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ORIGINAL ARTICLE

Zinc oxide nanoparticles and bioinoculants on the postharvest quality of eggplant subjected to water deficit[1]

Nano-óxido de zinco e bioinoculantes na qualidade pós-colheita da berinjela submetidas a déficit hídrico

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HIGHLIGHTS:
Foliar zinc sulfate application increases the Hue angle on eggplant fruit skin under water deficit conditions.
Water deficit increases chromaticity, lightness, and vitamin C in eggplant.
Zinc sulfate, zinc oxide nanoparticles, and plant growth-promoting bacteria have potential for improving eggplant quality.

ABSTRACT: Eggplant (*Solanum melongena*) is widely cultivated. It shows moderate tolerance to water deficit, but suffers yield losses in the arid and semi-arid regions where it is grown. The aim of this study was to investigate the influence of zinc oxide nanoparticles (NPZnO), in association with plant growth-promoting bacteria (PGPB), on the post-harvest quality of eggplant subjected to water deficit. Two irrigation percentages relative to potential evapotranspiration-ETo (50 and 100% ETo) and five combinations involving NPZnO or PGPB were studied. Number of commercial fruits per plant and weight of commercial fruits per plant, diameter, length, skin color, firmness, titratable acidity, soluble solids, SS/TA, vitamin C and total soluble sugars were evaluated. There was strong positive correlation between weight of commercial fruits per plant, SS/TA, total soluble sugars, titratable acidity, lightness and vitamin C in the treatments containing $ZnSO_4$, NPZnO and PGPB. Water deficit and nanoparticles containing zinc, associated or not with bacteria that promote plant growth, did not influence the weight and average size of the fruits and the post-harvest quality of the eggplant crop. Water deficit reduced the chromaticity and lightness of the skin color and the vitamin C content of eggplant.

Key words: *Solanum melongena*, drought, fruit quality

RESUMO: A berinjela (*Solanum melongena*) é amplamente cultivada. Apresenta tolerância moderada ao défice hídrico, mas sofre perdas de rendimento nas regiões áridas e semiáridas onde é cultivada. O objetivo deste estudo foi investigar a influência das nanopartículas de óxido de zinco (NPZnO), em associação com bactérias promotoras de crescimento vegetal (BPCV), na qualidade pós-colheita de berinjela submetida a déficit hídrico. Foram estudadas duas percentagens de irrigação referentes à evapotranspiração potencial -ETo (50 e 100% de ETo) e cinco combinações envolvendo NPZnO ou BPCV. Foram avaliados peso e número de frutos comerciais e não comerciais, diâmetro, comprimento, cor da casca, firmeza, acidez titulável, sólidos solúveis, SS/TA, vitamina C e açúcares solúveis totais. Houve forte correlação positiva entre peso de frutos comerciais, SS/TA, açúcares solúveis totais, acidez titulável, luminosidade e vitamina C nos tratamentos contendo $ZnSO_4$, NPZnO e BPCV. O déficit hídrico e as nanopartículas contendo zinco, associadas ou não a bactérias promotoras do crescimento das plantas, não influenciaram o peso e o tamanho médio dos frutos e a qualidade pós-colheita da cultura da berinjela. O déficit hídrico reduziu a cromaticidade e a luminosidade da cor da casca e o teor de vitamina C da berinjela.

Palavras-chave: *Solanum melongena*, seca, qualidade de fruto

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Introduction

The vegetable eggplant (*Solanum melongena* L. - Solanaceae) is widely grown and valued for its distinctive taste, texture, and nutritional qualities (Gürbüz et al., 2018). In Brazil, this vegetable is highly regarded for its nutritional and medicinal properties, including its ability to lower cholesterol levels. The trend of crop loss in eggplant farming is primarily attributed to climate change, marked by rising temperatures and shifts in precipitation patterns. Eggplant is a plant species with moderate tolerance to water scarcity, but it faces significant yield challenges when cultivated in arid and semi-arid regions (Kiran et al., 2022).

For these reasons, plant growth-promoting bacteria (PGPB) and nanofertilizers containing micronutrients, such as iron and zinc, have been used (Dimkpa et al., 2019). These micronutrients alleviate water deficit in plants, increase water use efficiency, maintain cell integrity and eliminate drought-induced free radicals (Karim & Rahman, 2015; Dimkpa et al., 2019; Ganguly et al., 2022). PGPB in the soil can increase the production of osmoregulatory substances in plants and thus act synergistically, cooperating in drought tolerance (Matos et al., 2019). These organisms can produce auxins, such as indoleacetic acid, which increase the length of plant roots, resulting in greater absorption of water and nutrients from the soil (Turatto et al., 2018).

Saglam et al. (2022) investigated the impact of plant growth-promoting bacteria and the potential use of the strain *Pseudomonas putida* KT2440 to induce drought tolerance in tomato plants during fruit ripening. These authors observed that inoculation with this strain resulted in an increase in fruit number and weight per plant. The number of fruits increased about 1.5 times after inoculation with this strain under conditions of water deficit. At the same time, treatment with bacteria resulted in an increase in fruit weight per plant compared to the control (non-inoculated). The authors concluded that the inoculation of bacterial strains in tomato plants can improve tolerance to water deficit and thus directly increase yield (Dias, 2022). The aim of this study was to investigate the influence of zinc oxide nanoparticles (NPZnO), in association with PGPB, on the post-harvest quality of eggplant subjected to water deficit.

Material and Methods

The experiment was conducted at the Fazenda Experimental do Centro de Ciência e Tecnologia Agroalimentar of the Universidade Federal de Campina Grande, located in the municipality of São Domingos, Paraíba, Brazil, at 6° 50' 4" S, 37° 53' 9" W, and altitude of 190.0 m. During the period experimental meteorological data were obtained from the weather station of São Gonçalo, district of Sousa (PB), (AGRITEMPO, 2023), as can be seen in Figure 1.

A randomized block experimental design in a split-plot scheme with four replicates was employed. The plots consisted of two irrigation percentages (50 and 100% of potential evapotranspiration - ETo). The subplots included five combinations involving zinc oxide nanoparticles (NPZnO) and bioinoculants (Bio), identified as follows: T1 (control group), T2 (foliar application of ZnSO4), T3 (foliar application of NPZnO), T4 (foliar application of NPZnO + Bio), and T5 (soil application of ZnSO4 + Bio).

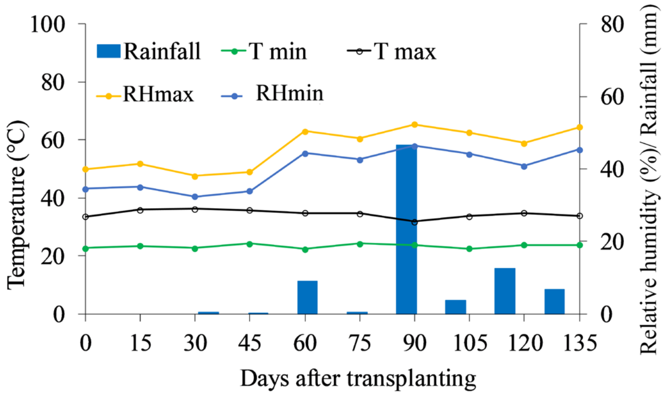


Figure 1. Climatological data on maximum (T max) and minimum air temperature (T min) air temperature, maximum (RHmax) and minimum (RHmin) air relative humidity and rainfall during the experimental period in the field (AGRITEMPO, 2023)

The soil was prepared through a series of steps, including plowing and harrowing, using a harrow plow to ensure proper soil conditioning. Following this soil preparation phase, substrate samples were collected from the experimental area at a depth of 0 to 20 cm. The purpose of this sampling was to assess the chemical and physical attributes of the soil (Table 1) according to the procedures described in EMBRAPA (2011).

Seedlings of the eggplant hybrid 'Ciça' were grown in expanded plastic trays, with 200 cells per tray. These seedlings were properly sanitized with a solution composed of bleach and detergent, and the substrate used was Basaplant™. Irrigation of the seedlings was carried out daily, in the early morning and late afternoon, using a watering can as the method of water application.

The plants were grown at a spacing of 1.2 m × 0.8 m, corresponding to an estimated stand of 10,417 plants per hectare. The subplots consisted of 20 plants, with 12 plants in the usable plot. The beds for planting were 0.4 meters wide and 0.30 meters high.

Planting fertilization and top-dressing fertilization were carried out according to the recommendation of Cavalcante

Table 1. Chemical and physical attributes of the soil used in the experiment

Chemical	Value	Physical	Value
pH ($CaCl_2$)	6.20	Sand (g kg^{-1})	444
P (mg kg^{-1})	291	Silt (g kg^{-1})	353
K^+ ($cmol_c$ dm^{-3})	1.19	Clay (g kg^{-1})	203
Na^+ ($cmol_c$ dm^{-3})	0.54	BD (g cm^{-3})	1.36
Ca^{2+} ($cmol_c$ dm^{-3})	5.80	PD (g cm^{-3})	2.59
Mg^{2+} ($cmol_c$ dm^{-3})	3.40	TP (m^3 m^{-3})	0.47
Zn^{2+} ($cmol_c$ dm^{-3})	1.69	FC (%)	12.87
H + Al ($cmol_c$ dm^{-3})	2.30	PWP (%)	5.29
OM (g kg^{-1})	6.40	AWC (%)	7.58
V (%)	83.0		
CEC (%)	4.10		

P, K^+, Na^+ and Zn^{2+} - Mehlich 1 extractant, H^+ + Al^{+3} - 0.5 mol L^{-1} Calcium acetate extractant at pH 7, Ca^{+2}, Mg^{+2} - 1 mol L^{-1} KCl extractant, OM - Organic matter, V - Base saturation, CEC - Cationic exchange capacity, BD - Bulk density, PD - Soil particle density, TP - Total porosity, FC - Field capacity, PWP - Permanent wilting point, AWC - Available water content

(2008), based on the interpretation of the soil analysis of the experimental area (Table 1).

Zinc nanofertilizers were prepared using nano-zinc oxide (NPZnO, Sigma-Aldrich™, purity of 97%), with particle size smaller than 100 nm and specific surface area of 10.8 m^2 g^{-1}. For treatment T1, a concentration of 1.0 g of Zn was applied through the leaves, which is equivalent to 4.54 g of $ZnSO_4$ L^{-1}. A total of 600 mL per plot of 20 plants was applied through the leaves, averaging about 30 mL per plant. For T2 and T3, 0.2 g of Zn was applied, which corresponds to 0.25 g of NPZnO L^{-1}. This resulted in 600 mL per plot of 20 plants, or approximately 30 mL per plant on average. For T4, a Zn solution with a concentration of 1.0 g of Zn = 4.54 g of $ZnSO_4$ L^{-1}.

The bioinoculation (Bio) procedures were carried out both through the leaves and in the soil. The microorganisms *Bacillus subtillis* BV-09 were used in liquid solutions Biobaci™ at 1.0 x 10^8 CFU mL^{-1}, while the product No-Nema™ at 3.0 x 10^9 CFU mL^{-1} was used for *B. amyloliquefaciens*. In treatment four, with zinc nanofertilizers, the microorganisms were mixed with 3 L ha^{-1} of Biobaci™ and 3 L ha^{-1} of No-Nema™, all applied at 50 mL per plant of a diluted suspension. The diluted suspension contained 45 mL of Biobaci™ and 45 mL of No-Nema™ in 8 L of water. After transplanting the seedlings, the solution was manually applied near the stem and on the leaves. The drip irrigation method was chosen for the irrigation system, with emitters spaced at 0.20 m and a nominal flow rate of 1.5 L h^{-1}. The total necessary irrigation (TNI) was calculated using Eq. 1.

$$TNI = \frac{\left[\left(Fc - Wp\right) \times Z \times BD \times F\right]}{10} \quad (1)$$

where:

TNI - total initial water depth to be applied, in mm;
Fc - field capacity;
Wp - wilting point;
Z - effective root system depth (30 cm);
BD - bulk density, g cm^{-3}; and,
F - water availability factor (0.5).

The Christiansen uniformity coefficient (CUC), proposed by Christiansen (1942), was used to assess the uniformity of water application. To achieve the reference evaporation proportions (ETc), the volume of water supplied at each depth was controlled daily every morning using the emitter flow rate to time ratio. Throughout the time interval for each volume of the respective depths, the corresponding drip tapes were sequentially turned off. The 100% depth was found by calculating ETc according to Eq. 2 (Jesen, 1968):

$$ETc = Kc \times ETo \quad (2)$$

where:

ETc - Crop evapotranspiration, mm per day;
Kc - Crop coefficient (dimensionless); and
ETo - Reference evaporation, mm per day.

The Kc values were used according to the phenological stages. Daily ETo values were calculated using the FAO Penman-Monteith model (Allen et al., 1998). A nearby automatic weather station, located in São Gonçalo, Paraíba, 55.9 km away from the experiment site, provided meteorological data throughout the experiment.

The characteristics of the cultivation system were taken into account to determine the daily water supply, as shown in Eq. 3.

$$Ti = \frac{ETo \times Kc \times A}{Ea \times n \times q} \quad (3)$$

where:

Ti - irrigation time, h;
ETo - reference evaporation, mm per day;
Kc - crop coefficient, dimensionless;
A - area occupied by one plant, m^2;
Ea - application efficiency (0.90);
n - number of emitters per plant; and
q - emitter flow rate, L h^{-1}.

Eggplant fruits were harvested at 105 days after sowing. To select the best eggplant fruits for harvesting, criteria were established, including a minimum length of 10 cm, a bright dark purple external color, presence of a green calyx, and firmness of the outer pulp (Henz & Silva, 2006). The fruits were then transported by vehicle to the Laboratório de Tecnologia Pós-Colheita of UFCG/CCTA. In the laboratory, the fruits underwent a rigorous process of separation, classification, and thorough cleaning, being prepared for subsequent quality analyses.

In order to determine which fruits would be classified as commercial, evaluations were conducted based on size, which should range from 17 to 20 cm in length, shape conformity, uniform color, and absence of mechanical or physiological damage caused by pests or diseases. Measurements were made using a digital caliper with 200 mm length equipped with a metal cursor. Diameter and length of the fruits were determined using this tool, thus allowing for a detailed evaluation to determine which fruits met the requirements to be considered commercial.

Fruit firmness was quantified using a fruit penetrometer (Fruit Hardness Tester) with a penetration depth of 2.0 mm. Two readings were taken, recording the values on opposite sides of the equatorial region of each fruit, which was free from the epicarp (outer skin). The measurement results were expressed in units of force, in Newtons (N).

The physical attributes of fruit color were measured using a Konica Minolta CR-400™ digital colorimeter, using the CIELAB system, which defines a three-dimensional color space with three axes in rectangular coordinates (L*a*b*). These coordinates represent lightness (L*), tones from red to green (*a positive to -a* negative) and tones from yellow to blue (*b positive to -b* negative). Furthermore, it defines cylindrical coordinates (L*, C*, H°), and the a* and b* values were converted into Hue angle (H°), representing the intensity of the color, and Chroma (C*), indicating the purity of the color, according to Pinheiro (2009). The analysis was carried out outside, with one reading per fruit for each experimental plot.

The determination of vitamin C was carried out using the Tillman method. The results of the analyses were expressed in mg per 100 g of the sample (AOAC, 2012).

The pH was measured using a digital benchtop pH meter, with direct readings taken from the homogenized pulp, according to IAL (2008).

Titratable acidity was determined following the methodology recommended by the AOAC (2012). The results were expressed in g of citric acid per 100 g of the sample.

Soluble solids content was determined directly in the homogenized pulp using a digital refractometer (model PR-100, Palette, Atago Co., LTD., Japan). The results were expressed in °Brix (AOAC, 2012). The SS/TA ratio was calculated as the ratio between soluble solids and titratable acidity (SS/TA).

Total sugar content was determined according to Yemm & Willis (1954), with analysis in a spectrophotometer at 620 nm, and the results were expressed as g per 100 g of pulp.

The data obtained were subjected to analysis of variance, followed by the comparison of means using the Tukey test ($p \leq 0.05$). Principal component analysis and Pearson correlation analysis were also conducted. These statistical analyses were performed using R statistical software (R Core Team, 2023).

Results and Discussion

Analysis of variance did not detect significant effect of irrigation percentages (IP), treatments based on zinc nanoparticles and biological products (T), as well as the interaction IP × T on the variables pH, soluble solids (SS), titratable acidity (TA), SS/TA ratio, total sugars, number of commercial and non-commercial fruits, weight of commercial and non-commercial fruits, fruit length, fruit diameter and fruit firmness (Tables 2 and 3). On the other hand, the irrigation percentages influenced the variables vitamin C content (Table 2) and the color characteristics of the fruits (lightness, chromaticity, and Hue angle) (Table 3).

According to Tukey's test, the treatments and irrigation percentages tested did not cause significant variation in the values of the studied variables, especially for pH, SS, TA, SS/TA and firmness (Table 4). However, the results of the current study surpassed those of other studies on eggplant cultivation (Radicetti et al., 2016; Çolak et al., 2018; Oliveira et al., 2019). Eggplant is one of the vegetables (fruits) with low acidity, with a pH greater than or equal to 4.5 (Oliveira et al., 2019). In the present study, pH values were above 4.9, and SS values ranged from 4.6 to 4.8.

In this study, soluble solids ranged from 4.6 to 4.8 °Brix (Table 4). In other studies, SS values in eggplant ranged from 3.57 to 3.97 °Brix (Radicetti et al., 2016) depending on types of soil management, from 4.38 to 4.55 °Brix, depending on irrigation levels (Çolak et al., 2018), and from 2.59 to 2.78 °Brix, depending on eggplant cultivars (Salas et al., 2020).

Nanoparticles (NPs) and PGPB have shown the ability to enhance the photosynthetic rate and accumulation of photosynthates in organs that require supplies, potentially

Table 2. Summary of analysis of variance (ANOVA) for pH, soluble solids (SS), titratable acidity (TA), SS/TA ratio, total sugars, vitamin C (Vit C), number of commercial (CF) and non-commercial (NCF) fruits, weight of commercial (WCF) and non-commercial (WNCF) fruits, fruit length (FL) and fruit diameter (FD) of 'Ciça' eggplant

SV	DF	Mean square					
		pH	SS	TA	SS/TA	Total sugars	Vit C
Irrigation percentages (IP)	1	0.00052^ns	0.1102 ^ns	0.0003 ^ns	18.6097 ^ns	0.0551 ^ns	0.3014*
Treatments (T)	4	0.0627 ^ns	0.0281 ^ns	0.0002 ^ns	2.4608^ns	0.1640 ^ns	0.0541 ^ns
Blocks	3	0.1818	0.3770	0.0002	4.9501	0.1540	0.4430
Error 1	3	0.0844	0.0876	0.0003	1.6406	0.0270	0.0369
IP x T	4	0.0613 ^ns	0.0418 ^ns	0.0001 ^ns	1.0063 ^ns	0.3810 ^ns	0.0056 ^ns
Error 2	24	0.0549	0.2662	0.0005	13.5334	0.2009	0.0253
CV1 (%)	-	5.81	6.23	9.41	4.96	7.42	14.22
CV2 (%)	-	4.69	10.86	11.83	14.25	20.20	11.79
		CF	NCF	WCF	WNCF	FL	FD
Irrigation percentages (IP)	1	1.6000 ^ns	2.0250 ^ns	4.2532 ^ns	32643.20 ^ns	0.8089 ^ns	2.0976 ^ns
Treatments (T)	4	12.6500^ns	20.9300 ^ns	751.190 ^ns	25372.80 ^ns	0.2359 ^ns	2.2917 ^ns
Blocks	3	111.1333	191.758	1111.79	23202.16	0.2837	22.7873
Error 1	3	73.9333	6.0917	789.43	38457.21	0.5378	21.8100
IP x T	4	20.1000 ^ns	18.8375 ^ns	770.64 ns	46038.57 ^ns	0.1979 ^ns	3.8745 ^ns
Error 2	24	27.8250	34.9042	1333.19	46145.59	0.4595	10.3114
CV1 (%)	-	78.88	16.59	10.64	98.73	4.15	7.44
CV2 (%)	-	48.39	39.72	13.83	108.14	3.84	5.11

SV - Source of variation; CV - Coefficient of variation; * $p \leq 0.05$ by 'F' test; ns - Non-significant; DF - Degrees of freedom

Table 3. Summary of analysis of variance for fruit firmness, Lightness (L*), Chroma (C*) and Hue angle on the skin, in the post-harvest quality of the eggplant

SV	DF	Mean square			
		Firmness	L*	C*	Hue
Irrigation percentages (IP)	1	12.0281^ns	2.4389*	6.7239*	0.2476*
Treatments (T)	4	5.2486 ^ns	0.0341 ^ns	0.1948 ^ns	0.0212 ^ns
Blocks	3	50.1616	0.3652	1.2256	0.0811
Error 1	3	69.1813	0.1821	0.6123	0.0147
IP × T	4	3.3523 ^ns	0.1812 ^ns	1.6361 ^ns	0.2584*
Error 2	24	12.7386	0.2103	0.7106	0.0751
CV1 (%)	-	19.62	1.65	13.92	15.40
CV2 (%)	-	8.42	1.77	15.00	34.81

SV - Source of variation; CV - Coefficient of variation; *$p \leq 0.05$ by F test; ns - Non-significant data at $p \leq 0.05$; DF - Degrees of freedom

Table 4. Means for the variables pH, soluble solids (SS), titratable acidity (TA), SS/TA ratio, total sugars, vitamin C (Vit C), number of commercial (CF) and non-commercial (NCF) fruits, weight of commercial (WCF) and non-commercial (WNCF) fruits, fruit length (FL) and fruit diameter (FD), of 'Ciça' eggplant

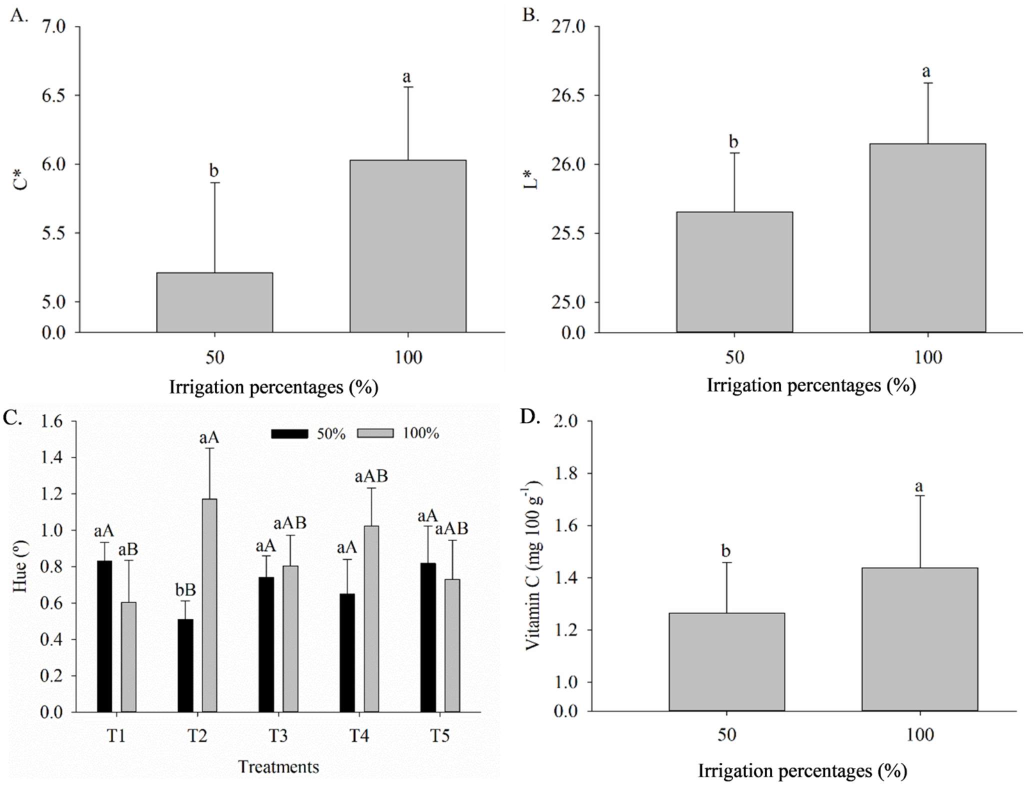
Treatments	pH	TA (g 100g^{-1})	SS (°Brix)	SS/TA	Total sugars (g 100g^{-1})	Firmness (N)
Control	4.927 a	0.184 a	4.779 a	26.441 a	2.182 a	42.810 a
$ZnSO_4$ foliar	4.895 a	0.190 a	4.767 a	25.243 a	2.337 a	42.651 a
NPZnO foliar	5.042 a	0.188 a	4.805 a	25.583 a	2.253 a	43.061 a
NPZnO foliar + Bio	5.113 a	0.186 a	4.746 a	25.461 a	2.333 a	41.002 a
$ZnSO_4$ soil + Bio	5.022 a	0.179 a	4.650 a	26.391 a	1.990 a	42.437 a
IP 50%	4.996 a	0.182 a	4.802 a	26.506 a	2.256 a	41.844 a
IP 100%	5.003 a	0.183 a	4.697 a	25.142 a	2.182 a	42.940 a

	CF	NCF	WCF (g)	WNCF (g)	FL (cm)	FD (cm)
Control	10.875 a	17.250 a	259.770 a	145.507 a	17.440 a	6.341 a
$ZnSO_4$ foliar	9.125 a	14.875 a	260.822 a	160.000 a	17.700 a	6.297 a
NPZnO foliar	10.375 a	14.375 a	257.349 a	140.870 a	17.735 a	6.272 a
NPZnO foliar + Bio	11.750 a	12.750 a	271.489 a	177.647 a	17.860 a	6.195 a
$ZnSO_4$ soil + Bio	12.375 a	15.125 a	250.909 a	173.223 a	17.515 a	6.290 a
IP 50%	11.100 a	14.650 a	257.838 a	153.857 a	17.792 a	6.256 a
IP 100%	10.700 a	15.100 a	262.243 a	163.311 a	17.508 a	6.302 a

NPZnO - Zinc oxide nanoparticles, $ZnSO_4$ - Zinc sulfate, Bio - Bioinoculants, IP - Irrigation percentages

resulting in increased fruit production and postharvest quality (Vinci et al., 2018; Ybaez et al., 2020; Farooq et al., 2023). Based on this, a positive effect of the application of NPZnO or $ZnSO_4$ in combination or not with PGPB on the biochemical and physical parameters of eggplant fruit quality was expected in this study, as observed in other studies (Landa et al., 2012; López-Vargas et al., 2018; Ybaez et al., 2020; Elsheery et al., 2020; Semida et al., 2021). In the present work, the fact that the analysis of variance and Tukey's test did not detect significant differences between treatments may be due to the initial zinc content of the soil, considered good (Alvarez et al., 1999), or due to adequate fertilization management and good soil fertility, which were sufficient to homogenize the effects of the tested treatments, especially on the biochemical parameters of fruit quality.

Chromaticity (C*) (Figure 2A), lightness (L*) (Figure 2B), and vitamin C content (Figure 2D) were not significantly affected by the application of nanoparticles and bioinoculants,



T1 - control, T2 - $ZnSO_4$ foliar, T3 - NPZnO foliar, T4 - NPZnO foliar + Bio, T5 - $ZnSO_4$ via soil + Bio.

T1 - Control, T2 - $ZnSO_4$ foliar, T3 - NPZnO foliar, T4 - NPZnO foliar + Bio, T5 - $ZnSO_4$ soil + Bio. Bars with the same lowercase letters do not differ for water stress, and bars with the same uppercase letters do not differ for combinations involving zinc oxide nanoparticles (NPZnO) or bioinoculants (Bio) by Tukey's test ($p \leq 0.05$)
Bars with the same letter do not differ by Tukey's test ($p \leq 0.05$)

Figure 2. Chromaticity (C* - A), lightness (L* - B), Hue angle (°Hue - C) and vitamin C (D) of 'Ciça' eggplants as a function of irrigation percentages and application of nanoparticles and biostimulants

but they were influenced by the irrigation levels (Figure 2). The irrigation level of 100% of potential evapotranspiration (ETo) promoted higher values for these variables compared to the 50% ETo irrigation level (Figure 2).

The Hue angle was affected by the interaction between the studied factors (Figure 2C). In the case of 100% irrigation level, treatment T2 ($ZnSO_4$ foliar application) had the highest mean. However, for the 50% irrigation level, the lowest mean was observed in treatment T2 ($ZnSO_4$ foliar application). On the other hand, treatments T1 (control), T3 (NPZnO foliar), T4 (NPZnO foliar + Bio), and T5 ($ZnSO_4$ soil + Bio) had higher means but did not show statistically significant differences among them.

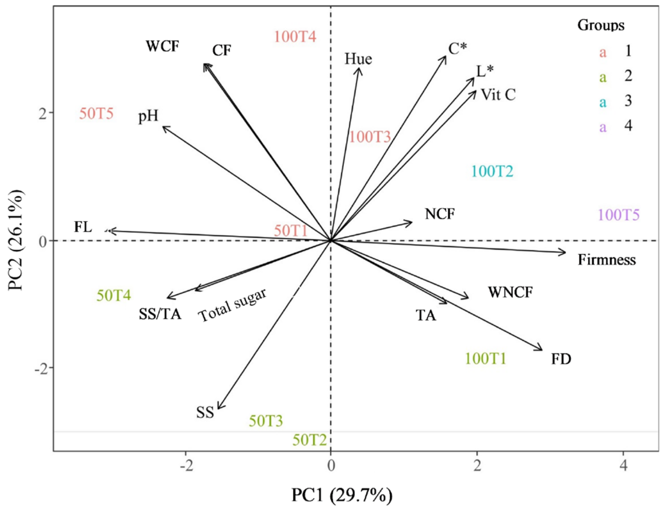
Changes in fruit color and lightness can be attributed to the increased amount of anthocyanins in the fruit peels. The decrease in L* and C* values, as well as vitamin C levels, under water restriction (50% ETo) may be a consequence of the decrease in photosynthetic rate and production of photoassimilates and pigments (Li et al., 2019; Badr et al., 2020). Water restriction decreased the value of the Hue angle in tomatoes, but did not change the values of C* and L* (Alordzinu et al., 2022). On the other hand, previous studies have also mentioned that zinc can increase the production of anthocyanins and flavonoids, influencing fruit color (Garcia-López et al., 2018).

Ascorbic acid plays crucial roles in plant metabolism, including its ability to regenerate vitamin C, protect cells against oxidative damage, and act as a cofactor for enzymes involved in the production of flavonoids and phytohormones (Al-Wadaani et al., 2021). The use of NPZnO increased the amount of ascorbic acid and fruit quality in tomatoes grown under abiotic stress conditions (Pinedo-Guerrero et al., 2020), but in the present study, this effect was not observed, probably due to the soil attributes already mentioned.

Although ANOVA and Tukey's test did not detect significant differences between the treatments tested, the multivariate analysis of principal components (PCA) revealed important trends for the effects of treatments and relationships between the variables studied (Figure 3). The PCA resulted in the formation of four distinct groups among the studied treatments.

The first group included the 50% potential evapotranspiration (ETo) irrigation level and treatments T1 (control) and T5 ($ZnSO_4$ soil + Bio), while the second group encompassed the 100% ETo irrigation level and treatments T3 (NPZnO foliar) and T4 (NPZnO foliar + Bio). It was noted that treatment 50T5 ($ZnSO_4$ soil + Bio) tended to move further to the right within this first group. Furthermore, a strong positive correlation was observed between weight of commercial fruits per plant (WCF) and the number of commercial fruits (CF). On the other hand, pH showed a negative correlation with transverse diameter, and longitudinal length had a negative correlation with fruit firmness.

The second group was formed by treatments T2 ($ZnSO_4$ foliar), T3 (NPZnO foliar), and T4 (NPZnO foliar + Bio) with a 50% irrigation level, while treatment T1 (control) had a 100% irrigation level. It is noteworthy that treatment 50T4 (NPZnO foliar + Bio) tends to stand out in this group. In this



T1 - Control; T2 - $ZnSO_4$ foliar; T3 - NPZnO foliar; T4 - NPZnO foliar + bioinoculants (Bio); T5 - $ZnSO_4$ soil + Bio; FL - Fruit length; pH - Hydrogen potential; WCF - Weight of commercial fruits; WNFC - Weight of non-commercial fruits; CF - Number of commercial fruits; NCF - Number of non-commercial fruits; Hue - Hue angle; C* - Chromaticity; L* - Lightness; Vit C - Vitamin C content; TA - Titratable acidity; FD - Fruit diameter

Figure 3. Principal component analysis for the post-harvest variables of 'Ciça' eggplant based on treatments composed of zinc sources and bioinoculants (Bio) under full irrigation (100% ETo) and water deficit (50% ETo)

context, a significant positive correlation is observed between the soluble solids to titratable acidity ratio (SS/TA) and total soluble sugars. Furthermore, there is a positive correlation between titratable acidity (TA) and fruit diameter (FD). The SS/TA ratio and total sugars showed a negative correlation with number of non-commercial fruits per plant (NCF). It is also important to note that soluble solids (SS) are negatively related to chromaticity (C*).

The ratio between soluble solids (SS) and titratable acidity (TA) is a common measure to assess the taste of fruits, as it provides a more accurate evaluation of taste compared to the individual measurements of sugars or acidity. When this ratio is high, fruits tend to have a more pleasant balance between sugars and acids, resulting in a sweeter taste (Chitarra & Chitarra, 2005). In general, higher values of SS/TA ratio are associated with a milder taste, while lower values are related to a more acidic taste, which is theoretically desirable for eggplant fruits (Paiva et al., 2018).

In the third group, which includes only the 100% irrigation level and treatment T2 (NPZnO foliar), a strong positive correlation between lightness and vitamin C content is observed. Additionally, there is a negative relationship between lightness and soluble solids content. This suggests that, in this treatment and under specific conditions, lightness and vitamin C are inversely related to soluble solids, which may affect fruit quality.

Conclusions

1. Water deficit and nanoparticles containing zinc, associated or not with bacteria that promote plant growth, did not influence the weight and average size of the fruits and the post-harvest quality of the eggplant crop. Therefore, the use of these products to mitigate water deficit in eggplant is not justified.

2. Water deficit reduced the chromaticity and lightness of the skin color and the vitamin C content of eggplant.

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