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Biostimulants mitigate drought-induced yield losses in tomato and modulate fruit quality traits

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Introduction: Tomato is one of the most widely consumed vegetable crops worldwide, and both high yield and quality are crucial for the economic success of its production. Biostimulants are emerging as an innovative and sustainable solution to enhance crop productivity and improve fruit quality.
Methods: A greenhouse experiment was conducted to assess the yield performance and fruit quality attributes of tomato in relation to biostimulant doses and irrigation regimes. Three biostimulant treatments: untreated control, D1 (1.5 g L^{-1} and 3 g L^{-1} of Algaren Twin and Drin On) and D2 (2 g L^{-1} and 4 g L^{-1} of Algaren Twin and Drin On) and two irrigation regimes (100% of crop water requirement and water-stressed treatment at 50% of crop water requirement) were applied.
Results: Water stress significantly reduced plant growth, as evidenced by a marked reduction in both total and aboveground dry biomass. Biostimulant application improved plant growth, particularly under water stress conditions. Irrigation regimes and biostimulant application significantly influenced tomato fruit quality and physiological traits. Under optimal water conditions, biostimulant-treated plants exhibited lower levels of total soluble solids, titratable acidity, and total sugar content in their fruits. However, neither lycopene nor total phenolic content was affected by the treatments. In contrast, under water stress (50% of crop water requirement), the application of biostimulants significantly increased lycopene content in the fruits of treated plants compared to the control samples. Moreover, a dose-dependent effect was noted for total sugar, total phenolic content, and antioxidant activity, with lower values observed at the lower biostimulant dose.
Conclusion: These results suggest that biostimulants can be considered a useful tool for improving fruit quality under optimal irrigation conditions and for alleviating the adverse effects of water stress. Their effectiveness depends on dose, application method, and environmental conditions.

KEYWORDS
biostimulants, lycopene content, plant yield, tomato quality, water stress

1 Introduction

Tomato (*Solanum lycopersicum* L.) is one of the most widely consumed vegetable crops worldwide, with nearly five million hectares dedicated to its cultivation annually (Alenazi and Khandaker, 2021).

In addition to their sensory appeal, tomatoes are mostly consumed for their nutritional, nutraceutical, and antioxidant content (Del Giudice et al., 2017). Tomato fruits are, in fact, rich in minerals, vitamins, essential amino acids, carbohydrates, dietary fibers (Chaudhary et al., 2018), as well as a diverse range of vitamins B and C, along with antioxidant compounds (Kaboré et al., 2022).

However, global tomato production is increasingly threatened by water scarcity. In fact, due to its high-water requirement, it is among the sectors most affected by drought. The effects of drought on crop productivity and yield have severe consequences, particularly for food security and the economies of drought-prone regions, such as the Mediterranean basin (Carrão et al., 2016). Water deficit negatively affects several plant characteristics and has wide-ranging detrimental impacts on plant growth, physiology, and productivity, leading to reduced turgor pressure, leaf rolling, stomatal closure, inhibited CO_2 assimilation, and impaired nutrient uptake (Aalam et al., 2024; Gall et al., 2015; Kadioglu et al., 2012; Hussain et al., 2018). As a consequence, these disruptions ultimately limit photosynthesis, biomass accumulation, and fruit yield, particularly in commercial tomato cultivars that are highly sensitive to water deficits (Soto-Cerda et al., 2019). In light of these challenges, sustainable strategies to improve drought resilience are urgently needed.

In recent years, plant biostimulants have gained attention as innovative solutions that can potentially mitigate the negative effects of abiotic stress (e.g., phytotoxicity, high temperatures, salinity, drought, or UV radiation) (Battacharyya et al., 2015). These substances, which include both microbial and non-microbial formulations or their combinations, enhance plant responses to environmental factors by stimulating physiological changes that improve their agronomic performance (Bhupenchandra et al., 2022; Turan et al., 2021). Usually, biostimulants are rapidly absorbed and metabolized, resulting in a very low energy cost to the plant.

Biostimulants promote plant growth, enhance productivity, and improve stress resilience through the synergistic action of bioactive compounds by acting even at very low dosages (Mannino et al., 2020). Among these, algae-based biostimulants are rich in bioactive molecules like vitamins, phytohormones and amino acids, which can stimulate root growth, enhance nutrient uptake, and improve both yield and quality attributes in horticultural crops (Quintarelli et al., 2025). Although the ability of biostimulants to alleviate drought-related growth limitations is well-documented, their effects on fruit quality, especially regarding the content of bioactive compounds such as lycopene and phenolics, remain less explored (e.g., Wang et al., 2022; Campobenedetto et al., 2021a).

In this context, no studies have specifically investigated the combined application of seaweed-based extracts and amino acid–based biostimulants on datterino-type tomato cultivars under greenhouse drought conditions. Furthermore, the dose-dependent physiological and qualitative responses to this specific biostimulant combination under severe water stress (50% of container capacity) remain unexplored. Therefore, the aim of this research was to evaluate, for the first time, the interactive effect of different doses of biostimulants on yield and fruit quality in tomato plants (*Solanum lycopersicum* L.) grown under different water regimes. Specifically, the research focused on assessing whether biostimulant doses can mitigate the negative effects of water stress while enhancing physiological and qualitative traits such as antioxidant activity, total soluble solids, titratable acidity, and lycopene content. The ultimate goal was to identify sustainable strategies to improve tomato production under suboptimal water availability.

2 Materials and methods

2.1 Plant materials

The experiment was conducted in an unheated greenhouse located at Milazzo (ME, Italy) using datterino tomato (*Solanum lycopersicum* L.), cultivar SV1201TC.

Seedlings of uniform size with 3–4 true leaves were transplanted into an open soilless system, consisting of 5 L cylindrical, black plastic pots (20 × 20 cm), filled with a coconut fiber-based substrate. A total of six treatments were established based on the factorial combination of two water regimes (100 and 50% of container capacity) and three biostimulant levels (untreated control plus two concentrations of biostimulant).

Environmental conditions inside the greenhouse varied as follows: the relative humidity ranged from 50 to 80%, and the minimum, maximum, and mean temperatures were 9, 46, and 20.2 °C, respectively. Temperature and relative humidity were monitored using a HOBO U23 Pro v2 Data Logger (Onset Computer Corporation, Bourne, MA, United States).

2.2 Biostimulant treatments

Two biostimulant treatments were applied and compared to an untreated control. The commercial products used in this study were Algaren Twin and Drin On supplied by Green Has Italia S.p.A. (Canale, Italy). Algaren Twin is a liquid organic biostimulant based on the brown seaweed *Ecklonia maxima* and bioactive yeast extracts, containing 2% organic nitrogen, 14% organic carbon, and 30% organic matter (w/w). The product is characterized by hormone-like compounds naturally present in *Ecklonia maxima*, as well as amino acids and vitamins derived from yeast extracts, which support root development, flowering, and fruit set. Drin On is a liquid biostimulant based on free amino acids of animal origin, reinforced with N-acetyl-thiazolidine-4-carboxylic acid (ATCA). It contains 6.3% organic nitrogen, 19% organic carbon, 38% organic matter, 39% total amino acids, 10% free amino acids, and 0.86% ATCA (w/w). ATCA is converted in planta into L-cysteine, playing a key role in stress metabolism and antioxidant defense.

Two biostimulant mixtures were applied: D1 (1.5 g L^{-1} of Algaren Twin plus 3 g L^{-1} of Drin On) and D2 (2 g L^{-1} of Algaren Twin plus 4 g L^{-1} of Drin On). Biostimulants were freshly prepared before each application by dissolving the commercial products in distilled water, applied as a foliar spray according to the label recommendations, and uniformly distributed until leaf runoff using a hand-held sprayer. To eliminate any potential effect of the application process on plant water requirements, the control plants were sprayed with an equivalent volume of distilled water.

2.3 Irrigation system

A drip irrigation system with self-compensating microflow sprinklers was used. Two irrigation regimes were applied: Control (well-watered): 100% of crop water requirement (2 L h^{-1}); water-stressed treatment: 50% of crop water requirement (1 L h^{-1}). Irrigation volumes were calculated based on the hydration level of the substrate, taking the 100% treatment as a representative sample and maintaining the readily available water at levels close to 10% and the volume necessary to produce drainage between 10 and 15%. The irrigation frequency was determined using a lysimetric system, which continuously monitored the crop's water status and automatically managed irrigation events. Irrigation was triggered whenever the water level dropped below the critical threshold needed for optimal plant uptake. Irrigation treatments were initiated 7 days after transplanting (Figure 1).

A complete nutrient solution was used for fertigation with the following composition in macroelements: (mmol L^{-1}) 13.59 N-NO_3^-, 1.42 N-NH_4^+, 2.21 P-PO_4^-, 7.23 K^+, 5.28 Ca^{2+}, 2.99 Mg^{2+}, 4.87 S-SO_4^{2-}, and microelements (µmol L^{-1}): 18.44 Fe^{2+}, 34.72 B^{2-}, 0.96 Cu^{2+}, 6.40 Zn^{2+}, 12.01 Mn^{2+}, 0.72 Mo^{2-}. The solution had an electrical conductivity of 1.9 dS m^{-2} and a pH of 5.5–6.2.

Fruits from the first cluster were harvested at commercial maturity, corresponding to 75 days after transplanting, when they had reached the light-red color stage. Subsequent harvests were carried out until the fruits of the eighth cluster. After each harvest, fruits were detached from the rachis and classified as marketable (normal) or non-marketable (i.e., misshapen or cracked). Data on fruit number, weight, size, total and commercial yield were recorded. At the end of the trial, plants from each treatment were separated into stems, leaves, and roots, and the dry biomass was determined in an oven at 65 °C for 72 h until a constant weight was achieved. Quality parameters were determined using fruits from the 3rd and 6th cluster (representative harvest).

2.4 Fruit shape index and color

Fruits' longitudinal (L) and transversal (D) diameters were measured with a digital caliper, and the fruit shape index (L/D, FSI) was calculated as the ratio of maximum height to maximum width (Brewer et al., 2006).

Tomato color, including brightness (L*), redness or greenness (a*), and yellowness or blueness (b*), was assessed using a CR-200 (Konica Minolta, Inc., Tokyo, Japan) colorimeter.

2.5 Quality trait assessment

Fruits were transported to the laboratory, washed under cold running water, and dried with a cloth. A representative sample of 10 fruits for each replicate was used for TSS (Total Soluble Solids) and dry matter determination. The remaining fruits were quickly frozen using liquid nitrogen, labeled, and stored at −40 °C for further analyses. Just before analysis, tomato samples (10 fruits for each replicate) were taken from the freezer, allowed to thaw for 10 min, and then mashed in a mortar. All determinations were performed in triplicate.

2.5.1 Total soluble solids

Total soluble solids (TSS), expressed as °Brix, were determined using a portable digital refractometer (Hanna Instruments). Before use, the refractometer was calibrated by adding a few drops of distilled water (0 °Brix).

2.5.2 pH, titratable acidity, and total sugar content

An aliquot of 30 g of the mashed tomato samples was homogenized using an Ultraturrax T18 homogenizer (Janke & Kunkel, IKA Instruments, Staufen, Germany), quantitatively transferred to Falcon tubes and centrifuged at 1250 g for 10 min. The supernatant was filtered through Whatman 90 paper and used to determine pH, titratable acidity, and total sugar content.

pH was measured using a benchtop XS pH 8 standard pH meter (XS Instruments, Carpi (MO), Italy), equipped with a Hamilton Polyte Lab electrode (Hamilton, Bonaduz, Switzerland).

For titratable acidity (TA), a 10 mL aliquot of each tomato juice was manually titrated with 0.100 N NaOH using phenolphthalein (1% ethanolic solution) as an indicator until the pink endpoint. The 159 titratable acidity was expressed as % of citric acid and calculated according to the following 160 expression:

$$TA\ \left(\%citric\,acid\right)=\frac{V\left(ml\right)\,of\ NaOH\times 0.64}{V\left(ml\right)\,of\ tomato\ juice}$$

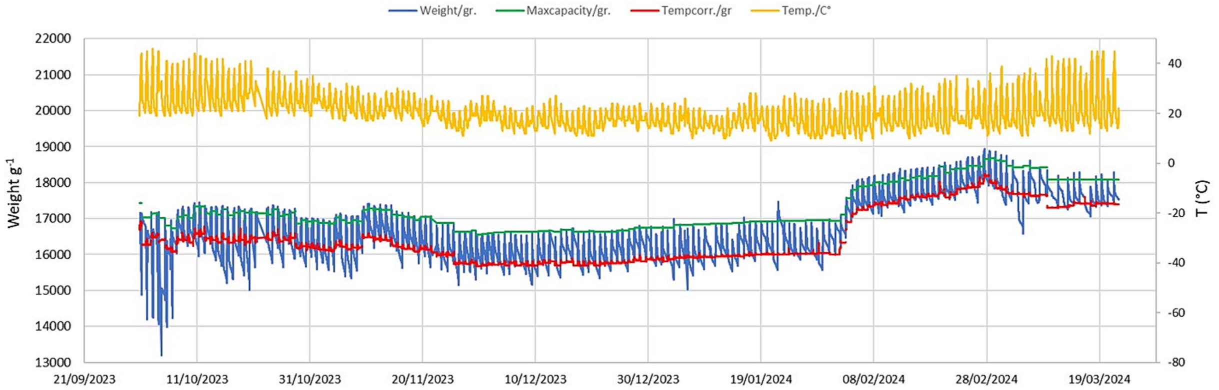

FIGURE 1
Trend of irrigation during the experiment.

Total sugar content was determined using the 2-phenoxyethanol-sulphuric acid assay as reported by Rajendar et al. (2020). In brief, 1 mL of each supernatant was properly diluted (1:2000–1:1500) with distilled water, then a 500 µL aliquot was transferred into a clean glass tube and added with 20 µL of 2-phenoxyethanol and 1,000 µL of H_2SO_4 conc. The mixture was gently vortexed and incubated in a water bath at 90 °C for 5 min. The absorbance of the mixture was read at 517 nm using a double-beam UV–Vis spectrophotometer (UV-2550, Shimadzu, Milan, Italy). Quantification was based on a five-point calibration curve constructed using standard glucose solutions whose concentrations ranged between 10 µg mL^{-1} and 80 µg mL^{-1}.

2.5.3 Maturity index

For each tomato sample, the maturity index was calculated by dividing its total soluble solid (TSS) by the titratable acidity (TA).

2.5.4 Lycopene content

Lycopene content was determined according to Sadler et al. (1990) with some modifications. Homogenized tomato samples (0.25 g) were mixed with hexane/acetone/ethanol (2:1:1, v/v/v) (20 mL) and magnetically stirred for 30 min in the dark at room temperature. After this, 3 mL of water was added, stirred for 5 min more, and then left to stand until the aqueous and organic phases were separated. The absorbance of the organic phase containing lycopene was measured at 475 nm. Lycopene was quantified using a molar extinction coefficient of $E_{475,1cm} = 18.5 \times 10^4$ according to the following equation:

$$Lycopene\ (mg/100gFW) = \frac{A_{475} \times 536.9}{18.5 \times 10^4} \times \frac{V_{ml}}{0.25} \times 100$$

2.5.5 Total phenolic content

About 1 g of fresh weight was mixed with 5 mL of MeOH/H_2O 80:20, sonicated for 30 min, and centrifuged at 5000 × g for 10 min at 5 °C. The supernatant was removed, and the pulp was extracted again with 5 mL of MeOH/H_2O mixture. The extraction was carried out in duplicate. The hydroalcoholic extracts were used for the determination of both total phenolic content and primary antioxidant activity, as reported below.

The total phenolic content (TPC) in hydroalcoholic extracts was determined using the Folin–Ciocalteu procedure. In brief, 25 µL aliquot of the supernatant was combined with 200 µL of distilled water, 125 µL of Folin-Ciocalteau's reagent (Sigma Aldrich Inc., St Louis, MO, United States), and 375 µL of 20% sodium carbonate/water (w/v). The mixture was incubated at 40 °C for 30 min. The absorbance was read at 765 nm using a UV–Vis spectrophotometer, and the result was expressed as mg gallic acid per 100 g dry weight. The Folin–Ciocalteu assay was performed in duplicate.

2.5.6 Antioxidant activity

The primary antioxidant activity was determined using 2,2-diphenyl-1-picrylhydrazyl radical (DPPH). For the test, 0.2 mL of the hydroalcoholic extract (prepared as above reported) was mixed with 2.8 mL of 1.50 10^−4 M DPPH solution in methanol and incubated at room temperature in the dark for 1 h. The absorbance was read at 517 nm. The DPPH assay was performed in duplicate. The percentage radical scavenging activity, RSA (%), was calculated using the following equation:

$$RSA\ (\%) = \frac{A_{Blank} - A_{Sample}}{A_{Blank}} \times 100$$

Results were expressed as IC_{50}, representing the concentration needed to scavenge 50% of the initial 202 DPPH radicals, calculated from the RSA (%) values.

2.6 Physiological parameters

At day 75 after transplanting, the gas exchange in six plants per treatment was measured using a CO_2/H_2O infrared gas analyzer (LCi, ADC Bioscientific Ltd., Hoddesdon, United Kingdom) from 09:00 to 13:00. For each treatment, the net photosynthetic rate (A_N) and stomatal conductance (gs) were recorded.

At the same time, in six plants per replicate, chlorophyll *a* fluorescence was measured using an OS1-FL (Opti-Sciences Corporation, Tyngsboro, MA, United States) modulated chlorophyll fluorimeter after dark-adapting leaves for 20 min. The chlorophyll *a* fluorescence was reported as the Fv/Fm ratio, which shows the maximal quantum yield of PSII photochemistry, where Fm = the maximal fluorescence and Fv = the variable fluorescence.

The SPAD index was measured on fully expanded leaves of six plants per replicate by a portable chlorophyll meter SPAD-502 (Minolta Camera Co., Osaka, Japan).

2.7 Statistical analysis

Data were checked for normality using the Shapiro–Wilk test and for homogeneity of variances using Levene's test prior to statistical analysis. Data were analyzed by a two-way analysis of variance (ANOVA), according to the complete randomized design with three replications per treatment, and water regimes and biostimulant dose as fixed factors. Means were separated using Tukey's Multiple Range Test at $p \leq 0.05$. All analyses were conducted using CoStat® 159 software version 6.003 (Cohort Software, Monterey, CA, United States). Six plants per replicate were used for all measurements.

3 Results

The effects of water deficit and biostimulant application on the growth of the tomato plants were assessed by measuring several relevant growth parameters, such as the total and aboveground dry biomass, as well as the root-to-shoot ratio (R/S) (Table 1).

Water stress significantly inhibited plant growth, as evidenced by a marked reduction in both total and aboveground dry biomass. Biostimulant treatments enhanced plant growth, particularly under water stress conditions (Table 1; Figures 2A–C). Significant differences in total dry biomass were observed for plants treated with D2 under 100%WC as well as for both biostimulant doses under 50%WC, compared to their respective controls (Figure 2A).

The effects of water deficit and biostimulant treatments were more evident in the root-to-shoot ratio (Table 1): water deficit resulted in a 14% increase in root biomass compared to full irrigation. D2 dose

TABLE 1 Total and aboveground dry weight (g plant^{-1}), root-to-shoot ratio (R/S), total fruit number (plant m^{-2}), and characteristics of marketable fruits (number and average fruit weight) in the tomato genotype "SV1201TC" grown greenhouse as affected by water content (100%WC and 50%WC) and biostimulant application (C, D1, and D2).

Source of variance	Total dry biomass (g plant^{-1})	Aboveground dry biomass (g plant^{-1})	R/S ratio	Total fruit number (plant m^{-2})	Marketable fruit	
					Number (plant m^{-2})	Average fruit weight (g fruit^{-1})
Water content						
100%WC	118.3±3.68a	85.3±2.90a	0.39±0.03a	230.9±11.9a	203.7±8.69a	14.9±0.60a
50%WC	83.0±7.01b	56.9±4.62b	0.45±0.05b	180.9±5.5b	152.6±6.14b	12.6±0.49b
Biostimulant						
C	86.2±11.29b	65.3±9.66	0.33±0.02b	194.8±13.2b	165.8±8.69b	12.8±0.78b
D1	98.8±5.79b	72.8±5.79	0.36±0.03b	194.7±10.2b	170.9±9.95ab	15.5±0.69a
D2	117.0±6.40a	75.2±6.40	0.57±0.03a	228.4±18.8a	197.7±15.51a	12.9±0.45b
Significance						
WC	***	***	*	***	***	***
B	**	ns	***	*	*	***
WC × B	*	*	ns	ns	ns	*

Values are mean ± SE. Asterisks indicate significant effects of limited water content (WC), biostimulant treatment (B), and their interaction (WC × B) according to ANOVA. ns, not significant; * = $p < 0.05$; ** = $p < 0.01$; *** = $p < 0.001$. Within each factor, different letters indicate significant differences based on Tukey's test (p<0.05).

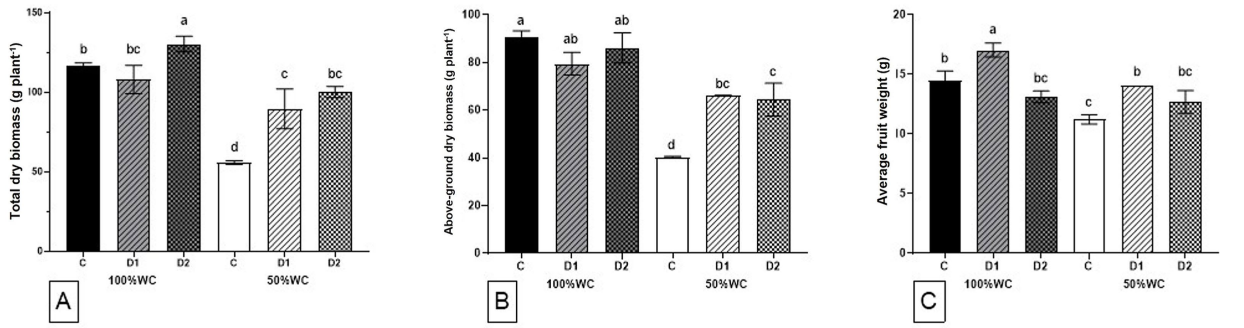

FIGURE 2
Interaction effects of water content and biostimulant doses on total **(A)** and aboveground **(B)** dry biomass, and average fruit weight **(C)**. Each value represents mean ± SE of three replicates. Bars with the same letters are not significantly different, as determined by Tukey's test (p < 0.05).

significantly increased the root-to-shoot ratio compared to both the control and D1 treatment (+39%).

Water deficit significantly reduced the total fruit number per plant (−34%). However, the D2 treatment partially mitigated the effect of water deficit (50%WC), as evidenced by a 15% higher number of fruits per plant compared to the 50%WC control (Table 1). A similar trend was observed for marketable fruit yield. While water stress reduced the number of marketable fruits by 25%, D2 increased this yield by 19% (197.7 fruits vs. 165.8 in the control). Additionally, D1 treatment also increased the average fruit weight under both water treatments, with increases of 19 and 15% for 100%WC and 50%WC, respectively. No significant differences were observed in D2 treatment compared to the control (Figure 2C).

Peel chromatic parameters L* and b* were significantly affected by "water x biostimulant" interaction (Table 2). The highest L* values were detected in the 50%WC D2, while the highest b* value in 100%WC D1 (Figures 3A,B). No statistical differences were observed for green intensity (a*) and fruit shape index (Table 2).

Regarding the total soluble solids (TSS) content, expressed as °Brix, the highest values were observed in the control plants (100%WC) and plants treated with D1 (Table 3). Under 50%WC conditions, the highest TSS values were detected at the D1 dose with an increase of 20% compared to the control (Figure 4A).

Fruit pH ranged from 4.00 to 4.10 and was not significantly affected by water regime, biostimulant treatment, or their interaction (Table 3). In contrast, the titratable acidity (expressed as g of citric acid per ml of tomato juice) and the total sugar content (mg of glucose per ml of tomato juice) were significantly influenced by water regime, biostimulant treatment, and their interaction (Table 3). The highest levels of titratable acidity were observed in plants treated with D1 under water stress (50%WC), as well as in control plants under both irrigation regimes (Figure 4B). As regards total sugar content, the lowest values were recorded in D2 100%WC and D1 50%WC, whereas the highest value was measured in plants treated with D2 under 50%WC (Figure 5B).

The maturity index, quantified by the sugar-to-acidity ratio, was found to be significantly influenced by both water treatment and

TABLE 2 Color parameters (L*: brightness; a*: green intensity, chroma component ranging from green (−60) to red (+60); b*: chroma component ranging from blue (−60) to yellow (+60)) and fruit shape index (adimensional) as affected by water content (100%WC and 50%WC) and biostimulant application (C, D1, and D2).

Source of variance	L*	a*	b*	Fruit shape index (FSI)
Water content				
100%WC	27.28±0.32b	28.80±0.99	28.75±2.13	1.39±0.01
50%WC	29.29±0.98a	28.67±0.90	26.08±1.01	1.39±0.01
Biostimulant				
C	28.17±0.61ab	28.58±1.05	26.08±1.22	1.39±0.01
D1	26.81±0.20b	30.03±0.84	29.56±2.05	1.38±0.01
D2	29.86±0.36a	27.58±1.38	26.20±2.61	1.39±0.01
Significance				
WC	**	ns	ns	ns
B	**	ns	ns	ns
WC × B	**	ns	*	ns

Values are mean ± SE. Asterisks indicate significant effects of water content (WC), biostimulant treatment (B), and their interaction (WC × B) according to ANOVA. ns, not significant; * = $p < 0.05$; ** = $p < 0.01$; *** = $p < 0.001$. Within each factor, different letters indicate significant differences based on Tukey's test ($p<0.05$).

biostimulant application. When examining water treatment, the highest maturity index was observed in the fruits of tomato plants grown under optimal water conditions. In terms of biostimulant application, the maturity index of tomato fruits of treated plants was higher than that of the control group, with the highest value observed at the highest dose applied (Table 3).

The content of lycopene was significantly affected by water treatment, biostimulant application, and their interaction. The lowest lycopene concentration was observed in fruits of control plants under 50%WC (Figure 5A). In contrast, the lycopene content of the other samples showed no statistically significant differences. Total phenolic content did not show any significant differences due to water treatment or biostimulant use alone, but it varied significantly in response to "water x biostimulant" interaction (Table 3). Fruits from D2-treated plants under 100%WC and D1-treated plants under 50%WC (Figure 5C) exhibited TPC values significantly ($p<0.05$) lower than D2 50%WC samples, which, on the other hand, had the highest TPC.

The primary antioxidant capacity, expressed as IC_{50} value (the concentration needed to inhibit 50% of the DPPH radicals), varied significantly in relation to water regime, biostimulant application, and their interaction (see Table 3). The highest scavenging ability (indicated by the lowest IC_{50}) was observed in fruits from plants treated with D2 dose under drought stress conditions, as well as in fruits from control and D1-treated plants under 100%WC. The lowest antioxidant capacity was recorded in fruits from plants treated with the D2 dose under 100%WC, followed by the D1 dose under 50%WC (Figure 5D). A significant effect of water deficit and biostimulant dose application was observed on net photosynthesis (A) (Figure 6A). Plants under 100%WC showed a 19.4% higher photosynthetic rate than those under 50%WC. D1 treatment also significantly enhanced photosynthesis (+18%) compared to the control and D2. A similar trend was observed for stomatal conductance (gs). The D1 biostimulant treatment had a significant effect, increasing gs by 17% compared to C and D2 (Figure 6B).

The Chlorophyll *a* fluorescence (Fv/Fm) did not show any differences in relation to water treatment but was enhanced by biostimulant application compared to control (Figure 7A). No significant differences were detected for the Spad index (Figure 7B).

Principal Component Analysis (PCA) revealed that the first three principal components accounted for 85.5% of the variance, with PC1, PC2, and PC3 explaining 46.4, 24.2, and 14.9% of the total variance, respectively. The biplot resulting from the PCA is reported in Figure 8.

PC1 (46.4%) showed a positive correlation with TSC, TPC, Brix°, and L*, while exhibiting a negative correlation with b*, Lycopene, and fruit unit weight. PC2 (24.2%) revealed marked positive correlations with DPPH, while negative for all remaining variables.

The score plot shows a clear separation of treatment groups. Fully irrigated regime (100%WC) was primarily located on the left side of PC1, particularly 100%WC D1 and D2, while treatments with reduced water content (50%WC) were positioned on the right side, such as 50%WC and 50%WC D2. The 50%WC D1 treatment was located closer to the origin, indicating intermediate behavior.

4 Discussion

In this study, foliar application of biostimulants significantly alleviated the negative effect of drought stress on tomato plant growth by modulating photosynthesis, regulating stomatal aperture, and improving quality parameters. Drought stress substantially reduced total and aboveground dry biomass as well as unit fresh weight. However, the application of biostimulants markedly counteracted these reductions, highlighting their potential to mitigate drought-induced growth reduction.

Water scarcity negatively affects cell differentiation, division, and elongation, ultimately limiting photosynthesis and dry matter accumulation (Manavalan et al., 2009). Biostimulants in various forms (protein hydrolysates, algae extracts, or humic acids) are recognized as useful tools for enhancing plant tolerance to different abiotic stresses (du Jardin, 2015). As reported by Alshallash et al. (2023), N-acetylthiazolidine 4-carboxylic acid (ATCA) acts as a plant bioregulator promoting the absorption of major and micronutrients. Drin on, one of the biostimulants tested in our trial, improved enzymatic activity and photosynthesis, promoting protein synthesis because it contains the above-mentioned amino acid, increasing the valine and glutamine content, thereby contributing to improve drought tolerance.

Our results showed that the biostimulant application enhanced marketable yield in both water regimes, either by enhancing total yield per plant or by reducing the proportion of unmarketable fruits. These beneficial effects may be ascribed to bioactive compounds contained in algae extracts, such as hormones or hormone-like substances and chelating agents that enhance nutrient use efficiency or stimulate chlorophyll biosynthesis and increase photosynthetic rate. Together, these factors contribute to improved plant growth and fruit production (Oancea et al., 2013; Özdemir et al., 2018; Araghian et al., 2015).

Ahmed et al. (2023) reported that applying extracts of the seaweed *Ascophyllum nodosum* combined with silicone to tomato plants under moderate drought stress (75% container capacity) increased

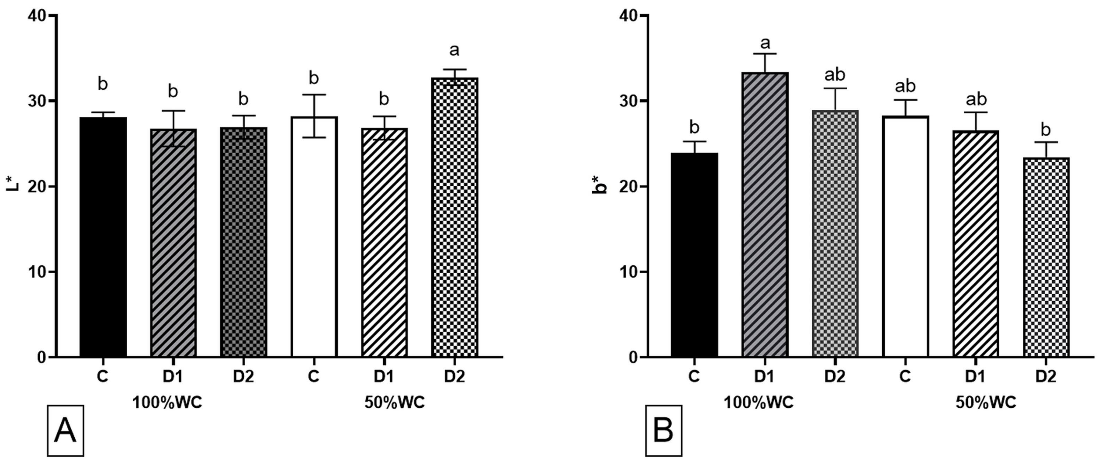

FIGURE 3
Interaction effects of water content and biostimulant doses on brightness (L*) **(A)** and chroma component ranging from blue (−60) to yellow (+60) (b*) **(B)**. Each value represents mean ± SE of three replicates. Bars with the same letters are not significantly different, as determined by Tukey's test ($p < 0.05$).

TABLE 3 Tomato fruit quality traits as affected by water content (100%WC and 50%WC) and biostimulant application (C, D1, and D2).

Source of variance	TSS (°Brix)	pH	Titratable acidity (g CA 100 mL^{-1})	Maturity Index	Total sugar content (mg glucose ml^{-1})	Lycopene (mg 100 g^{-1})	TPC (mg AGE 100 g^{-1})	DPPH IC_{50} (mg ml^{-1})
Water content								
100%WC	5.33±0.16	4.09±0.01	0.50±0.02b	12.0±0.01a	31.2±0.05b	7.47±0.01a	52.7±0.03	361±0.28b
50%WC	5.40±0.15	4.00±0.04	0.57±0.00a	10.2±0.01b	33.1±0.06a	7.06±0.01b	53.8±0.06	388±0.09a
Biostimulant								
C	5.34±0.18b	4.04±0.05	0.57±0.00a	9.88±0.02c	35.20±0.05a	6.70±0.01b	52.83±0.05	366±0.36b
D1	5.74±0.10a	4.00±0.04	0.54±0.03b	11.22±0.02b	28.20±0.10c	7.49±0.01a	52.10±0.11	390±0.24a
D2	5.02±0.14b	4.10±0.01	0.50±0.03c	12.19±0.04a	32.93±0.17b	7.61±0.02a	54.82±0.16	368±0.69b
Significance								
WC	ns	ns	***	***	**	**	ns	*
B	***	ns	***	***	***	***	ns	**
WC × B	***	ns	***	ns	***	**	**	**

Values are mean ± SE. Asterisks indicate significant effects of water content (WC), biostimulant treatment (B), and their interaction (WC × B) according to ANOVA. ns, not significant; * = $p < 0.05$; ** = $p < 0.01$; *** = $p < 0.001$. Within each factor, different letters indicate significant differences based on Tukey's test (p<0.05). IC_{50} = extract concentration required to scavenge 50% of the initial DPPH radical.

fruit yield even compared to well-irrigated plants. Similarly, Qin and Leskovar (2020) reported increases in root and leaf biomass in horticultural crops treated with humic acid-based products. Consistent with previous research (Parkash and Singh, 2020; Campobenedetto et al., 2021b), we observed that drought significantly reduced biomass, showing a marked decrease in total and shoot dry weight in stressed plants compared to those grown under optimal conditions. However, this effect was mitigated in biostimulant-treated plants, likely due to improved root growth and soil exploration, which enhanced water and nutrient uptake (Rouphael and Colla, 2020). Cai et al. (2013) also demonstrated that algal extracts stimulate plant growth regulation and foliar application and can consequently accelerate their absorption in plants via stomata faster than root absorption (Quintarelli et al., 2025).

Mannino et al. (2020) observed that application of biostimulants derived from algae extracts and yeast accelerated fruit ripening, and determined higher yield and larger fruit size, thus increasing the commercial value of tomato fruits.

The positive effects observed on tomato plants can be directly related to the chemical composition of the biostimulants, particularly those based on brown seaweed and yeast extracts, which are rich in polyphenols, flavonoids, carotenoids, and other antioxidant compounds capable of modulating plant stress responses (Campobenedetto et al., 2021a).

Sugars and acids play a key role in shaping the flavor profile of tomato fruits. Tomatoes with low acidity and high sugar content can be perceived as overly sweet and lacking complexity, while those with high acidity contribute to a more tangy and palatable taste profile

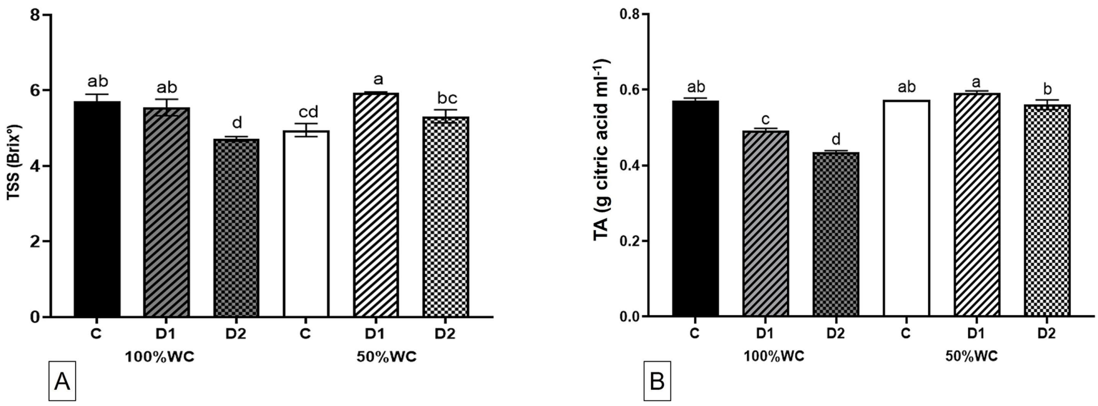

FIGURE 4
Interaction effects of water content and biostimulant application on the total soluble solids (°Brix) **(A)** and the titratable acidity (g citric acid per ml tomato juice) **(B)** of tomato fruits.

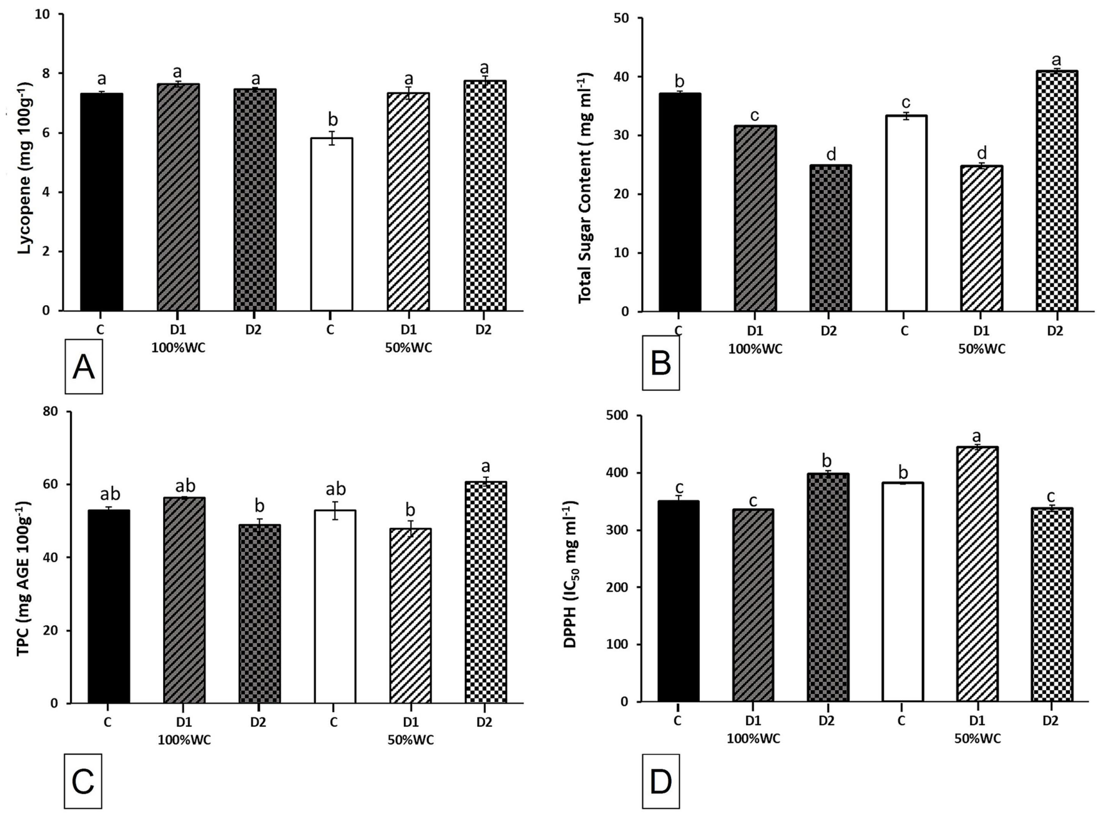

FIGURE 5
Interaction effects of water content and biostimulant application on the lycopene content (mg per 100 g of tomato) **(A)**, total sugar content (mg of glucose per ml of tomato juice) **(B)**, total phenolic content (mg gallic acid equivalent per 100 g of tomato) **(C)**, and radical scavenging ability as IC_{50} **(D)** of tomato fruits.

(Casals et al., 2018). Moreover, reduced titratable acidity (TA) has been linked to blandness and diminished flavor intensity (Bapary et al., 2024). Therefore, an optimal balance between sweetness and acidity is crucial for ensuring tomato quality and consumer acceptance.

In the present study, fruits from biostimulant-treated plants under full irrigation showed reduced sugar content and total acidity compared to untreated controls. This reduction was likely due to a dilution effect, as fruits from D1 100%WC and D2 100%WC exhibited higher moisture percentages than those from C 100%WC (data not shown). Similarly, Liava et al. (2023) reported that biostimulant application under regular irrigation significantly increased fruit moisture content relative to the control. This phenomenon occurs because, under optimal irrigation, biostimulants promote water accumulation in fruits while favoring carbohydrate allocation to vegetative tissues rather than fruit development (Liava et al., 2023). As a result, although biostimulants enhance vegetative growth under full irrigation, they do not typically lead to a proportional increase in fruit sugar concentration (Liava et al., 2023), as observed in this study. Consistent with our findings, Patanè et al. (2025) reported that biostimulant application negatively affected total solids, titratable acidity, and reducing sugars in greenhouse-grown tomatoes

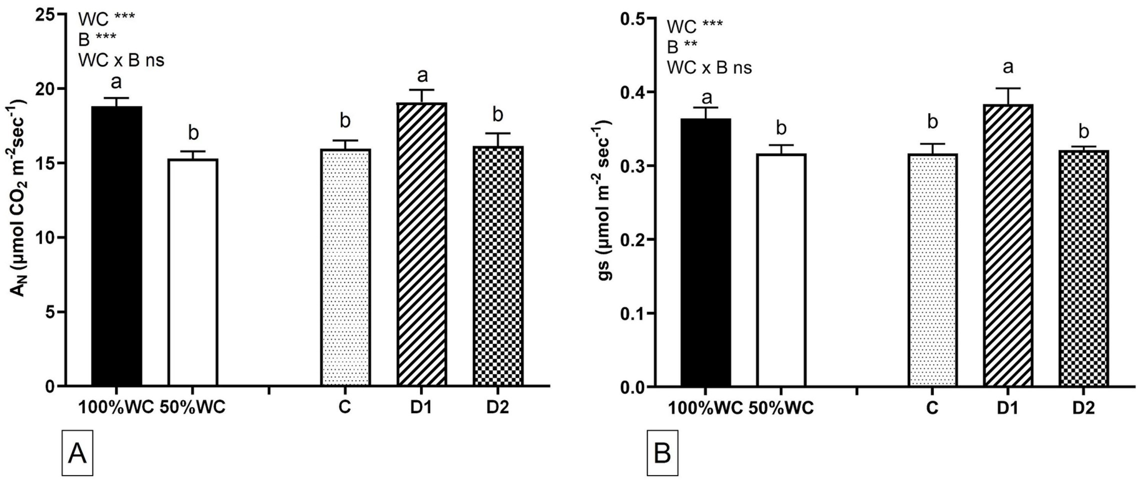

FIGURE 6
Mean effects of water content and biostimulant doses on net photosynthesis **(A)** and stomatal conductance **(B)** of tomato leaves. Different letters indicate significant differences according to Tukey's test ($p < 0.05$). The values are means of three replicates. Vertical bars indicate mean ± SE.

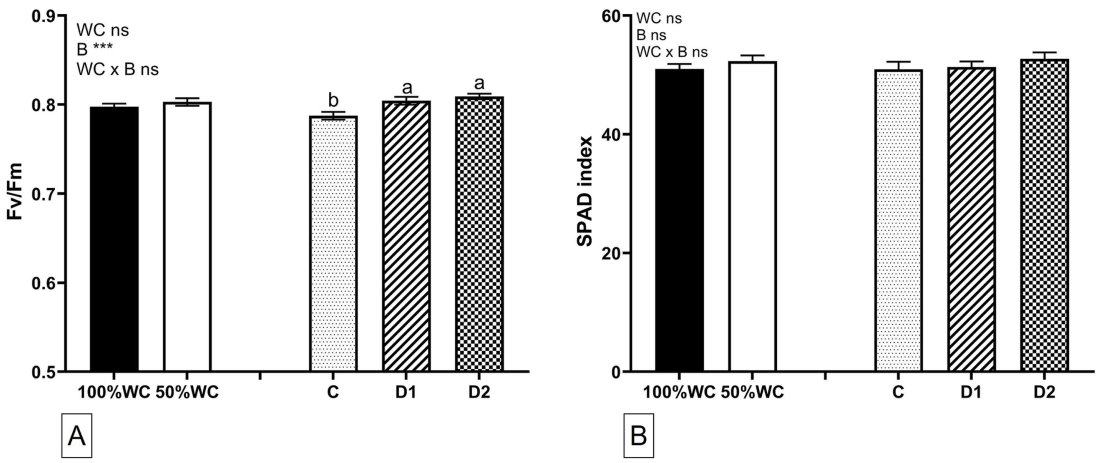

FIGURE 7
Mean effects of water content and biostimulant doses on Fv/Fm **(A)** and SPAD index **(B)** of tomato leaves. Different letters indicate significant differences according to Tukey's test ($p < 0.05$). The values are means of three replicates. Vertical bars indicate mean ± SE.

under regular irrigation. In contrast, other studies have reported no significant effects of biostimulants on total solids or acidity in greenhouse-grown tomatoes (Rouphael et al., 2017; Colla et al., 2017).

Regarding plants cultivated under water stress, our results demonstrated that biostimulant application enhanced fruit quality. These findings align with those of Liava et al. (2023), who reported an increase in total sugar content in tomatoes treated with biostimulants under water-deficit conditions. Similarly, other studies have documented an increase in soluble solids (TSS) resulting from the application of biostimulants to plants subjected to limited irrigation (Ahmed et al., 2022; Villa e Vila et al., 2023). Under water stress conditions, biostimulants are known to enhance photosynthetic efficiency and promote the flow of carbon towards osmoprotectant metabolites, such as sugars (Jin et al., 2022). However, our findings indicate a dose-dependent effect, with the lowest dose (D1) negatively affecting fruit sugar content compared to the control samples (C 50%WC). At both D1 and D2 doses, biostimulants positively influenced photosynthetic activity and stomatal conductance (Figure 7), with no significant differences between the two. However, at the D1 dose, carbohydrates were primarily allocated to vegetative tissues, rather than to fruits. Additionally, the total phenolic content (TPC, Figure 5C) was lower than that of the control, suggesting that the sub-optimal dose did not fully activate the stress-defense priming response necessary for the synthesis of secondary metabolites. Conversely, the highest dose not only sustained vegetative growth but also activated the production and accumulation of osmolites (sugars) in the fruits, along with the synthesis of secondary metabolites (phenolics), which serve as a defense mechanism against oxidative damage.

These findings suggest that, at a sub-optimal dose, biostimulants may interfere with the plant's endogenous water-stress signaling, weakening the adaptive response in terms of quality metabolite accumulation, and reveal the critical importance of optimizing the biostimulant concentration. Patanè et al. (2025) similarly reported no effect—or even a negative effect—of biostimulant application on total soluble solids (TSS) under certain conditions. The Authors attributed this outcome to reduced efficacy at non-optimal doses and suggested that a higher dose could provide a solution. This aligns with our findings, suggesting that dose optimization is critical, as a sub-optimal dose (D1) may reduce biostimulant efficacy.

Under optimal water conditions, treatment with biostimulants did not produce statistically significant changes in the levels of bioactive

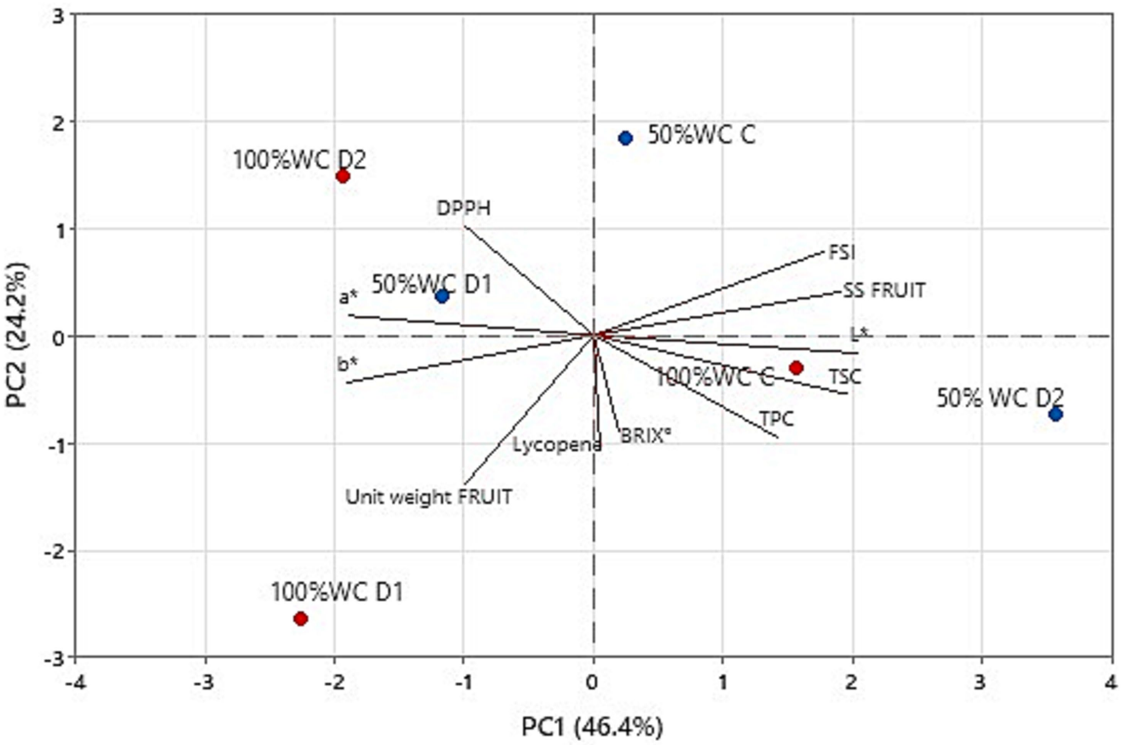

FIGURE 8
Principal component loading and score plot of principal component analysis (PCA) of quality traits of tomato in relation to water content and biostimulant doses.

compounds (lycopene and total phenolics). However, under water stress conditions, a statistically significant increase in lycopene content was observed in the fruits from treated plants compared to the control, with no differences based on the applied dose. In contrast, the biostimulant dose had a significant effect on total phenolic compounds (TPC) due to the previously mentioned sub-optimal dose.

In terms of antioxidant activity, assessed through radical scavenging capacity and expressed as IC_{50} values, the application of biostimulants, under both optimal irrigation and water-stress conditions, did not lead to any enhancement and, in some cases, even resulted in reduced activity. However, the trend in antioxidant activity among all samples correlated with the TPC trend. In particular, the lowest IC_{50} values were observed in samples that showed the highest TPC. This indicates that phenolic compounds primarily contributed to the scavenging activity of tomato fruits, while other metabolites likely played a secondary and complementary role.

Biostimulants containing plant-derived amino acids and lignin derivatives have also been shown to enhance plant tolerance to abiotic stress by activating the antioxidant machinery, as demonstrated by the up-regulation of ROS-scavenging enzymes and the strong reduction of hydrogen peroxide levels under heat stress (Campobenedetto et al., 2020).

Literature data on the effects of water deficit and/or biostimulant treatments on bioactive compounds of tomato fruits are rather inconsistent. Patanè et al. (2025) reported higher lycopene levels under optimal soil water conditions as well as under biostimulant treatment; they also found a higher antioxidant activity in fruits subjected to prolonged soil water deficit. Moreover, Liava et al. (2023) observed a reduction of lycopene and TPC in fruits from well-watered biostimulant-treated plants. In contrast, Mannino et al. (2020) found no differences in TPC, lycopene, and β-carotene contents in fruits from biostimulant-treated tomato plants, although they did report an enhancement in scavenging activity. In our study, the higher water content observed in the fruits from biostimulant-treated plants under optimal water conditions, compared to the control plants, may have diluted the concentration of bioactive compounds, potentially masking any positive effects of biostimulants on their biosynthesis.

Regarding the trend of bioactive compound accumulation in the fruits from biostimulant-treated plants under water stress conditions, previous studies have shown that mild water stress (Riggi et al., 2008) or the application of seaweed-based biostimulants (Mannino et al., 2020) increases the content of lycopene and β-carotene compared to well-irrigated plants. Liava et al. (2023) observed higher lycopene and lower TPC in fruits from water-stressed biostimulant-treated plants.

Photosynthetic activity was significantly reduced in plants subjected to water stress; however, the application of biostimulants at the lowest concentration led to increases in both photosynthetic activity and stomatal conductance. In fact, when plants are exposed to drought conditions, transpiration decreases due to stomatal closure, which prevents water loss from leaves and stems but also restricts CO_2 uptake, thereby reducing photosynthetic efficiency (Ahluwalia et al., 2021; dos Santos et al., 2022). It has been reported that protein-derived biostimulants can induce metabolic changes in plants, enhancing photosynthetic performance even under abiotic stress conditions (Francesca et al., 2020). The treatments with *Ascophyllum nodosum* extract on broccoli (Kałuzewicz et al., 2017) and spinach (Xu and Leskovar, 2015) have been shown to improve gas exchange by reducing stomatal closure and thereby increasing resistance to water stress. The improvement in photosynthesis, stomatal conductance, and antioxidant-related traits observed in treated plants can be explained by the combined action of hormone-like compounds from *Ecklonia maxima* and stress mitigating amino acids and

ATCA supplied by Drin On, which promote osmotic adjustment, redox homeostasis, and metabolic recovery under drought conditions.

Chlorophyll *a* fluorescence is widely used for monitoring photosynthetic performance in plants. In this study, the chlorophyll *a* fluorescence (Fv/Fm) in tomato was significantly increased with biostimulant application. This suggests that the efficiency of excitation energy captured by open PSII centers was increased, while the proportion of excitation energy (dissipation as heat) in the PSII antennae was relatively decreased. These findings are in agreement with Zhu et al. (2016), who suggested that a greater number of PSII reaction centers were open in biostimulant-applied plants, thereby allowing more excitation energy to be used for electron transport under drought.

Our results showed that water content and biostimulant combinations strongly influence tomato fruit quality characteristics, as evidenced by their separation in PCA space. Similar findings have been reported by Rouphael et al. (2017), who observed that biostimulant applications changed fruit biochemical traits under suboptimal conditions. Furthermore, research by Colla et al. (2017) and Bulgari et al. (2019) underlined that biostimulants not only enhance yield but also positively affect antioxidant compounds and soluble solids content in tomato fruits, especially under water-limited conditions. These results confirm that both water availability and biostimulant doses are important factors determining the metabolic profile and nutritional quality of tomato, reinforcing the potential of biostimulants as a sustainable tool in stress mitigation strategies.

Actually, the effects of biostimulant treatment on fruit quality traits are influenced by several factors, including the composition of the biostimulant, the method and dosage of application, crop species and variety, whether the cultivation occurs in open fields or greenhouses, and the presence and severity of abiotic stresses. These numerous variables make it difficult to compare results across different studies.

The effects of the biostimulant were clearly dose-dependent, with each dose promoting distinct functional responses. The lower dose (D1) proved most effective in enhancing physiological performance under drought, as shown by the highest increases in photosynthetic rate, stomatal conductance, total soluble solids, and titratable acidity. Conversely, the higher dose (D2) was more successful in mitigating drought-induced yield reductions, improving root–shoot allocation, and maximizing total phenolic content and antioxidant activity. Taken together, these results indicate that D1 predominantly supports short-term physiological adjustment to water deficit, whereas D2 more strongly reinforces structural and biochemical traits related to long-term drought resilience.

Overall, these findings confirm that the effectiveness of the tested biostimulants on tomato performance is strictly dependent on their bioactive composition, particularly on the presence of antioxidant molecules, hormone-like compounds, and amino acid fractions capable of sustaining photosynthesis, osmotic adjustment, and oxidative stress control under adverse environmental conditions.

5 Conclusion

This study demonstrates that foliar application of the two commercial biostimulants Algaren Twin and Drin On effectively mitigates drought-induced stress in tomato plants by enhancing photosynthetic activity, stomatal regulation, and plant growth. Drought stress significantly reduced biomass, yield, and fruit quality, while biostimulants alleviated these negative effects. Under water stress conditions, biostimulant application improved marketable yield and enhanced lycopene content.

The observed responses can be mechanistically explained by the complementary action of the bioactive components of the two products. Hormone-like compounds derived from the brown seaweed *Ecklonia maxima* stimulated root development, flowering, and carbon assimilation, whereas free amino acids and N-acetyl-thiazolidine-4-carboxylic acid (ATCA) supplied by Drin On contributed to osmotic adjustment, redox homeostasis, and metabolic recovery under drought stress.

Photosynthetic performance and chlorophyll fluorescence were enhanced in treated plants, indicating an improved physiological capacity to cope with drought stress. Effects on sugar content, antioxidant activity, and total phenolic content were dose-dependent. In particular, D1 was more effective in enhancing photosynthetic performance and acidity-related traits, whereas D2 better mitigated drought-induced yield loss and promoted higher total phenolic content and antioxidant activity. These findings underscore the complementary nature of the two doses and highlight the importance of optimizing both biostimulant dosage and water regime.

Although biostimulants exhibit great potential for enhancing crop resilience, their effectiveness varies depending on environmental conditions, dosage, and composition. The combined use of seaweed- and amino acid–based biostimulants represents a promising and sustainable strategy to improve drought resilience and fruit quality in greenhouse tomato production. However, further research is needed to refine their use and to develop tailored application protocols for sustainable tomato production.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

ST: Methodology, Validation, Visualization, Writing – original draft, Writing – review & editing, Conceptualization, Software. AM: Formal analysis, Investigation, Writing – original draft. TLM: Formal analysis, Investigation, Writing – original draft. FrC: Formal analysis, Investigation, Writing – original draft. MM: Validation, Visualization, Writing – original draft, Writing – review & editing. FaC: Software, Validation, Writing – original draft. CC: Formal analysis, Investigation, Methodology, Validation, Visualization, Writing – original draft, Writing – review & editing. FG: Conceptualization, Methodology, Validation, Visualization, Writing – original draft, Writing – review & editing.

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Conflict of interest

The author(s) declared that this work was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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