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Original Article

Gas exchanges and thermal index of strawberry cultivars grown under hydrogel doses[1]

Trocas gasosas e índice térmico de cultivares de morango cultivadas sob doses de hidrogel

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HIGHLIGHTS:

Increasing hydrogel doses in the growing medium boosts strawberry plant growth.
Hydrogel reduces gas exchange in strawberry crops 90 days after transplanting.
Increasing hydrogel doses in the substrate provides conditions for reducing the thermal index of strawberry plants.

ABSTRACT: The Northeast region of Brazil is characterized by a tropical climate and high air temperatures, which can negatively affect the growth and physiological processes of strawberry plants (*Fragaria x ananassa* Duch) in the short- or long-term. In this context, the use of adapted varieties and technologies such as soil conditioners is necessary. Thus, the objective of this study was to assess the physiological responses and the thermal index of strawberry cultivars grown under hydrogel doses in the substrate. The study was conducted in a protected environment in Guaraciaba do Norte, Ceará state, Brazil, using a randomized block experimental design with four replicates, in a 5 × 2 factorial arrangement consisting of five hydrogel doses in the substrate (0, 1, 2, 3, and 4 g L^{-1}) and two strawberry cultivars (‘Albion’ and ‘San Andreas’). Growth variables (number of leaves, crown diameter, and plant height) were evaluated at 15 and 45 days after transplanting (DAT). Gas exchanges (stomatal conductance, transpiration rate, CO_2 assimilation rate, and intercellular CO_2 concentration), physiological indices (intrinsic water use efficiency, instantaneous carboxylation efficiency, and instantaneous water use efficiency), and thermal index were evaluated at 90 DAT. Strawberry plant growth increased significantly as the hydrogel dose in the substrate was increased. The hydrogel dose of 4 g L^{-1} reduced gas exchanges at 90 DAT, regardless of the cultivar. Plants of the cultivar San Andreas showed higher intrinsic water use efficiency and lower thermal index when grown under the hydrogel dose of 4 g L^{-1}.

Key words: *Fragaria x ananassa* Duch, polymer, infrared thermography

RESUMO: A região Nordeste do Brasil é caracterizada por clima tropical e altas temperaturas do ar em curto ou longo prazo, o que pode afetar negativamente o crescimento e os processos fisiológicos do morangueiro (*Fragaria x ananassa* Duch). Nesse contexto, para mitigar os impactos do estresse térmico, destaca-se a necessidade de empregar variedades adaptadas e tecnologias, como uso de condicionadores de solo. Assim, o objetivo deste estudo foi avaliar as respostas fisiológicas e o índice térmico de cultivares de morango cultivadas sob doses de hidrogel no substrato. O estudo foi conduzido em ambiente protegido em Guaraciaba do Norte, Ceará, Brasil, utilizando delineamento experimental em blocos casualizados com quatro repetições, em arranjo fatorial 5 × 2 composto por cinco doses de hidrogel no substrato (0, 1, 2, 3, e 4 g L^{-1}) e duas cultivares de morango (‘Albion’ e ‘San Andreas’). As variáveis de crescimento (número de folhas, diâmetro da coroa e altura das plantas) foram avaliadas aos 15 e 45 dias após o transplantio (DAT). As trocas gasosas (condutância estomática, taxa de transpiração, taxa de assimilação de CO_2 e concentração intercelular de CO_2), índices fisiológicos (eficiência intrínseca do uso da água, eficiência instantânea de carboxilação e eficiência instantânea do uso da água) e índice térmico foram avaliados aos 90 DAT.

Palavras-chave: *Fragaria x ananassa* Duch, polímero, termografia infravermelha

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Introduction

Strawberry (*Fragaria x ananassa* Duch) is a commercially important fruit species resulting from an 18th-century hybridization in Europe, valued for its nutraceutical properties (Rapuru & Bathula, 2022). Strawberry crops have been increasingly grown in tropical and subtropical regions, where factors such as air temperature and photoperiod pose challenges (Lema-Rumińska et al., 2021; Moreira et al., 2022).

The Northeast region of Brazil is characterized by a tropical climate, with high air temperatures that can negatively affect the growth and physiological processes of strawberry plants (Chagas et al., 2018). High temperatures delay leaf emergence and affect phytochrome activity, essential for plant development (Diel et al., 2017). Furthermore, excessive heat leads to physiological imbalances, hindering stomatal opening, CO_2 uptake, source-sink ratio, hormonal balance, and causing chlorophyll depletion and deformation, all vital factors for flowering, particularly in strawberry plants (Taiz et al., 2017; Liu & Lin, 2020; Moreira et al., 2022).

Therefore, using adapted varieties and technologies, such as soil conditioners, is necessary to mitigate the impacts of heat stress on plants. The use of day-neutral cultivars is recommended for tropical climate regions, as they require moderate temperatures and are not dependent on photoperiod (Strassburger et al., 2010; Chiomento et al., 2021).

Hydrogels stand out among soil conditioners, as they are water-absorbent polymers that can store 100 times their weight in water (Nascimento et al., 2021). Increases in water and nutrient retention in the soil or substrate due to the presence of the hydrogel can favor plant growth and gas exchanges (Rizwan et al., 2021). The positive effect on gas exchanges may contribute to leaf cooling, reducing heat stress. Therefore, the objective of this study was to assess physiological responses and thermal index of strawberry cultivars grown under hydrogel doses in the substrate.

Material and Methods

The experiment was conducted from June to September 2022 in a greenhouse at Estufa Timbaúba, in Guaraciaba do Norte, Ceará state, Brazil (03° 52' 47" S, 40° 57' 50" W, and average altitude of 920 m). The climate of the region is classified as Aw', predominantly hot and humid, with minimum and maximum air temperatures of 15 and 32 °C, respectively, and a rainy season from February to May (Köppen, 1948). The maximum, mean, and minimum air temperatures and relative air humidity collected during the experimental period are shown in Figure 1.

A randomized block experimental design with four replicates was used, in a 5 × 2 factorial arrangement consisted of five hydrogel doses (0, 1, 2, 3, and 4 g L^{-1}) and two strawberry cultivars ('Albion' and 'San Andreas'). The experimental unit consisted of two grow bags (slabs) with substrate, containing 13 plants per slab, totaling 26 plants per experimental unit and a total of 1,040 plants.

The hydrogel doses in the substrate were obtained by removing 300 mL of substrate from each planting hole, which

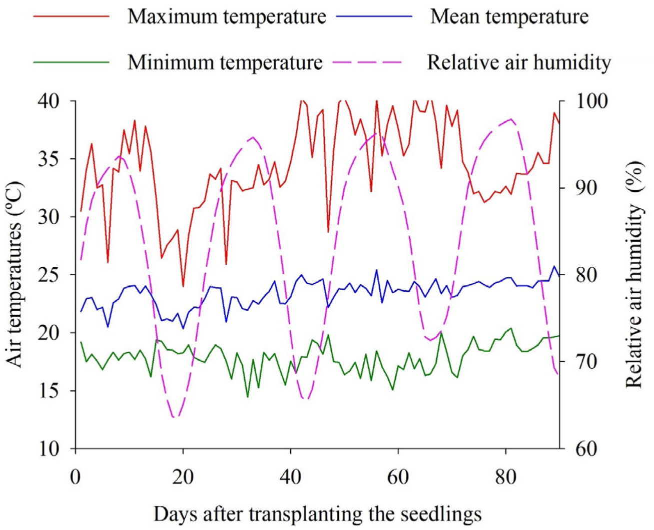


Figure 1. Maximum, mean, and minimum air temperatures and relative air humidity during the experimental period (June to September 2022)

was homogenized and mixed with the respective concentration of dry hydrogel (Polyter®). The slabs used were 1.40 × 0.30 m, white on the outside and black on the inside; they were filled with a commercial coconut fiber substrate and placed on wooden benches at 0.70 m height.

The strawberry seedlings were obtained from a commercial nursery (Viveiros California). The cultivar Albion was developed from a cross (Diamante' × Cal 94.16-1) and is characterized as a day-neutral (DN) cultivar. Similarly, San Andreas is characterized as a DN cultivar, but was developed from the cross Albion × Cal 97.86-1 (Diel et al., 2017; Chiomento et al., 2021). The seedlings were manually transplanted in double rows and triangular rows with a spacing of 0.20 and 0.15 m between plants and between rows, respectively, totaling 26 seedlings per experimental unit.

Fertigation with nutrient solutions was carried out following the recommendations of EMBRAPA (2014). An open system was used, in which the nutrient solution containing sulphates and phosphates was stored in a 1000-liter tank, whereas a nutrient solution containing calcium nitrate was stored in a 200-liter tank. Two tanks were needed due to the incompatibility between fertilizers containing calcium and those containing phosphates and sulphates. The nutrient solution was applied through a drip irrigation system, with one emitter for every two plants, at a flow rate of 1.6 L h^{-1}.

A water balance was carried out using irrigation pulses, with variation in amount and timing depending on the plant development and electrical conductivity of the drained solution (ECs), considering a ECs limit of 1.4 dS m^{-1}, as recommended by Miranda et al. (2014). The substrate water retention capacity was maintained based on the flow rate of the drippers, irrigation time, and drainage percentage. Pulses of one to two four-minute pulses were used in the first 15 days after transplanting, with a maximum of four five-minute pulses per day, on average, using an automated system. The drained solution volume was collected daily for monitoring electrical conductivity and pH.

Five plants per experimental unit were evaluated at 15 and 45 days after transplanting (DAT), considering the following biometric variables: number of leaves, by directly counting the number of fully expanded leaves; crown diameter (mm) at 2 cm above the substrate, measured using a digital caliper (MOD. MPD-300); and plant height (cm) from the base to the apex of the seedling, measured using a ruler.

Leaf gas exchange, canopy temperature, and air temperature were measured at 90 DAT. Gas exchanges were measured on fully expanded leaves in two plants per experimental unit in the morning (between 8:00 h and 10:00 h) using an infrared gas analyzer (IRGA; LCi, ADC, BioScientific, England). The evaluated gas exchange variables were: stomatal conductance (gs; mol H_2O m^{-1} s^{-1}), transpiration rate (E; mmol H_2O m^{-2} s^{-1}), CO_2 assimilation rate (A, μmol CO_2 m^{-2} s^{-1}), and intercellular CO_2 concentration (Ci; μmol CO_2 mol^{-1}), The gas exchange data were used to obtain the physiological indices: intrinsic water use efficiency [iWUE (A/gs); μmol CO_2 m^{-2} s^{-1}/mol m^{-1} s^{-1}], instantaneous carboxylation efficiency [iCE (A/Ci); μmol CO_2 m^{-2} s^{-1}/ μmol mol^{-1}], and instantaneous water use efficiency [WUE (A/E); μmol CO_2 m^{-2} s^{-1}/ mmol m^{-2} s^{-1}).

Canopy temperature (TCanopy; °C) was measured using a thermal camera (FLIR ONE PRO®) with thermal sensitivity range between -20 and 120 °C, accuracy of ±3 °C, and thermal resolution of 160 × 120 pixels. Thermal images were captured on the same leaves used to measure gas exchanges, in the morning (between 8:00 h and 10:00 h) under cloudless conditions, at 1.0 m from the plants. The thermal images were then analyzed using the FLIR Tools software, obtaining the mean canopy temperature. Air temperature (TAir; °C) was measured using a thermo-hygrometer (THAL-300) placed near the plant when the thermal images were captured, following the methodology described by Sousa et al. (2022). The thermal index (ΔT) was estimated by the difference between canopy and air temperatures (Eq. 1):

$$\Delta T = TCanopy - TAir \quad (1)$$

The obtained data were subjected to normality analysis using the Kolmogorov-Smirnov test ($p \leq 0.05$) followed by analysis of variance. Significant means found for the hydrogel doses or the interaction between factors were subjected to polynomial regression analysis. Means found for the strawberry cultivars were subjected to the Tukey's test ($p \leq 0.05$), using the Assistat 7.7 Beta software (Silva & Azevedo, 2016).

Results and Discussion

Number of leaves, crown diameter, and plant height at 15 and 45 days after transplanting (DAT) were affected by the cultivar factor and fitted to linear regression models, except plant height at 45 DAT, which was affected by the interaction between cultivars and hydrogel doses in the substrate. According to the mean comparison test (Table 1), strawberry plants of the cultivar Albion differed significantly from those of the cultivar San Andreas in all evaluation periods. These differences represented 17.19, 21.31, and 17.02% for number of leaves, crown diameter, and plant height at 15 DAT, respectively. Differences of 7.97 and 1.58% were found for number of leaves and crown diameter, respectively, at 45 DAT.

Table 1. Mean comparison test for number of leaves (NL), crown diameter (CD), and plant height (PH) in strawberry plants (*Fragaria x ananassa* Duch) at 15 and 45 days after transplanting (DAT) as a function of the cultivar factor

Cultivars	NL	CD	PH	NL	CD
	15 DAT			45 DAT	
'Albion'	2.85 a	9.01 a	9.05 a	6.15 a	13.92 a
'San Andreas'	2.36 b	7.09 b	7.51 b	5.66 b	13.70 b

Means followed by the same letter are not significantly different from each other by the Tukey's test ($p \leq 0.05$)

The superiority of the strawberry cultivar Albion can be attributed to genetic factors. Although genetic materials may belong to the same species, variations in qualitative and quantitative genetic characteristics can significantly affect plant growth (Jannat et al., 2022). Ahn et al. (2021) assessed characteristics and trends throughout the growing cycle of five strawberry cultivars (Arihyang, Jukhyang, Keumsil, Maehyang, and Seollhyang) grown under greenhouse conditions and found differences in biometric variables among the cultivars. Similarly, Lema-Rumińska et al. (2021) found differences among genetic materials when evaluating the cultivars San Andreas and Ostara and the wild strawberry cultivars Baron von Solemacher and Regina.

Number of leaves at 15 and 45 DAT increased linearly as the hydrogel dose in the substrate was increased, differing significantly from those found in the control treatment (0 g L^{-1}) when using the highest hydrogel dose (4 g L^{-1}), corresponding to differences of 32.58 and 19.21%, respectively (Figures 2A and B). Additionally, number of leaves increased by 0.1380 (15 DAT) and 0.264 (45 DAT) per unit increase in hydrogel dose, as shown by the regression equations (Figures 2A and B).

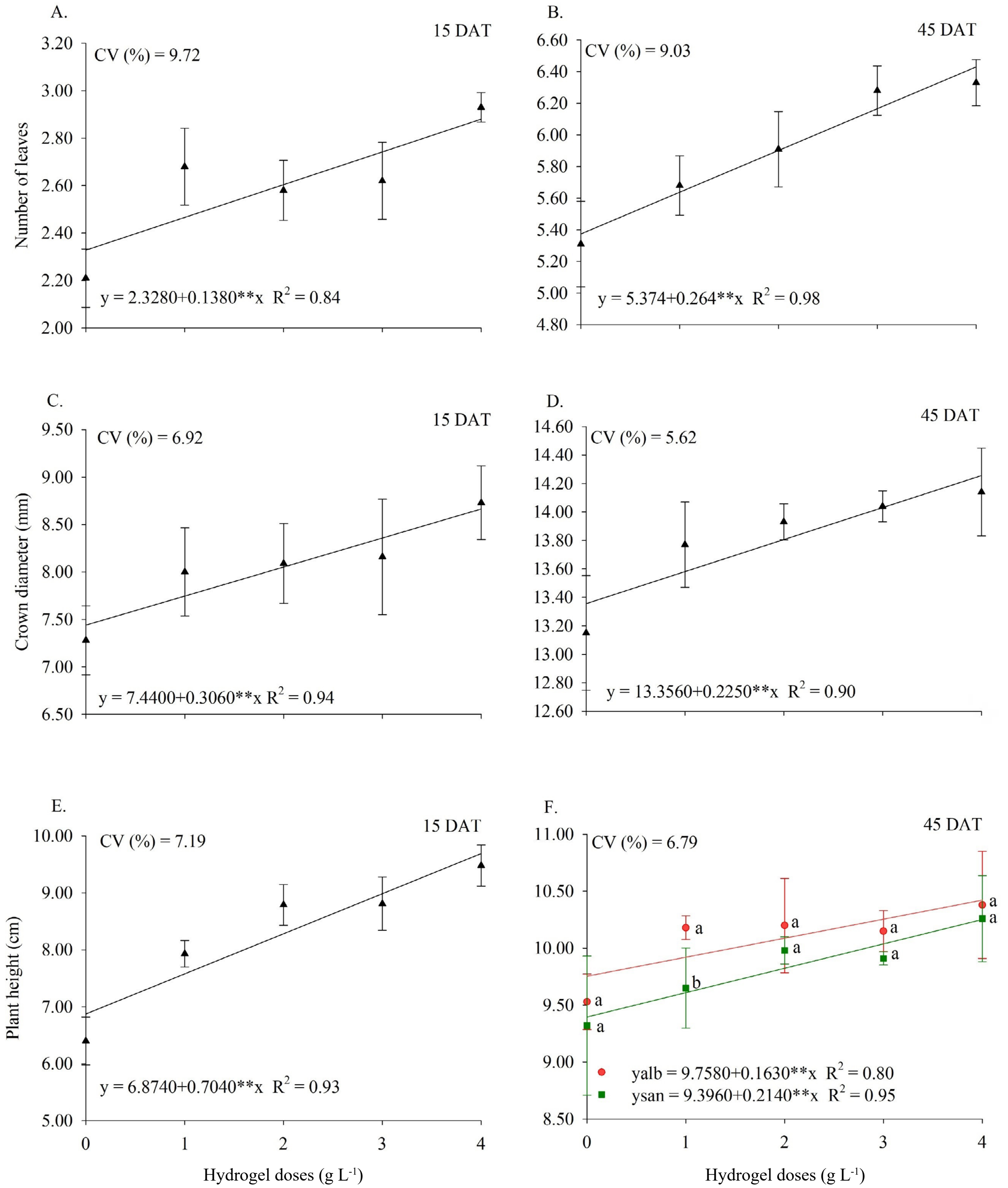
Similarly, crown diameter at 15 and 45 DAT increased linearly as the hydrogel dose was increased (Figures 2C and D); according to the regression equations, crown diameter increased by 0.3060 and 0.2250 mm per unit increase in hydrogel dose, respectively.

Plant height data as a function of hydrogel doses obtained at 15 DAT fitted to a linear regression model (Figure 2E), with increase of 0.704 cm per unit increase in hydrogel dose. The mean plant height of the cultivars Albion and San Andreas at 45 DAT showed a linear response to the interaction between factors (Figure 2F). The cultivars showed their highest growth potential, with plant height of 10.36 cm (Albion) and 10.26 cm (San Andreas), when subjected to the highest hydrogel dose (4 g L^{-1}).

The increases in biometric variables as the hydrogel dose was increased can be attributed to the capacity of hydrogels to absorb significant quantities of water and nutrients and release them gradually to plant roots according to the plant demand (Rizwan et al., 2021). Water is an essential universal solvent that directly participates in the synthesis of glucose, which is a vital energy compound utilized in metabolic and growth processes in plants (Nassaj-Bokharaei et al., 2021).

The analysis of cultivars within each hydrogel dose (Figure 2F) showed significant differences in plant height between cultivars for the hydrogel dose of 1 g L^{-1}, with Albion showing higher plant height than San Andreas.

These positive effects of increasing hydrogel doses on biometric variables may have a positive impact on the



Vertical lines represent the standard error of the mean (n = 4); ** - Significant at $p \leq 0.01$ by the F-test. Means followed by the same letter are not significantly different from each other by the Tukey's test ($p \leq 0.05$); (●) cultivar Albion; (■) cultivar San Andreas, DAT - Days after transplanting; CV - Coefficient of variation

Figure 2. Number of leaves at 15 DAT (A) and 45 DAT (B); crown diameter at 15 DAT (C) and 45 DAT (D); and plant height at 15 DAT (E) as a function of hydrogel doses; and plant height at 45 DAT (F) as a function of hydrogel doses and strawberry (*Fragaria x ananassa* Duch) cultivars

final crop yield. An increased vegetative growth may affect photosynthetic activity and, consequently, result in greater capture and conversion of energy, increasing the production of photoassimilates in reproductive organs (Lema-Rumińska et al., 2021).

Melo et al. (2019) evaluated the growth and development of tomato seedlings (hybrid BRS Nagai) grown in substrates containing different hydrogel additives and found improvements in plant growth when using a hydrogel dose of 1.5%. Studies on *Tagetes patula* L. (marigold) (Sousa et al., 2022) and maize plants (Abdallah et al., 2021) also showed the benefits of using hydrogels for vegetative development, which may be connected to a greater leaf water potential, favoring plant growth.

Stomatal conductance (gs), transpiration rate (E), intercellular CO_2 concentration (Ci), and instantaneous water use (WUE) efficiency were significantly affected by the cultivar factor. Regarding the effect of the hydrogel dose factor, the data of gs, E, Ci, and intrinsic water use efficiency (iWUE) fitted to linear regression models (Figure 3). The interaction between factors significantly affected iWUE (Figure 3D) and thermal index (Figure 4) at 90 DAT. However, CO_2 assimilation rate and instantaneous carboxylation efficiency were not significantly affected by the factors.

The results found for gs, E, and Ci at 90 DAT showed significant differences between cultivars; Albion presented 18.75, 7.72, and 5.60% higher gs, E, and Ci, respectively (Table 2).

Responses of gs may vary between cultivars of the same species, which may explain the superiority of the cultivar Albion. Furthermore, it is a complex system affected by leaf water potential, transpiration, and environmental factors, including external CO_2 concentration, soil moisture, air temperature, and light intensity (Taiz et al., 2017; Bertolino et al., 2019; Hatfield & Dold, 2019).

Lema-Rumińska et al. (2021) evaluated commercial and wild strawberry cultivars and found differences in gs among them: the cultivar Ostara showed a mean of 0.090 mol m^{-2} s^{-1}, which was higher than that found for the cultivar San Andreas (0.080 mol m^{-2} s^{-1}), indicating a significant effect of the genotype factor. Regarding WUE as a function of the cultivar factor, plants of the cultivar San Andreas presented higher means compared to those of the cultivar Albion (Table 2), representing a difference of 7.87%. This result denotes that 'San Andreas' can be more photosynthetically efficient by presenting less water loss, which is an important factor when considering the acclimation of species to different growing environments (Hatfield & Dold, 2019).

Martínez-Ferri et al. (2016) evaluated seven strawberry cultivars and found differences in WUE among them, regardless of the water replacement; they reported that the use of strawberry cultivars with high WUE is an agronomic advantage in terms of increasing water use and economic benefits of growing strawberry crops.

The gs at 90 DAT showed a decreasing linear response to the increasing hydrogel doses (Figure 3A); plants grown without hydrogel (0 g L^{-1}) had a difference of 21.42% in gs compared to those grown under the highest hydrogel dose (4 g L^{-1}).

Table 2. Stomatal conductance (gs), transpiration (E), intercellular CO_2 concentration (Ci), and instantaneous water use efficiency (WUE) in strawberry plants (*Fragaria x ananassa* Duch) at 90 days after transplanting (DAT) as a function of the cultivar factor

Cultivars	90 DAT			
	gs	E	Ci	WUE
'Albion'	0.38 a	5.30 a	249.42 a	3.56 b
'San Andreas'	0.32 b	4.92 b	236.20 b	3.84 a

Means followed by the same letter are not significantly different from each other by the Tukey's test ($p \leq 0.05$)

The reduction in gs as the hydrogel dose was increased may be attributed to the significant water retention capacity of hydrogel polymer networks. This implies that water absorbed by the hydrogel may not be readily available to plant roots, resulting in a potential reduction in water uptake by plants (Ahluwalia et al., 2021). Therefore, despite the potentially higher water availability in the substrate due to the hydrogel, this water may not be easily accessible to plants, which may result in decreases in gs and E (Figure 3B), as observed in this evaluation stage in strawberry crops. Contrastingly, Sandoval et al. (2017) found that increasing hydrogel doses increased soil moisture content by 20.8% compared to the control, promoting increases in gs in maize crops.

Partial stomatal closure resulted in linear decreases in strawberry transpiration as the polymer rate was increased (Figure 3B). According to the equation, E was 5.35 mmol m^{-2} s^{-1} in the control treatment (0 g L^{-1}) and 4.99 mmol m^{-2} s^{-1} in the treatment with the highest dose (4 g L^{-1}), representing a difference of 7.26%.

Thus, strawberry plants reduced their transpiration rate due to reduced stomatal opening caused by adverse conditions resulting from increased hydrogel doses. Stomata are directly responsible for water loss as water vapor and entry of carbon dioxide (Lema-Rumińska et al., 2021), thus, these increases led to decreases in CO_2 absorption, as well as reduced absorption of water and nutrients.

Araújo et al. (2022) found similar results, with linear decreases in E of passion fruit crops, reaching 1.118 mmol m^{-2} s^{-1} per unit increase in hydrogel dose.

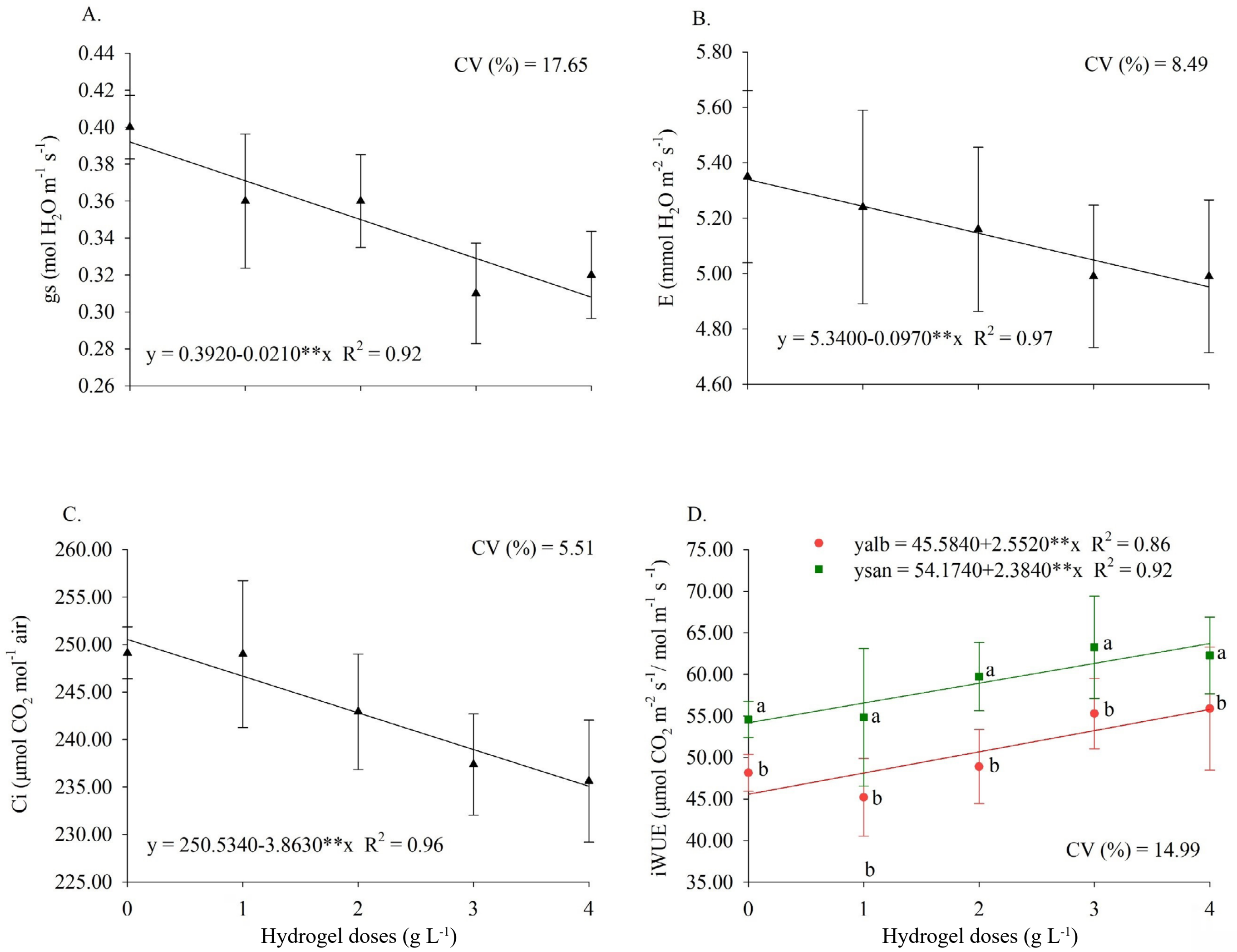
The Ci at 90 DAT (Figure 3C) showed a linear decrease as the hydrogel dose was increased; the equation showed a difference of 6.16% between plants grown without hydrogel and those grown under the highest dose (4 g L^{-1}).

Plants grown under harmful environments reduce stomatal conductance to reduce water loss to the atmosphere through transpiration due to secondary effects such as induction of abscisic acid (ABA) accumulation (Taiz et al., 2017). However, this strategy reduces CO_2 assimilation and diffusion, which can affect photosynthetic processes (Martínez-Ferri et al., 2016).

Beltramin et al. (2020) evaluated the use of a water-retaining polymer under different water regimes for *Schinus terebinthifolia* crops and found similar Ci for all water regimes, with or without the hydrogel, until the resuming of daily irrigation.

The iWUE at 90 DAT was affected by the interaction between factors; the crops presented a linear and positive response (Figure 3D). The iWUE of the cultivar Albion increased by 5.60% per unit increase in hydrogel dose, whereas the iWUE of the cultivar San Andreas increased by 4.40% per unit increase in hydrogel dose.

Considering the analysis of cultivars within hydrogel doses (Figure 3D), San Andreas was significantly superior to Albion at all doses. The iWUE of San Andreas was 54.58 μmol CO_2 mol H_2O^{-1} in the control treatment (0 g L^{-1}) and 63.28 and 62.28 μmol CO_2 mol H_2O^{-1} at the highest hydrogel doses (3 and 4 g L^{-1}), respectively, corresponding to differences of 13.20 and 17.60%, respectively. Similarly to the cultivar San Andreas, Albion showed a lower iWUE (48.16 μmol CO_2 mol H_2O^{-1})



Vertical lines represent the standard error of the mean (n = 4); ** - Significant at $p \leq 0.01$ by the F-test. Means followed by the same letter are not significantly different from each other by the Tukey's test ($p \leq 0.05$); (●) cultivar Albion; (■) cultivar San Andreas; CV - Coefficient of variation

Figure 3. Stomatal conductance (gs) (A), transpiration rate (E) (B), and intercellular CO_2 concentration (Ci) (C) of strawberries cultivars as a function of hydrogel doses in the substrate; and intrinsic water use efficiency (iWUE) as a function of hydrogel doses and strawberry (*Fragaria x ananassa* Duch) cultivars (D) at 90 days after transplanting

in the control treatment (0 g L^{-1}) and higher iWUE (55.88 µmol CO_2 mol H_2O^{-1}) at the highest hydrogel dose (4 g L^{-1}), representing a difference of 16.79%.

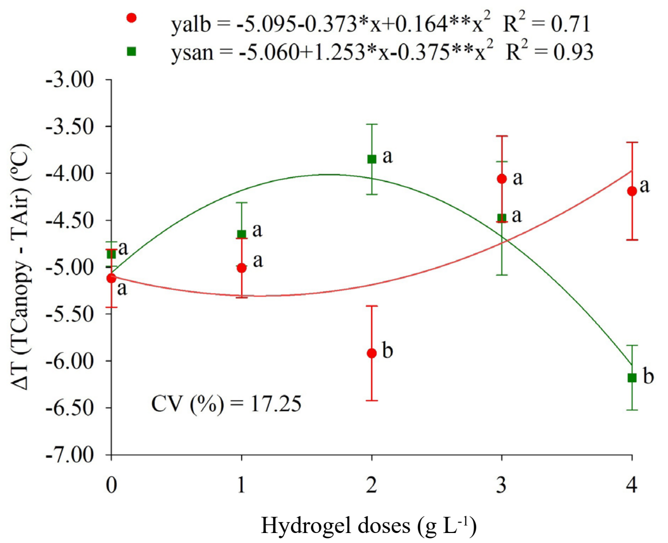
These differences in iWUE according to the hydrogel dose in the substrate may be connected to the genetic characteristics of each cultivar, which are adjusted during the developmental stage for acclimation, resulting in maintenance of water use efficiency. This is evidenced by reductions in gs and the preservation of photosynthesis (Zhang et al., 2019; Haworth et al., 2021).

These results confirm those of Rasouli et al. (2022), who reported that iWUE can reflect plant responses to environmental factors due to the rapid stomatal response to efficiently assimilate CO_2 and prevent water loss, resulting in greater adaptability to the environment.

The thermal index of strawberry plants at 90 DAT (Figure 4) was affected by the interaction between hydrogel doses and cultivars, showing different responses to polymer doses, fitting a quadratic polynomial model. Plants of the cultivar Albion showed a minimum estimated thermal index of -5.30 °C under a hydrogel dose of 1.13 g L^{-1}. Plants of the cultivar San Andreas showed a maximum estimated thermal index of -4.01 °C under a hydrogel dose of 1.67 g L^{-1}.

The cultivars presented significant differences in thermal index at the hydrogel dose of 2 and 4 g L^{-1} (Figure 4). Plants of the cultivar San Andreas presented lower thermal indices when grown under the hydrogel dose of 4 g L^{-1}, whereas plants of the cultivar Albion presented lower thermal indices under the hydrogel dose of 2 g L^{-1}. These results indicate that these hydrogel doses effectively helped the plants to reduce leaf temperature; however, there are differences in maximum efficiency and hydrogel use for canopy cooling among cultivars (Sousa et al., 2022). Leaf cooling occurs when thermal energy is released from the leaf through evaporation (Taiz et al., 2017).

Although the results of gs and E with increasing hydrogel doses alone (Figures 3A and B) indicate a reduction in thermal energy, the findings for the interaction between cultivars and hydrogel doses in the thermal thermographic analysis (Figure 4) showed that leaf surface temperature was lower than the ambient temperature. This indicates that reductions in leaf temperature in strawberry plants due to hydrogel use can be identified in a pre-visual analysis (Gerhards et al.,



Vertical lines represent the standard error of the mean (n = 4); ** and * - Significant at $p \leq 0.01$ and $p \leq 0.05$, respectively, by the F-test. Mean followed by the same letter do not differ statistically by Tukey's test ($p \leq 0.05$); (●) cultivar Albion; (■) cultivar San Andreas; CV - Coefficient of variation

Figure 4. Thermal index as a function of hydrogel doses and strawberry (*Fragaria x ananassa* Duch) cultivars

2019). Therefore, maintaining an adequate plant water status contributes to reducing leaf temperature, improving plant growth and gas exchanges (Haworth et al., 2021). Several plant processes are affected when leaf temperature exceeds a certain threshold, particularly phytochemical and carbon metabolism processes (Liu & Lin, 2020).

Conclusions

1. The vegetative growth of strawberry plants (*Fragaria x ananassa* Duch) significantly increased as the hydrogel dose in the substrate was increased.

2. The cultivar Albion was superior to San Andreas in biometric variables at 15 and 45 days after transplanting (DAT) and in gas exchanges at 90 DAT, but San Andreas showed greater instantaneous water use efficiency.

3. The application of 4 g L^{-1} of hydrogel to the substrate reduced stomatal conductance, transpiration rate, and intercellular CO_2 concentration at 90 days after transplanting, regardless the strawberry cultivar.

4. Plants of the cultivar San Andreas showed greater intrinsic water use efficiency and lower thermal index when grown under a hydrogel dose of 4 g L^{-1}.

Contribution of authors: José T. M. de Sousa worked on research, data acquisition, data analysis, implementation of the computational simulations, and writing of the manuscript. Alan B. O. de Sousa served as a research advisor, contributing to the conceptualization of the problem and refining simulation models through insightful corrections and enhancements. Gilbenes B. Rosal, Juarez C. de L. Junior, and Antônio M. S. de Oliveira worked on performing the experiment and collecting data. Claudivan F. de Lacerda worked collecting data and administration and acquisition of financing.

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