greenhouse covered with a 200 µm thickness low-density polyethylene film to prevent rainfall on the plants. Minimum and maximum temperature, relative humidity and vapor pressure deficit was measured daily inside the plastic greenhouse near the plants using a digital thermo-hygrometer from Brookstone (indoor model), installed inside the greenhouse. The device has a temperature measurement range of 0 °C to 50 °C, with an accuracy of ± 1 °C, and a relative humidity range of 20% to 90%, with an accuracy of ± 5%. Measurements were recorded daily in the late afternoon throughout the experimental period.

The hybrid Vincent’s Choice was chosen because of its earliness and because of its widespread use among farmers in Brazil. The phenological stages of this hybrid during the crop cycle, based on the PhenoGlad scale (Tomiozzo et al., 2024), is in Fig. 1. The experimental design was completely randomized, with two water regimes: no water deficit (T1) and water deficit (T2), with 10 replicates per treatment. These water regimes followed the approach originally proposed by Sinclair and Ludlow (1986) and later used by Muchow and Sinclair (1991).

Each experimental unit (replicate) consisted of an 8 L plastic pot filled with soil and organic compost previously fertilized with NPK (05-20-20) at a rate of 50 g pot^{-1}. To minimize soil heating and reduce experimental errors, the outer walls of the pots were painted with white ink. The pots were placed on wooden benches, and three seeds were sown per pot. After emergence, only one seedling per pot was kept, selecting the most vigorous one.

Plant phenology was monitored daily using the PhenoGlad developmental scale for cut sunflower (Fig. 1, Tomiozzo et al., 2024). A leaf was considered visible when the apical leaflet reached at least 2 cm in length. The imposition of the water deficit began when the plants entered the visible but stage (R1 stage). Before starting the treatments T1 and T2, all pots were saturated with water and allowed to drain for 24 hours to reach field capacity. To prevent soil evaporation, each pot was covered with a white plastic film, and the initial mass of each pot was recorded.

The FTSW (Fraction of Transpirable Soil Water) methodology, developed by Sinclair and Ludlow (1986) and later expanded by Muchow & Sinclair (1991), was used to assess plant water stress based on transpiration. This methodology focuses on the plant physiological response to water availability, representing the fraction of available soil water that the plant can still utilize for transpiration. In order to ensure that the weight loss observed was due only to transpiration, three pots without plants were included to estimate and subtract any evaporation. This method ensures that the measured weight loss is exclusively attributed to transpiration, allowing accurate determination of the plant’s water use under different treatments. During the experimental period, plants under the water deficit treatment (T2) were irrigated with 50% of the water lost through transpiration, while plants in the no water deficit treatment (T1) were irrigated with 100% of the transpired water. The mass of all pots was measured daily in late afternoon using an electronic scale. Water lost through transpiration was determined by the difference between the pot mass on a given day and its initial mass. Average evaporation values were subtracted from the daily transpiration values to calculate plants relative transpiration.

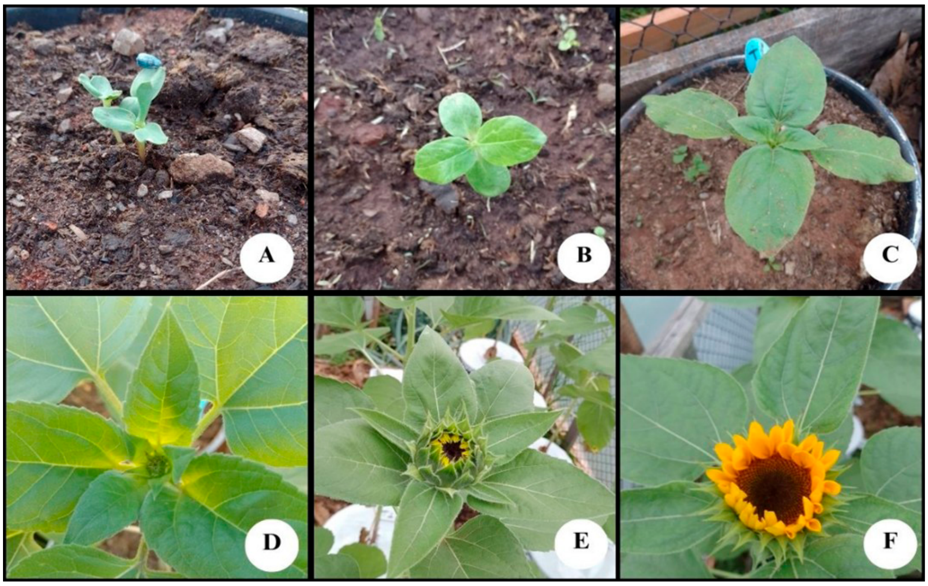

Fig. 1. Phenological stages of the cut sunflower Vincent’s Choice according to the PhenoGlad scale (Tomiozzo et al., 2024): A (V0), B (V2), and C (V6) correspond to developmental stages during the vegetative phase; D (R1), E (R4), and F (R5) correspond to developmental stages during the reproductive phase.

The following development, growth, and floral stem quality variables were measured: daily accumulated number of leaves, daily plant height (measured from soil level to the apex), stem diameter at the onset and at the end of the soil drying period, and capitulum diameter at the onset and at the end of the soil drying period. Although stem length, stem diameter, and capitulum diameter are growth variables, they were used as quality indicators in the context of this study due to their importance in classifying ornamental plants. “Stem length” and “stem diameter” reflect the plant structural robustness, while “capitulum diameter” is a crucial parameter for the aesthetic appeal of the flower, which is a fundamental criterion in floriculture.

The area of each leaf (LA) in each plant was measured daily from the start of the water deficit imposition until the end of the experiment. The LA of each leaf was calculated using the equation proposed by Maldaner et al. (2009):

$$LA = 0.733 \text{ x } (L \text{ x } W)$$

In which:
LA = leaf area ($cm^2\ leaf^{-1}$);
L = maximum leaf length (cm);
W = maximum leaf width (cm).

The total leaf area (TLA) was obtained by summing the leaf areas of all the individual leaves of the plant each day. The Fraction of Transpirable Soil Water (FTSW) was calculated using the equation described by Sinclair and Ludlow (1986):

$$FTSW = (MT2j - MT2final) / (MT2initial - MT2final)$$

In which:
MT2 = mass of each pot ($g\ pot^{-1}$) in the water deficit treatment (T2);
MT2initial = mass of the pot at the onset of the water deficit application;
MT2final = mass of the pot at the last day of the experiment;
j = day of measurement.

The experiment finished when all plants in the water deficit treatment (T2) reached a relative transpiration (RT) below 10% of the average transpiration of the plants in the no water deficit treatment (T1), assuming that below this transpiration rate stomata are closed and water loss occurs only through epidermal conductance (Sinclair and Ludlow, 1986). To describe the relationship between the reduction in transpiration and the decline in soil moisture, a logistic equation was used. This model allows for the estimation of the threshold at which plants begin to significantly reduce their transpiration rate in response to decreasing water availability. The logistic function has been widely adopted in plant physiology to model stomatal behavior under water-limited conditions (Sinclair and Ludlow, 1986).

The logistic equation used is (Muchow & Sinclair, 1991):

$$Y = 1 / [1 + \exp(-a (X - b))]$$

In which:
Y = dependent variable (RT);
X = FTSW;
a and b = empirical coefficients were estimated using nonlinear regression analysis performed in Microsoft Excel.

The threshold FTSW for RT was estimated using the logistic equation, considering 0.95 as the threshold value, as proposed by Weisz et al. (1994). The data were subjected to analysis of variance (ANOVA), and the means were compared using the Tukey test at a 5% probability of error.

Results and Discussion

During the experiment, the minimum and maximum air temperatures varied from 11.2 to 22.9 °C and from 29.3 to 40.8 °C, respectively. Relative humidity ranged from 53% to 92%, while the vapor pressure deficit varied between 5.6 and 33.1 kPa (Fig. 2).

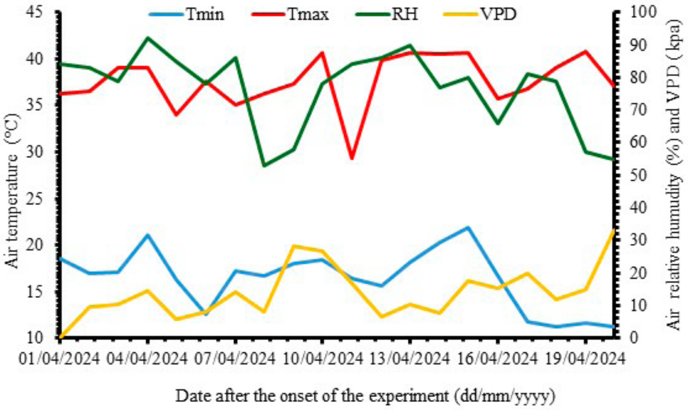

Fig. 2. Daily minimum (Tmin) and maximum (Tmax) air temperature, relative humidity (RH), and vapor pressure deficit (VPD) during the experiment.

Significant differences in floral stems quality variables were observed between the two water treatments (Table 1). Water deficit negatively impacted stem growth, reducing stem length from 96.9 cm (no deficit) to 87.5 cm (with deficit). Stem diameter also decreased from 0.86 cm to 0.59 cm, and capitulum diameter was reduced from 5.5 cm to 4.0 cm. These negative effects were visually evident at the end of the experiment (Fig. 3), where the impact of water deficit on plant vigor and overall quality was clear. Moura et al. (2022) reported that water availability plays a fundamental role in maintaining floral longevity and visual appeal, reinforcing the importance of a proper irrigation management to optimize flower durability and market value. This finding aligns with the present study, as water deficit negatively affected the morphological parameters essential for commercialization.

Table 1. Quality variables of floral stems of cut sunflower hybrid Vincent's Choice without and with soil water deficit.

Quality variables of floral stem	Treatments		CV (%)
	Without water deficit	With water deficit	
Stem length (cm)	96.9 a	87.5 b	6.80
Stem diameter (cm)	0.86 a	0.59 b	12.72
Capitulum diameter (cm)	5.5 a	4.0 b	13.08

Means followed by different lower-case letters in each row are statistically different according to Tukey test at a 5% probability of error. CV = Coefficient of variation.

Fig. 3. Visual comparison of cut sunflower hybrid Vincent's Choice plants under different soil water treatments. Plants on the left were subjected to soil water deficit while those on the right received full irrigation.

Dry mass of plant parts also showed significant reductions due to soil water deficit (Table 2). This reduction indicates the direct impact of soil water deficit on plant growth. These results indicate that reduced water availability in the soil directly affects plant growth and development, compromising quality and productivity, as reported previously for several agricultural crops (Alberto et al., 2006; Porto et al., 2014).

The roots of a plant are essential for the absorption of water and nutrients, which ensures its proper growth and development. Under water stress conditions, the root system may become less efficient at absorbing water and nutrients, leading to a further reduction in growth and yield (Souza et al., 2024). The reduction in root growth under water stress in this study agrees with the reduction on root growth of rice and maize under water stress (Kondo et al., 2000). Above-ground growth is generally more sensitive to water stress than root growth, and abscisic cid (ABA) produced in the roots is blamed to be responsible for non-hydraulic signals from those roots exposed to dry soil (Sharp and LeNoble, 2002).

Table 2. Dry mass of plant parts of cut sunflower hybrid Vincent's Choice at the end of the experiment without and with soil water deficit.

Plant part	Treatments		CV (%)
	Without water deficit	**With water deficit**	
Root (g pl^{-1})	7.8 a	3.6 b	29.24
Stem (g pl^{-1})	35.2 a	11.8 b	31.89
Leaves (g pl^{-1})	15.7 a	9.9 b	21.24
Capitulum (g pl^{-1})	10.4 a	4.6 b	24.50
Total dry mass (g pl^{-1})	69.3 a	28.9 b	23.74

Means followed by different letters in each row are statistically different according to Tukey test at a 5% probability of error. CV = Coefficient of variation.

The response of transpiration of cut sunflower plants as a function of the Fraction of Transpirable Soil Water (FTSW) followed a sigmoidal response curve (Fig. 4). The FTSWth for transpiration, which is the value of FTSW where stomata start to close, of the Vincent's Choice hybrid was estimated as 0.62 and values of FTSW above 0.62 enable plant to keep stomata open and therefore full intake of CO_2 for photosynthesis. The FTSWth for Vincent's Choice cut sunflower is close to the values for other flower crops such as the chrysanthemum cultivar Cherie White, whose stomatal closure occurs between 0.62 and 0.65 (Kelling et al., 2015), and for gladiolus in the between 0.60 and 0.65, depending on developmental stage (Becker et al., 2021).

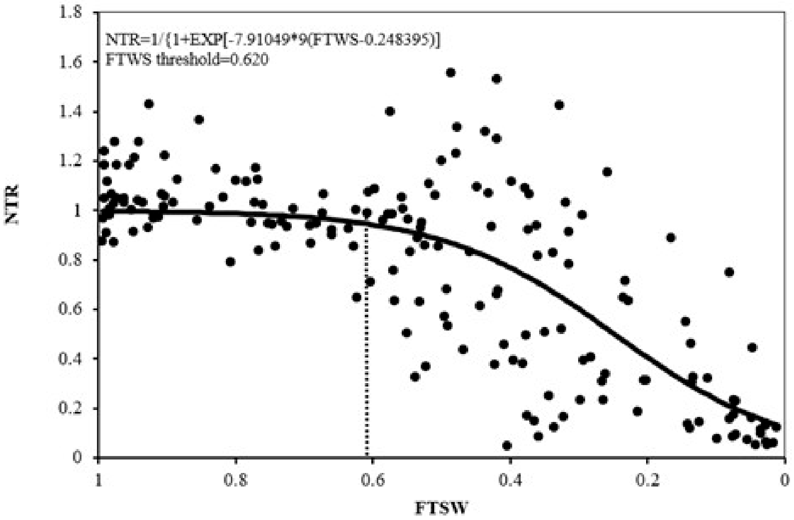

Fig. 4. Normalized relative transpiration (NTR) as a function of the fraction of transpirable soil water (FTSW) for cut sunflower cultivar Vincent's Choice during the soil water deficit period from 01/04/2024 to 20/04/2024. Dashed vertical line indicates the FTSW threshold where stomata start to close.

The leaf area dynamics of Vincent's Choice cut sunflower plants with and without soil water deficit are presented in Fig. 5. At the beginning of the experiment, plants in both treatments had the same leaf area. As soil moisture decreased, the plants grown under water stress (dashed line) consistently exhibited a lower leaf area than those in the well-watered treatment (solid line). The difference between the two treatments became more pronounced when the fraction of transpirable soil water (FTSW) dropped below 0.5. This decrease in leaf area can be attributed to stomatal closure as a way to minimize water loss and to a reduction in leaf growth capacity due to the lack of available soil water. In contrast, the plants in the no water deficit treatment (T1) maintained a constant leaf area and showed continuous healthy leaf growth throughout the experiment. The well-watered plants did not show signs of stomatal closure or limitations in leaf growth, resulting in a larger leaf area. This impact of water deficit on leaf growth reflects a physiological adaptation of the plants to water stress, where resource allocation is redirected to maintaining essential survival processes at the expense of vegetative growth. Leaf area is an important indicator of plant vigor and health, and its reduction indicates a decrease in photosynthetic capacity and, consequently, in plant productivity.

The findings in this study suggest that leaf growth became increasingly restricted by water availability after stomatal started to close (FTSWth = 0.62). The response is a direct consequence of a primary plant adaptation to soil water deficit (partial stomatal closure), which helps maintain mesophyll cell turgor and sustain cell elongation, ultimately influencing leaf area expansion (Streck, 2004; Becker et al., 2021). Similar results were reported by Zhou et al. (2022), who observed that under mild water deficit, stomatal limitation was the primary factor reducing the photosynthetic capacity of sunflower leaves, while under severe water stress, non-stomatal limitations became dominant, further constraining leaf growth.

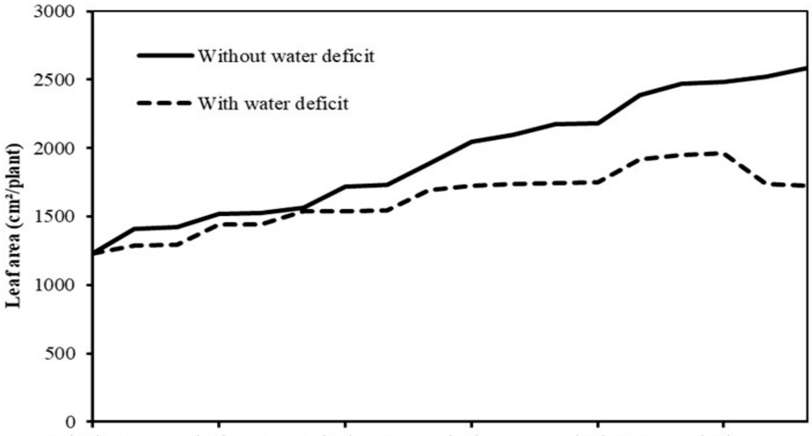

Fig. 5. Leaf area per plant of Vincent's Choice cut sunflower throughout the experimental period under two water regimes: no water deficit (T1) and water deficit (T2).

Plants with and without soil water deficit reached the R5 stage (open flower) 15 days after the start of the experiment indicating that although water deficit affected quality variables of floral stems (Table 1), the development rate was not affected by water stress. The hypothesis for these results is that water stress started after the plants entered the reproductive phase and there was no enough time for water stress to cause negative impacts on cell differentiation and other underling processes that drive development of the cut sunflower plant towards completing the reproductive phase.

Conclusions

The use of the Transpirable Soil Water Fraction (FTSW) approach was effective in evaluating the effects of water deficit on cut sunflower, demonstrating its applicability as a tool to identify transpiration threshold and impacts on plant growth and quality. The results showed that water deficit significantly reduces morphological and physiological parameters essential for commercialization, reinforcing the importance of water management strategies based on FTWS. This method can be extended to other ornamental crops, contributing to more effective management under water stress conditions.

Acknowledgments

This study was conducted during the 13rd phase of the Flowers for All Project, that provided the management practices throughout the experiment.

Author Contribution

MLS: Conceptualization, Investigation, Data Curation, Formal Analysis, Writing – Original Draft, Writing – Review & Editing. **MESF**: Conceptualization, Investigation, Data Curation, Writing – Review & Editing. **ALS**: Investigation. **RT:** Investigation, Data Curation, Formal Analysis. **LOU**: Investigation, Supervision, Writing – Review & Editing. **LLB**: Supervision. **AJZ**: Supervision. **NAS**: Conceptualization, Methodology, Supervision, Formal Analysis, Project Administration. Writing – Review & Editing

Conflict of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability

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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