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Article

Evaluation of strawberry crop water stress in humid climates

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Abstract

Strawberries (*Fragaria* x *ananassa* Duch.) are a crop of high commercial value whose productivity depends on efficient irrigation management, given their sensitive nature to water deficit. In humid regions, high relative humidity reduces evaporative demand and limits the effectiveness of indicators based on leaf temperature, such as the crop water stress index (CWSI). The objective of this research was to evaluate the usefulness of the crop water stress index as a criterion for irrigation management in strawberries under humid climate conditions. The study was conducted in 2022 in a greenhouse at the Faculty of Agricultural and Livestock Sciences of the Benemérita Universidad Autónoma de Puebla, Mexico. A completely randomized design was used with four crop evapotranspiration (ETc) replacement treatments: 70, 80, 90 and 100% ETc. Leaf water potential (Ψh), CWSI, yield and fruit quality (total soluble solids, TSS) were monitored. CWSI values remained low and homogeneous (0.3-0.55), with no significant differences between treatments (p> 0.05). The 80 and 90% ETc treatments achieved yields similar to 100% ETc, although with lower TSS content. The CWSI showed limitations as the sole irrigation indicator under high humidity due to low evaporative demand. It is concluded that deficit irrigation at 80-90% of ETc is a viable strategy to optimize water without significantly compromising yield, although complementing the CWSI with other physiological indicators is required to improve the precision of water management.

Palabras clave:

crop water stress index, deficit irrigation, *Fragaria x ananassa*, fruit quality, relative humidity, water efficiency. *Rubus fructicosus* var. Tupi.

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Introduction

Freshwater scarcity for agricultural use is one of the most critical environmental, economic, and social challenges of the 21st century. Agriculture is estimated to consume approximately 70% of the freshwater available on the planet, making its rational and efficient use a priority in the face of increasing food demand and growing climate variability (FAO, 2021). This scenario demands the adoption of technologies and strategies that improve water use efficiency in highly water-sensitive crops.

Strawberry (*Fragaria* x *ananassa* Duch.) is a fruit and vegetable crop of high commercial and nutritional value widely grown in temperate and tropical regions. However, its shallow root system and high water demand make it especially vulnerable to water stress conditions, which can negatively affect its phenological development, yield, and fruit quality (Pires *et al*., 2006; Gutiérrez-Colín *et al*., 2017). Several studies have shown that inadequate irrigation management in strawberries can lead to both decreased productivity and inefficient use of water resources (Baronti *et al*., 2019).

In this context, drip irrigation has positioned itself as one of the most effective techniques to optimize water use in agricultural systems, as it allows maintaining constant moisture in the root zone, reducing evaporation losses, and applying water precisely (Liotta *et al*., 2015). Nevertheless, the persistent limitation is determining the opportune moment for irrigation application, especially in humid regions where potential evapotranspiration is low and traditional stress indicators may be insensitive (Ferreyra *et al*., 2002).

To solve this problem, plant water status monitoring tools have been developed. One of the most recognized is the crop water stress index (CWSI), proposed by Jackson *et al*. (1981). This index estimates the degree of water stress by comparing the canopy temperature, ambient temperature, and vapor pressure deficit. Its main advantage is that it integrates environmental and physiological information, allowing a dynamic diagnosis of the plant's water status (Jones, 2004). The CWSI has been validated in different crops such as grapevine (Ferreyra *et al*., 2002), apple, peach (Giuliani *et al*., 2001), and recently in strawberry under semi-arid conditions (López *et al*., 2009).

However, its applicability in humid climates remains limited, as high relative air humidity can reduce plant transpiration without there being a real limitation in water availability in the soil (Idso *et al*., 1982). Consequently, CWSI values could underestimate water stress, affecting the precision of irrigation scheduling. Based on the above, it is hypothesized that, under humid climate conditions, the crop water stress index (CWSI) does not accurately reflect the differences between irrigation treatments and therefore, its usefulness as an indicator of irrigation timing is limited. However, it is also considered that controlled deficit irrigation could maintain an acceptable yield in the strawberry crop, with lower water consumption.

In this sense, the general objective of this study was to evaluate the behavior of the CWSI and its usefulness as a technical criterion for decision-making in irrigation management in strawberry (*Fragaria* x *ananassa* Duch.) under humid climate conditions in Teziutlán, Puebla. Specifically, an analysis of the physiological and productive response of the crop under different irrigation levels was developed and the sensitivity of the CWSI to variations in the irrigation sheet was determined in order to identify the agronomic implications of the use of the CWSI in regions with high relative humidity.

Materials and methods

Description of the experimental site

The study was carried out in a 210 m^2 tunnel-type greenhouse, located at the facilities of the Faculty of Agricultural and Livestock Sciences of the Benemérita Universidad Autónoma de Puebla (BUAP), in San Juan Acateno, municipality of Teziutlán, Puebla, Mexico. The geographical location corresponds to 19° 52' 30'' north latitude and 97° 21' 34'' west longitude, at an altitude of 1

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938 m. Agronomic management (fertilization, pest and disease control) was maintained according to standard production system practices, avoiding differential interventions not associated with irrigation treatments. All measurements were made under the usual environmental conditions of the site. The region is characterized by a humid temperate climate with summer rains, classification C(w2) according to García (2004), with a mean annual temperature of 15 °C and average rainfall of 1 609 mm, conditions that favor the development of the strawberry crop, although they also represent a challenge for monitoring water stress due to high relative humidity.

Plant material and crop preparation

Strawberry cv. Monterrey (*Fragaria* x *ananassa* Duch.) was used as plant material, selected for its adaptation to temperate climates and its high commercial yield (Gutiérrez-Colín *et al*., 2017). The plants were transplanted into cultivation beds 60 cm wide by 14 m long, covered with black plastic mulch to conserve moisture, reduce weed growth, and improve soil temperature. The spacing between plants was 30 cm and between rows 40 cm.

Irrigation system and treatments

The irrigation system used was drip, with self-compensating emitters (Netafim™) installed at a rate of one dripper per plant, with a flow rate of 2 L h^{-1}. Water supply was manually controlled using stopcocks, allowing differentiated irrigation treatments to be applied. This system was selected for its water use efficiency and its ability to maintain a constant moisture level in the root zone, a fundamental aspect for water stress studies (Liotta *et al*., 2015). The experimental design was completely randomized with four irrigation treatments based on the crop evapotranspiration (ETc) sheet, estimated using the crop coefficient and reference evapotranspiration (ET_0) based on local meteorological data. The four levels (T1-T4) and four replicates (R1-R4) treatments were: irrigation at 100% of ETc, irrigation at 90% of ETc, irrigation at 80% of ETc, and irrigation at 70% of ETc.

Each replicate consisted of a homogeneous set of plants assigned to the same treatment, and on each date the variables canopy temperature (Tc, °C), air temperature (Ta, °C) and relative humidity (RH, %) were recorded, in addition to the vapor pressure deficit (VPD, kPa) and derivatives. The design allows contrasting the effect of the treatment on plant-based indicators (Jones, 2004) with control by replicate and date. Canopy temperature (Tc) was obtained by point infrared thermometry (long-wave thermal band), according to the principles of energy exchange and its relationship with transpiration (Jackson *et al*., 1981; Monteith and Unsworth, 2013). Air temperature (Ta) and relative humidity (RH) were recorded with co-located environmental sensors. From Ta and RH, VPD (kPa) was verified/derived using standard psychrometric formulation:

$$e_s(T_a) = 0.6108\exp\left(\frac{17.27T_a}{T_a+237.3}\right)(kPa),\ e_a = \frac{HR}{100}e_s,\ VPD = e_s - e_a$$

Where: Ta= is in °C (Monteith and Unsworth, 2013). The thermal differential was calculated as ΔT= Tc – Ta. A database was integrated per record with the fields: date, treatment, replicate (°C), and VPD (kPa). Records without any of the essential fields were excluded, and evidently spurious values in Tc, Ta, RH, and VPD were reviewed. To minimize the influence of outliers on baseline calibration, a quantile-based strategy was adopted (Rousseeuw and Hubert, 2011; Wilcox, 2012).

CWSI calculation and physiological measurements

The crop water stress index (CWSI) was defined within the Idso-Jackson framework as the normalization of the thermal differential with respect to baselines representing the well-watered (lower limit, ll) and highly stressed (upper limit, ul) limit states, dependent on VPD (Jackson *et al*., 1981; Jones, 2004):

$$CWSI = \frac{\Delta T - ll_{(VPD)}}{ul_{(VPD)} - ll_{(VPD)}},\ 0 \le CWSI \le 1$$

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To estimate ll (VPD) and ul (VPD), the procedure was as follows: the observed VPD range was partitioned into 10 approximately equidistant intervals; in each bin, records located in the 0.2 quantile of ΔT (proxy for 'well-watered') and in the 0.8 quantile (proxy for 'stressed') were selected, following the logic of physiological extremes (Katimbo *et al*., 2022; Liu *et al*., 2022; Mertens *et al*., 2023), with the selected points, straight lines ΔT= a+b(VPD) were fitted for ll and ul (ordinary regression), providing linear functions of VPD for each limit (Jackson *et al*., 1981; Jones, 2004). For each record (ΔT, VPD), the CWSI was calculated with the previous expression and bounded to [0,1] to preserve physical interpretation. This was aimed at mitigating bias from outliers and operational variations, aligned with recent recommendations on CWSI sensitivity to computation schemes (Katimbo *et al*., 2022; Liu *et al*., 2022; Mertens *et al*., 2023).

The calibration of the crop water stress index (CWSI) baselines was performed based on the relationship between the canopy-air temperature difference (ΔT= Tc-Ta) and the vapor pressure deficit (VPD). For this purpose, foliage temperature (Tc) was obtained using a FLUKE 62 MAX+ portable infrared thermometer directed at the adaxial surface of fully expanded leaves, avoiding direct incidence of reflected solar radiation. Air temperature (Ta) and relative humidity were recorded simultaneously with environmental sensors placed at canopy level, with which the VPD was calculated. With these data, the baselines were constructed: the lower one (ΔT_{ll}), representing the state of well-watered plants, and the upper one (ΔT_{ul}), corresponding to maximum stress. These references allowed recalculating the CWSI for each treatment and sampling date. Measurements were taken during solar noon between 12:00 and 14:00 h, when radiation and stomatal activity reach their maximum levels (Jones, 2004).

Evaluated variables

Morphological and fruit quality variables were evaluated 45 days after transplantation, including: number of open flowers per plant, number of set and harvested fruits per plant, polar and equatorial diameter of the fruits, measured with a digital vernier caliper (Truper™, 0.01 mm precision), and total soluble solids (TSS) content in degrees Brix, measured with a digital refractometer (Atago PAL-1). Evaluations were carried out at three key moments of the production cycle (start of flowering, maximum fruiting, and final harvest stage), selected to capture physiological dynamics under different levels of water availability.

Statistical analysis

The data obtained were analyzed using a one-way analysis of variance (ANOVA) under a completely randomized design, in order to determine significant differences between the four irrigation treatments (100, 90, 80 and 70% of ETc). The statistical program Statistical Analysis System (SAS®), version 9.4 for Windows, was used for information processing. Significance was evaluated with a 95% confidence level (p≤ 0.05), and when differences were detected, Tukey's mean comparison test was applied to identify contrasts between treatments.

Results and discussion

The experimental set integrated 752 records of date x treatment x replicate combinations, with complete values for the variables air temperature (Ta), relative humidity (RH), vapor pressure deficit (VPD) and canopy temperature (Tc). From these measurements, the thermal differential ΔT= Tc-Ta was derived, and the CWSI was recalculated with the adjusted baselines. The absence of extreme values outside physiologically plausible ranges supports the consistency and quality of the sampling, consistent with recommendations for canopy temperature monitoring studies (González-Dugo *et al*., 2006; Jones, 2004).

During the evaluation cycle, the average relative humidity (RH) was 78%, with minimum values of 65% and maximums of 92%, confirming the humid climate character of the experimental site. These conditions explain the low expression of water stress in plants, as a saturated atmosphere limits evaporative demand, reducing the vapor pressure deficit (VPD) and, consequently, the sensitivity of the CWSI to detect differences between treatments (Idso et al., 1982; López et al., 2009).

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Regarding the number of flowers per plant, statistically significant differences were observed with the Tukey test (p≤ 0.05) only in the first evaluation date (05/02/2022, equivalent to 45 days after transplantation), where the 100% ETc treatment reached the highest average (2.75 flowers per plant). In subsequent dates, differences ceased to be significant, with convergent values between treatments (Table 1). This suggests that, under humid conditions, the early floral response may be influenced by full water availability, but as the cycle progresses, high RH attenuates contrasts in water status between plants.

Table 1. Comparison of means of flower number on different dates.

Percentage of ETc	02/05/22	09/05/22	16/05/22	23/05/22	30/05/22
100	2.75 a	1.25 a	1.25 a	0.75 a	0 a
90	2 ab	2 a	1.75 a	1.25 a	0 a
80	2.25 ab	3 a	2 a	0.5 a	0.75 a
70	1 b	1.75 a	0 a	0.5 a	0 a
CV (%)	38.52	53.03	96.60	90.26	235.31

Values with the same letter within columns are equal according to Tukey's test at p≤ 0.05.

Regarding the number of fruits per plant (Table 2), statistical differences were recorded on the third date (05/16/22, 59 days after transplantation). The 80% treatment presented the highest average (8.25 fruits per plant), not differentiating from 100%. This finding confirms that controlled deficit irrigation does not reduce immediate yield and may even favor productivity under specific conditions, as reported by Ferreyra *et al*. (2002); Pires *et al*. (2006).

Table 2. Number of strawberry fruits per plant, on different dates.

Percentage of ETc	02/05/22	09/05/22	16/05/22	23/05/22	30/05/22
100	6 a	8.25 a	7.25 ab	6.5 a	2.5 a
90	3.25 a	5.5 a	5.25 ab	5.25 a	5.25 a
80	7 a	9.75 a	8.25 a	8.5 a	7 a
70	4.75 a	4.75 a	3.25 b	3.25 a	2.25 a
CV (%)	63.53	51.9	32.98	51.88	60.94

Values with the same letter within columns are equal according to Tukey's test at p≤ 0.05.

Regarding fruit quality, polar diameter (PD) showed no significant differences between treatments, with values ranging from 26.25 to 29.9 mm. However, equatorial diameter (ED) did present differences, being greater in 90% ETc (27.66 mm) compared to 100% (21.62 mm). This indicates that moderate water deficit did not reduce lateral growth and, in certain cases, may have favored carbohydrate partitioning towards the fruit. It is important to specify that the statistical tool only demonstrates differences between treatments and does not indicate a causal relationship (Table 3).

Table 3. Fruit quality at the third harvest.

Percentage of ETc	Polar diameter (mm)	Equatorial diameter (mm)	TSS (°Brix)
100	28 a	21.62 b	15.43 a
90	29.83 a	27.66 a	8.55 b
80	29.9 a	23.9 ab	10.13 b
70	26.25 a	25.62 ab	9.18 b
CV (%)	13.14	5.46	4.85

Values with the same letter within columns are equal according to Tukey's test at p≤ 0.05. TSS= total soluble solids.

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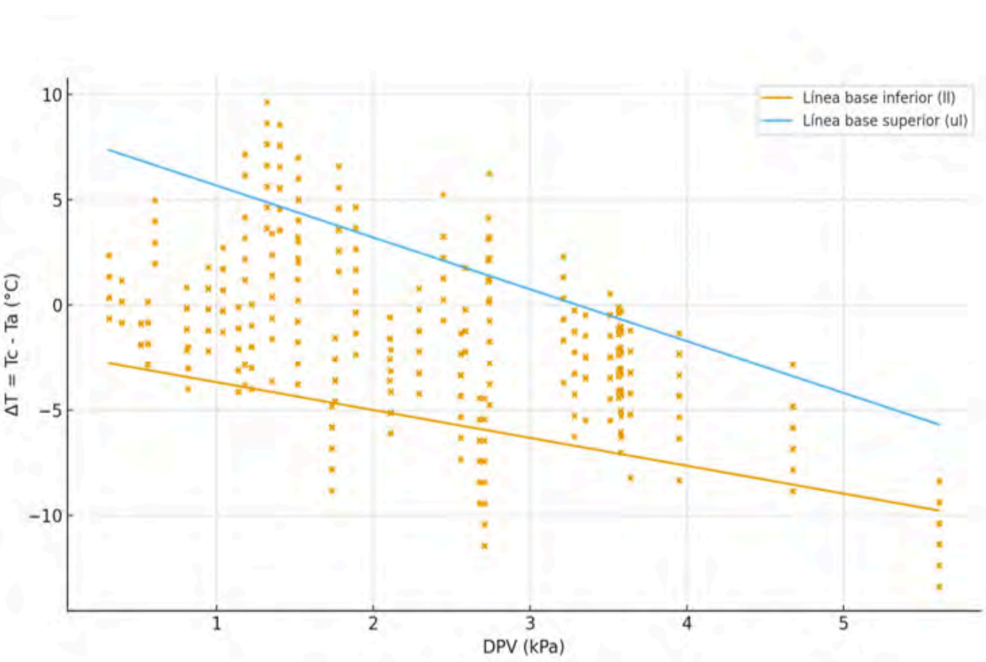
Furthermore, we can observe that there are significant differences between the 90% treatment and the 100% treatment, while 80% and 70% are intermediate (ab). This indicates that the 90%treatment allowed greater lateral fruit thickening, possibly because the plant was not under severe stress and efficiently allocated carbohydrates to the fruit. Fruits from plants with 100% ETc showed the highest sugar content (15.43 °Brix). This result coincides with Baronti *et al*. (2019), who highlighted that full irrigation improves fruit sensory quality, although at the expense of lower water efficiency.

For the 80 and 90% treatments, the highest PD and ED values were recorded, but with low TSS records, so it is considered that under these conditions the plant favors volumetric fruit growth, but being close to its mild stress threshold, there is less sugar accumulation. In general, TSS in treatments less than 100% of ETc present lower sugar content, which is attributed to moderate water stress affecting sugar production and transport metabolism. Irrigation at 80-90% of ETc allows fruit size to be maintained without severely affecting its shape. However, only 100% irrigation guarantees optimal quality in terms of sweetness. Observing the lowest coefficients of variation (CV) in the TSS variable (4.85%) indicates high consistency in this variable, evidencing the relationship that greater water use leads to greater fruit sweetness.

CWSI analysis

Dispersion analysis evidenced the inverse relationship between #T and VPD (Figure 1), consistent with energy balance theory: at higher evaporative demand, the canopy transpires more and moderates thermal increase, generating reduced differentials (Jackson *et al*., 1981). Robust baseline calibration using quantiles confirmed this trend: lower baseline (ll): intercept= -2.35, slope= -1.33. Upper baseline (ul): intercept= 8.14, slope= -2.47.

Figure 1. Dispersion analysis of thermal differential (ΔT) and vapor pressure deficit (VPD).



These lines adequately delimit the point cloud and coincide with values reported in other high-value commercial crops under controlled deficit irrigation (Katimbo *et al*., 2022; Mertens *et al*., 2023). The adopted procedure reduces CWSI sensitivity to outliers and constitutes a methodological improvement over traditional estimation based on absolute minimums and maximums.

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The time series of average CWSI per treatment showed stability throughout the sampling period. Values ranged between 0.3 and 0.55, indicating a range of mild to moderate water stress. No treatment was systematically positioned at the extremes of the scale (close to 0 or 1), suggesting that under management conditions, irrigation levels did not generate marked contrasts in plant water status. This convergence can be attributed to the buffering capacity of the strawberry root system and the short duration of the observation period.

Statistical analysis (one-way ANOVA) detected no significant differences between treatments (F= 0.8; df between= 3; df within= 700; p= 0.497). The interpretation in agronomic terms is that the range of irrigation sheets or strategies applied was not sufficient to induce detectable contrasts in the index. In methodological terms, the recalculated CWSI exhibits internal consistency, but its discriminative power critically depends on the magnitude of the experimentally generated water availability gradient (Liu *et al*., 2022). Although this result may seem limiting, it actually reinforces the recommendation that CWSI should be used in conjunction with an experimental design guaranteeing contrasting water differences and preferably, include block analysis or mixed models integrating temporal variability.

Intermediate CWSI values (0.3-0.55) reflect a partial water stress condition compatible with moderate deficit irrigation strategy, commonly applied to improve water use efficiency without critically compromising production (Jones, 2004). In strawberry, this stress level can induce compensatory responses at stomatal and osmotic levels, modulating photosynthetic efficiency without deteriorating vegetative growth. Nevertheless, it is recommended to deepen the association between CWSI and productive variables (yield, biomass, fruit quality), which would strengthen the practical validation of the index in this crop.

The results agree with the findings of López *et al*. (2009), who reported that CWSI tends to underestimate water stress in humid environments due to the reduction in vapor pressure deficit, which decreases the sensitivity of the indicator. Likewise, Giuliani *et al*. (2001) observed that the use of infrared thermometry as a tool to detect water deficit may not be effective in temperate or humid conditions, where evaporation is limited.

In cause-effect terms, the obtained data show that high ambient relative humidity acts as a modulating factor decreasing physiological expression of water stress in the plant, even when there is reduction in the irrigation sheet. This explains why variables such as flower number or CWSI did not show a clear response to applied treatments. However, fruit number and TSS did show differences, indicating that these variables are more sensitive to changes in water availability, even under humid climatic conditions. The coincidence between the 80% treatment and a yield equal to or higher than the 100% treatment was also reported by Ferreyra *et al*. (2002), who highlighted that controlled deficit irrigation can induce favorable adaptive responses, such as greater water use efficiency. However, the decrease in TSS observed in deficit treatments indicates that there is a trade-off between yield and quality that must be considered when designing irrigation strategies.

Given that CWSI did not consistently reflect differences in water availability between treatments, it is concluded that its application in humid climates must be accompanied by other complementary methods, such as soil moisture sensors or leaf water potential measurement, as recommended by Parkash and Singh (2020). In summary, statistical analysis revealed no significant differences in most variables between treatments, attributable to the high relative humidity of the environment preventing water stress conditions. CWSI behavior remained close to zero during most of the cycle, indicating absence of stress. Only on two dates were values observed indicating moderate stress. This contrasts with studies conducted in semi-arid climates where CWSI has shown greater sensitivity. The results suggest that in humid environments, the use of CWSI as an irrigation management tool should be complemented with other indicators. Canopy temperature remained close to ambient temperature during most of the cycle, resulting in low CWSI values (0.3-0.55) with no significant differences between treatments (Figure 2).

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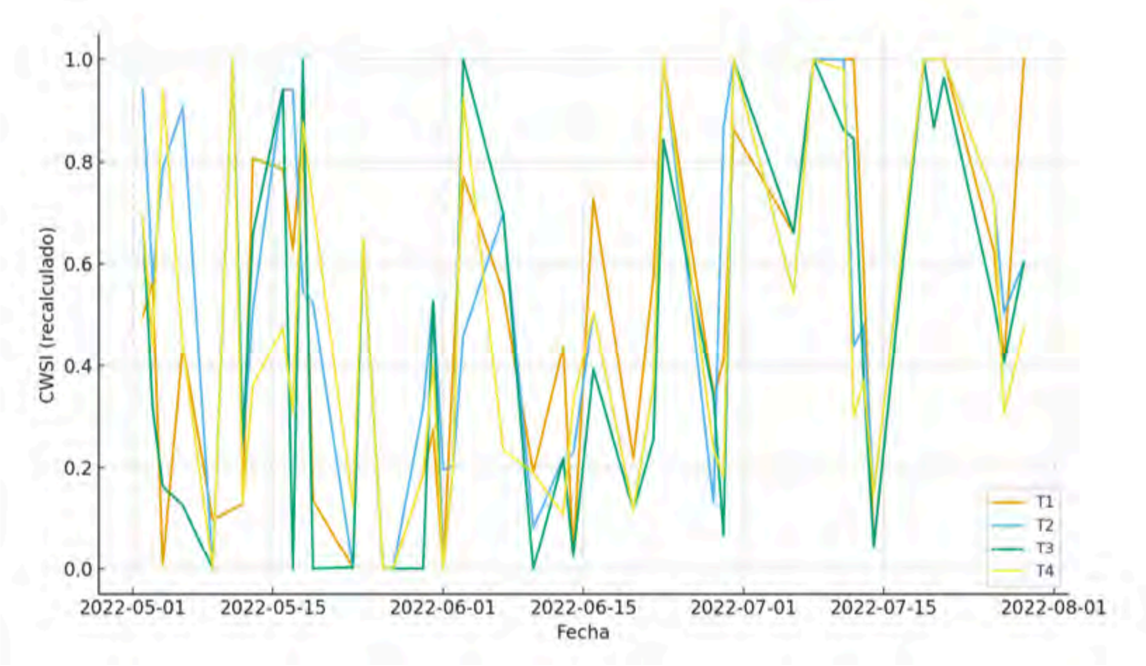
Figure 2. Time series of average CWSI by treatment.



Only on two dates 05/16/22 and 05/23/22, moderate increases in the index were observed, coinciding with measurements taken at noon, when radiation and temperature peaked. The subsequent decrease is attributed to high relative humidity, reducing the environment's evaporative demand. This behavior is consistent with documentation by Giuliani *et al*. (2001) and Jones (2004), who highlight CWSI's limited utility in humid climates due to its VPD dependence.

Analysis of variance confirmed the absence of significant differences in recalculated CWSI between treatments (F= 0.8; p= 0.497), reinforcing the conclusion that the index did not discriminate between irrigation levels under experimental conditions. These results contrast with studies in semi-arid environments, where CWSI has shown high sensitivity (Katimbo *et al*., 2022; Liu *et al*., 2022). Overall, the results show that the high RH of the experimental site acted as a modulator reducing physiological expression of water stress, even in plants with deficit irrigation. Variables such as fruit number and TSS were more sensitive to changes in water availability than CWSI itself, coinciding with Parkash and Singh's (2020) review on water stress indicators in horticultural crops.

Comparable yield between 80% and 100% ETc suggests it is possible to optimize water use through controlled deficit irrigation, albeit with a partial sacrifice of quality in terms of sweetness. From a methodological perspective, it is confirmed that CWSI should be complemented with other physiological or soil moisture indicators when applied in humid climates (González-Dugo *et al*., 2006; Rousseeuw and Hubert, 2011).

Conclusions

The recalculated water stress index (CWSI) showed low and homogeneous values between treatments (0.3-0.55), which is explained by the high relative humidity of the environment, which reduced evaporative demand and limited the index's ability to discriminate irrigation differences. Under these conditions, the CWSI is confirmed as an indicator consistent with theory, but of restricted sensitivity in humid climates, so its practical application should be considered complementary to other physiological and productive variables.

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In terms of production, the treatments with 80 and 90% ETc maintained yields comparable to those of the 100% treatment, demonstrating that moderate deficit irrigation is viable for optimizing water use in strawberries. However, there was a trade-off between productivity and quality: while the fruits with full irrigation had higher sweetness (TSS), the deficit treatments produced larger fruits with lower sugar concentration. Overall, applying irrigation at 80-90% of ETc is recommended as an efficient management strategy in humid environments, with the consideration of adjusting the final decision according to market objectives (yield vs quality).

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