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

ARTICLE

Water deficit affects transpiration, growth and flower quality of cut sunflower even after rehydration

O déficit hídrico afeta a transpiração, o crescimento e a qualidade das flores do girassol de corte mesmo após a reidratação

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Abstract
Low soil water availability limits agricultural productivity, including that of cut sunflower (*Helianthus annuus* L.). Two experiments were conducted using a completely randomized design under two water regimes: with and without water deficit. In Experiment 1, the Vincent's Choice hybrid was evaluated. In Experiment 2, the Vincent's Choice and Vincent's Fresh hybrids were evaluated. In both experiments, plants subjected to water deficit were subsequently rehydrated to field capacity. Evaluations were based on the Fraction of Transpirable Soil Water (FTSW) methodology. In Experiment 1, water deficit followed by rehydration significantly reduced floral stem quality. Stem length decreased from 86.8 to 66.4 cm, stem diameter from 0.82 to 0.62 cm, and capitulum diameter from 7.5 to 4.6 cm. Dry biomass was also reduced. The FTSW threshold (FTSWth) was 0.63. In Experiment 2, stem length, stem diameter, and capitulum diameter decreased from 122.4 to 103.2 cm, 0.87 to 0.61 cm, and 7.9 to 5.7 cm, respectively, in Vincent's Choice. In Vincent's Fresh, these variables decreased from 132.9 to 97.6 cm, 0.99 to 0.62 cm, and 9.0 to 6.3 cm, respectively. The FTSWth was 0.58 for Vincent's Choice and 0.52 for Vincent's Fresh. Water deficit followed by rehydration caused persistent reductions in growth, biomass accumulation, and floral stem quality, and rehydration was insufficient to restore plant performance.
Keywords: Gas exchange, *Helianthus annuus,* Transpirable water fraction, Water restriction.

Resumo
A baixa disponibilidade de água no solo limita a produtividade agrícola, incluindo a do girassol de corte (*Helianthus annuus* L.). Foram conduzidos dois experimentos em delineamento inteiramente casualizado, sob dois regimes hídricos: com e sem déficit hídrico. No Experimento 1, foi avaliado o híbrido Vincent's Choice. No Experimento 2, foram avaliados os híbridos Vincent's Choice e Vincent's Fresh. Em ambos os experimentos, plantas submetidas ao déficit hídrico foram posteriormente reidratadas até a capacidade de campo. As avaliações foram baseadas na metodologia da fração de água transpirável no solo (FATS). No Experimento 1, o déficit hídrico seguido de reidratação reduziu significativamente a qualidade das hastes florais. O comprimento da haste diminuiu de 86,8 para 66,4 cm, o diâmetro da haste de 0,82 para 0,62 cm e o diâmetro do capítulo de 7,5 para 4,6 cm. A biomassa seca também foi reduzida. A FATS crítica foi 0,63. No Experimento 2, o comprimento da haste, o diâmetro da haste e o diâmetro do capítulo diminuíram de 122,4 para 103,2 cm, de 0,87 para 0,61 cm e de 7,9 para 5,7 cm, respectivamente, em Vincent's Choice. Em Vincent's Fresh, essas variáveis diminuíram de 132,9 para 97,6 cm, de 0,99 para 0,62 cm e de 9,0 para 6,3 cm, respectivamente. A FATS crítica foi 0,58 para Vincent's Choice e 0,52 para Vincent's Fresh. O déficit hídrico seguido de reidratação causou reduções persistentes no crescimento, no acúmulo de biomassa e na qualidade das hastes florais, e a reidratação foi insuficiente para restabelecer o desempenho das plantas.
Palavras-chave: Fração de água transpirável, *Helianthus annuus*, Restrição hídrica, Trocas gasosas.

Introduction

The flower and ornamental plant industry is a strategic segment of Brazilian agribusiness and contributes to income generation throughout the production and retail chain. In 2026, Mother's Day sales reached the 10% growth projected by Ibraflor, marking the third consecutive year of retail growth, although performance varied among regions (Ibraflor, 2026). Cut flowers were also highlighted among the main products marketed during commemorative dates.

Among cut flower crops, sunflower (*Helianthus annuus* L.) combines agronomic and ornamental characteristics that favor its production and commercialization. These include high planting density, a short cycle of approximately 50 to 70 days, simple field management, low production costs, and adaptability to different soil and climatic conditions (Tomasi et al., 2024). Its ornamental value is associated with its visual appeal in bouquets and floral arrangements and a vase life ranging from 10 to 15 days (Tomiozzo et al., 2024).

These characteristics motivated its introduction in 2021 in the seventh phase of the Flowers for All Project, the largest inclusive floriculture extension initiative in Brazil (Streck and Uhlmann, 2021; Fonseca et al., 2024, 2026; Tomiozzo et al., 2024; Alves et al., 2025).

Low soil water availability is a major abiotic factor limiting crop productivity, including that of cut sunflower (Tran et al., 2024; Simon et al., 2025). In sunflower, drought stress reduces leaf expansion, root growth, stem elongation, and capitulum development, while assimilates are redirected to survival processes at the expense of growth and yield (Shen et al., 2023). Water deficit reduces photosynthesis and carbon assimilation (Earley et al., 2024), with stomatal regulation playing a key role in minimizing water loss but also restricting biomass accumulation (Smaeili et al., 2022). Plant responses to drought involve an interaction between hydraulic and chemical signals, especially abscisic acid (ABA) synthesized in roots, transported to leaves, and interacting with leaf hydraulic networks (Luo et al., 2021; Shen et al., 2023).

Cut sunflower is highly sensitive to water deficit, making irrigation a key practice to ensure high-quality floral stems and satisfactory postharvest performance (Tomiozzo et al., 2024). A mechanistic approach widely used to evaluate plant responses to soil water deficit is the Fraction of Transpirable Soil Water (FTSW), which quantifies the fraction of available water used by plants for transpiration, ranging from field capacity (maximum transpiration) to the point where transpiration declines to 10% of maximum (Sinclair and Ludlow, 1986). The transpiration vs. FTSW response curve has been applied in various species, both agricultural and ornamental, to identify drought-tolerant genotypes and understand physiological responses, such as rice (Davatgar et al., 2009), beans (Pohlmann et al., 2022), soybean (Goergen et al., 2023), potato (Lago et

*Corresponding author: marizanesimon@gmail.com | https://doi.org/10.1590/2447-536X.v32.e3119 | Editor: Gilmar Schafer, Universidade Federal do Rio Grande do Sul, Brasil. | Received: May 04, 2026 | Accepted: Oct 02, 2026 | Available online: Nov 16, 2026 | Licensed by CC BY 4.0 (https://creativecommons.org/licenses/by/4.0/)

al., 2012), chrysanthemum (Kelling et al., 2015), gladiolus (Becker et al., 2021), and cut sunflower (Simon et al., 2025). In addition to transpiration, FTSW has been successfully used in crop simulation models and irrigation management (Lago et al., 2012; Kelling et al., 2015; Becker et al., 2021).

Periods of water deficit may be followed by rainfall or irrigation that restores soil moisture. However, it remains unclear whether this return of water availability is sufficient for commercial cut sunflower hybrids to recover transpiration, growth, biomass accumulation, and floral stem quality.

A previous study evaluated the response of the cut sunflower hybrid Vincent's Choice to soil water deficit and reported an FTSW threshold (FTSWth) of 0.62 (Simon et al., 2025). The present study extends this work by evaluating responses to water deficit followed by rehydration and their effects on floral stem quality. Vincent's Fresh was selected as the second hybrid because it is used in cut sunflower research conducted by the PhenoGlad team and seeds were available for the experiment. Its inclusion allowed these responses to be evaluated in a second commercial hybrid alongside Vincent's Choice.

The objective of this study was to evaluate the effects of soil water deficit followed by rehydration on transpiration, growth, biomass accumulation, and floral stem quality in the commercial cut sunflower hybrids Vincent's Choice and Vincent's Fresh, and to estimate the fraction of transpirable soil water threshold (FTSWth) for each hybrid.

Materials and Methods

Two pot experiments were conducted using cut sunflower hybrids in a rain shelter covered with low-density polyethylene (200 µm thickness), located in Jaguari, Rio Grande do Sul, Brazil (latitude: 29.4973° S; longitude: 54.6916°W). Experiment 1 was sown on February 13, 2025, using the hybrid Vincent's Choice, and Experiment 2 was sown on October 2, 2025 using the hybrids Vincent's Choice and Vincent's Fresh.

A completely randomized design was adopted in both experiments, with two water regimes: with and without water deficit. In Experiment 1, thirty plants of Vincent's Choice were divided into three groups of ten: plants maintained without water deficit, plants harvested at the end of the water deficit phase, and plants subjected to water deficit followed by rehydration. In Experiment 2, twenty plants per hybrid were used: ten maintained without water deficit and ten subjected to water deficit followed by rehydration. Once the relative transpiration of plants with water deficit decreased to less than 10% of the average transpiration of plants without water deficit, these same plants were rehydrated and maintained until flowering, constituting the with water deficit followed by rehydration treatment.

Each experimental unit consisted of one plant grown in a 5 L plastic pot. To reduce solar radiation absorption and minimize soil heating, the outer surface of the pots was painted white. The pots were filled with a loamy-textured soil collected from the A horizon of the São Pedro mapping unit, according to the Brazilian Soil Classification System (Santos et al., 2025).

Three seeds were sown per pot. After emergence, when plants reached the V0 phenological stage, characterized by fully expanded cotyledons forming an angle of approximately 180°, seedlings were thinned, leaving one plant per pot. Plant development was monitored daily according to the PhenoGlad developmental scale for cut sunflower (Tomiozzo et al., 2024) until the beginning of the water treatments.

Before the water treatments were imposed, all pots were saturated with water and allowed to drain freely for 20-24 h until field capacity was reached. Subsequently, the opening of each pot was covered with plastic film, with the white side facing upward. The film was secured around the pot rim with a rubber strip cut from a tire inner tube, leaving only the plant exposed so that water loss through plant transpiration could be quantified by weighing the pots. The initial mass of each pot was then recorded. Pot mass was measured daily in the late afternoon using an electronic balance. Daily water loss was determined as the difference between the pot mass on the day of measurement and the mass of the same pot on the previous day.

Plant responses to soil water deficit were evaluated using the Fraction of Transpirable Soil Water (FTSW) methodology proposed by Sinclair and Ludlow (1986) and later adapted by Muchow and Sinclair (1991). To ensure that pot weight loss resulted exclusively from plant transpiration, three pots without plants were included to estimate soil evaporation. The average evaporation was subtracted from the daily weight loss of the planted pots before calculating relative transpiration (TR). The data were analyzed individually for each pot by relating TR to FTSW. Relative transpiration was calculated according to Sinclair and Ludlow (1986) as the ratio between the daily water loss of plants subjected to the with water deficit treatment and the average daily water loss of plants maintained without water deficit. The resulting TR values were subjected to the first normalization (TR), as proposed by Sinclair and Ludlow (1986), so that normalized values ranged from 0 to 1. The Fraction of Transpirable Soil Water (FTSW) was calculated according to Sinclair and Ludlow (1986) using the initial pot mass at the beginning of the water deficit treatment, the final pot mass at the end of the water deficit period, and the pot mass measured on each evaluation day.

In Experiment 1, water deficit was imposed on March 9, 2025, at 24 days after sowing, when plants were between the V7 and V8 phenological stages. Rehydration began on March 29, at 44 days after sowing, when plants were at R1. Rehydrated and well-watered plants were harvested at R5 on April 15, at 61 days after sowing. Plants under water deficit received daily irrigation equivalent to 50% of the water lost through transpiration, resulting in a gradual reduction in soil water availability. Plants without water deficit received daily replacement of 100% of the transpired water. The water deficit period ended when plants reached a relative transpiration below 10% of the average transpiration of plants without water deficit. Plants assigned to the with water deficit followed by rehydration treatment were then irrigated until field capacity was restored and maintained until flowering, allowing the evaluation of growth recovery and floral quality.

In Experiment 1, dry biomass was evaluated in three groups of ten plants each. One group was harvested at the end of the water deficit period, when TR was below 10% of the control and plants were at R1. Another group was rehydrated to field capacity at R1 and maintained until flowering. These plants were harvested together with the ten plants maintained without water deficit to compare biomass accumulation between well-watered and rehydrated plants. Thus, plants harvested at the end of the deficit and after rehydration were sampled at different developmental stages.

In Experiment 2, water deficit was imposed on October 26, 2025, at 24 days after sowing, when plants were between the V7 and V9 phenological stages. Plants without water deficit received daily irrigation equivalent to 100% of the transpired water, whereas plants with water deficit received no irrigation throughout the stress period. After relative transpiration decreased below 10% of the average transpiration of plants without water deficit, these same plants were rehydrated to field capacity and maintained until flowering, constituting the with water deficit followed by rehydration treatment. Rehydration began on November 7, at 36 days after sowing, when plants were at R1. Rehydrated and well-watered plants were harvested at R5 on November 25, at 54 days after sowing. For each hybrid, dry biomass was evaluated at flowering using ten well-watered plants and ten plants subjected to water deficit followed by rehydration.

The variables evaluated included plant height, leaf area, final leaf number, stem diameter, capitulum diameter, phenological development, relative transpiration (TR), Fraction of Transpirable Soil Water (FTSW), and dry biomass of roots, stems, leaves, capitula, and total plant biomass. Stem length corresponded to final plant height at harvest, measured from the base of the plant to the capitulum.

Air temperature and relative humidity were monitored using a digital thermo-hygrometer placed on the bench near the plants. Because the sensor was not housed in a radiation shield, the records were considered only as an approximate characterization of the experimental environment and were not used for quantitative analyses. The following growth and floral stem quality variables were measured: daily leaf number, daily plant height (measured from soil level to the apex), and stem and capitulum diameters at the end of the water deficit phase and at harvest. 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. For dry biomass determination, harvested plants were separated into roots, stems, leaves, and capitula, and the material was oven-dried at 65 °C before weighing.

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):

$$LA = 0.733\ x\ (L\ x\ W)$$

In which:
LA = leaf area (cm²/leaf);
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 on the last day of the water deficit phase, before rewatering;
j = day of measurement.

The logistic function has been widely used in plant physiology to model stomatal response under water-limited conditions (Sinclair and Ludlow, 1986).

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

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

Where Y is normalized relative transpiration (NTR), X is FTSW, and a and b are empirical coefficients estimated by nonlinear regression using the Solver tool in Microsoft Excel, by minimizing the sum of squared residuals between observed and predicted TR values.

The FTSW threshold (FTSWth) was calculated as the FTSW value corresponding to TR = 0.95 on the fitted logistic curve, following (Weisz et al. 1994). Differences between threshold estimates were interpreted descriptively, as no formal statistical comparison was performed.

The dates of the R1 (visible flower bud), R4 (petal color visible), and R5 (harvest stage) stages were recorded through daily observations of all plants, following the PhenoGlad developmental scale for cut sunflower (Tomiozzo et al., 2024).

Growth, biomass, and floral stem quality variables were subjected to analysis of variance (ANOVA) using SISVAR. In Experiment 2, a two-way ANOVA was performed with hybrid and water regime as factors, including their interaction. Means were compared using Tukey's test at the 5% significance level.

Results and Discussion

During Experiment 1, the recorded minimum air temperature ranged from 10 to 23 °C, with a mean of 17.4 °C, whereas maximum temperature ranged from 23 to 40 °C, with a mean of 33.1 °C. Relative humidity ranged from 31% to 81%, averaging 56.7%.

Before rehydration, plants subjected to water deficit showed visible symptoms of water stress, including leaf wilting, whereas plants maintained without water deficit showed no evident wilting (Fig. 1). These symptoms are consistent with reduced leaf turgor under limited water availability. The photograph documents plant appearance before rehydration; subsequent recovery was assessed using growth, biomass, and floral stem quality measurements. The effects of water replacement levels on growth and production have also been investigated in gladiolus (Porto et al., 2014). In the present study, the visual symptoms complement the measured responses of cut sunflower to water deficit.



Fig. 1. Plants of the cut sunflower hybrid Vincent's Choice with and without water deficit in Experiment 1, photographed before rehydration. Plants from both treatments are intercalate in the photograph.

Significant differences in floral stem quality variables were observed between well-watered and rehydrated water-deficit sunflower plants in Experiment 1 (Table 1). Water deficit even followed by rehydration negatively impacted stem growth and quality. Stem length decreased from 86.8 cm (without deficit) to 66.4 cm (rehydrated), corresponding to a 23.5% reduction. Stem diameter decreased from 0.82 cm to 0.62 cm (a 24.4% reduction), while capitulum diameter reduced from 7.5 cm to 4.6 cm (a 38.7% reduction).

Stem length, stem diameter, and capitulum diameter are also used to characterize cut sunflower production in the Flowers for All Project. These traits provide a practical basis for evaluating floral stem quality and interpreting the growth responses observed in the present study (Streck et al., 2022).

Lechner et al. (2008) showed that sunflower leaves can resume expansion after rewatering, but the extent of recovery decreases as the interval between growth cessation and rewatering increases. Although their study evaluated leaf expansion rather than floral stem quality, it demonstrates that growth recovery depends on the timing of water restoration. In the present study, rehydration at R1 was insufficient to restore stem length, stem diameter, and capitulum diameter to the levels observed in plants maintained without water deficit.

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

Quality variables of floral stem	Treatments			
	Without water deficit	With water deficit and rehydration	CV (%)	Reduction (%)
Stem length (cm)	86.8 ± 2.25 a	66.4 ± 2.25 b	9.29	23.5
Stem diameter (cm)	0.82 ± 0.03 a	0.62 ± 0.03 b	12.76	24.4
Capitulum diameter (cm)	7.5 ± 0.19 a	4.6 ± 0.19 b	9.66	38.7

Values are presented as means ± standard error of the mean (SEM). Means followed by different lowercase letters in the same row differ according to Tukey's test ($p \leq 0.05$). CV = coefficient of variation.

Rehydration was insufficient to restore biomass accumulation in Vincent's Choice plants to the levels observed in plants maintained without water deficit (Table 2). At harvest (R5), total dry mass was 48.2 g plant^{-1} in plants without water deficit and 18.5 g plant^{-1} in plants subjected to water deficit followed by rehydration. Rehydrated plants also had lower dry mass in leaves (7.8 versus 14.7 g plant^{-1}), capitula (3.2 versus 5.0 g plant^{-1}), stems (5.8 versus 23.3 g plant^{-1}), and roots (1.7 versus 5.2 g plant^{-1}). These results indicate that the effects of water deficit on biomass accumulation persisted until harvest, despite the restoration of soil water availability.

The lower dry biomass observed in rehydrated plants at R5 indicates that restoring soil water availability at R1 was insufficient to compensate for the effects of the preceding water deficit on biomass accumulation by harvest. This finding is consistent with the reductions in stem length, stem diameter, and capitulum diameter, showing that both biomass accumulation and floral stem quality remained below the levels observed in plants maintained without water deficit.

Simon et al. (2025) reported adverse effects of soil water deficit on transpiration, growth, and floral quality of cut sunflower. The present study extends these findings by evaluating plants maintained until harvest after rehydration. Although water availability was restored, the differences between rehydrated plants and plants maintained without water deficit persisted at R5. These results highlight the importance of preventing soil water deficit during production, since subsequent rehydration may not be sufficient to restore biomass accumulation and commercial floral stem quality.

Limited water availability has been shown to reduce stem and root dry mass in potted ornamental sunflower Choco Sun (Li et al., 2020). Although that study did not evaluate rehydration, the present results show that lower stem and root dry mass persisted until harvest in Vincent's Choice plants subjected to water deficit followed by rehydration. Together with the reductions in floral stem quality, these findings indicate that restoring soil water availability at R1 was insufficient to bring plant performance to the levels observed in plants maintained without water deficit. The incomplete recovery of biomass after rehydration was consistent with the persistent reductions observed in floral stem quality, demonstrating that visual recovery of leaf turgor does not necessarily represent complete recovery of plant performance. Similar negative effects of soil water deficit on transpiration, growth, and floral quality of cut sunflower were reported by Simon et al. 2025. From a practical perspective, these results indicate that irrigation management in cut sunflower should prioritize the prevention of soil water deficit, since subsequent rehydration may restore plant water status but may not fully recover biomass accumulation and floral stem quality.

Table 2. Dry mass of plant parts of cut sunflower hybrid Vincent's Choice at the end of the Experiment 1 without and with soil water deficit.

Plant part	Treatments			
	Without water deficit	With water deficit	With water deficit and rehydration	CV (%)
Roots (g plant^{-1})	5.2 ± 0.42 a	1.3 ± 0.42 b	1.7 ± 0.42 b	48.65
Stem (g plant^{-1})	23.3 ± 0.63 a	4.8 ± 0.63 b	5.8 ± 0.63 b	25.23
Leaves (g plant^{-1})	14.7 ± 1.20 a	4.2 ± 1.20 b	7.8 ± 1.20 b	42.63
Capitulum (g plant^{-1})	5.0 ± 0.22 a	0.83 ± 0.22 c	3.2 ± 0.22 b	22.57
Total dry mass (g plant^{-1})	48.2	11.13	18.5	

Means followed by different letters in each row are different according to Tukey's test ($p \leq 0.05$). CV = Coefficient of variation.

The leaf area dynamics of Vincent's Choice cut sunflower plants under different water regimes are presented in Fig. 2. Plants subjected to water deficit (dashed line) showed lower leaf area than plants maintained without water deficit (solid line) during the drying phase. In plants subjected to water deficit followed by rehydration (dotted line), leaf area increased again during the later evaluations but remained below that of plants maintained without water deficit. These results indicate that restoring water availability was insufficient to bring leaf area to control levels during the evaluated period. Plants subjected to water deficit followed by rehydration also reached R4 (petal color visible) later than plants maintained without water deficit.

Sunflower leaves can resume expansion after rewatering, but the extent of this response depends on the interval between growth cessation and water restoration (Lechner et al., 2008). In the present study, leaf area increased during the later evaluations after rehydration but remained below that of plants maintained without water deficit (Fig. 2). Thus, the renewed increase in leaf area did not compensate for the difference established during the water deficit period within the evaluated timeframe. These results highlight the distinction between resumption of leaf growth and restoration of leaf area to the levels observed in plants maintained without water deficit.

Responses to water restoration have also been investigated in *Isatis indigotica*, in which compensatory growth occurred after mild water deficit, whereas moderate and severe deficits reduced total dry matter accumulation (Zhou et al., 2022). Although the species and irrigation protocols differed, these findings provide context for the lower biomass observed at harvest in rehydrated cut sunflower plants, highlighting that restoring water availability does not necessarily compensate for the preceding effects of water deficit.

Reduced leaf growth under declining water availability has also been reported in chrysanthemum, where leaf growth began to decrease before transpiration was restricted (Kelling et al., 2015). Although recovery after rehydration was not evaluated in that study, its findings support the sensitivity of leaf growth to water limitation in ornamental plants.

Plant height increased during the evaluation period in Experiment 1 (Fig. 3). During the initial evaluations, plants showed similar growth across water regimes. As the water deficit progressed, plants maintained without water deficit showed a greater increase in height than plants

subjected to water deficit. Plants subjected to water deficit followed by rehydration continued to grow after rewatering but remained shorter than plants maintained without water deficit. At harvest, mean plant height was 86.8 cm in plants without water deficit and 66.4 cm in rehydrated plants (Table 1), representing a difference of 20.4 cm. Thus, continued growth after rehydration was insufficient to compensate for the height difference established during the water deficit period. Adequate water supply is important for floral stem growth and quality in ornamental species. In gladiolus, irrigated plants produced longer floral stems and spikes, larger stem diameters, and more flowers per spike than non-irrigated plants (Lima et al., 2022). These findings support the importance of water availability for commercial stem characteristics, although recovery after rehydration was not evaluated in that study. Thus, restoring water availability did not compensate for the difference in stem length by harvest.

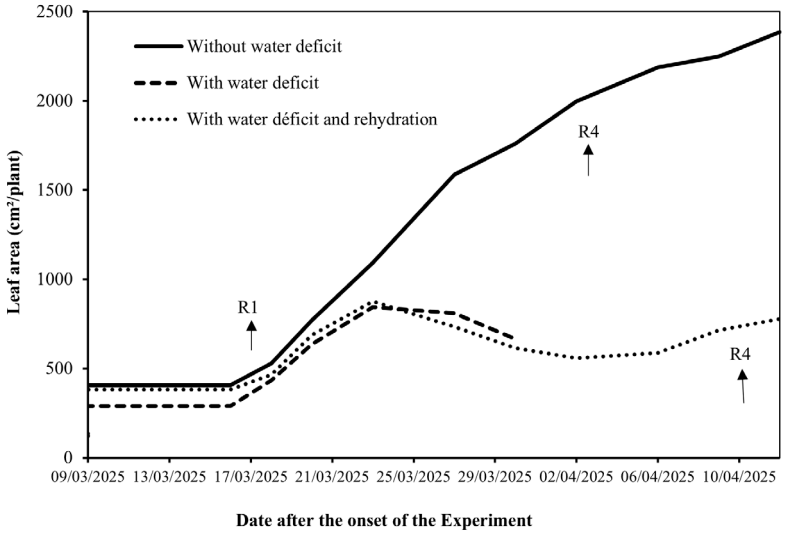

Fig. 2. Leaf area per plant of cut sunflower hybrid Vincent's Choice throughout Experiment 1 under water regimes: without water deficit (solid line), with water deficit (dashed line), and with water deficit followed by rehydration (dotted line). Arrows indicate the developmental stages R1 (visible flower bud) and R4 (petal color visible).

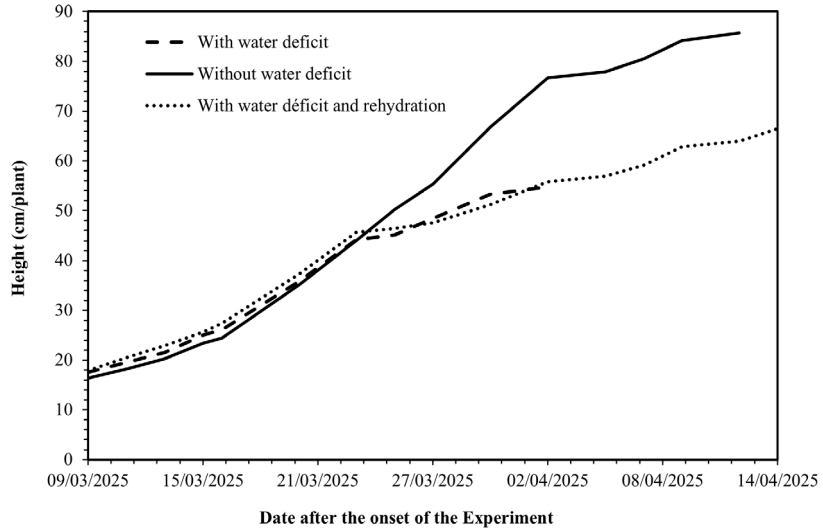

Fig. 3. Plant height of cut sunflower hybrid Vincent's Choice throughout the Experiment 1 under water regimes: without water deficit (solid line), with water deficit (dashed line), and with water deficit followed by rehydration (dotted line).

Normalized relative transpiration of Vincent's Choice cut sunflower plants decreased sigmoidally with declining Fraction of Transpirable Soil Water (FTSW) in Experiment 1 (Fig. 4). The FTSW threshold (FTSWth), calculated at normalized relative transpiration = 0.95, was estimated at 0.63 in plants subjected to water deficit beginning at the vegetative stage. This estimate was numerically close to the threshold of 0.62 previously reported for the same hybrid under water deficit imposed at the reproductive stage (Simon et al., 2025). Although no formal statistical comparison was performed, these values indicate that transpiration began to decline at similar fractions of available soil water under the conditions of the two studies.

The decline in relative transpiration as soil water availability decreased is consistent with responses reported in sunflower under deficit irrigation. Lower transpiration rates and stomatal conductance were observed as water deficit intensified (Chen et al., 2023). These findings provide physiological context for the response observed in Vincent's Choice, although stomatal conductance was not measured in the present study. Here, the fitted curve identified the soil water fraction at which relative transpiration began to decline, helping characterize the hybrid's response to progressive soil drying.

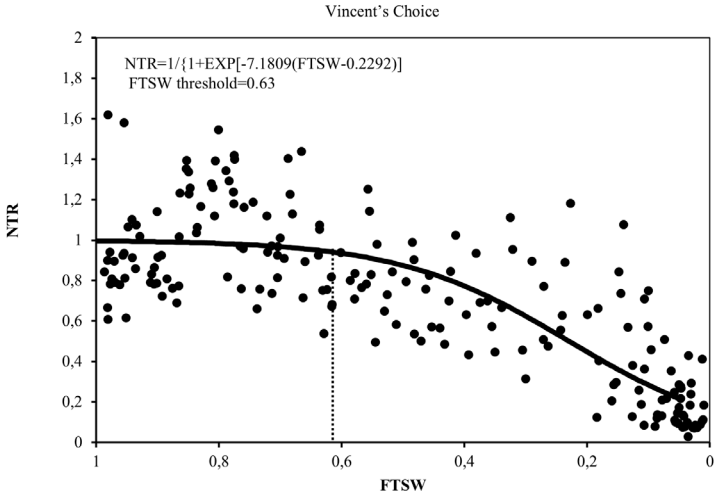

Fig. 4. Normalized relative transpiration (NTR) as a function of the fraction of transpirable water in the soil (FTSW) for the cut sunflower hybrid Vincent's Choice during the soil water deficit period in Experiment 1 from 09/03/2025 to 29/03/2025

The factorial analysis revealed that floral stem quality was significantly affected by soil water deficit followed by rehydration (Table 3). A significant hybrid × water regime interaction was observed for stem length and stem diameter, indicating that the response of these traits depended on the combination of hybrid and water regime. Under well-watered conditions, Vincent's Fresh produced longer stems (132.9 cm) and greater stem diameter (0.99 cm) than Vincent's Choice (122.4 cm and 0.87 cm, respectively). However, after soil water deficit followed by rehydration, these differences between hybrids were no longer observed, as both hybrids exhibited similar stem length and stem diameter. In contrast, capitulum diameter was significantly influenced by hybrid and water regime independently, since no hybrid × water regime interaction was detected. Regardless of the hybrid, soil water deficit followed by rehydration reduced capitulum diameter, while Vincent's Fresh maintained larger capitula than Vincent's Choice.

The reductions in floral stem quality persisted until harvest despite rehydration, indicating that restoring soil water availability was insufficient to bring stem length and stem diameter to the levels observed in plants maintained without water deficit. These results demonstrate a lasting effect of the preceding water deficit on the evaluated commercial traits, without establishing whether the underlying growth limitations were irreversible.

From a commercial perspective, stem length and capitulum diameter are among the most important quality attributes of cut sunflower because they directly determine the commercial classification and market value of floral stems. Commercial standards classify stems into length categories of 50, 60, 70, 80, and 90 cm, while the minimum acceptable capitulum diameter ranges from 4.5 to 7.5 cm, depending on stem length and flower opening stage (Tomiozzo et al., 2024). In the present study, although stem length remained within the commercial standards after soil water deficit followed by rehydration, the significant reductions observed in both stem length and capitulum diameter demonstrate that water limitation negatively affected floral quality. While the floral stems would still meet the minimum commercial requirements, these reductions could limit their classification into higher commercial grades and consequently reduce their market value, particularly because flower size is one of the main attributes determining the ornamental appeal of cut sunflower.

Although Vincent's Fresh showed greater stem length and stem diameter under well-watered conditions, these advantages disappeared after soil water deficit followed by rehydration. This response suggests that the superior growth potential of Vincent's Fresh depends on adequate water supply and is substantially reduced under water-limited conditions. In contrast, Vincent's Choice exhibited lower values under favorable conditions but maintained performance similar to Vincent's Fresh after rehydration, indicating a more stable response under water deficit. However, because no hybrid × water regime interaction was detected for capitulum diameter, the effects of hybrid and water regime on this trait should be interpreted separately.

Table 3. Quality variables of floral stems of cut sunflower hybrids Vincent's Choice and Vincent's Fresh without and with soil water deficit and rehydration in Experiment 2.

	Hybrids			
	Vincent's Choice		**Vincent's Fresh**	
Treatments	Without water deficit	Water deficit and rehydration	Without water deficit	Water deficit and rehydration
Quality variables of floral stem				
Stem length (cm)	122.4 ± 2.32 aB	103.2 ± 2.32 bA	132.9 ± 2.32 aA	97.6 ± 2.32 bA
Stem diameter (cm)	0.87 ± 0.026 aB	0.61 ± 0.026 bA	0.99 ± 0.026 aA	0.62 ± 0.026 bA
Capitulum diameter (cm)	7.9 ± 0.27 aB	5.7± 0.27 bA	9.0 ± 0.27 aA	6.3 ± 0.27 bA

Values are means ± standard errors based on the residual mean square of the factorial ANOVA (n = 10 plants per combination). For stem length and stem diameter, different lowercase letters indicate differences between water regimes within each hybrid, whereas different uppercase letters indicate differences between hybrids within each water regime, according to Tukey's test ($p \leq 0.05$). These variables showed a significant hybrid × water regime interaction. Capitulum diameter showed no significant interaction; its treatment-combination means are presented descriptively, and statistical interpretation is based on the main effects of hybrid and water regime.

Capitulum appearance at harvest differed between water regimes in both cut sunflower hybrids (Fig. 5). In Vincent's Choice, plants subjected to soil water deficit followed by rehydration (Fig. 5A-B) produced smaller capitula than plants maintained without water deficit (Fig. 5E-F). A similar response was observed in Vincent's Fresh, in which capitula from plants subjected to water deficit followed by rehydration (Fig. 5C-D) were smaller than those from plants maintained without water deficit (Fig. 5G-H).



Fig. 5. Capitulum of cut sunflower hybrids at harvest in Experiment 2. Vincent's Choice subjected to soil water deficit followed by rehydration (A-B), Vincent's Fresh subjected to soil water deficit followed by rehydration (C-D), Vincent's Choice maintained without water deficit (E-F), and Vincent's Fresh maintained without water deficit (G-H).

The factorial analysis showed that dry matter accumulation was affected by soil water deficit followed by rehydration, although the response varied among plant organs (Table 4). Significant hybrid × water regime interactions were observed for stem, leaf, and capitulum dry mass, whereas root dry mass was independently affected by hybrid and water regime. In both hybrids, water deficit followed by rehydration reduced dry matter accumulation in all plant organs. However, the magnitude of these reductions differed between hybrids depending on the evaluated organ.

Under well-watered conditions, Vincent's Choice and Vincent's Fresh exhibited similar leaf and capitulum dry mass, whereas Vincent's Fresh accumulated less stem dry mass than Vincent's Choice. After water deficit followed by rehydration, Vincent's Choice maintained greater dry mass in leaves and capitula than Vincent's Fresh, indicating a greater capacity to preserve biomass accumulation in these organs after water stress. Root dry mass was also consistently higher in Vincent's Choice than in Vincent's Fresh under both water regimes, although the hybrid × water regime interaction was not significant. Total dry mass was lower after water deficit followed by rehydration in both hybrids, reflecting the cumulative reduction in biomass production across all plant organs.

Water deficit reduced biomass accumulation because plant growth is one of the physiological processes most sensitive to reductions in soil water availability. Reduced stomatal conductance limits CO_2 uptake and photosynthetic carbon assimilation, while decreased cell turgor restricts cell expansion and dry matter accumulation. Although rehydration restored leaf turgor and resumed plant growth, it was insufficient to fully compensate for the biomass losses accumulated during the stress period, indicating that part of the reduction in structural growth was irreversible.

Differences between hybrids suggest distinct growth strategies under contrasting water regimes. Vincent's Fresh showed high biomass accumulation under well-watered conditions but experienced greater reductions in leaves and capitula after water deficit followed by rehydration. In contrast, Vincent's Choice maintained greater dry matter accumulation in these organs after stress, suggesting a more conservative growth strategy that contributed to better maintenance of biomass under limited water availability. Similar responses have been reported in sunflower and other ornamental crops, where water deficit reduces dry matter production even after irrigation is resumed, reinforcing that preventive irrigation management is more effective than corrective rehydration (Becker et al., 2021; Lima et al., 2022; Smaeili et al., 2022).

The greater reductions observed in leaf and capitulum dry mass in Vincent's Fresh after water deficit followed by rehydration suggest that this hybrid was less effective in maintaining biomass accumulation in these organs under water-limited conditions.

Table 4. Dry mass of plant parts of cut sunflower hybrid Vincent's Choice and Vincent's Fresh at the end of the Experiment 2 without water deficit and with water deficit followed by rehydration.

	Hybrids				
Plant part	**Vincent's Choice**		**Vincent's Fresh**		**CV (%)**
	Without water deficit	Water deficit and rehydration	Without water deficit	Water deficit and rehydration	
Roots (g plant^{-1})	9.5 ± 0.35 aA	5.0 ± 0.35 bA	8.0 ± 0.35 aB	3.5 ± 0.35 bB	17.20
Stem (g plant^{-1})	32.0 ± 1.51 aA	21.7 ± 1.51 bA	25.6 ± 1.51 aB	13.4 ± 1.51 bB	20.58
Leaves (g plant^{-1})	11.7 ± 0.34 aA	9.2 ± 0.34 bA	11.8 ± 0.34 aA	7.9 ± 0.34 bB	10.67
Capitulum (g plant^{-1})	9.8 ± 0.27 aA	8.7 ± 0.27 bA	9.5 ± 0.27 aA	6.9 ± 0.27 bB	11.32
Total dry mass (g plant^{-1})	63.0	44.6	54.9	31.7	—

Means followed by different lowercase letters in the same row differ between water regimes, whereas uppercase letters in the same column compare hybrids within the same water regime according to Tukey's test ($p \leq 0.05$). Total dry mass corresponds to the sum of root, stem, leaf, and capitulum dry mass.

Cumulative transpired water during the experimental period was similar between the two cut sunflower hybrids under well-watered conditions (Table 5). Vincent's Choice transpired 11.84 L plant^{-1}, whereas Vincent's Fresh transpired 12.09 L plant^{-1}, representing a difference of only 2.1%. Despite the similar cumulative transpired water, the hybrids differed in growth, biomass accumulation, and floral stem quality, indicating that differences in plant performance were not associated with the total amount of water transpired during the evaluation period.

Table 5. Values represent the cumulative transpired water per plant, calculated as the sum of daily transpiration measured throughout the experimental period in plants maintained without water deficit.

Hybrid	Cumulative transpired water (L plant^{-1})
Vincent's Choice	11.84
Vincent's Fresh	12.09

Although cumulative transpired water was similar between hybrids, Vincent's Choice maintained greater dry matter accumulation in roots, leaves, and capitula after water deficit followed by rehydration, whereas Vincent's Fresh exhibited greater reductions in these organs. These results indicate that the contrasting responses of the hybrids were associated with differences in growth recovery and biomass accumulation following water deficit.

Plant height increased progressively in both hybrids during Experiment 2 (Fig. 6). Under well-watered conditions, Vincent's Fresh showed greater stem elongation than Vincent's Choice, reaching 132.9 and 122.4 cm at harvest, respectively. Under water deficit followed by rehydration, however, this pattern was reversed: Vincent's Choice reached 103.2 cm, whereas Vincent's Fresh reached 97.6 cm. Thus, water deficit reduced final plant height in both hybrids, but the reduction was more pronounced in Vincent's Fresh. Although stem elongation resumed after rehydration, neither hybrid recovered the height attained by plants maintained without water deficit.

The different responses of the hybrids are consistent with the significant hybrid × water regime interaction observed for stem length (Table 3), indicating that the effect of water availability depended on the hybrid. Stem elongation is particularly sensitive to water deficit because reduced cell turgor limits cell expansion during the stress period. Adequate water availability is also essential for the production of commercially desirable floral stems in ornamental species; in gladiolus, irrigation resulted in longer and thicker stems than those produced without irrigation (Lima et al., 2022). In the present study, the stronger reduction observed in Vincent's Fresh indicates that its greater growth potential under well-watered conditions was not maintained after water deficit, whereas Vincent's Choice showed a comparatively smaller reduction in final plant height.

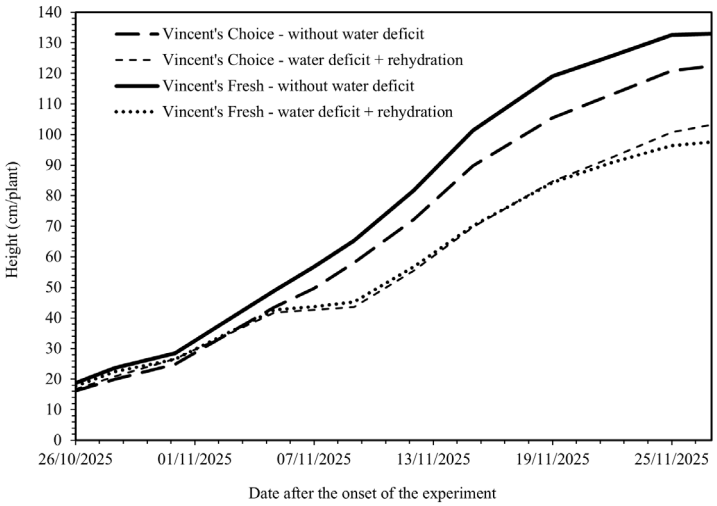

Fig. 6. Plant height of cut sunflower hybrids Vincent's Choice and Vincent's Fresh throughout Experiment 2 under well-watered conditions and water deficit followed by rehydration.



Fig. 7. Cut sunflower plants during Experiment 2. (A) Plants at the critical Fraction of Transpirable Soil Water (FTSW), corresponding to the onset of stomatal closure and the first symptoms of leaf wilting. (B) Plants at the end of the soil water deficit period, showing severe leaf wilting. (C) Plants after rehydration, with recovery of leaf turgor.

The visual changes in cut sunflower plants during soil drying and after rehydration. At the FTSW threshold, corresponding to the onset of stomatal closure, plants showed the first symptoms of leaf wilting, while most leaves still maintained their turgor (Fig. 7A). As soil water depletion progressed, leaf wilting became more pronounced, and plants reached the end of the water deficit period with severe loss of turgor (Fig. 7B). After rehydration, leaf turgor was restored (Fig. 7C). However, despite the visual recovery, stem growth, dry biomass

accumulation, and floral stem quality were not restored to the levels observed in well-watered plants.

The visual recovery observed after rehydration contrasted with the persistent reductions in growth and floral quality, indicating that restoration of leaf turgor did not result in complete recovery of plant performance. The response of transpiration as a function of FTSW also followed a sigmoidal pattern in Experiment 2 (Fig. 8). However, differences in FTSWth were observed between the two commercial hybrids. The FTSWth was estimated at 0.58 for Vincent's Choice and 0.52 for Vincent's Fresh. Vincent's Choice started reducing transpiration at a higher soil water content, whereas Vincent's Fresh maintained transpiration until lower soil water availability.

Genotypes exhibiting higher FTSW thresholds tend to adopt a more conservative water-use strategy by reducing transpiration earlier, whereas genotypes with lower thresholds maintain transpiration for longer during soil drying. However, these contrasting strategies do not necessarily indicate differences in drought tolerance, since their adaptive value depends on drought intensity, duration, and environmental conditions (Casadebaig et al., 2023).

The FTSWth values observed in the present study are consistent with those reported for other ornamental species. In chrysanthemum Cherie White, stomatal closure begins between 0.62 and 0.65 (Kelling et al., 2015), whereas in gladiolus the FTSWth ranges from 0.60 to 0.65 depending on the developmental stage (Becker et al., 2021). These findings indicate that elite commercial cut sunflower hybrids exhibit stomatal responses to soil drying comparable to those reported for other ornamental crops.

This threshold-type response is also consistent with findings in other crops, such as cassava, in which transpiration and leaf growth decline progressively as FTSW decreases, with critical values typically ranging from 0.45 to 0.50 (Lago et al., 2012). Plant growth is highly sensitive to soil water deficit because cell expansion depends directly on turgor pressure, which declines as soil water availability decreases. Consequently, transpiration decreases progressively below the FTSW threshold, and the structural limitations imposed during the stress period are not completely reversed after rehydration.

Overall, the lower FTSWth observed in Vincent's Fresh indicates that this hybrid maintained transpiration for a longer period during soil drying, whereas Vincent's Choice adopted a more conservative water-use strategy by initiating stomatal closure earlier. However, despite these contrasting strategies, both hybrids exhibited persistent reductions in growth and floral quality after rehydration.

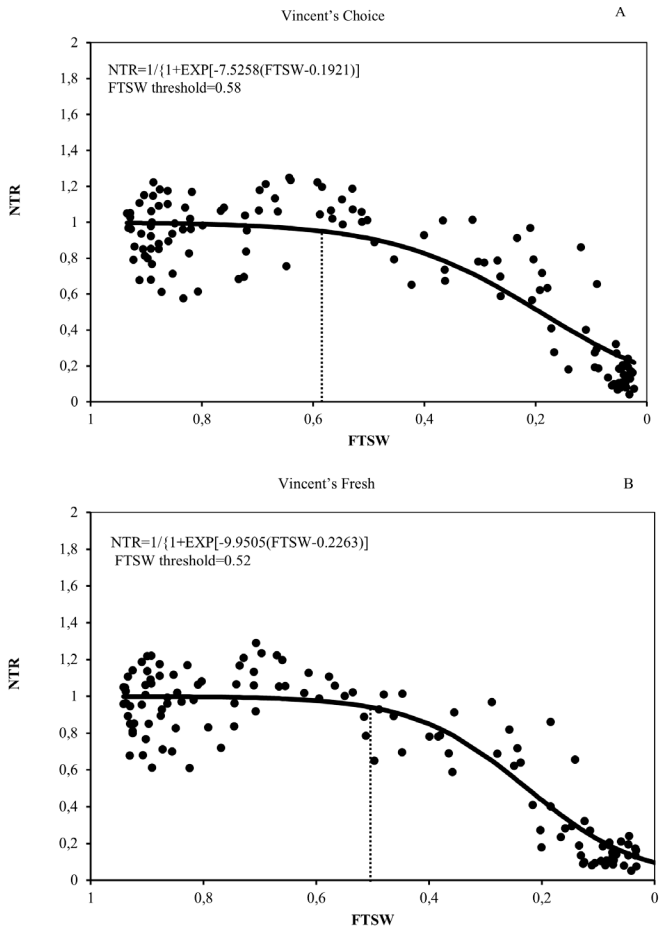

Fig. 8. Normalized relative transpiration (NTR) as a function of the fraction of transpirable water in the soil (FTSW) for the cut sunflower for Vincent's Choice (A) and Vincent's Fresh (B) in Experiment 2 from 27/10/2025 to 25/11/2025.

The estimated FTSWth for Vincent's Choice was 0.63 in Experiment 1 and 0.58 in Experiment 2. This numerical difference should be interpreted descriptively because the threshold estimates were not formally compared. The experiments were conducted in different seasons, from February to April in Experiment 1 and from October to November in Experiment 2, and were therefore exposed to different environmental conditions. Mean minimum and maximum temperatures were 17.4 and 33.1 °C in Experiment 1 and 15.7 and 34.8 °C in Experiment 2, respectively. Mean relative humidity was 56.7% in Experiment 1 and 37.1% in Experiment 2. Previous studies using the FTSW approach have shown that atmospheric evaporative demand and growing conditions can influence the soil-water threshold at which transpiration begins to decline (Lago et al., 2012; Kelling et al., 2015; Becker et al., 2021). However, because the experiments were conducted at different times and the environmental factors were not controlled independently, their individual effects could not be isolated. Therefore, the difference between the FTSWth values cannot be conclusively attributed to a specific environmental condition.

Conclusions

Soil water deficit significantly reduced transpiration, biomass accumulation, and floral stem quality in cut sunflower. Although rehydration restored leaf turgor, it promoted only partial recovery, demonstrating that the negative effects of water deficit on biomass accumulation and floral stem quality persisted after rewatering.

The commercial hybrids exhibited distinct physiological responses to soil water deficit, with FTSWth values of 0.58 for Vincent's Choice and 0.52 for Vincent's Fresh, indicating differences in stomatal regulation during soil drying.

These findings demonstrate that irrigation management should prioritize preventing soil water deficit rather than relying on rewatering to restore floral stem quality. In addition, the contrasting responses observed between hybrids provide useful information for selecting cut sunflower genotypes for environments with different water availability.

Acknowledgments

This study was conducted during the 15th 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 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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