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Gas exchange and yield of yellow passion fruit under different irrigated depths, planting hole volumes, and hydroretentive polymer application

Trocas gasosas e produtividade do maracujazeiro-amarelo sob irrigação, volumes de cova e polímero hidrorretentor

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Highlights

Hydrogel in 128 dm³ planting hole increases leaf chlorophyll in yellow passion fruit.
Water depth reductions do not harm gas exchange in yellow passion fruit.
Yellow passion fruit photosynthesis is improved in 128 dm³ planting hole and polymer.
Polymer and 128 dm³ planting hole increase passion fruit yield with lower water depth.

Abstract

Passion fruit cultivation relies on irrigation to increase yields in the semiarid of northeastern Brazil. Water scarcity is one of the factors that most affect crop physiology, leading to lower yields. Therefore, this study aimed to assess the influence of planting hole volume and application of a hydroretentive polymer on physiological and productive aspects of irrigated yellow passion fruit cv. BRS GA1 in the Northeast semi-arid region of Brazil. The experiment was conducted in randomized blocks, in a split-plot design 2 × (2 × 2). Treatments consisted of irrigation depths (100% and 70% of the crop's evapotranspiration requirement - ETc), planting hole volumes (64 dm³ and 128 dm³), and soil with and without application of hydroretentive Polymer (1.5 g dm³), with four replicates and three plants per plot. The analyzed variables

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included chlorophyll a and b indices, gas exchange, and yellow passion fruit yield. The findings showed that hydroretentive polymer application to the soil increases chlorophyll content and gas exchange in yellow passion fruit. Moreover, photosynthetic rates were not limited by a 30% reduction in irrigation depth and increased in plants grown in 128-dm^3 planting holes with hydroretentive polymer. Based on yield results, irrigation depths can be reduced to 70% of the ETc by applying hydroretentive polymer in 64-dm^3 planting holes.

Key words: *Passiflora edulis* f. flavicarpa Degener. Irrigation water depths. Management. Hydrogel. Plant physiology. Crop production.

Resumo

Na região semiárida do Nordeste brasileiro, a cultura do maracujazeiro-amarelo depende da irrigação para conseguir elevada produtividade. A escassez de água é um dos fatores que mais afeta a fisiologia das culturas, acarretando em baixas produtividades. Com isso, objetivou-se com a pesquisa avaliar a influência do volume de cova e aplicação de polímero hidrorretentor sob os aspectos fisiológicos e produtivos do maracujazeiro-amarelo cv. BRS GA1 irrigado no semiárido do Nordeste. O experimento foi conduzido em blocos casualizados, em parcela subdividida 2 × (2 × 2), referente às lâminas de irrigação de 100% e 70% da exigência evapotranspirativa da cultura, aos volumes de cova de 64 dm3 e 128 dm^3, no solo sem e com 1,5 g dm^3 do polímero hidrorretentor, com quatro repetições e três plantas por parcela. As variáveis analisadas foram índices de clorofila a e b, as trocas gasosas e a produtividade do maracujazeiro-amarelo. A adição do polímero hidrorrententor no solo proporciona maiores teores de clorofila e trocas gasosas no maracujazeiro-amarelo. A taxa fotossintética do maracujazeiro-amarelo cv. BRS GA1 não foi limitada com a redução da lâmina de irrigação em 30% da ETc e aumentou nas plantas cultivada no volume de cova de 128 dm^3 com polímero hidrorrententor. Pelos resultados de produtividade do maracujazeiro-amarelo cv. BRS GA1, indica-se reduzir a lâminas de irrigação para 70% da ETc através da aplicação de polímero hidrorrententor nas covas de 64 dm^3.

Palavras-chave: *Passiflora edulis* f. *flavicarpa* Degener. Lâminas de água. Manejo. Hidrogel. Fisiologia. Produção.

Introduction

Brazil is considered the world's largest producer of yellow passion fruit (*Passiflora edulis* Sims f. flavicarpa Deg.), standing out in the national fruit production scenario as one of the main fruit species (Aguiar et al., 2015). In 2020, Brazilian production reached about 690,000 tons within a harvested area of 46,436 hectares, with the Northeast region contributing 69.6% of the national production (Instituto Brasileiro de Geografia e Estatística [IBGE], 2021). This can be attributed to the favorable market acceptance, ease of crop management, quick economic returns, and evenly distributed revenue throughout the year, making it ideal for small and medium-scale rural producers (Cavichioli et al., 2017; Costa et al., 2023).

In the Northeast, the primary production areas are located in semi-arid regions, which, despite ideal soil and climatic conditions for yellow passion fruit cultivation, face temporal and spatial limitations in rainfall and low availability of water in terms of quantity and quality in reservoirs, necessitating supplemental irrigation (Freire et al., 2014; Araújo et al., 2022). According to Uchoa et al. (2021), inadequate water supply to yellow passion fruit is one of the most limiting factors for production and, in general, plants under water deficit conditions reduce their physiological processes, limiting gas exchange and carbon assimilation, thereby resulting in reduced yields (Cavalcante et al., 2020).

As a result, there is a need in these regions for management techniques that enhance water use efficiency by plants, and soil preparation for transplanting seedlings is one of the critical factors for orchard success. In this regard, planting hole preparation can favor root development, improve the use of soil water and nutrients, and facilitate cultural practices such as irrigation and fertilization (Sousa et al., 2005; Rosa et al., 2017; Oliveira et al., 2023). For Lucas et al. (2012), root development of yellow passion fruits occurs up to a depth of 0.5 meters and a distance of 0.6 meters from the plant stem, where water and nutrient management should be carried out.

To avoid water and nutrient losses and enable their more efficient use by plants, hydroretentive polymers (hydrogel) have been increasingly employed (Monteiro et al., 2017; Abobatta, 2018; Song et al., 2020). In the soil, the root zone can be kept moist by applying hydrogel, which adheres to water due to the polymer's structure, preventing losses through percolation and lateral drainage. This way farmers can reduce irrigation frequency without harming plants (Souza et al., 2016; Felippe et al., 2021). Additionally, hydrogel reduces nutrient losses through leaching, primarily of nitrogen and potassium, applied through fertilization (Pattanaaik et al., 2015; Felippe et al., 2020).

Based on the above, our goal was to assess the influence of planting hole volume and hydroretentive polymer application on physiological and production aspects of irrigated yellow passion fruit cv. BRS GA1 in the semiarid region of northeastern Brazil.

Materials and Methods

Characterization of the experimental area, soil, and climate

The experiment was conducted on the farm Macaquinhos, which is located in the city of Remígio, state of Paraíba, Brazil, from September 2018 to January 2020. The experimental area is georeferenced at coordinates 07° 00′ 1.95′′ S, 35° 47′ 55′′ W, with an altitude of 562 meters. According to the Köppen classification (Alvares et al., 2013), the local climate is type "*As,*" which stands for hot and humid with a rainy period from March to July.

The soil in the area was classified as per the Brazilian Soil Classification System – SIBCS (Santos et al., 2018) as eutrophic Regolithic Neosol. Before experiment implementation, soil samples were collected at a depth of 0.0-0.40 meters, transformed into a composite sample, and taken to the laboratory for physical and chemical characterization related to soil fertility (Teixeira et al., 2017), as shown in Table 1.

Table 1
Physical and chemical characterization of soil fertility in the experimental area, in the 0.0-0.40 m depth layers

Physical properties		Chemical properties	
Cs (g kg^{-1})	602	pH in water (1:2.5)	5.37
Fs (g kg^{-1})	194	SOM (g dm^{-3})	4.0
Silt (g kg^{-1})	132	P-rem (mg dm^{-3})	49.6
Clay (g kg^{-1})	72	P (mg dm^{-3})	5.6
WDC (g kg^{-1})	10.5	S (mg dm^{-3})	6.5
SD (kg dm^{-3})	1.54	K^+ ($cmol_c$ dm^{-3})	0.13
PD (kg dm^{-3})	2.77	Ca^{2+} ($cmol_c$ dm^{-3})	1.19
TP (%)	44.5	Mg^{2+} ($cmol_c$ dm^{-3})	0.37
FD (%)	86	Na^+ ($cmol_c$ dm^{-3})	Trace
DI (%)	14	SB ($cmol_c$ dm^{-3})	1.34
FD/DI	7.75	H^++Al^{3+} ($cmol_c$ dm^{-3})	1.8
VWCfc (%)	8.0	Al^{3+} ($cmol_c$ dm^{-3})	0.09
VWCpwp (%)	2.3	CEC ($cmol_c$ dm^{-3})	2.52
AW (%)	4.3	BS (%)	53.0
Texture class	LS	Fertility class	Eutrophic

Cs and Fs = coarse and fine sand, respectively; WDC = water-dispersed clay; SD and PD = soil and particle density, respectively; TP = total porosity [TP = (1-SD / PD) × 100]; FD = flocculation degree [FD = (Clay-WDC)/clay) × 100]; DI = dispersion index (DI = 100-FD); VWC_{fc} and VWC_{pwp} = volumetric water content at field capacity and permanent wilting point, respectively, determined on deformed samples using Richards' chambers at tensions of -0.01 and -1.50 MPa; AW = available water (AW = VWC_{fc} - VWC_{pwp}); LS = Loamy sand; P-rem = remaining soil phosphorus; SOM = soil organic matter; SB = sum of bases in the soil (SB = Ca^{2+}+Mag^{2+}+K^+); CEC = cation exchange capacity = SB + (H^++Al^{3+}); BS = base saturation = [(SB/CEC) × 100]. Extractors: a) SOM - Walkley-Black; P, K^+, and Na^+- Mehlich 1; Ca^{2+}, Mg^{2+}, and Al^{3+} - KCl at 1mol L^{-1}; S – monocalcium phosphate in acetic acid; H^++Al^{3+} (potential acidity) - 0.5 M calcium acetate solution at pH 7.0.

Throughout the experiment, air temperature and relative humidity were daily recorded using a Datalogger model HT-70, as well as rainfall in a rain gauge and water evaporation using a Class 'A' pan set near the area (Figure 1). Dry periods during the experiment occurred between September 2018 and February 2019 and from November to December 2019. Air temperatures had no significant variations during the experiment, with an average of 25.6 °C. Relative humidity ranged from 67.8% to 85.3%, and the highest average evaporation occurred in months with high air temperatures and low rainfall, with daily average values of 6.8 mm.

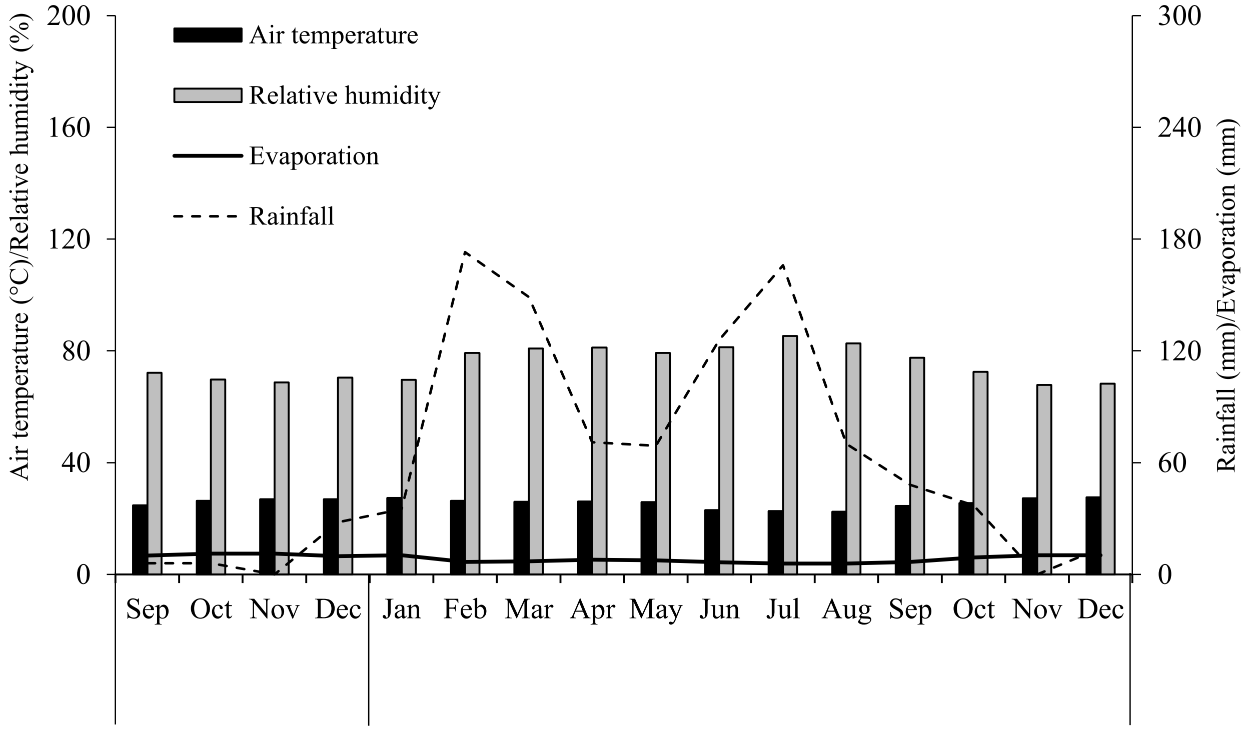

Figure 1. Mean air temperature, relative humidity, rainfall, and evaporation values in the experimental area during the experiment.

Experimental design and plant material

The experimental design employed was randomized blocks in a split-plot arrangement 2 × (2 × 2), with the main plot representing irrigation depths of 70% and 100% of the crop's evapotranspiration requirement (ETc), and subplots representing planting holes with volumes of 64 and 128 dm^3, both in soil with and without hydroretentive polymer application at 1.5 g per dm^3 soil (Figure 1). There were four replications, each with three plants per plot. Irrigation was determined based on the evapotranspiration demand of yellow passion fruit (Cavalcante et al., 2020), and planting hole volumes were based on Lucas et al. (2012), while hydroretentive polymer application followed the manufacturer's recommended dosage

The plant material under study was yellow passion fruit cv. BRS Gigante Amarelo (cv. BRS GA1), which is propagated from seeds with 95% germination viability. Seeds were acquired from a nursery accredited by the Brazilian Ministry of Agriculture, Livestock, and Supply (MAPA). This cultivar produces yellow fruits with an oblong shape, flattened bases, and apex, fruit mass ranging from 120 to 350 g, pulp yield close to 40%, and potential yields of around 42 t ha^{-1}.

Experiment conduct

Planting holes were dug in the middle of row spacing, and plants were trained diagonally at 2.2 m to reach the top of the trellis system. Planting holes were spaced 3 m between plants and 2 m between rows, a depth of 0.4 m, and diameters of 0.45 and 0.64 m for volumes of 64 and 128 dm^3, respectively.

The planting holes with volumes of 64 and 128 dm^3 were prepared with soil material from the top 0.2 m mixed with 17 and 34 dm^3 of bovine manure, respectively (Table 2), to raise the initial average soil organic matter content from 0.4% to 2.0%. Additionally, 50 and 100 g per planting hole of FTE-BR12 (containing 3.9% S, 1.8% B, 0.85% Cu, 2.0% Mn, and 9.0% Zn), 45 and 90 g per planting hole of dolomitic limestone (Relative Total Neutralization Power = 80% and 28% CaO, 7-9% MgO) were added to increase soil base saturation from 48% to 70%, and 9 and 18 g of potassium chloride (KCl) were applied to raise soil potassium content from 60 to 90 mg dm^{-3}. The commercial hydroretentive polymer Hydroplan™-EB/HyA, consisting of particles measuring 0.3 to 1 mm, anionic, with neutral pH when water is adsorbed, and a bulk density of 0.8 g cm^{-3}, capable of absorbing 60% of its volume in 30 min., composed of copolymers of acrylamide (C_3H_5NO) and acrylate ($C_4H_6O_2$) of potassium, was used (Cavalcante et al., 2020).

Table 2
Chemical characterization of the bovine manure used in the experiment in terms of fertility

Macronutrient	Value	Micronutrient	Value
C (g kg^{-1})	159	B (mg kg^{-1})	21.3
N (g kg^{-1})	8.3	Cu (mg kg^{-1})	8
P (g kg^{-1})	2.8	Fe (mg kg^{-1})	991
K (g kg^{-1})	10.4	Mn (mg kg^{-1})	250
Ca^{2+} (g kg^{-1})	8.2	Zn (mg kg^{-1})	58
Mg^{2+} (g kg^{-1})	5	Na+ (mg kg^{-1})	790
S (g kg^{-1})	1.8	pH (H_2O)	8.81
C/N	19:1		

Determination according to methods proposed by Texeira et al. (2017).

The substrate for seedling formation was composed of the same soil obtained from the top 0.2 m of the experimental area (Table 1) and the same bovine manure used in preparing the planting holes (Table 2), in a 2:1 ratio, with the addition of 1 kg of single superphosphate (20% P_2O_5, 16% Ca, and 8% S) to prepare 100 kg of the mixture. Subsequently, 1.5 dm3 of the substrate was placed in black polyethylene bags with 12 cm in diameter and 18 cm in height. Three seeds were sown in each substrate unit, and emergence, as determined by the first count of normal seedlings, occurred seven days after sowing (DAS) and stabilized at 28 DAS.

Ten days after emergence stabilization, seedlings were thinned out, keeping only the most vigorous one per polyethylene bag. At 60 DAS, seedlings were ready for transplanting to the field. To do so, they were standardized with four pairs of fully expanded leaves, a height ranging from 30 to 35 cm, and a stem diameter of 3.5 to 4.0 mm.

Transplanting took place on August 21, 2018. Single stems of plants were trained on a trellis system with #12 plain wire set at the top of stakes at a height of 2.2 m. When they reached the trellis, the main shoots of plants were pruned to induce the growth of lateral branches on opposite sides (east and west), following the recommendations by Almeida (2012).

Irrigation was performed with unrestricted agricultural water (ECai = 0.5 dS m^{-1} and RAS = 2.2 mmol $L^{-1})^{1/2}$, with daily volume application following ETc-related water demands. Micro-sprinkler localized irrigation was used, with one emitter per plant at a flow rate of 60 L h^{-1}, operating at a service pressure of 0.2 MPa. ETc was calculated as the product of reference evapotranspiration (ET0) and crop coefficient (kc), according to Equation 1 (Eq. 1). ET0 was obtained by multiplying the water evaporation from the Class 'A' pan (ETa) installed near the experimental area by the pan correction coefficient (kp), which was 0.75 (Eq. 2). Crop coefficients were 0.43 during the vegetative phase, 0.94 during the flowering phase, and 1.04 during the fruiting phase (Cavalcante et al., 2020).

$$ET_c = ET_0 \times kc \text{ (Eq. 1)}$$

$$ET_0 = ET_a \times kp \text{ (Eq. 2)}$$

Top-dressing fertilizations were carried out according to the initial soil analysis and crop requirements. Top-dressings with nitrogen (N) in the form of urea (45% N) and potassium (K) from potassium chloride (60% K_2O) were applied monthly from 30 DAT, providing 10 g of N and 10 g of K, with a 1:1 ratio, in October, November, and December (30, 60, and 90 DAT) during the vegetative growth phase. During flowering and fruiting phases, in January, February, and March, 15 g of N and 15 g of K were applied at 120, 150, and 180 DAT. From this point until the end of the first fruit harvest, in April, May, and June, 20 g of N and 20 g of K were applied at 210, 240, and 270 DAT. Phosphorus (P) top-dressing started at 60 DAT and was applied every two months, providing 10 g per plant of P_2O_5 in the form of single superphosphate (20% P_2O_5, 16% Ca, and 8% S), with three applications between vegetative growth and the beginning of fruiting. Subsequently, two more applications of 20 g per plant of P_2O_5 were made, two months after the start of fruiting and one month before the end of the first fruit harvest.

Parameters analyzed

Chlorophyll indices and gas exchange

Chlorophyll indices and gas exchange were assessed at the onset of flowering (120 DAT) between 08:30 am and 11:00 am, on the intact midsection leaf of the intermediate branch of the plants (Freire et al., 2014).

Chlorophyll *a* (Cl*a*) and chlorophyll *b* (Cl*b*) indices were determined using an electronic chlorophyll meter, ClorofiLOG™ brand, model CFL 1030. Three leaves per plant were selected for all treatments, with readings taken on the upper, middle, and lower parts of each leaf, and an average value was obtained (El-Hendawy et al., 2005).

Gas exchange measurements were conducted using a portable infrared carbon dioxide analyzer (IRGA), LCPro+ Portable Photosynthesis System™ model (ADC BioScientific Limited, UK), with the temperature set at 25 °C, irradiance at 1,800 μmol photons m^{-2} s^{-1}, and airflow at 200 mL min^{-1} (Freire et al., 2014). Gas exchange variables included stomatal conductance (*gs,* mol of H_2O m^{-2} s^{-1}), transpiration (*E*, mmol of H_2O m^{-2} s^{-1}), net photosynthesis rate (*A*, μmol CO_2 m^{-2} s^{-1}), and internal carbon concentration (Ci, μmol CO_2 mol^{-1}). Water use efficiency (WUE) was determined as the ratio *A/E* ([μmol CO_2 m^{-2} s^{-1} / mmol of H_2O m^{-2} s^{-1}]), and instantaneous carboxylation efficiency (iWUE) was calculated as the ratio *A/*Ci ([μmol CO_2 m^{-2} s^{-1} / μmol CO_2 mol^{-1}]).

Yield components

Fruits were harvested daily from May to December 2019. Fruits were counted, and their average weight was determined by weighing them on a semi-analytical scale (precision < 0.01 g). Accumulated yield during the period (t ha^{-1}) was calculated by multiplying production per plant by planting density (1,667 plants per hectare).

Statistical analysis

The obtained data were subjected to analysis of variance (ANOVA) using the F-test ($p \leq 0.05$). Comparisons of values related to irrigation depths, planting hole volumes, and hydroretentive polymer were performed using the Tukey test at a 5% probability level. Data analysis was conducted using the R statistical software (R Core Team [R], 2017).

Results and Discussion

Chlorophyl indices

The leaf chlorophyll indices of yellow passion fruit cv. BRS GA1 responded to the interaction of irrigation depths × planting hole volumes × hydrogel polymer (Cl*a* – F = 28.09; p = 0.0001**; Cl*b* – F = 6.14; p = 0.029*) (Figure 2).

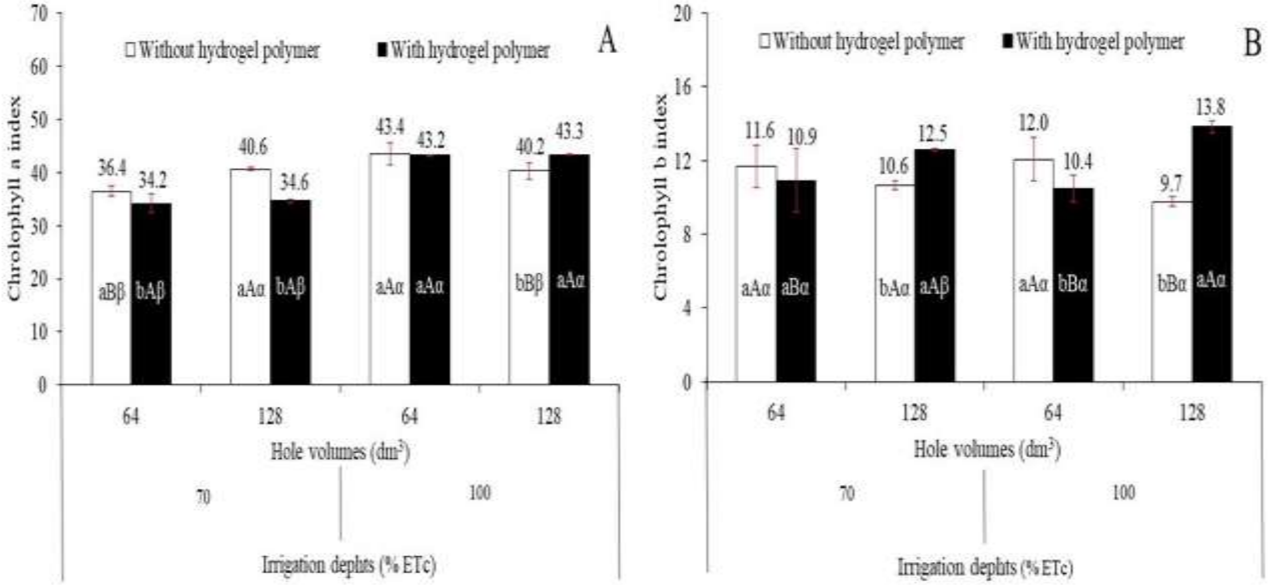

Figure 2. Chlorophyll *a* (A) and chlorophyll *b* (B) indices in leaves of yellow passion fruit cv. BRS GA1 grown under different irrigation depths, in planting hole volumes, and in soil with or without hydrogel polymer.

Yellow passion fruit irrigated with 70% ETc showed higher Cl*a* indices in treatments without hydrogel polymer regardless of the planting hole volume (Figure 1A). Therefore, the increase in chlorophyll in yellow passion fruit irrigated with less water depth may indicate that it did not experience water restriction to the point of inhibiting chlorophyll synthesis. When evaluating irrigation depths ranging from 50% to 100% ETc in yellow passion fruit seedlings, Barros et al. (2021) did not find significant differences in leaf chlorophyll indices, with values ranging from 26.51 to 27.80.

In the 100% ETc depth, hydrogel polymer application increased the leaf Cla index in plants grown in the 128-dm^3 planting hole volume. The results show that increased hole volumes allowed for greater root development and water absorption (Souza et al., 2016) and did not inhibit Cl*a* in the soil with hydrogel polymer, especially in the first 40 cm of depth, where 60% of the yellow passion fruit roots are located (Lucas et al., 2012). In addition, the application of hydrogel polymer in planting holes has proved to increase moisture levels near the root system of eucalyptus seedlings (Abobatta, 2018; Felippe et al., 2020, 2021).

Notably, except for plants grown in the 128-dm^3 planting hole volume without the polymer, the highest Cla indices were in those irrigated with 100% ETc. The greatest increases were observed in yellow passion fruit in the soil with the polymer and grown in the 64-dm^3 (+26.31%) and 128-dm^3 (+25.14%)

planting hole volumes. Therefore, when under a proper water supply, yellow passion fruit plants can achieve their maximum yield (Uchoa et al., 2021).

Application of hydrogel polymer in the largest planting hole volume increased the CI*b* index in irrigated yellow passion fruit, with plants irrigated with 100% ETc showing a significant increase of 42.26% (Figure 2B). Hydro-absorbent polymers can absorb and retain a large amount of water and fluids, reducing nutrient losses by leaching, such as nitrogen, which is a constituent element of chlorophyll molecules (Felippe et al., 2016, 2020) and is present in fertilizers such as urea and organic matter. Comparable results were obtained by Araújo et al. (2022) in yellow passion fruit cv. BRS GA1 irrigated in soil with mulching and hydrogel polymer; these authors found that applying 1.5 g dm^{-3} of the polymer increased leaf chlorophyll indices.

Gas exchange

Stomatal conductance of yellow passion fruit cv. BRS GA1 leaves responded negatively to the interactions irrigation depths × hydrogel polymer ($F = 14.70$; $p = 0.002$**), irrigation depths × hydrogel polymer ($F = 29.84$; $p = 0.0001$***), and planting hole volumes × hydrogel polymer ($F = 24.36$; $p = 0.0003$***), exerting significant effects on net photosynthetic rate (Figure 3).

Hydrogel polymer application had no significant effect on gs in plants irrigated with 70% ETc but increased it by between 0.07 and 0.13 mmol m^{-2} s^{-1} in plants irrigated with 100% ETc (Figure 3A). However, this result shows that combining increased irrigation depths with hydrogel polymer provides a larger wetted area near the root of yellow passion fruit plants, hence promoting favorable conditions for plant development and avoiding water stress (Testezlaf, 2017; Felippe et al., 2021). Under water deficit conditions, hydrogel polymer increases water retention in the soil, promoting a gradual release and availability of water to plants, and preventing stomatal limitation (Araújo et al., 2022).

Increasing irrigation depth from 70% to 100% ETc reduced gs in yellow passion fruit by 56.25% in treatments without the hydrogel polymer but did not differ in plants from those without the polymer. Cavalcante et al. (2020) found equivalent results where irrigation depths greater than 81% ETc reduced stomatal conductance in yellow passion fruit ‘Guinezinho’ in soil without hydrogel polymer. According to these authors, stomatal closure in yellow passion fruit reduces CO_2 influx into cells, which is one of the main factors that reduce photosynthesis.

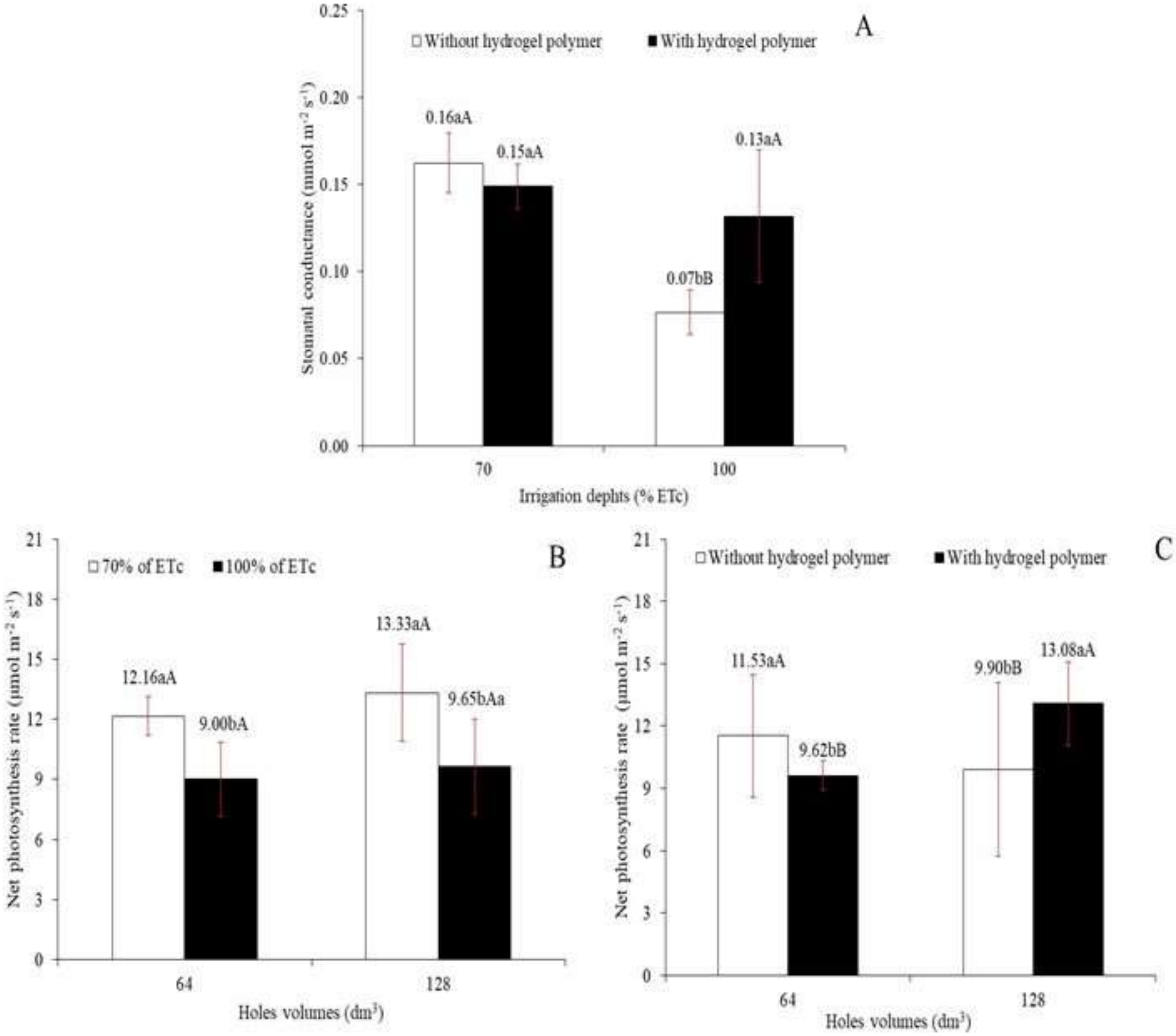

Figure 3. Stomatal conductance in yellow passion fruit cv. BRS GA1 grown under different irrigation depths in soil with hydrogel polymer (A), net photosynthetic rate of yellow passion fruit cv. BRS GA1 grown in different planting hole volumes and irrigated with different irrigation depths (B) and grown in different planting hole volumes in soil with hydrogel polymer (C).

Net photosynthetic rates in yellow passion fruit increased as irrigation depth decreased from 100% to 70% ETc but did not differ between planting hole volumes. These rates increased by 35.11% and 38.13% in plants grown in the 64-dm^3 and 128-dm^3 planting hole volumes, respectively (Figure 3B). Irrigation depths can be reduced to below the yellow passion fruit's requirement without affecting physiological processes, such as carbon influx and assimilation, as observed by Cavalcante et al. (2020) in yellow passion fruit 'Guinezinho' under irrigation depths and hydrogel polymer in the soil.

Net photosynthetic rate behaved distinctly with the use of the hydrogel polymer in different planting hole volumes (Figure 3C). In the 64-dm^3 planting hole volume, the highest A values were in plants without hydro-absorbent polymer, while in the 128-dm^3 volume, polymer application increased the photosynthetic rate by 32.12%. In planting holes with hydrogel polymer, cultivation in larger volumes increased photosynthetic rate from 9.62 to 13.08 μmol m^{-2} s^{-1}, which may be due to increased water uptake, especially by fine and absorbent roots that have a larger contact surface and are located in the top 40 cm of the soil and 80 cm from the plant's stem (Tecchio et al., 2005; Lucas et al., 2012; Oliveira et al., 2023). In addition, application of hydrogel polymer reduces water and nutrient losses by leaching, such as nitrogen (NO_3^-, NH_4^+) and phosphorus, besides increasing potassium availability near the root growth zone (Monteiro et al., 2017; Song et al., 2020).

Leaf transpiration ($F = 5.89$; $p = 0.031$*), water use efficiency ($F = 14.37$; $p = 0.002$**), and instantaneous carboxylation efficiency ($F = 14.04$; $p = 0.002$**) in yellow passion fruit cv. BRS GA1 were significantly influenced by the multiple interaction irrigation depths × planting hole volumes × hydrogel polymer (Figure 4).

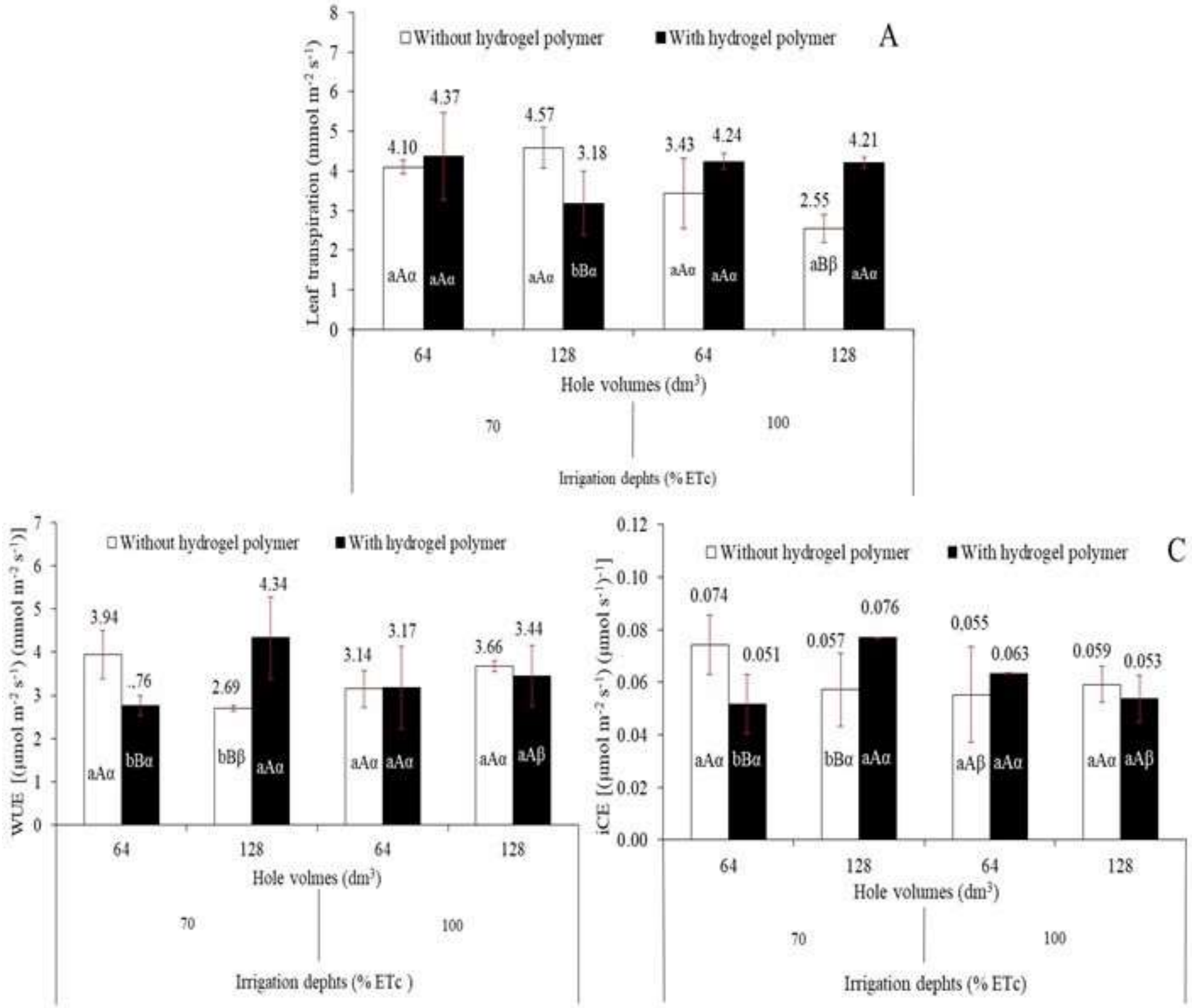

Figure 4. Transpiration (A), water use efficiency (B), and instantaneous carboxylation efficiency (C) of yellow passion fruit cv. BRS GA1 irrigated with irrigation depths and grown in distinct planting hole volumes, and with and without hydrogel polymer application to the soil.

Leaf transpiration in yellow passion fruit cv. BRS GA1 cultivated in the 128-dm³ planting hole without the polymer increased by 43.71% when irrigated with 70% ETc (Figure 4A). The opposite behavior was observed in plants irrigated with 100% ETc, where there was an increase in leaf transpiration of yellow passion fruit in the 128-dm³ planting hole with the polymer, showing an increase of 65.1%. The larger planting hole volume has high interaction with increased irrigation depth due to the greater water supply provided by the irrigation depth in a larger volume of soil explored by the roots of yellow passion fruit plants, as roots are concentrated within the topmost soil layer up to 40 cm deep (Sousa et al., 2005; Lucas et al., 2012; Rosa et al., 2017). Araújo et al. (2022) also found that the application of hydro-absorbent polymer doses associated with mulching increased leaf transpiration in yellow passion fruit plants irrigated with maximum water depth.

In yellow passion fruit irrigated with 70% ETc, water use efficiency and carboxylation efficiency behaved differently with increasing planting hole volume and polymer application (Figure 4B and 4C). In plants grown in the 64-dm^3 planting hole, the highest WUE and iCE values were obtained in treatments without the polymer, while in the 128-dm^3 planting hole, the highest values were in plants with the polymer, which showed the highest increases of 61.33% and 33.33%, respectively.

The higher WUE and iCE in yellow passion fruit irrigated with 70% ETc, grown in larger planting hole volumes with the hydrogel-absorbent polymer, reflect improvements in the root growth environment of plants in increased planting hole volumes, enhancing aeration, structure, and water dynamics (Sousa et al., 2016), besides reducing water losses by percolation and lateral flow and nutrient losses by leaching with polymer application (Abobatta, 2018; Behera & Mahanwar, 2020).

Yield components

The multiple interaction irrigation depths × planting hole volumes × hydrogel polymer had a significant effect on number of fruits ($F = 41.50$; $p = 0.00003$***), fruit weight ($F = 33.94$; $p = 0.00008$***), and yield ($F = 121.89$; $p = 0.0000001$***) of yellow passion fruit cv. BRS GA1 (Figure 5).

When the hydrogel polymer was applied, the number of fruits, average fruit weight, and yield of yellow passion fruit from the 64-dm^3 planting hole irrigated with 70% ETc increased by 63.98%, 23.78%, and 200%, respectively (Figure 5A, 5B, and 5C). However, the application of hydrogel polymer in the 128-dm^3 planting hole increased the number of fruits, average fruit weight, and yield in plants irrigated with 100% ETc, showing increases of 62.6%, 30.83%, and 114.06%, respectively.

The good crop nutrition, even with a 30% reduction in water depth, combined with the hydrogel polymer's soil benefits in retaining and gradually releasing water, reducing nutrient losses (especially N and K), and enhancing soil resource utilization (Monteiro et al., 2017; Behera & Mahanwar, 2020; Song et al., 2020) might have contributed to the improved production of yellow passion fruit cv. BRS GA1. These findings differ somewhat from those of Cavalcante et al. (2020), who observed a reduction in fruit numbers but increased average fruit weight and yield with hydrogel polymer application. The yields observed here (28.5 t ha^{-1}) exceeded by 91.66% the national figure (15.26 t ha^{-1}) and by 196.56% that of Paraíba State (9.36 t ha^{-1}) (IBGE, 2021).

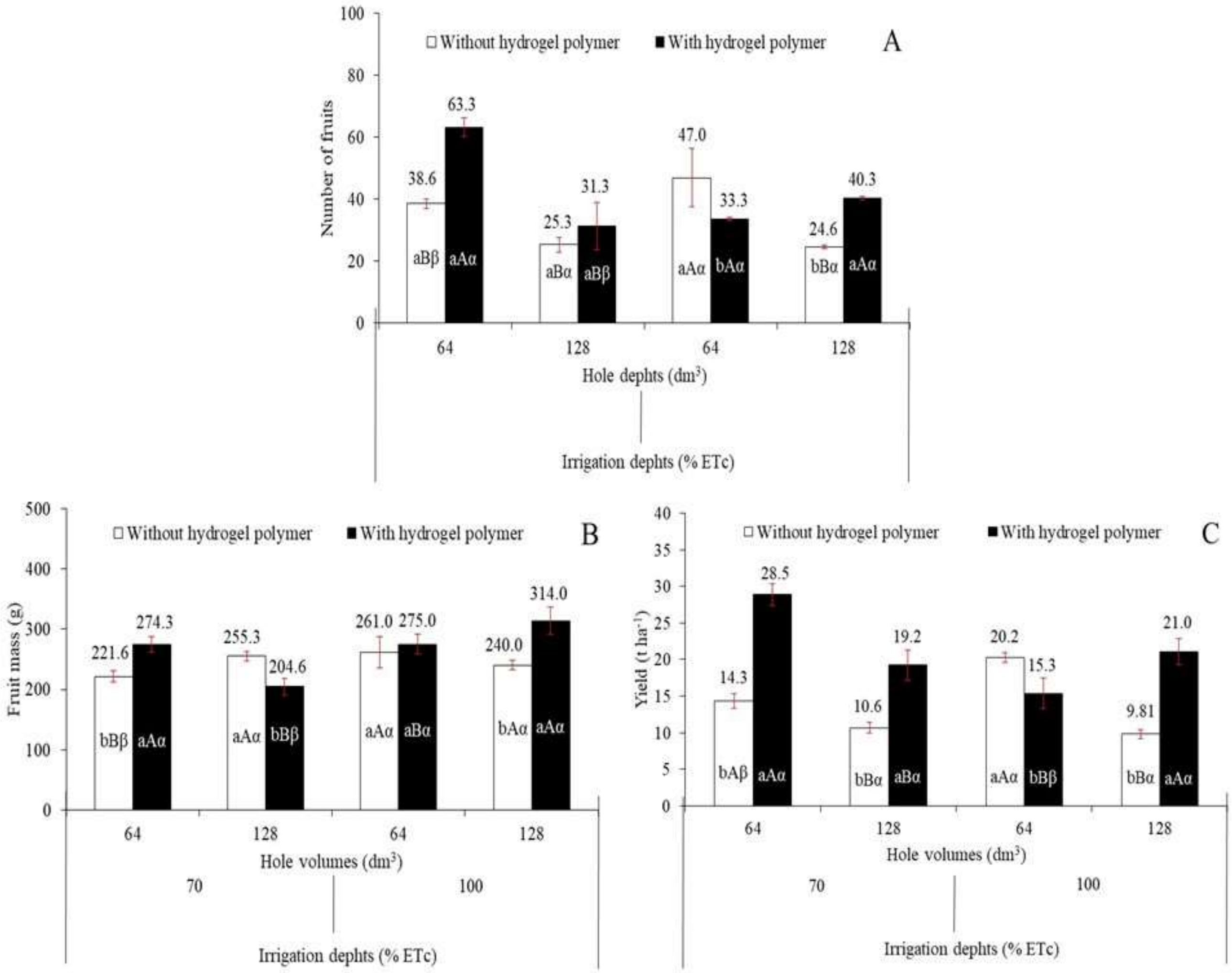

Figure 5. Number of fruits (A), fruit weight (B), and yield (C) of yellow passion fruit cv. BRS GA1 irrigated with irrigation depths, grown in different planting hole volumes, and with or without hydrogel polymer application to the soil.

Conclusions

Foliar chlorophyll levels in yellow passion fruit cv. BRS GA1 irrigated with 100% ETc increase when associated with a 128-dm^3 planting hole applied with hydrogel.

Photosynthetic rate of yellow passion fruit cv. BRS GA1 is not limited by a 30% reduction in irrigation depth or 128-dm^3 planting holes with hydrogel polymer.

Increasing planting hole volumes combined with hydrogel polymer application to the soil improves water use efficiency and carboxylation efficiency of yellow passion fruit cv. BRS GA1 irrigated with 70% of ETc.

Based on the increased fruit numbers, average weights, and yields, irrigation depth could be reduced to 70% of ETc with the application of hydrogel polymer into 64-dm^3 planting holes without affecting the yield components of yellow passion fruit cv. BRS GA1.

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