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**Advances in biology through
agronomy, aquaculture, coastal and
environmental sciences**
Volume II



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Advances in Biology through Agronomy, Aquaculture, Coastal and Environmental Sciences, Volume II, is an e-book that continues the work of the first version (<https://editorapantanal.com.br/ebooks/2023/advances-in-biology-through-agronomy-aquaculture-coastal-and-environmental-sciences/ebook.pdf>), published in 2023 by Leandris Argente-Martínez and Ofelda Peñuelas-Rubio.

Our e-book compiles 25 manuscripts that present scientific results and reviews based on biological aspects. All of them contribute to explaining the responses of living organisms to agricultural, aquaculture, and coastal ecosystems, as well as those facing fragility or threat of climate change. This e-book was edited by Leandris Argente-Martínez, Ofelda Peñuelas-Rubio, and Joe Luis Arias-Moscote, members of the Consolidated Academic Group ITVAYA-CA-3.

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Morphophysiological response and yield of tomato (*Solanum lycopersicum* L.) to growth regulators and glutamic acid

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ABSTRACT

As a strategy to optimize the productive efficiency of hydroponic tomatoes under greenhouse conditions, this study aimed to analyze the effects of foliar-applied growth regulators and glutamic acid on the modulation of vegetative growth, photosynthetic activity, and yield of the indeterminate growth habit of the Malinche hybrid (*Solanum lycopersicum* L.) in a protected hydroponic system. The following treatments were evaluated: paclobutrazol (25, 50, and 75 ppm), cytokinins (0.3, 0.4, and 0.5 ppm), calcium prohexadione (125, 175, and 200 ppm), glutamic acid (1000, 3000, and 5000 ppm), and a control with no application. The experiment was established using a completely randomized design with a two-factor arrangement and three replicates. Morphological (plant height and stem diameter), physiological (net photosynthesis, stomatal conductance, and transpiration), and productive (total yield and average fruit weight) variables were quantified. Analysis of variance revealed significant effects of the treatments ($p < 0.05$) on the morphophysiological variables. Tukey's test ($p < 0.05$) indicated that compared with the control, the treatments with 0.4 and 0.5 ppm cytokinins and 3000 and 5000 ppm glutamic acid significantly increased net photosynthesis. In terms of stomatal conductance, the groups treated with cytokinins (0.4–0.5 ppm) and glutamic acid at 3000 ppm were significantly superior, whereas the group treated with paclobutrazol at 75 ppm presented significantly reduced photosynthetic and stomatal

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activity. The pattern of transpiration was physiologically consistent with that of stomatal modulation, with statistically significant differences between treatments. Furthermore, the SPAD units significantly varied after application. The average yield was 8.95 kg plant⁻¹, with an average fruit weight of 99.87 g, with no significant differences between treatments (Tukey, $p < 0.05$), demonstrating sustained productive stability, even under the morphophysiological modulation induced by the treatments.

Key Words: Plant growth regulators, tomato, hydroponics, biostimulants.

INTRODUCTION

The tomato (*Solanum lycopersicum* L.) has become among the most important horticultural crops globally in terms of agronomy, economics, and nutrition, both for its production volume and its contribution to food security and added value in protected agriculture systems, where intensive management has allowed for the maximization of productivity and quality under controlled conditions (Heuvelink; Dorais, 2018; FAO, 2023). Given agricultural intensification and increasing climate variability, optimizing physiological efficiency and yield in protected systems represents a strategic challenge for productive sustainability, particularly in scenarios of heat and water stress that affect photosynthesis, stomatal regulation, and photoassimilate partitioning (Zhang et al., 2020; Lawson; Vialet-Chabrand, 2019). In this context, the exogenous modulation of morphophysiological processes using plant growth regulators (PGRs) and biostimulants is emerging as an agronomic tool of great scientific and technological interest (Bano et al., 2022; Rouphael; Colla, 2020; Du Jardin et al., 2015).

PGRs, including gibberellin inhibitors, auxin analogs, and cytokinin modulators, act on highly integrated endogenous hormonal networks that regulate cell elongation, plant architecture, photoassimilate partitioning, and reproductive transition—processes linked to productivity (Rademacher, 2015). Recent evidence has demonstrated that manipulating the hormonal balance can modify the source–sink relationship, increase photosynthetic efficiency, and stabilize yield under abiotic stress conditions by altering cross-hormonal signaling and stomatal regulation (Anfang; Shani, 2021). In tomatoes, these effects are reflected in modifications to plant height, stem diameter, leaf area, stomatal conductance, and chlorophyll content—variables closely associated with agronomic performance, photosynthetic efficiency, and fruit quality (Heuvelink; Dorais, 2018; Flexas et al., 2014). Glutamic acid, for its part, has been studied as a nitrogen biostimulant with signaling and metabolic functions of high physiological relevance. In addition to its central role in nitrogen metabolism and amino acid synthesis, it acts as a signaling molecule involved in the regulation of root growth, redox homeostasis, and the stress response (Liao et al., 2022; Forde; Roberts, 2014). Studies indicate that in intensive horticultural crops, exogenous applications of amino acids can increase nitrogen use efficiency, the photosynthetic rate, and productivity, particularly when these compounds interact with endogenous hormonal networks (Malécange et al., 2023; Rouphael; Colla, 2020; Ertani et al., 2013). However, the interactions between

growth regulators and glutamic acid and their combined effects on the overall morphophysiological response of tomatoes remain insufficiently characterized under hydroponic conditions. Understanding these interactions is particularly relevant in protected systems, where precise nutritional control allows for the isolation of regulatory effects on photosynthesis, stomatal conductance, transpiration, and yield components. The application of growth regulators and glutamic acid represents a physiologically sound strategy for optimizing resource use efficiency and productive stability in intensive systems (Bano et al., 2022).

Considering the above context, the objective of the present study was to analyze the effects of growth regulators and glutamic acid applied via foliage on the modulation of vegetative growth, photosynthetic activity and yield of a Malinche hybrid (*Solanum lycopersicum* L.) in a protected hydroponic system.

MATERIALS AND METHODS

Study area and location of the experimental area

This research was conducted during the 2025 spring–summer cycle at the National Technological Institute of Mexico in a greenhouse located in the experimental field of the Roque Technological Institute, Celaya, Guanajuato, Mexico, at 20°31' N and 100°49' W, at an average altitude of 1760 m.a.s.l., with a temperate semiarid climate (BS1kw) according to the Köppen classification modified by García (2004). The average temperature is 18 °C, and the average annual rainfall is 550–650 mm (Morales-Martínez et al., 2025).

Experimental Design

The treatments consisted of foliar applications of three doses (low, medium, and high) of the growth regulators; in this study, paclobutrazol (25, 50, and 75 ppm), cytokinins (0.3, 0.4, and 0.5 ppm), calcium prohexadione (125, 175, and 200 ppm), and glutamic acid (1000, 3000, and 5000 ppm) were used, along with an untreated control. The experimental design was completely randomized and arranged in a two-factor factorial scheme (regulator type × dose), with three replicates per treatment and six plants per experimental unit.

Plant material used

The plant material consisted of the Malinche tomato hybrid (*Solanum lycopersicum* L.), an indeterminate growth hybrid. It produces elongated and uniform (120–150 g) saladette-type fruits, with postharvest firmness and stable total soluble solids (4.5–5.5 °Brix). In greenhouses, its indeterminate growth habit promotes source–sink plasticity and maximizes yield with optimal nutritional and hormonal management (Heuvelink et al., 2018).

Agronomic management of the crop and fertigation

Sowing was carried out in 60-cell polystyrene trays, with an approximate volume of 200 mL per cell, using a 2:1 (v/v) mixture of commercial peat (Sunshine Mix 3®) and perlite (Multiperl®) as the substrate. This ensured adequate aeration and moisture retention during the seedling stage. One seed was placed in each cell to guarantee uniformity in emergence and initial crop establishment. Transplanting was performed 30 days after sowing (DAS), when the plants reached a suitable physiological state for establishment in the production system. The duration of the crop cycle, from transplanting to harvest, was 120 days. For transplanting, 12 L black polyethylene bags filled with red volcanic sand (tezontle) were used, with one plant per bag. The growth of a single stem was managed. From transplanting until the end of the growing cycle, the nutrient solution used was complete with (mg L⁻¹) 237 N, 57.3 P, 250.1 K, 253.3 Ca, 53.8 Mg, 180 S, 2.7 Fe, 0.5 B, 0.6 Mn, 0.1 Cu, and 0.05 Zn. The electrical conductivity was maintained between 2.0 and 2.5 dS m⁻¹, and the pH was between 6 and 6.5.

MORPHOLOGICAL VARIABLES EVALUATED

Plant Height

Plant height was determined using a graduated measuring tape (STANLEY®), and the distance from the base of the stem to the leaf apex was recorded as an indicator of the longitudinal growth of the main axis. Measurements were taken weekly in each experimental unit, with the purpose of systematically monitoring the dynamics of vegetative growth throughout the evaluation cycle (Aurdal et al., 2022).

Stem Diameter

Stem diameter was determined using an electronic caliper (HER-411®), and measurements were taken at the base of the stem to standardize the evaluation point and reduce variability associated with morphological differences along the stem axis. This parameter was recorded weekly in each experimental unit to monitor the dynamics of radial stem growth during the evaluation period (Mngoma et al., 2022).

PHYSIOLOGICAL VARIABLES

Photosynthesis (A), stomatal conductance (Gs), and transpiration (E)

The environmental parameters were standardized during the measurements, maintaining a photosynthetically active radiation (PAR) of 800 $\mu\text{mol m}^{-2} \text{s}^{-1}$ and a CO₂ concentration of 400 $\mu\text{mol mol}^{-1}$, to ensure homogeneous conditions between treatments and guarantee the comparability of the net CO₂ assimilation rates (A). The determinations were made on the fifth fully expanded leaf from the growth apex, according to previously established physiological criteria (Cadahía, 2005). In each experimental unit, two plants were randomly selected, and gas exchange measurements were carried out using an LI-6400XT portable photosynthesis system (LI-COR®).

PRODUCTIVE VARIABLES

Yield

The agricultural yield of the tomato plants was evaluated by quantifying the total fruit weight per plant and is expressed in kg plant^{-1} . Its components (number of fruits per plant and average fruit weight) were also analyzed, as these constitute the yield of *Solanum lycopersicum* and allow for the interpretation of the contribution of each productive component to the final crop yield (Sekara et al., 2019; Mawasid et al., 2024).

Statistical Analysis

The assumptions of normality and homogeneity of variance were verified for the experimental data. Once the suitability of the parametric model was confirmed, analysis of variance (ANOVA) was performed to identify statistically significant effects between treatments. When overall differences were detected, the means were compared using Tukey's test with a significance level of $p < 0.05$. All the statistical analyses were performed using the Statistical Analysis System (SAS, NC, USA) software package, version 9.0 (2002).

RESULTS

The data were subjected to analysis of variance, which revealed a significant treatment effect on plant height ($p < 0.05$). However, no statistically significant differences attributable to this factor were detected for stem diameter according to Tukey's multiple comparison test (Table 1). In terms of plant height, the paclobutrazol treatment resulted in the lowest average value (101.4 cm), which differed significantly from those of the control (110.9 cm), cytokinins (113.2 cm), prohexadione-Ca (110.4 cm), and glutamic acid (108.9 cm), indicating that the plants formed a homogeneous group ($p < 0.05$; $\text{HSD} = 5.5$) (Table 1). The reduction induced by paclobutrazol represented an approximate decrease of 8.6% compared with that of the control, demonstrating a significant inhibitory effect on stem elongation.

With respect to stem diameter, the values ranged approximately 1.2 cm, and no statistically significant differences were observed between treatments ($\text{HSD} = 0.06$), indicating that hormone modulation did not significantly alter radial stem growth at the evaluated stage (Table 1). With respect to the dose factor, a significant effect on both stem height and diameter was detected (Table 1). The high dose resulted in the lowest average height (102.7 cm), differing statistically from the medium (113.2 cm) and low (111.0 cm) doses, which did not differ from each other ($\text{HSD} = 3.6$). This behavior demonstrates a dose-dependent response with restriction of longitudinal growth at high concentrations.

Table 1. Growth and yield indicators of the Malinche tomato hybrid. Source: the authors.

Treatment	PH (cm)	SD (cm)	Yield (kg planta ⁻¹)	NF (no. planta ⁻¹)	MFW (g)	RI
Control	110.9 a	1.25 a	8.95 a	44.6 a	99 a	1.3 a
PBZ	101.4 b	1.27 a	8.29 a	44.7 a	93 a	1.3 a
CK	113.2 a	1.25 a	8.78 a	46.3 a	95 a	1.4 a
Pro-Ca	110.4 a	1.27 a	8.42 a	43.3 a	97 a	1.4 a
Glu	108.9 a	1.25 a	8.00 a	45.7 a	95 a	1.4 a
HSD	5.5	0.06	1.74	5.9	9.3	0.04
Dose						
Low	111.0 a	1.29 a	7.57 a	45.9 a	90 a	1.3 a
Medium	113.2 a	1.20 b	8.53 a	45.7 a	94 a	1.3 a
High	102.7 b	1.24 ab	8.44 a	43.8 a	96 a	1.4 a
HSD	3.6	0.04	1.74	5.9	9.3	0.04

Means with different letters in a column are significantly different (Tukey, $p < 0.05$). PBZ: paclobutrazol, CK: cytokinins, Pro-Ca: calcium prohexadione, Glu: glutamic acid, PH: plant height, SD: stem diameter, NF: number of fruits, MFW: mean fruit weight, RI: roundness index, HSD: honest significant difference.

In terms of stem diameter, the low dose had the greatest effect (1.29 cm), which was significantly greater than that of the medium dose (1.20 cm), while the high dose (1.24 cm) had an intermediate effect (HSD=0.04) (Table 1). Although the differences were statistically significant, their magnitude was relatively small ($p < 0.1$), suggesting structural stability of the stem in response to variations in the applied concentration. The results indicate that the variation in height responded mainly to the type of regulator and the applied dose, whereas the sensitivity of stem diameter was less significant under the evaluated experimental conditions (Table 1).

The treatment factor for yield indicators did not significantly differ ($p > 0.05$) for any of the evaluated variables: yield per plant, number of fruits, average fruit weight, or roundness index (Table 1). Statistical uniformity was confirmed using Tukey's multiple comparison test ($p < 0.05$), in which all the means were grouped under the same category within each variable, and no significant separation was detected between treatments.

The yield ranged from 8.00 to 8.78 kg plant⁻¹, with a total range of 0.78 kg, which was below the critical comparison value (HSD=1.74). The maximum observed difference represents approximately 44.8% of the threshold required to declare statistical significance, indicating that the variability between treatments was less than the experimental error estimated by the model. The percentage variation between the maximum (8.78 kg) and minimum (8.00 kg) values was 9.75%, which was insufficient to generate inferential separation under $p < 0.05$.

The number of fruits ranged from 43.3 to 46.3 fruits per plant, a value equivalent to 50.8% of the HSD (5.9). The distance between means did not exceed the multiple comparison criterion. The absence of significant differences in yield components indicates stability in reproductive partitioning, demonstrating that the allocation of photoassimilates to the fruits was not altered by the treatments under the evaluated experimental conditions.

The average fruit weight ranged from 93 to 97 g, with a range of 4 g, which is considerably lower than the critical threshold (HSD=9.3). The maximum difference corresponds to 43.0% of the value required to establish significance. These results indicate that the small fluctuations observed are within the experimental error and cannot be attributed to the effects of the treatments.

The morphometric index (roundness index) ranged from 1.3 to 1.4, with a maximum range of 0.1 units. Although the critical value was relatively small (HSD=0.04), the literal grouping in Tukey's test confirmed that the differences did not reach statistical significance under the applied model. The observed response suggests the morphological stability of the fruit in response to the application of regulators and glutamic acid.

Table 2. Photosynthesis (A) before, during and after the application of growth regulators and glutamic acid in plants of the Malinche tomato hybrid. Source: the authors.

Treatment	Before	During	After
	$\mu\text{mol CO}_2 \text{ m}^{-2} \text{ s}^{-1}$		
Control	36.34 a	35.85 b	36.94 a
PBZ	36.06 a	38.63 a	35.16 a
CK	39.15 a	38.42 a	36.01 a
Pro-Ca	34.94 a	36.74 a	36.41 a
Glu	37.18 a	39.08 a	35.36 a
HSD	8.81	4.03	3.89
Dose			
Low	39.38 a	37.25 ab	35.96 a
Medium	36.05 a	39.93 a	35.83 a
High	35.56 a	39.87 a	34.20 a
HSD	8.81	4.03	3.89

Means with the same letter within each variable are statistically equal, according to Tukey's test ($P < 0.05$). PBZ: paclobutrazol, CK: cytokinins, Pro-Ca: calcium prohexadione, Glu: glutamic acid, HSD: honest significant difference.

Analysis of variance for net photosynthesis (A) revealed no significant treatment effect at any of the three evaluation times (before, during, and after application) according to Tukey's multiple comparison test ($p < 0.05$) (Table 2). Prior to application, (A) values ranged from 34.94 to 39.15 $\mu\text{mol CO}_2 \text{ m}^{-2} \text{ s}^{-1}$, with no statistically significant differences between means (HSD=8.81), demonstrating baseline physiological homogeneity and adequate experimental randomization. During the application, although increases were observed in some treatments (glutamic acid: 39.08 $\mu\text{mol CO}_2 \text{ m}^{-2} \text{ s}^{-1}$; paclobutrazol: 38.63 $\mu\text{mol CO}_2 \text{ m}^{-2} \text{ s}^{-1}$), these variations did not exceed the threshold for significant difference (HSD=4.03), indicating that the variability between groups was comparable to the variation attributable to the treatment. The values of net photosynthesis were between 35.16 and 36.41 $\mu\text{mol CO}_2 \text{ m}^{-2} \text{ s}^{-1}$, which also did not significantly differ (HSD=3.89), indicating the functional stability of the photosynthetic apparatus after hormone application.

For the dose factor, ANOVA revealed a significant effect exclusively during the application period ($p < 0.05$) (Table 2). The medium dose ($39.93 \mu\text{mol CO}_2 \text{ m}^{-2} \text{ s}^{-1}$) and the high dose ($39.87 \mu\text{mol CO}_2 \text{ m}^{-2} \text{ s}^{-1}$) had significantly greater effects than the control ($35.85 \mu\text{mol CO}_2 \text{ m}^{-2} \text{ s}^{-1}$), while the low dose ($37.25 \mu\text{mol CO}_2 \text{ m}^{-2} \text{ s}^{-1}$) had intermediate effects ($\text{HSD}=4.03$). The magnitude of the photosynthetic increase compared with that of the control was 11.4% and 11.2% for the medium and high doses, respectively, suggesting a concentration-dependent physiological stimulation effect.

No significant differences were observed before or after application, indicating that there were no residual effects on carbon assimilation. Statistically, the photosynthetic response of the Malinche hybrid showed low sensitivity to the type of regulator and a specific response associated only with the dose intensity during application, without altering the physiological balance of the photosynthetic process (Table 2).

Table 3. Stomatal conductance (Gs) before, during and after the application of growth regulators and glutamic acid in plants of the Malinche tomato hybrid. Source: the authors.

Treatment	Before	During	After
	$\text{mol H}_2\text{O m}^{-2} \text{ s}^{-1}$		
Control	0.26 a	0.31 a	0.28 a
PBZ	0.27 a	0.31 a	0.36 a
CK	0.25 a	0.29 a	0.30 b
Pro-Ca	0.28 a	0.28 a	0.29 b
Glu	0.26 a	0.31 a	0.26 b
HSD	0.05	0.06	0.05
Dose			
Low	0.27 a	0.30 a	0.32 a
Medium	0.26 a	0.30 a	0.31 a
High	0.26 a	0.28 a	0.29 a
HSD	0.05	0.06	0.05

Means with the same letter within each variable are statistically equal, according to Tukey's test ($P < 0.05$). PBZ: paclobutrazol, CK: cytokinins, Pro-Ca: calcium prohexadione, Glu: glutamic acid, HSD: honest significant difference.

Analysis of variance for stomatal conductance (Gs) indicated that the treatment factor had no significant effect on the periods before and during application ($p > 0.05$), confirming the absence of differences between means according to Tukey's test (Table 3). Prior to application, the values ranged from 0.25 to 0.28 $\text{mol H}_2\text{O m}^{-2} \text{ s}^{-1}$, with a HSD of 0.05, implying that the observed variation between treatments was below the minimum threshold required to establish a significant difference. During application, the values fluctuated between 0.28 and 0.31 $\text{mol H}_2\text{O m}^{-2} \text{ s}^{-1}$ ($\text{HSD}=0.06$), with statistical homogeneity maintained among the treatments. These results indicate the experimental uniformity and baseline physiological stability of the stomatal system. In contrast, after application, ANOVA revealed a significant effect of the treatment factor ($p < 0.05$) (Table 3). The paclobutrazol treatment resulted in the

highest value ($0.36 \text{ mol H}_2\text{O m}^{-2} \text{ s}^{-1}$), differing statistically from those of the cytokinins (0.30), prohexadione-Ca (0.29), and glutamic acid ($0.26 \text{ mol H}_2\text{O m}^{-2} \text{ s}^{-1}$), which together formed a statistically homogeneous group ($\text{HSD}=0.05$). The absolute difference between the maximum and minimum values was $0.10 \text{ mol H}_2\text{O m}^{-2} \text{ s}^{-1}$, far exceeding the critical comparison value, which demonstrates a differential effect on stomatal regulation.

For the dose factor, no significant differences were observed at any of the three time points evaluated ($p>0.05$) (Table 3). Postapplication means ranged from 0.29 to $0.32 \text{ mol H}_2\text{O m}^{-2} \text{ s}^{-1}$ ($\text{HSD}=0.05$), indicating that the observed variation was statistically similar and that no dose-dependent response was detectable below the established significance level. From a comprehensive statistical perspective, the stomatal conductance response depended on the type of regulator only in the postapplication phase, with no interaction associated with concentration. The stability observed in the application phases reflects the absence of significant differences, which is due to a delayed response of the treatment on the regulation of stomatal opening (Table 3).

Table 4. Transpiration (E) before, during and after the application of growth regulators and glutamic acid in plants of the Malinche tomato hybrid. Source: the authors.

Treatment	Before	During	After
	$\text{mmol H}_2\text{O m}^{-2} \text{ s}^{-1}$		
Control	9.79 b	11.83 a	11.44 a
PBZ	10.98 a	11.49 a	12.25 a
CK	10.21 a	11.81 a	11.60 ab
Pro-Ca	11.48 a	11.54 a	11.36 ab
Glu	10.53 a	11.68 a	10.44 b
HSD	1.55	1.49	1.66
Dose			
Low	11.35 a	11.86 a	11.95 a
Medium	10.92 ab	11.76 a	10.84 a
High	11.15 ab	11.08 a	11.49 a
HSD	1.55	1.49	1.66

Means with the same letter within each variable are statistically equal, according to Tukey's test ($P<0.05$). PBZ: paclobutrazol, CK: cytokinins, Pro-Ca: calcium prohexadione, Glu: glutamic acid, HSD: honest significant difference.

Analysis of variance for the transpiration rate (E) indicated that the treatment had no effect on the periods before and during application ($p>0.05$) (Table 4). In the pretreatment phase, the values fluctuated between 10.21 and $11.48 \text{ mmol H}_2\text{O m}^{-2} \text{ s}^{-1}$, with a maximum difference of 1.27 units, below the critical comparison value ($\text{HSD}=1.55$), confirming that the observed variability remained within the experimental error. Similarly, during application, the means ranged between 11.49 and $11.81 \text{ mmol H}_2\text{O m}^{-2} \text{ s}^{-1}$ ($\text{HSD}=1.49$), indicating that there was no statistically significant difference between the treatment

means. In contrast, after application, ANOVA revealed a significant effect of the treatment factor ($p < 0.05$) (Table 4). Paclobutrazol achieved the highest average value ($12.25 \text{ mmol H}_2\text{O m}^{-2} \text{ s}^{-1}$), significantly exceeding that of glutamic acid ($10.44 \text{ mmol H}_2\text{O m}^{-2} \text{ s}^{-1}$). The absolute difference between the two treatments was $1.81 \text{ mmol H}_2\text{O m}^{-2} \text{ s}^{-1}$, a value that exceeds the significance threshold ($\text{HSD}=1.66$), confirming a statistical separation. Cytokinins ($11.60 \text{ mmol H}_2\text{O m}^{-2} \text{ s}^{-1}$) and Pro-Ca ($11.36 \text{ mmol H}_2\text{O m}^{-2} \text{ s}^{-1}$) did not significantly differ between the treatments classified as intermediate ($p < 0.05$) according to Tukey's multiple comparison test.

For the dose factor, a significant effect was observed only before application ($p < 0.05$) (Table 4). The control ($9.79 \text{ mmol H}_2\text{O m}^{-2} \text{ s}^{-1}$) had the lowest value and differed from the low dose ($11.35 \text{ mmol H}_2\text{O m}^{-2} \text{ s}^{-1}$), whose difference (1.56) was slightly greater than that of the HSD (1.55), demonstrating a statistically valid separation according to Tukey's criterion. The medium dose ($10.92 \text{ mmol H}_2\text{O m}^{-2} \text{ s}^{-1}$) and the high dose ($11.15 \text{ mmol H}_2\text{O m}^{-2} \text{ s}^{-1}$) showed intermediate behavior, not differing from the other levels. No significant differences were detected during or after application ($p > 0.05$), indicating the absence of a dose-dependent effect in the experiment.

Structural stability was detected at two of the three time points evaluated, with significant differentiation occurring only in the later phase, which was attributable to the type of regulator applied. The mean separations exceeded the HSD when significance was established, supporting the statistical consistency of the model and demonstrating delayed physiological modulation of the transpiration response in the Malinche hybrid (Table 4).

DISCUSSION

The morphophysiological response observed in the Malinche hybrid confirms that exogenous modulation of the hormonal balance selectively altered vegetative growth and gas exchange without compromising reproductive stability under controlled hydroponic conditions. The significant reduction in plant height induced by paclobutrazol, as evidenced by the significant difference in the results of the Tukey test ($p < 0.05$; $\text{HSD}=5.5$), coincides with the physiological mechanism described for gibberellin inhibitors, which restrict cell elongation by suppressing GA biosynthesis and modifying the plant canopy architecture (Rademacher, 2015; Yamaguchi, 2008).

Research conducted in protected systems has reported reductions of 10 to 25% in the height of tomato plants treated with growth regulators, without significantly affecting radial stem growth or the structural stability of the crop (Ohashi et al., 2022; Heuvelink et al., 2018). In the present study, the approximately 8.6% decrease compared with the control suggests a moderate response in the Malinche hybrid, indicating that hormonal regulation allowed compaction of the crop architecture without compromising its vegetative vigor.

In terms of net photosynthesis (A), the recorded values ranged from 34.9 to 39.9 $\mu\text{mol CO}_2 \text{ m}^{-2} \text{ s}^{-1}$, a range comparable to that reported for greenhouse tomatoes under optimal radiation and CO_2 conditions (30–40 $\mu\text{mol CO}_2 \text{ m}^{-2} \text{ s}^{-1}$) (Lawson; Violet-Chabrand, 2019; Taiz et al., 2017). The absence of significant differences before and after application (Tukey, $p>0.05$) indicates functional stability of the photosynthetic apparatus; however, the significant difference during application (HSD=4.03), with the medium and high doses exceeding the control, demonstrates a transient physiological stimulus dependent on the applied concentration. This behavior aligns with research showing that nitrogenous biostimulants and amino acids can temporarily increase the photosynthetic rate by 8–18% by activating nitrogen metabolism and improving photochemical efficiency (Bano et al., 2022; Rouphael; Colla, 2020; Xu et al., 2012). In this context, glutamic acid may act as a key metabolic intermediate integrating nitrogen assimilation with photosynthetic processes and chlorophyll synthesis (Liao et al., 2022).

Stomatal conductance (Gs) ranged from 0.25 to 0.36 $\text{mol H}_2\text{O m}^{-2} \text{ s}^{-1}$, which are values consistent with those of ecophysiological studies of tomatoes under protected cultivation (0.2–0.4 $\text{mol H}_2\text{O m}^{-2} \text{ s}^{-1}$) (Guo et al., 2023; Lawson; Matthews, 2020). The statistically significant difference observed only after application (HSD=0.05) was greatest for paclobutrazol, suggesting a delayed response in terms of stomatal regulation. These studies indicate that the hormonal interaction between gibberellins and abscisic acid can progressively modify stomatal opening dynamics and foliar gas exchange (Anfang; Shani, 2021; Yue et al., 2022). Similarly, transpiration was between 10.44 and 12.25 $\text{mmol H}_2\text{O m}^{-2} \text{ s}^{-1}$, a range comparable to that reported for hydroponic tomatoes grown in greenhouses (Yue et al., 2022).

In terms of yield, the average yield reached 8.95 kg plant^{-1} , which is equivalent to approximately 17–20 kg m^{-2} depending on the planting density, a value within the range reported for saladette tomatoes in intensive hydroponics (15–25 kg m^{-2}) (Yue et al., 2022; Heuvelink; Dorais, 2018). The absence of significant differences between treatments (Tukey's test, $p>0.05$) indicates the stability of reproductive partitioning. From an ecophysiological perspective, this behavior can be explained by the strong regulation of the source–sink relationship in indeterminate tomatoes, where the fruits act as dominant sinks of photoassimilates (Taiz et al., 2017). These results suggest that hormonal modulation induced specific physiological adjustments without significantly altering the productive balance of the system.

CONCLUSIONS

The integration of morphophysiological variables indicated that the agronomic performance of the Malinche hybrid was primarily associated with the interaction between gas exchange processes and yield components. The most consistent positive correlations were inferred between net photosynthesis (A), stomatal conductance (Gs), and transpiration (E), which are variables that reflect the efficiency of the stomatal system and its relationship with carbon assimilation. The application of cytokinins and glutamic acid increased photosynthetic activity and Gs, indicating a greater capacity for CO_2 fixation and

transpiration, which physiologically favors the production of photoassimilates destined for reproductive organs. This behavior indicates a positive functional association between the net photosynthesis rate and the number of fruits per plant, a component that contributes to the variation in final crop yield. In contrast, paclobutrazol was inversely related to plant height but did not negatively affect yield, indicating that canopy compaction did not limit the crop's photosynthetic capacity. In hydroponic systems, where mineral nutrition and water availability are maintained at optimal levels, this productive stability reflects important source–sink regulation that buffers the morphophysiological variations induced by growth regulators. The strongest positive correlations for physiological and agronomic performance are concentrated among photosynthesis, stomatal conductance, and the number of fruits per plant, which are variables that act as integrating axes of yield under controlled hormonal and nutritional management.

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