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Physiological, Yield, and Fruit Quality Responses of Tomato to Irradiated Carrageenan under Drought Stress

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Abstract

This study evaluates the effects of Irradiated Carrageenan Biostimulant (ICB) on fruit yield, quality attributes, biomass allocation, and nutrient assimilation in the commercial tomato hybrid *Diamante Max F1* under varying levels of water stress. The experiment, conducted under greenhouse conditions in Los Baños, Laguna, Philippines, included five treatments: T1 – moderate (partial) drought with ICB foliar spray (PD + S), T2 – moderate (partial) drought without ICB (PD + US), T3 – severe drought with ICB (SD + S), T4 – severe drought without ICB (SD + US), and T5 – a fully irrigated, unsprayed control (WW + US). Results revealed significant main and interaction effects of water deficit and ICB on multiple plant indicators. Among the treatments, T2 (PD + S) resulted in the highest total dry biomass. Nutrient uptake, specifically nitrogen (N), phosphorus (P), and potassium (K), showed marked improvement under T1. Drought stress led to an increased root-to-shoot ratio, indicating adaptive allocation toward root development. Yield traits including fruit count, weight, length, and diameter peaked in the PD + S treatment. Furthermore, ICB application enhanced fruit quality parameters such as total soluble solids and titratable acidity particularly under partial drought. These findings suggest that foliar application of ICB under moderate water stress can improve tomato productivity, nutrient uptake, and fruit quality, indicating its potential as a viable biostimulant for drought-resilient tomato cultivation.

Keywords: Biostimulant, Dry matter partitioning, Fruit quality, Irradiated carrageenan, Nutrient uptake, Tomato yield

1. Introduction

Tomato (*Solanum lycopersicum* L.) is a nutritionally important crop valued for its antioxidant content, particularly lycopene, as well as essential vitamins and minerals associated with reduced risks of cardiovascular diseases and certain cancers. However, tomato production in tropical regions such as the Philippines is increasingly constrained by climate change, particularly reduced rainfall and elevated temperatures [1]. Water deficit during critical phenological stages, especially flowering and fruit development, markedly limits tomato productivity, with yield loss strongly dependent on drought severity. Mild drought stress restricts cell expansion and fruit enlargement, leading to reduced fruit size and marketable yield, with losses reported to exceed 50% [2]. Moderate drought further suppresses photosynthetic efficiency and assimilates translocation, resulting in fewer and lighter fruits, while severe drought induces pronounced physiological dysfunction, including stomatal closure, chlorophyll degradation, oxidative stress, and flower and fruit abortion, culminating in drastic yield reductions. These responses are closely linked to alterations in plant water status, chlorophyll content, and physiological and spectral indicators commonly used to characterize water stress in tomato.

Conventional management of drought stress often relies on intensive use of synthetic agrochemicals, which raises concerns regarding environmental sustainability and human health [3]. Consequently, there is growing interest in eco-friendly alternatives such as plant biostimulants. Irradiated carrageenan, a seaweed-derived sulfated

polysaccharide produced through controlled irradiation, has gained attention due to its enhanced bioactivity and reduced molecular weight, which improve its absorption and signaling efficiency in plants [4,5]. Previous studies have shown that irradiated carrageenan can stimulate root and shoot growth, enhance nutrient uptake, improve photosynthetic performance, and activate antioxidant and stress-responsive pathways, thereby increasing plant tolerance to abiotic stresses. These effects are attributed to its polysaccharide structure, sulfate groups, and ability to modulate hormonal balance, carbon assimilation, and nutrient transport.

Despite its reported benefits in other crops, information on the physiological, yield, and fruit quality responses of tomato to irradiated carrageenan under varying levels of water deficit remains limited [6]. Therefore, the objective of this study was to evaluate the potential of irradiated carrageenan as a sustainable biostimulant to mitigate drought stress while reducing dependence on synthetic agrochemicals. We hypothesized that irradiated carrageenan application would enhance physiological performance, nutrient uptake, biomass partitioning, fruit quality, and yield of tomato plants subjected to mild, moderate, and severe water deficit conditions.

2. Materials and Methods

2.1 Experimental site and tomato genotype

The study was conducted from July to October 2022 at the Plant Tissue Culture Facility (PTCF) screen house, Institute of Crop Science, University of the Philippines Los Baños. The tomato hybrid ‘Diamante Max F1’ was used. Irradiated carrageenan biostimulant (ICB) was obtained as a commercial formulation (Vitalgro Carrageenan Foliar Fertilizer, Vitalgro C-PGP), developed by the Philippine Nuclear Research Institute and distributed by VVZ Corporation Inc. Seeds were pre-soaked in an aqueous ICB solution at a concentration of 1 g L⁻¹, consistent with the manufacturer’s specification, and germinated in seedling trays containing a mixture of carbonized rice hull, cocopeat, and garden soil. The trays were maintained under shaded conditions with adequate moisture. One week prior to transplanting, seedlings were fertilized with a urea solution at a rate equivalent to 7.5 g L⁻¹ of water to promote early seedling growth. Transplanting into individual polyethylene bags was done 31 days after sowing, following a hardening period.

2.2 Drought induction and treatment application

Water stress was imposed based on percent pot water-holding capacity (PWHC) following a modified method from [7]. Partial drought represented moderate drought stress, while severe drought represented high-intensity stress. Treatments were consistently designated as follows: T1 – moderate (partial) drought, unsprayed (PD + US); T2 – moderate (partial) drought, ICB-sprayed (PD + S); T3 – severe drought, unsprayed (SD + US); T4 – severe drought, ICB-sprayed (SD + S); and T5 – well-watered control, unsprayed (WW + US). The experiment was laid out using a Completely Randomized Design (CRD) with five replications per treatment. Percent pot water-holding capacity was determined gravimetrically by saturating the dried growth medium, allowing drainage for 3 h, and recording weight gain. Irrigation levels were set at 60% PWHC (control), 30% PWHC (partial drought), and 15% PWHC (severe drought). Target moisture levels were maintained by daily pot weighing and water replenishment to the assigned PWHC. The irradiated carrageenan biostimulant was applied at the recommended seasonal rate of 9 L ha⁻¹, diluted at 300 mL per 16 L of water, and administered biweekly from 30 days after transplanting until the final fruit harvest (approximately 8 weeks of application).

2.3 Crop establishment and cultural management

Fertilizers were applied following the standard recommendation of 90 kg N ha⁻¹, 120 kg P₂O₅ ha⁻¹, and 60 kg K₂O ha⁻¹ [9]. A complete fertilizer (14-14-14) was used as a basal dose. At 14 days after transplanting (DAT), urea (46-0-0) and muriate of potash (0-0-60) were applied, with remaining nitrogen and potassium split between 30 and 55 DAT. Manual weeding was carried out as needed. Plants were staked using trellises to support vegetative growth. Biopesticides derived from chili and garlic were applied only when pest pressure warranted intervention to avoid interfering with ICB effects. [10]

2.4 Sampling and data gathering

2.4.1 Growth parameters

Total plant dry weight. It was determined 60 days after transplanting (DAT), corresponding to the fruit maturity stage. Five plants per replicate were randomly selected and harvested. Plants were carefully cleaned to remove adhering soil, then oven-dried at 70 °C for 72 hours and weighed using an analytical balance.

Dry matter partitioning. At 60 DAT, the dried plant samples were separated into roots, stems, leaves, flowers, and fruits. The oven-dry weight of each organ was recorded. Dry matter partitioning was expressed as partitioning coefficients (PC), calculated using the formula:

$$PC = \frac{\text{oven dry weight of organ}}{\text{total dry weight of plant}}$$

Nutrient uptake. Nutrient uptake was assessed at final harvest (60 DAT). Five randomly selected plants per treatment were analyzed for nitrogen (N), phosphorus (P), and potassium (K) content at DA-STIARC, Lipa City, Batangas. Nutrient uptake was calculated as:

$$\text{Nutrient uptake (kg/ha)} = \text{Total dry matter (kg/ha)} \times \text{nutrient content in plant (kg/kg)}$$

Root-to-shoot ratio. Root and shoot portions were separated at 60 DAT, oven-dried at 70 °C for 72 hours and weighed. The root-to-shoot ratio was computed as:

$$\text{Root/shoot ratio} = \frac{\text{oven dry weight of root}}{\text{oven dry weight of shoot}}$$

2.4.2 Yield components

Individual fruit weight. Individual fruit weight was measured at each harvest using a digital scale. Fruits were collected at 60, 67, and 74 days after transplanting (DAT), corresponding to the first, second, and third harvests, respectively.

Fruit size. At each harvest (60, 67, and 74 DAT), fruit length and diameter were measured using a digital caliper. Measurements were taken from marketable fruits only.

2.4.3 Fruit yield

Marketable yield (kg m⁻²). Marketable yield was determined as the cumulative fresh weight of ripe red, undamaged fruits harvested at weekly intervals from 60 DAT until 74 DAT (three harvests). Yield was expressed on an area basis (kg m⁻²).

Total number of marketable fruits per plant. The total number of marketable fruits per plant was obtained by counting all unblemished fruits harvested from each plant across the three weekly harvests (60, 67, and 74 DAT) until termination of the experiment.

2.4.4 Fruit quality

Total Soluble Solids. The extracted tomato juice was filtered and measured using a digital refractometer (ATAGO PAL-α, Tokyo, Japan), and the °Brix values were recorded.

Titrateable Acidity. Titrateable acidity (TA), represented as a percentage of citric acid, was measured based on the procedure outlined by [10]. A 10 mL portion of tomato juice was titrated manually with 0.1 N NaOH until reaching a pH endpoint of 8.2, as monitored with a digital pH meter (LAQUA, Horiba, Japan). The volume of sodium hydroxide used was recorded, and acidity was computed as the percentage of citric acid relative to the juice volume using the appropriate formula:

$$\text{Titrateable Acidity (\%)} = \frac{\text{volume of NaOH (mL)} \times \text{acid factor} \times 100}{\text{Volume of juice (mL)}} (1) * (\text{Factor of citric acid} = 0.0064 \text{ meq})$$

TSS to TA ratio. The TSS:TA ratio was calculated as the ratio of total soluble solids (°Brix) to titrateable acidity (% citric acid).

Fruit juice pH. A 10 mL juice aliquot was mixed with an equal volume of distilled water and measured using a calibrated pH meter (LAQUA, Horiba, Japan).

3. Results and discussion

3.1 Effects on growth indicators

Total plant dry weight. Variations in plant dry mass often reflect responses to environmental and management factors. [11]. In this study, total dry biomass was significantly influenced by water availability, ICB application, and their interaction (Figure 1). Among the treatments, T2 (PD + S) recorded the highest dry weight accumulation, exceeding even the well-watered control (T5, WW + US). This indicates that the application of ICB under moderate water stress enhanced biomass production more effectively than non-stress conditions without biostimulant application.

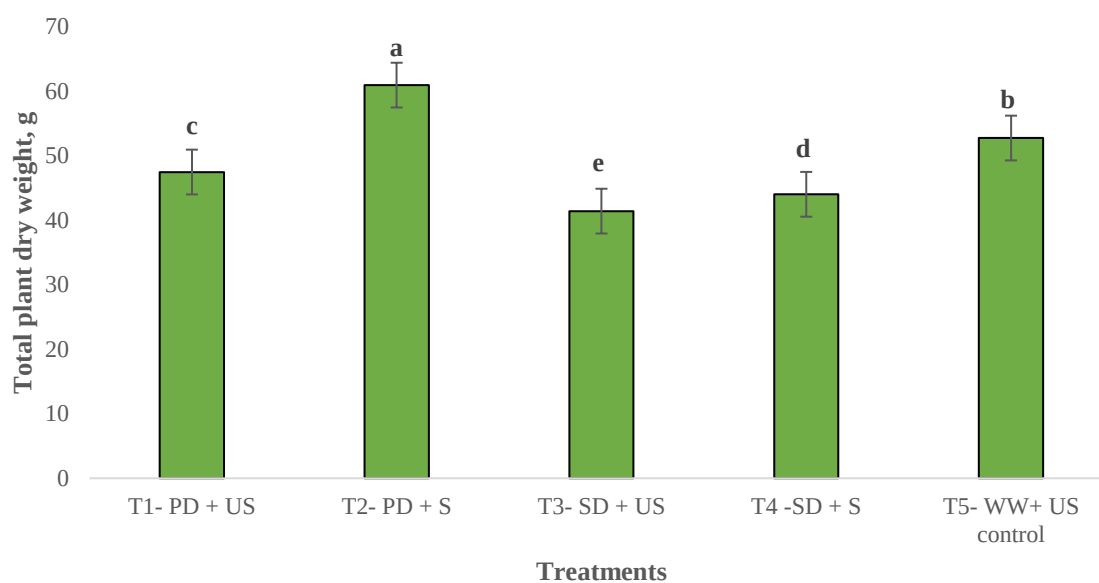


Figure 1 Total dry weight of tomato plants as affected by Irradiated Carrageenan Biostimulant and drought treatments.

Values with the same letters are not significantly different at $\alpha = 5\%$ using Tukey's HSD. Treatments: T1-Partial Drought + Unsprayed, T2-Partial Drought + Sprayed, T3- Severe Drought + Unsprayed, T4-Severe Drought + Sprayed, T5- Control: Well Watered + Unsprayed. CV= 7.88%

This finding aligns with previous studies demonstrating the positive influence of irradiated oligo-carrageenan on plant growth. For instance, [13] reported improved biomass in tobacco following oligo-carrageenan application, while [14] observed significant increases in both fresh and dry weights of peppermint (*Mentha piperita* L.) when treated with 80 ppm irradiated carrageenan, attributing the improvement to enhanced metabolic activity, nutrient assimilation, and cellular proliferation.

Dry matter partitioning coefficient. The distribution of dry matter among plant organs, as measured by the partitioning coefficient (PC), provides information into how plants adapt resource allocation under stress. As shown in Figure 2, stems accumulated the greatest proportion of dry mass across treatments by 60 days after transplanting (DAT), followed sequentially by leaves, roots, fruits, and flowers. This pattern indicates a physiological prioritization toward supporting structures under experimental conditions.

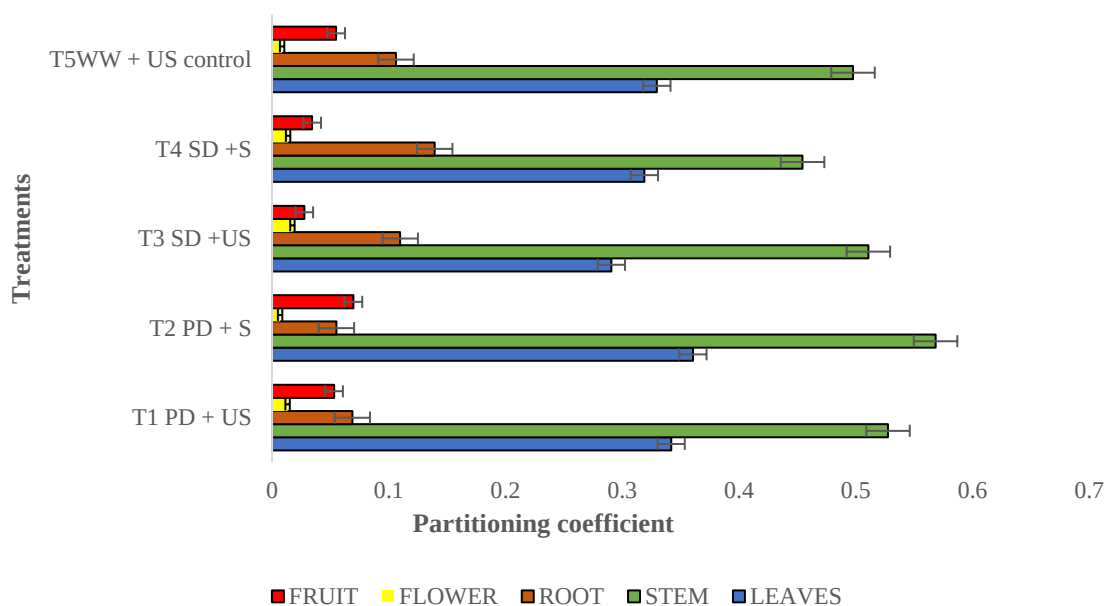


Figure 2 Dry matter partitioning of tomato as affected by Irradiated Carrageenan Biostimulant and drought treatments at 60 DAT (fruit maturity stage).

Treatments: T1-Partial Drought + Unsprayed, T2- Partial Drought + Sprayed, T3- Severe Drought + Unsprayed, T4-Severe Drought + Sprayed, T5- Control: Well Watered + Unsprayed. CV= 12.54%

Severe drought stress reduced the proportion of dry matter allocated to leaves (Figure 2), which is consistent with reports that water deficit impairs photosynthetic efficiency and limits leaf expansion in tomato [13]. Interestingly, T2 (partial drought + sprayed) showed the highest partitioning coefficient (PC) in leaves, suggesting enhanced photosynthetic investment under moderate drought conditions when ICB was applied. In contrast, T3 (severe drought + unsprayed) exhibited elevated PC values in roots and flowers. Increased allocation to roots under severe drought likely reflects an adaptive response to enhance water acquisition, while greater allocation to flowers may indicate stress-induced acceleration of reproductive development, a common drought escape strategy [14]. However, the absence of ICB in this treatment was also associated with lower dry matter allocation to fruits, as confirmed by yield metrics presented in subsequent sections.

Nutrient uptake. Plants acquire essential elements primarily through root absorption from the soil, with foliar uptake providing a secondary pathway. In this study, total nutrient uptake specifically nitrogen (N), phosphorus (P), and potassium (K) was significantly influenced by the levels of drought stress, the application of irradiated carrageenan biostimulant and their interaction (Table 1). The T2 treatment (partial drought + ICB spray) demonstrated the highest uptake across all three nutrients, followed by the well-watered control (T5), the unsprayed partial drought treatment (T1), the sprayed severe drought treatment (T4), and the lowest uptake was observed under T3 (severe drought + unsprayed). Although biostimulants typically do not provide sufficient quantities of essential nutrients on their own, they can enhance a plant's physiological response under stress conditions, often by stimulating antioxidant mechanisms or improving root architecture [15]. As observed in this study, applying ICB under moderate drought conditions enhanced nutrient acquisition, suggesting improved nutrient use efficiency when coupled with appropriate fertilization practices [16].

Table 1 Nutrient uptake of tomato plants as affected by Irradiated Carrageenan Biostimulant and drought.

Treatment ¹	Nutrient uptake ²		
	N (kg ha ⁻¹) ³	P (kg ha ⁻¹) ³	K (kg ha ⁻¹) ³
T1 – PD + US	8.97 ± 1.01 ^c	2.47 ± 0.17 ^c	13.24 ± 1.16 ^c
T2 – PD + S	24.80 ± 2.78 ^a	7.55 ± 0.53 ^a	29.73 ± 2.61 ^a
T3 – SD + US	4.39 ± 0.49 ^e	1.20 ± 0.08 ^e	5.46 ± 0.48 ^e
T4 – SD + S	7.83 ± 0.88 ^d	1.54 ± 0.11 ^d	8.36 ± 0.73 ^d
T5 – WW + US (Control)	16.14 ± 1.81 ^b	4.11 ± 0.29 ^b	21.30 ± 1.87 ^b
CV (%) ⁴	11.21	6.98	8.76

¹ T1- Partial drought (30% Pot capacity) + Unsprayed, T2- Partial drought (30% Pot capacity) + Sprayed, T3- Severe drought (15% Pot capacity) + Unsprayed, T4- Severe drought (15% Pot capacity) + Sprayed, T5- Control: Well Watered (60% Pot capacity).

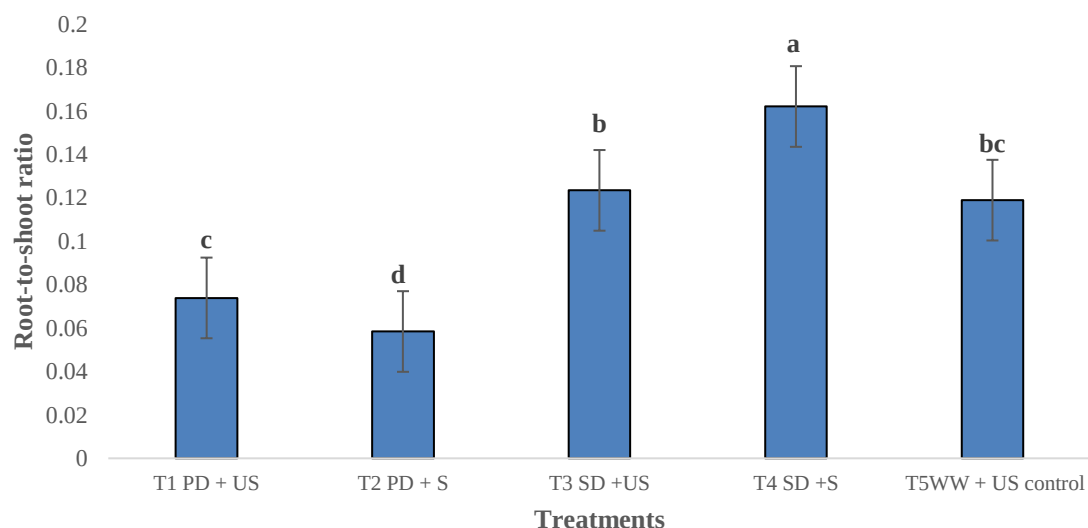
² For each growing period, means sharing the same letter for both main effects and interactions do not differ significantly, based on Tukey's HSD test at a 5% significance level ($\alpha = 0.05$).

³ N- Total nitrogen uptake, P total phosphorus uptake, K- total potassium uptake (kg ha⁻¹). Values are means ± standard deviation (SD).

⁴ Coefficient of Variance

These findings are aligned with previous research, where improved mineral uptake (e.g., magnesium, potassium, and calcium) was observed in lettuce treated with seaweed-based products [17], and similar effects were reported in grapevines and cucumbers [18]. Marine-derived biostimulants can enhance stomatal conductance and foliar absorption [19], as well as boost the uptake efficiency of mineral fertilizers applied to soil [20]. In contrast, the limited nutrient uptake in T3-severe drought with ICB (SD + S), may be attributed to impaired physiological processes due to severe water restriction. Previous studies suggest that alginate and carrageenan oligosaccharides derived from brown algae may regulate nitrogen metabolism and promote assimilation pathways [21], offering further support for the positive effects of ICB observed in this work.

Root-to-shoot ratio. The root-to-shoot (R:S) ratio is a critical indicator of plant adaptation to environmental stress and reflects the balance of carbon allocation between below-ground and above-ground tissues. Resource availability in both the rhizosphere (water, nutrients) and the atmosphere (light, CO₂) modulates this ratio during plant development [22]. As shown in Figure 3, the R:S ratio varied significantly across treatments. T4 (severe drought + ICB spray) exhibited the highest ratio, followed closely by T3 (severe drought + unsprayed), indicating enhanced investment in root biomass under severe water stress conditions. The well-watered control (T5) and T1 (partial drought + unsprayed) exhibited intermediate values, while T2 (partial drought + ICB spray) had the lowest R:S ratio.

**Figure 3** Root-to-shoot ratio of tomato plants at 60 DAT as affected by Irradiated Carrageenan Biostimulant and drought treatments

Values with the same letters are not significantly different at $\alpha = 5\%$ using Tukey's HSD. Treatments: T1-Partial Drought + Unsprayed, T2-Partial Drought + Sprayed, T3- Severe Drought + Unsprayed, T4-Severe Drought + Sprayed, T5- Control: Well Watered + Unsprayed. CV= 8.98%

The elevated ratio under drought-stressed treatments supports the hypothesis that plants under water deficit prioritize root development to maximize water uptake [23]. Interestingly, the relatively low R:S in T2, despite

being under partial drought, may reflect balanced growth enabled by ICB, which appears to mitigate drought stress and sustain shoot development alongside adequate root support

3.2. Effects on yield components

Number of fruits per plant. Drought intensity, ICB application, and their interaction significantly affected fruit number (Table 2). At 60 DAT, T2 (partial drought + ICB) produced the most fruits (13 fruits plant⁻¹), outperforming the control T5 (well-watered + unsprayed) with 10 fruits. T2 maintained the lead across all harvests, with ~30% more fruits than the control. In contrast, T3 (severe drought + unsprayed) had the fewest (6 fruits plant⁻¹), ~40% less than T5.

Table 2 Effects of Irradiated Carrageenan Biostimulant and drought on yield components of tomato subjected to drought stress

Treatement ¹	No. of fruits (plant ⁻¹)	Yield Components ²		
		1 st Harvest ³ Individual fruit fresh weight (g)	Fruit length (mm)	Fruit diameter (mm)
T1- PD + US	10.00 ± 1.89 ^b	22.68 ± 4.28 ^c	37.20 ± 7.03 ^b	32.30 ± 6.10 ^c
T2- PD + S	13.00 ± 2.46 ^a	27.97 ± 5.28 ^a	38.62 ± 7.30 ^a	35.64 ± 6.73 ^a
T3- SD + US	6.00 ± 1.13 ^d	19.26 ± 3.64 ^c	32.28 ± 6.10 ^c	31.12 ± 5.88 ^c
T4-SD + S	7.00 ± 1.32 ^c	21.93 ± 4.14 ^d	35.34 ± 6.68 ^c	31.86 ± 6.01 ^c
T5- WW+ US (Control)	10.00 ± 1.89 ^b	23.78 ± 4.49 ^b	37.18 ± 7.02 ^b	33.56 ± 6.34 ^b
CV (%) ⁴	18.89	12.67	14.54	17.51
		2 nd Harvest ³		
T1- PD + US	7.00 ± 0.86 ^b	19.44 ± 2.40 ^c	33.92 ± 4.18 ^c	31.48 ± 3.88 ^c
T2- PD + S	10.00 ± 1.23 ^a	26.02 ± 3.21 ^a	38.90 ± 4.80 ^a	35.94 ± 4.43 ^a
T3- SD + US	6.00 ± 0.74 ^c	15.82 ± 1.95 ^c	32.42 ± 4.00 ^c	28.88 ± 3.56 ^c
T4-SD + S	6.00 ± 0.74 ^c	20.25 ± 2.50 ^b	34.06 ± 4.20 ^b	32.01 ± 3.95 ^d
T5- WW+ US (Control)	10.00 ± 1.23 ^a	21.20 ± 2.61 ^b	36.66 ± 4.52 ^b	31.96 ± 3.94 ^b
CV (%) ⁴	12.33	19.55	17.92	22.84
		3 rd Harvest ³		
T1- PD + US	6.00 ± 1.01 ^c	22.26 ± 3.73 ^c	37.82 ± 6.34 ^c	32.20 ± 5.40 ^c
T2- PD + S	9.00 ± 1.51 ^a	29.43 ± 4.93 ^a	42.14 ± 7.06 ^a	37.48 ± 6.28 ^a
T3- SD + US	4.00 ± 0.67 ^d	14.14 ± 2.37 ^c	32.22 ± 5.40 ^c	27.36 ± 4.59 ^c
T4-SD + S	6.00 ± 1.01 ^c	20.33 ± 3.41 ^d	35.02 ± 5.87 ^d	32.10 ± 5.38 ^d
T5- WW+ US (Control)	8.00 ± 1.34 ^b	26.38 ± 4.42 ^b	38.38 ± 6.43 ^b	33.60 ± 5.63 ^b
CV (%) ⁴	16.76	12.55	21.56	16.98

¹ T1- Partial drought (30% Pot capacity) + Unsprayed, T2- Partial drought (30% Pot capacity) + Sprayed, T3- Severe drought (15% Pot capacity) + Unsprayed, T4- Severe drought (15% Pot capacity) + Sprayed, T5- Control: Well Watered (60% Pot capacity).

² For each growing period, means sharing the same letter for both main effects and interactions do not differ significantly, based on Tukey's HSD test at a 5% significance level ($\alpha = 0.05$).

³ Harvesting Periods'. Values are means ± standard deviation (SD).

⁴ Coefficient of Variance

Fruit fresh weight. Mean fruit weight was also significantly influenced. T2 (PD + S) consistently produced the heaviest fruits at all harvest stages, followed by T5 and T1. T3 (SD + US) had the lightest fruits, reflecting the negative impact of severe drought without biostimulant.

Fruit length. The longest fruits were recorded in T2 (PD + S) at 38.62 mm, followed closely by T5 and T1 (~37 mm). T3 (SD + US) again showed the shortest fruits (32.28 mm). T2 consistently produced the longest fruits across all harvests.

Fruit diameter. Drought and ICB treatments significantly influenced fruit diameter (Table 2, Figure 4). At initial harvest, T2 (Partial Drought + Sprayed) produced the widest fruits (35.64 mm), followed by T5, T1, T4, and T3 (Severe Drought + Unsprayed) with the smallest (31.12 mm). T2 consistently had the largest fruit diameters across all harvests (35.94 mm and 37.48 mm in the 2nd and 3rd), while T3 remained the lowest (28.88 mm and 27.36 mm). This shows ICB's role in maintaining fruit development under moderate drought.

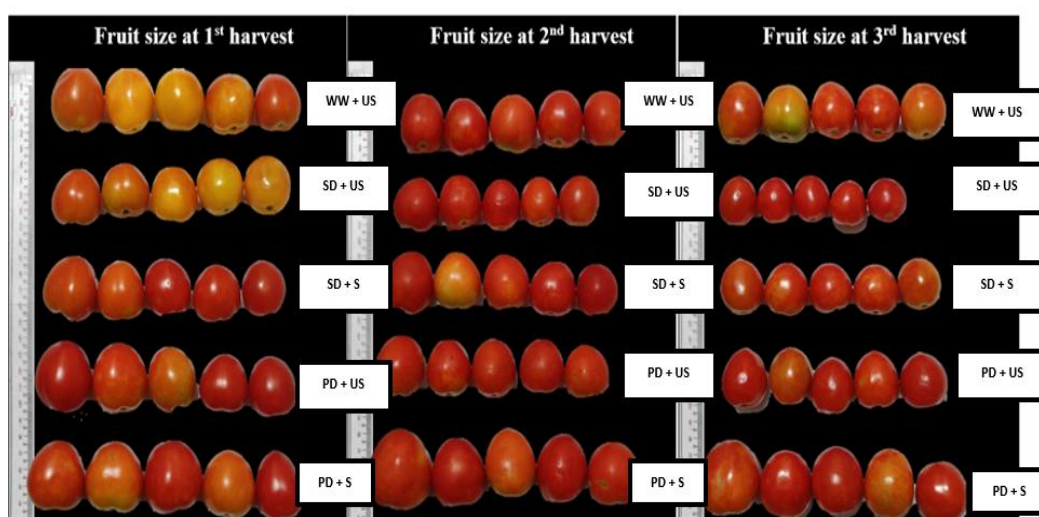


Figure 4 Fruit size of tomato from first to final harvest under drought and Irradiated Carrageenan Biostimulant treatments.

3.3. Effects on fruit yield

The most important aspect of crop production is to determine the effect of treatments on plant's yield and quality. The plants may grow vigorously during vegetative growth as a result of ICB treatment but failure to produce marketable yield would still be a failure in crop production.

Total marketable yield. Marketable yield (kg m^{-2}) was highest in T2 (0.14 kg m^{-2}), followed by T5 (0.12 kg m^{-2}), with T1 and T4 both at 0.11 kg m^{-2} . T3 again had the lowest yield (0.10 kg m^{-2}), highlighting the negative effect of severe drought without biostimulant support.

Total number of marketable fruits per plant. T2 also had the most marketable fruits (32 per plant), outperforming the control (28). T1, T4, and T3 followed with 23, 19, and 16 fruits, respectively. These improvements may be linked to the phytohormones and induced hormonal responses stimulated by seaweed-based biostimulants [24].

Table 3 Yield of tomato as affected by drought and Irradiated Carrageenan Biostimulant treatments.

Treatments ¹	Fruit Yield ² Total marketable yield (kg m^{-2})	Total number of marketable fruits (plant ⁻¹)
T1 (PD + US)	0.11 ± 0.01^c	23 ± 2.20^{bc}
T2 (PD + S)	0.14 ± 0.02^a	32 ± 3.06^a
T3 (SD + US)	0.10 ± 0.01^d	16 ± 1.53^d
T4 (SD + S)	0.11 ± 0.01^c	19 ± 1.81^c
T5 (WW + US): control	0.12 ± 0.02^{bc}	28 ± 2.68^b
CV (%) ³	12.65	9.56

¹ T1- Partial drought (30% Pot capacity) + Unsprayed, T2- Partial drought (30% Pot capacity) + Sprayed, T3- Severe drought (15% Pot capacity) + Unsprayed, T4- Severe drought (15% Pot capacity) + Sprayed, T5- Control: Well Watered (60% Pot capacity).

² Yield parameters, means sharing the same letter for both main effects and interactions do not differ significantly, based on Tukey's HSD test at a 5% significance level ($\alpha = 0.05$). Values are means $\pm$ standard deviation (SD).

³ Coefficient of Variance

3.4. Effects on fruit quality

Fruit quality is a key economic factor in crop production, with attributes like sweetness, acidity, and flavor influencing market value [8].

Total soluble solids. TSS indicates maturity and sweetness. At the first harvest, T2 (PD + S) had the highest TSS (5.25°Brix), followed by T1, T4, T3, and the lowest in T5 (3.97°Brix). TSS typically rises with ripening and is crucial for tomato flavor [25, 26]. Subsequent harvests showed no significant differences. High TSS is linked to improved carbohydrate metabolism and better shelf life [27, 28].

Titrateable acidity (TA). TA (% citric acid) significantly varied across treatments (Table 4). At the first harvest, T2 showed the highest acidity (0.73%), while T3 had the lowest (0.50%). In later harvests, T5 and T2 maintained high acidity ($\sim 0.9\%$), consistent with prior findings [29]. Higher TA is often observed in larger fruits, as seen in T2 and T5 [30].

TSS-to-TA ratio. The TSS:TA ratio, an important indicator of tomato flavor balance and eating quality, was influenced by drought stress and irradiated carrageenan biostimulant (ICB) application. Across harvests, drought-stressed treatments generally exhibited higher TSS:TA ratios than the well-watered control, indicating increased sweetness relative to acidity, likely due to stress-induced concentration of soluble sugars.

During the first and second harvests, severe drought treatments, particularly the unsprayed treatment (T3), recorded the highest TSS:TA ratios, while the control showed the lowest values, reflecting dilution effects under adequate water supply. By the third harvest, differences among treatments were less pronounced, although drought-stressed plants still tended to maintain slightly higher ratios than the control. ICB application under drought conditions moderated excessive increases in the TSS:TA ratio, suggesting a stabilizing effect on sugar–acid balance [31].

Table 4 Fruit quality of tomato as affected by drought and Irradiated Carrageenan Bisotimulant treatments.

Treatment ¹	Total soluble solids (°Brix)	Fruit quality ² Titratable acidity (%)	TSS-to-TA ratio	Fruit juice pH
1st Harvest³				
T1- PD + US	4.90 ± 0.44 ^{ab}	0.62 ± 0.05 ^{bc}	7.90 ± 0.67	4.12 ± 0.50
T2- PD + S	5.25 ± 0.47 ^a	0.73 ± 0.06 ^a	7.19 ± 0.61	4.14 ± 0.50
T3- SD + US	4.20 ± 0.38 ^{ab}	0.50 ± 0.04 ^d	8.40 ± 0.71	4.03 ± 0.49
T4 -SD + S	4.32 ± 0.39 ^{ab}	0.53 ± 0.04 ^c	8.15 ± 0.69	4.05 ± 0.49
T5- WW+ US (Control)	3.97 ± 0.35 ^b	0.65 ± 0.05 ^b	6.11 ± 0.52	4.23 ± 0.51
CV (%)	8.93	8.07	11.56	12.12
2nd Harvest³				
T1- PD + US	5.07 ± 1.11	0.81 ± 0.13 ^c	6.26 ± 1.19	4.10 ± 0.45
T2- PD + S	4.90 ± 1.07	0.87 ± 0.14 ^b	5.63 ± 1.07	4.23 ± 0.46
T3- SD + US	5.95 ± 1.30	0.74 ± 0.12 ^d	8.04 ± 1.53	4.00 ± 0.44
T4 -SD + S	6.07 ± 1.33	0.85 ± 0.14 ^b	7.14 ± 1.36	4.07 ± 0.44
T5- WW+ US (Control)	5.95 ± 1.30	0.97 ± 0.16 ^a	6.13 ± 1.17	4.10 ± 0.45
CV (%)	21.86	16.29	14.12	10.89
3rd Harvest³				
T1- PD + US	6.30 ± 0.81	0.84 ± 0.13 ^b	7.50 ± 1.05	4.20 ± 0.61
T2- PD + S	6.30 ± 0.81	0.85 ± 0.13 ^b	7.41 ± 1.04	4.60 ± 0.67
T3- SD + US	6.42 ± 0.83	0.77 ± 0.12 ^c	8.34 ± 1.17	4.00 ± 0.58
T4 -SD + S	6.30 ± 0.81	0.83 ± 0.13 ^b	7.59 ± 1.06	4.00 ± 0.58
T5- WW+ US (Control)	6.07 ± 0.78	0.89 ± 0.13 ^a	6.82 ± 0.95	4.10 ± 0.60
CV (%)	12.88	15.10	11.35	14.56

¹ T1- Partial drought (30% Pot capacity) + Unsprayed, T2- Partial drought (30% Pot capacity) + Sprayed, T3- Severe drought (15% Pot capacity) + Unsprayed, T4- Severe drought (15% Pot capacity) + Sprayed, T5- Control: Well Watered (60% Pot capacity).

² For each growing period, means sharing the same letter for both main effects and interactions do not differ significantly, based on Tukey's HSD test at a 5% significance level ($\alpha = 0.05$). Values are means ± standard deviation (SD).

³ Harvesting periods (DAT- Days after transplanting): 1st Harvest- 60 DAT, 2nd Harvest- 67 DAT, 3rd Harvest -74 DAT.

⁴ Coefficient of Variance

Fruit juice pH. pH levels ranged from 4.0 to 4.6. At first harvest, T5 had the highest pH (4.23), with T3 the lowest (4.03). In later harvests, T2 maintained the highest pH, suggesting better acid-sugar balance. These values fall within the typical tomato pH range [32, 33]. Overall, drought reduced fruit quality, but ICB application under partial drought (T2) improved TSS, TA, and pH balance indicators of flavor and shelf life. Seaweed-based biostimulants have been shown to boost sugar and acid synthesis and lycopene content, improving both sensory quality and economic value [34]. Without intervention, drought has the greatest impact on fruit quality. However, under partial drought, ICB appeared to mitigate stress effects, as fruit set remained comparable to or better than the control. According to [34], fruit quality traits in red-matured tomato fruits such as TSS, titratable acidity, and lycopene content were significantly influenced by seaweed-based biostimulants compared to untreated controls. The rise in TSS was linked to enhanced metabolic activity leading to greater synthesis of acids, metabolites, and sugars. Soluble solids, mainly sugars and organic acids, affect the sweetness, sourness, and flavor of tomatoes and their products. Similarly, previous studies have reported that lycopene levels responsible for the red coloration of ripe tomatoes can increase under seaweed-based biostimulant treatments, resulting in potential economic benefits. These effects have been attributed to natural polysaccharides such as cellulose and starch present in seaweed extracts, as well as sulfate groups (SO₄) and carbohydrates, which contribute to enhanced plant growth, yield, and fruit quality [35].

4. Conclusion

The interactions between drought stress and ICB treatments significantly affected plant growth, nutrient uptake, yield, and fruit quality. T2 (Partial Drought + Sprayed) showed the highest dry weight, nutrient uptake, and yield, while severe drought treatments (T3 and T4) had higher root-to-shoot ratios. Irradiated Carrageenan Biostimulants treatment also improved fruit quality, including total soluble solids and titratable acidity, especially under partial drought. These results suggest that ICB treatments can mitigate drought stress, enhancing tomato growth, yield, and fruit quality.

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6. Author Contributions

Fredelino E. Vecina Jr.: Conceptualization, Methodology, Investigation, Data curation, Formal analysis, Writing – original draft, Writing – review & editing, Visualization, Project administration.; Annalissa L. Aquino: Conceptualization, Methodology, Supervision, Validation, Writing – review & editing, Resources.; Hazel Anne F. Makahiya: Investigation, Data curation, Validation, Visualization, Writing – review & editing.

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