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Effects of Seaweed-Derived Biostimulants on Flowering, Fruit Ripening and Quality Attributes in Tomato

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Abstract

Tomato reproductive development is influenced by both environmental and genetic factors. Climate change modifies these factors, necessitating the development of tools to optimize reproductive processes. This study evaluated seaweed extracts from *Macrocystis* sp., *Lessoni*a sp., and *Ascophyllum nodosum* as biostimulants. The effects of these extracts on flowering, fruit set (the transition of flowers into fruit), and fruit ripening were assessed following foliar application at 0.25% w/v. A significant improvement in floral fertilization (successful pollination and fruit formation) was observed, with DuoAlgae resulting in a 100% increase compared to the control. Anisotropic growth was also recorded: Fertimar SC increased fruit length by 13.77% and the number of mature fruits by 130.41% relative to the control. Regarding fruit quality, chlorophyll content increased at the breaker stage (the initial stage of color change). At the red stage, elevated levels of NO3- (nitrate), K+ (potassium), TSS (total soluble solids), lycopene, and β-carotene were detected. Collectively, these results indicate that biostimulants modulate reproductive development and fruit quality, underscoring the potential of Peruvian algae to enhance crop productivity.

Keywords: tomato; seaweed extracts; *Macrocystis* sp.; *Lessoni*a sp.; *Ascophyllum nodosum*

1. Introduction

Tomato (*Solanum lycopersicum* L.) is the second-most-cultivated solanaceous crop worldwide. Production reached 181 million tons in 2021 [1,2]. Early reproductive and metabolic regulation during development determines yield and quality. Floral transition and inflorescence formation link environmental signals—photoperiod, temperature, and nutrition— to hormonal and gene networks. These processes balance vegetative and reproductive growth [3,4]. Source-sink balance determines final fruit number and growth.

Fruit ripening involves extensive metabolic reprogramming. This process defines sensory and nutraceutical properties [5,6]. Starch degrades, and soluble sugars accumulate. The metabolism of organic acids reorganizes, shaping the flavor profile. Chloroplasts convert to chromoplasts. This enables the biosynthesis of carotenoids—mainly lycopene and β-carotene—that determine color and antioxidant potential [7,8].

Mineral nutrition affects carbon partitioning, metabolic signaling, and fruit quality. For example, potassium mobilizes photoassimilates. This increases the levels of soluble solids, sugars, pigments, and other organic compounds. Meanwhile, excess nitrogen can disrupt the C/N balance, negatively impacting the transition from vegetative to reproductive growth [4–12]. However, mineral nutrition management alone is insufficient to optimize physiological processes during crop development, leading growers to seek complementary alternatives.

Biostimulants, especially seaweed extracts (SWE), enhance nutrient use efficiency, stress tolerance, and fruit quality. These benefits result from their bioactive compounds—phytohormones, polysaccharides, phenolic compounds, and signaling peptides—which act on plant metabolism. Specifically, these compounds increase the levels of carbohydrates and amino acids, such as proline, and activate immune system enzymes [13,14].

Recent evidence shows that SWEs modulate gene expression at the molecular level. For instance, the application of *A. nodosum* and *Sargassum* sp. upregulates key floral regulation genes—Single Flower Truss (SFT), Self-Pruning (SP), Jointless (J), Anantha (AN), Falsiflora (FA), and Constans-1 (CO)—leading to better flowering and fruiting in tomatoes [15]. In addition to floral regulation, *A. nodosum* extracts have been found to modulate genes associated with hormone biosynthesis, such as auxins (IAA), gibberellins (Ga2Ox), and cytokinins (IPT), thereby supporting vegetative growth [16]. Furthermore, transcriptomic studies demonstrate that *A. nodosum* extract (Stimplex) also modulates multiple metabolic pathways, including carbon fixation, hormone signal transduction, glutathione metabolism, and nutrient transport (K, Ca, P, and micronutrients), among others [17].

Although extensive research has been conducted, the mechanisms by which biostimulants influence fruit development and ripening remain unclear, thereby limiting the repeatability and scalability of agricultural applications. In particular, the ways in which seaweed-derived biostimulants modulate metabolic reprogramming and nutrient partitioning during fruit maturation are not well understood. Addressing this knowledge gap requires the use of well-characterized and reproducible model systems. The Micro-Tom tomato has re-emerged as a valuable model due to its short life cycle, sequenced genome, and the availability of numerous mutant lines [18–22]. This variety has been extensively utilized in studies of fruit development and ripening, carbohydrate metabolism, hormonal regulation and interactions, as well as Solanaceae genomics, among other research areas [23–25]. These attributes may facilitate elucidation of the mechanisms underlying biostimulant action.

In this context, we hypothesize that seaweed extracts from *Ascophyllum nodosum*, *Macrocystis* sp., and *Lessonia* sp. influence fruit development, ripening, yield and quality in the Micro-Tom tomato model. This study specifically evaluates their effects on key quality parameters. These include total soluble solids (TSS), nitrate and potassium content, and pigment accumulation (chlorophylls and carotenoids).

2. Materials and Methods

2.1. Plant Material

Seeds of *Solanum lycopersicum* var. Micro-Tom was sown at a depth of 1.5 cm in seedling trays containing PLUGMIX substrate (KLASSMAN), primarily composed of oligotrophic Sphagnum peat moss with silt, NPK mineral fertilizers, trace micronutrients, and a wetting agent. The substrate's pH was 6.0 ± 0.3, and electrical conductivity was 0.3–0.4 mS/cm, as specified by the manufacturer.

The trays were watered with deionized water (pH: 7.43; EC: 1.502 µS m^{-1}), then placed in the growth chamber of the Laboratorio de Fisiologia Molecular de Plantas del PIPS en Cereales y Granos Nativos, Universidad Nacional Agraria La Molina, where growing conditions were set at 22 °C, 12h light/12h dark photoperiod, light intensity of 150 µmol m^{-2} s^{-1} from LED lamps, and 55% relative humidity.

After four weeks, seedlings with 3 to 4 true leaves, uniform in size and undamaged, were selected. These selected plants—sixty in total—were then transplanted individually, one per pot, into pots (0.19 L, 8.5 cm diameter, 6.0 cm height) filled with PLUGMIX substrate.

2.2. Experimental Design

The experiment was conducted in the growth chamber of the of the Laboratorio de Fisiologia Molecular de Plantas del PIPS en Cereales y Granos Nativos, Universidad Nacional Agraria La Molina from February to July 2025. Tomato plants were grown under controlled conditions: 22 °C, a 12-hour light/12-hour dark photoperiod, 55% relative humidity, and a light intensity of approximately 150 μmol m^{-2} s^{-1} provided by LEDs. The study evaluated the effects of seaweed extracts (SWE) on fruit ripening, yield, and quality.

A completely randomized design with five treatments and ten replicates each was used. Plants were watered weekly as needed and fertilized with Solucion hidroponica La Molina [26] prepared from deionized water, 5 mL of solution A, and 2 mL of solution B (Table 1). During flowering, 2 g of 10-30-20 fertilizer (Peters) was added to each watering to support reproductive development.

Table 1. Chemical composition of the Solución Hidroponica La Molina applied to tomato plants during the test [26].

Fertilizer	Amount dissolved in 20 L of Deionized Water
Potassium Nitrate (KNO_3)	11.0 g
Ammonium nitrate (NH_4NO_3)	7.0 g
Triple superphosphate of calcium	3.6 g
Magnesium sulphate	1.76 g
Iron chelate6% Fe	0.136 g
Micronutrient Solution	3.2 mL

Treatments used various SWE, deriver applied by foliar. Key physiological parameters—fruit ripening indicators, yield, and quality—were monitored for consistent, reproducible results.

2.3. Biostimulant Treatments

Four commercial biostimulants derived from seaweed were evaluated: Agrostemin Grow, DuoAlgae, Fertimar SC, and NeoAlgae. Complete compositional disclosure is unavailable for commercial biostimulant formulations due to proprietary restrictions; technical specifications are provided as supplementary data (S1). These products were supplied by Grupo Silvestre (Lima, Peru). NeoAlgae and Agrostemin Grow are formulated from *Ascophyllum nodosum*. DuoAlgae and Fertimar SC are derived from brown algae in the genera *Macrocystis* and *Lessonia*.

The treatments included a control with distilled water and the four biostimulants at 2.5 mL L^{-1}. To prepare each solution, mix 1.25 mL of the specific biostimulant with 0.5 L of distilled water. Add 0.125 mL L^{-1} of Trumex surfactant to enhance leaf coverage and absorption. Apply the solutions as foliar sprays, delivering 100 mL per treatment or 10 mL per plant.

Applications were made weekly for 6 weeks, starting with the appearance of the flower buds. During flowering and fruit set, reproductive parameters—number of open flowers, fertilized flowers, and developing fruits—were evaluated and recorded weekly. Yield was quantified by monitoring fruit production per plant.

Fruit quality was evaluated at harvest across different physiological maturity stages, as defined by USDA classification (Breaker, Turning, Pink, Red). Measured parameters included nitrate content, soluble solids (°Brix), chlorophyll a, chlorophyll b, total chlorophyll, lycopene, and β-carotene.

Each treatment consisted of 10 replicates each, where each replicate consisted of a single plant grown in an individual pot, resulting in a total of 50 experimental units.

2.4. Flowering and Fertilization

Reproductive development was evaluated weekly by recording the number of open and fertilized flowers. Measurements started when the first flower opened and continued until all flowers were fertilized or abscised [27].

2.5. Fruit Growth and Yield Components

During the cell expansion stage (Immature Green and Breaker), fruit polar and equatorial diameters were measured at 52 DAF. Evaluations of mature fruits were omitted, as main growth occurs before color changes [28,29].

To estimate yield during an increased crop cycle duration, all fruits that reached physiological maturity (Red stage) were counted at 90 DAF.

2.6. Quality Parameters

Fruits were collected between 30 DAD and 50 DAF from each treatment by random sampling of different plants, selecting only those without visible defects and of uniform size. These samples were immediately frozen in liquid nitrogen and stored at -80 °C. To prepare for analysis, the fruits were thawed at 4 °C for 24 hours, releasing the exudate required. For each treatment, three replicates of fruit tissue (1 g per replicate) were prepared and used for further analysis.

2.7. Total Soluble Solids

Total soluble solids (TSS) were determined by a modified version of Lobos et al. [30]. A 150 µL aliquot of tomato juice was placed on a temperature-compensated digital refractometer (Hanna Instruments HI96811, Woonsocket, RI, USA). Results were expressed in degrees Brix, reflecting the fruit's sugar concentration. After each sample, the prism was washed with distilled water and dried with tissue paper.

2.8. Nitrate and Potassium Content

NO_3^- and K^+ ion contents were measured in ripe fruit using modified methods from Butler et al. [31] and Tsukagoshi et al. [32]. The collected sap was transferred to 2 mL Eppendorf tubes, vortexed for 15 seconds, and a 150 µL aliquot was applied onto the corresponding ionometer sensors. NO_3^- and K^+ concentrations were measured with the LAQUAtwin NO_3-11 and LAQUAtwin K-11 ionometers. After each sample, sensors were washed with distilled water and dried with tissue paper.

2.10. Chlorophyll, β-carotene, and Lycopene Content

The pigment content in the fruit was determined following the method of Nagata and Yamashita, with some modifications [33]. Pigments were extracted from 1.0 g of tomato tissue, ground in a mortar, and 15 mL of an acetone: n-hexane (4:6) mixture was added. The suspension was maintained at 4 °C for 1 h to promote extraction. Subsequently, the optical density of the supernatant was measured at 663, 645, 505, and 453 nm using a spectrophotometer. The values obtained were then used to calculate the pigment concentration. The calculations were performed using the following equations:

$$\text{Chlorophyll a (mg/100 ml)} = 0.999A663 - 0.0989A645$$

$$\text{Chlorophyll b (mg/100 ml)} = -0.328A663 + 1.77A645$$

$$\text{Total Chlorophyll (mg/100 ml)} = \text{Chlorophyll a} + \text{Chlorophyll b}$$

$$\beta\text{-carotene (mg/100 ml)} = 0.216A663 - 1.22A645 - 0.304A505 + 0.452A453$$

$$\text{Lycopene (mg/100 ml)} = -0.0458A663 + 0.204A645 + 0.372A505 - 0.0806A453$$

2.11. Statistical Analysis

Data were analyzed using InfoStat to identify significant differences. Variables were first tested for normality and homogeneity of variances. If these assumptions were met, a one-way ANOVA followed by Tukey's multiple comparisons test was conducted; otherwise, the non-parametric Kruskal-Wallis test was applied. The choice of test depended on the results of the normality and homogeneity tests. In all cases, significance was set at $p = 0.05$. Analyses were performed at each weekly interval after biostimulant application to evaluate reproductive growth, yield, and tomato quality parameters. Results are presented as mean ± standard error (SE).

3. Results and Discussion

3.1. Flowering and Flower Fertilization

SWE treatments did not significantly affect the number of open flowers ($p > 0.05$), although DuoAlgae showed a 24.18% increase compared to the control. The lack of effect on open flowers suggests a dose-dependent response. Concentrations near 1.0% w/v have been reported ineffective, while doses above 2.5% w/v induce significant responses [34,35]. In this study, the applied dose (0.25% w/v) falls within the reported ranges, which could explain the observed lack of response. Consequently, it is necessary to determine the minimum effective dose to maximize flowering under our experimental conditions.

Previous studies show that extracts of *Ascophyllum nodosum* and *Sargassum* spp., when applied at an intermediate dose (0.5% w/v) [15]. Although these results come from different experimental systems, they help us place our findings within a dose-response gradient, suggesting that the response to seaweed extracts depends on both the dose applied and the product's characteristics, highlighting the need to optimize biostimulant formulations for each specific experimental context.

In contrast, the number of fertilized flowers increased significantly ($p < 0.05$), with DuoAlgae (*Macrocystis integrifolia* and *Lessonia trabeculata*) showing the most significant increase, at 100% (Table 2). This increase is consistent with Ezura et al., who reported improvements in fruit set and fruit formation with SWE [36].

Table 2. Effect of seaweed extract–based treatments on the number of flowers and fertilized flowers in Micro-Tom tomato (14 DAF).

Treatments	Number of Open flowers	Number of fertilized Flowers
Control	2.50 ± 1.88 a	2.25 ± 1.76 b
NeoAlgae	3.42 ± 2.07 a	4.08 ± 1.31 ab
Agrostemin Grow	3.58 ± 2.35 a	3.08 ± 1.93 ab
Fertimar SC	3.58 ± 2.11 a	3.25 ± 1.71 ab
DuoAlgae	4.42 ± 1.56 a	4.50 ± 1.51 a

Values are means ± SE. Different letters indicate significant differences among treatments ($p \leq 0.05$).

3.2. Fruit Growth and Yield Components

3.2.1. Fruit Diameter

Fruit diameter, closely associated with yield and commercial value in tomatoes [37], showed differential responses across the variables evaluated. Polar diameter showed significant differences between treatments and the control ($p < 0.05$), with increases of 13.77% and 11.26% in Fertimar SC and Agrostemin Grow, respectively (Table 3). In contrast, equatorial diameter did not show significant differences, although an increasing trend was observed.

Table 3. Effect of seaweed extract–based treatments on the polar and equatorial diameter of Micro-Tom tomato fruits (52 DAF).

Treatments	Polar Diameter (mm)	Equatorial Diameter (mm)
Control	11.98 ± 3.85 a	11.17 ± 4.30 a
NeoAlgae	12.94 ± 3.26 ab	12.10 ± 3.63 a
Agrostemin Grow	13.33 ± 2.51 b	12.72 ± 2.89 a
Fertimar SC	13.63 ± 3.37 b	12.62 ± 3.52 a
DuoAlgae	12.83± 3.55 ab	11.84 ± 4.22 a

Values are means ± SE. Different letters indicate significant differences among treatments ($p \leq 0.05$).

The increase in polar diameter is consistent with previous studies reporting positive effects of SWEs on fruit size. For example, extracts of Ascophyllum nodosum have increased fruit size in solanaceous crops such as peppers and eggplants [37]. Similarly, algae- and yeast-based biostimulants, such as Expando, have increased tomato fruit size [38]. Likewise, extracts of Nizamuddinia zanardinii have been associated with increases in fruit volume [39], suggesting a consistent effect of SWEs on fruit growth. On the other hand, this differential response between polar and equatorial diameters (Table 3) may suggest an anisotropic effect on cell expansion associated with SUN and OVATE genes that determine fruit shape [40].

3.2.2. Fruit Number and Ripening

Mannino et al. [41] have reported that SWE-treated plants produced significantly more fruits during the sixth and seventh harvests than the control. Thus, the total number of fruits per plant was evaluated after 90 DAF, showing no significant difference between treatments and the control ($p > 0.05$). Meanwhile, DuoAlgae and Fertimar SC showed the highest values (Table 4), suggesting a dose-dependent response [35].

Table 4. Effect of seaweed extract–based treatments on the total number of fruits and mature fruits in Micro-Tom tomato (90 DAF).

Treatments	Fruits per plant	Mature fruits per plant
Control	5.00 ± 2.28 a	2.17 ± 1.33 b
NeoAlgae	5.11 ± 1.76 a	2.44 ± 1.51 b
Agrostemin Grow	6.60 ± 2.12 a	3.90 ± 1.91 ab
Fertimar SC	7.56 ± 2.46 a	5.00 ± 1.50 a
DuoAlgae	7.22 ± 3.31 a	3.78 ± 1.72 ab

Values are means ± SE. Different letters indicate significant differences among treatments ($p \leq 0.05$).

The number of ripe fruits differed significantly among treatments ($p < 0.05$) (Table 4). Specifically, Fertimar SC increased ripe fruit yield by 130.41% compared to the control, while DuoAlgae and Agrostemin Grow produced non-significant increases of 74.19% and 79.72%, respectively. These findings align with previous evidence that seaweed extracts (SWEs) can accelerate fruit ripening. For instance, in tomatoes, *Ascophyllum nodosum*- and yeast-based formulations have reduced ripening time by up to two weeks [38]. In ad-dition, extracts of *Sargassum horneri* and *Cystoseira barbata* have also been shown to in-crease the number of marketable fruits and advance ripening [42]. Moreover, the results presented in Figure 4 indicate that while SWE application does not necessarily in-crease the total fruit count, it does promote the transition of fruits to commercial maturity.

3.3. Tomato Fruit Quality Parameters

Table 2 shows that increased fertilization and the observed trend in open flowers are associated with significant differences in the number of mature fruits (Table 4) and fruit shape (Table 3). Therefore, NO_3^-, K^+, TSS, and pigments (total chlorophyll, chlorophyll a, chlorophyll b, lycopene, and β-carotene) were measured at the breaker, pink, and red stages to assess the effect of SWE.

3.3.1. Nitrate and Potassium Concentrations in Tomato Fruits

Nitrogen is an essential nutrient for fruit yield and quality, as it participates in the synthesis of amino acids, proteins, and nucleic acids [43,44]. In this study, NO_3^- content showed significant differences between treatments at all evaluated stages (Table 5). DuoAlgae showed increases in breaker (+26.15%), pink (+43.47%), and red (+15.86%), while Fertimar SC showed increases in pink (+26.09%) and red (+14.63%). These differences may be associated with the composition of the biostimulants, as brown algal extracts have been reported to modulate nutrient absorption and distribution [37].

Table 5. Effects of seaweed extract–based treatments on nitrate concentration in Micro-Tom tomato fruits.

Treatments	NO_3^- Breaker (mg/L)	NO_3^- Pink (mg/L)	NO_3^- Red (mg/L)
Control	216.67 ± 5.77 b	230 ± 0.00 ab	273.33 ± 15.28 b
NeoAlgae	233.33 ± 5.77 b	230 ± 5.77 a	263.33 ± 5.77 b
Agrostemin Grow	270.00 ± 10.00 a	250 ± 0.00 abc	246.67 ± 5.77 b
Fertimar SC	226.67 ± 11.55 b	290 ± 5.77 bc	313.33 ± 11.55 a
DuoAlgae	273.33 ± 5.77 a	330 ± 5.77 c	316.67 ± 20.82 a

Values are means ± SE. Different letters indicate significant differences among treatments ($p \leq 0.05$).

In this context, K^+ acts in a complementary manner to nitrate, due to its role in ionic balance and in the transport of photoassimilates [45,46]. Thus, K^+ increased significantly in the red stage (Table 6), with DuoAlgae (+31.53%) being the most prominent, followed by Fertimar SC (+22.17%) and Neoalgae (+18.22%). This effect, along with the greater accumulation of NO_3^-, indicates that SWEs—especially DuoAlgae and Fertimar SC—improve the fruit's mineral composition, contributing to its yield and nutritional and organoleptic quality.

Table 6. Effects of seaweed extract–based treatments on potassium concentration in Micro-Tom tomato fruits.

Treatments	K^+ Breaker (mg/L)	K^+ Pink (mg/L)	K^+ Red (mg/L)
Control	5900 ± 152.75 a	7033.33 ± 208.17 c	6766.67 ± 0.00 c
NeoAlgae	7200 ± 115.47 ab	8000.00 ± 0.00 b	8000 ± 100 b
Agrostemin Grow	8500 ± 230.94 c	7033.33 ± 57.74 c	7300 ± 264.58 c
Fertimar SC	7900 ± 550.76 abc	8266.67 ± 404.15 ab	8266.67 ± 115.47 b
DuoAlgae	8100 ± 33.33 bc	8666.67 ± 251.66 a	8900 ± 100 a

Values are means ± SE. Different letters indicate significant differences among treatments ($p \leq 0.05$).

3.3.2. Total Soluble Solids (TSS) Content

Total soluble solids (TSS) serve as an indicator of fruit quality, reflecting the accumulation of sugars, organic acids, and other solutes that contribute to both flavor and commercial value [4]. In this study, significant differences in TSS among treatments were observed during ripening. Notably, the DuoAlgae treatment resulted in a 14.49% increase in TSS compared to the control at the red stage (Table 7).

Table 7. Effects of seaweed extract–based treatments on total soluble solids (TSS) concentration in Micro-Tom tomato fruits.

Treatments	SST Breaker (° Brix)	SST Pink (° Brix)	SST Red (° Brix)
Control	6.07 ±0.06 b	5.20 ± 0.06 a	6.90 ± 0.06 ab
NeoAlgae	5.90 ± 0.00 c	6.10 ± 0.00 ab	6.60 ± 0.06 a
Agrostemin Grow	6.10 ± 0.00 ab	620 ± 0.06 abc	6.60 ± 0.00 a
Fertimar SC	6.23 ± 0.06 a	6.30 ± 0.06 bc	6.80 ± 0.06 ab
DuoAlgae	5.6 ± 0.1 d	7.20 ± 0.06 c	7.90 ± 0.06 b

Values are means ± SE. Different letters indicate significant differences among treatments ($p \leq 0.05$).

These results are consistent with previous studies. Those studies reported increases in total soluble solids (TSS) and other quality attributes, such as titratable acidity, vitamin C, and total carbohydrates, following the application of brown seaweed extracts, including *Nizamuddinia zanardinii*, *Sargassum johnstonii*, and *Ascophyllum nodosum* [39,42]. These effects have been linked to increased nutrient availability, especially N and K^+, which enhance photosynthetic activity and, consequently, increase the flow of photoassimilates to the fruit [39].

3.3.3. Chlorophyll Content in Fruits

Chlorophyll content reflects the photosynthetic state and fruit ripening [47]. In this study, total chlorophyll decreased steadily and reached nearly zero by the pink and red stages (Table 8). This pattern is consistent with tissue ripening.

Table 8. Effects of seaweed extract–based treatments on chlorophyll concentration (mg/100gFW) in Micro-Tom tomato fruits.

Treatments		Breaker	Pink	Red
Control	Total chlorophyll	1.66 ± 0.09 a	0.27 ± 0.05 d	0.00 ± 0.00 c
	Chlorophyll a	0.34 ± 0.06 a	0.00 ± 0.00 a	0.00 ± 0.00 a
	Chlorophyll b	1.32 ± 0.06 d	0.27 ± 0.05 ab	0.00 ± 0.00 a
NeoAlgae	Total chlorophyll	4.13 ± 0.35 ab	0.53 ± 0.00 c	0.00 ± 0.00 c
	Chlorophyll a	1.85 ± 0.49 a	0.00 ± 0.00 bc	0.00 ± 0.00 a
	Chlorophyll b	2.29 ± 0.16 bc	0.53 ± 0.00 a	0.00 ± 0.00 a
Agrostemin Grow	Total chlorophyll	5.63 ± 0.04 b	1.52 ± 0.07 a	0.15 ± 0.01 b
	Chlorophyll a	2.13 ± 0.03 a	0.10 ± 0.04 ab	0.00 ± 0.00 a
	Chlorophyll b	3.50 ± 0.02 a	1.42 ± 0.05 a	0.15 ± 0.10 b
Fertimar SC	Total chlorophyll	4.08 ± 0.07 ab	0.69 ± 0.08 b	0.63 ± 0.05 a
	Chlorophyll a	2.00 ± 0.07 a	0.69 ± 0.08 b	0.63 ± 0.05 b
	Chlorophyll b	2.08 ± 0.05 c	0.00 ± 0.00 a	0.00 ± 0.00 a
DuoAlgae	Total chlorophyll	4.33 ± 0.09 b	0.43 ± 0.04 c	0.02 ± 0.03 bc
	Chlorophyll a	1.97 ± 0.05 a	0.00 ± 0.00 a	0.00 ± 0.00 ab
	Chlorophyll b	2.36 ± 0.09 b	0.43 ± 0.04 abc	0.02 ± 0.0 ab

Values are means ± SE. Different letters indicate significant differences among treatments ($p \leq 0.05$).

During the breaker stage, biostimulant treatments produced distinct effects. Agrostemin Grow and DuoAlgae increased total chlorophyll content by 245.45% and 163.63%, respectively. The observed increase was primarily attributable to chlorophyll b, which rose in all treatments: Agrostemin Grow (+165.15%), DuoAlgae (+78.78%), and NeoAlgae (+73.48%). In contrast, chlorophyll a did not change significantly. Thus, biostimulant application at this stage enhances chlorophyll b accumulation.

During ripening (pink and red), chlorophyll decreased in all treatments, although Agrostemin Grow and Fertimar SC maintained residual levels of chlorophyll b and a, respectively, suggesting a partial slowdown of its degradation.

Overall, SWEs increase chlorophyll accumulation in early stages and modulate its degradation during ripening. This pattern was more evident in DuoAlgae, where a significant increase in total soluble solids (TSS) was observed, whereas the same response was not observed in Agrostemin Grow, suggesting differences in their mode of action on fruit metabolism.

3.3.4. Carotenoid (Lycopene and β-Carotene) Content in Fruits

Carotenoids, particularly lycopene and beta-carotene, determine the characteristic red color of ripe tomatoes as a result of the progressive degradation of chlorophyll and the coordinated accumulation of these pigments during ripening. This process not only defines the fruit's appearance but also its commercial value.

Lycopene content (Table 9) increased significantly in the Duo-Algae and Agrostemin Grow treatments from the breaker stage, indicating a possible temporal shift in ripening. At the red stage, NeoAlgae and Fertimar SC showed the greatest increases (125% and 87.5%, respectively). These changes coincided with significant increases in K^+ in the fruit (Table 6), particularly at the breaker, pink, and red stages. Since K^+ is involved in regulating the metabolic flux of isoprenoid precursors such as geranyl-geranyl pyrophosphate, these results are consistent with a possible effect on partitioning to carotenoids [48]. However, the lack of direct measurements of metabolic intermediates or enzyme activity prevents the establishment of a causal mechanism.

Table 9. Effect of seaweed extract–based treatments on lycopene concentration (mg/100gFW) in Micro-Tom tomato fruits.

Treatments	Breaker)	Pink)	Red
Control	0.00 ± 0.00 a	0.25 ± 0.01 c	0.08 ± 0.0015 e
NeoAlgae	0.07 ± 0.02 abc	0.18 ± 0.02 b	0.18 ± 0.00074 a
Agrostemin Grow	0.19 ± 0.01 c	0.49 ± 0.03 a	0.08 ± 0.00083 d
Fertimar SC	0.06 ± 0.003 ab	0.28 ± 0.02 b	0.15 ± 0.0027 b
DuoAlgae	0.11 ± 0.01 bc	0.54 ± 0.02 a	0.10 ± 0.0027 c

Values are means ± SE. Different letters indicate significant differences among treatments ($p \leq 0.05$).

In the case of β-carotene (Table 10), the greatest increases were observed in Fertimar SC and NeoAlgae (33.33% compared to the control), consistent with the overall increase in carotenoids. This pattern suggests a general stimulation of carotenoid biosynthesis rather than a specific redistribution among individual compounds, although differential regulation within the pathway cannot be ruled out.

Table 10. Effect of seaweed extract–based treatments on β-carotene concentration **(**mg/100gFW) in *Micro-Tom* tomato fruits.

Tratamientos	Breaker	Pink	Red
Control	0.22 ± 0.01 b	0.74 ± 0.03 bc	1.40 ± 0.03 b
NeoAlgae	0.00 ± 0.00 a	0.60 ± 0.03 ab	1.77 ± 0.06 a
Agrostemin Grow	0.00 ± 0.00 a	0.33 ± 0.05 a	0.87 ± 0.06 b
Fertimar SC	0.00 ± 0.00 a	1.71 ± 0.03 c	1.85 ± 00.03 a
DuoAlgae	0.00 ± 0.00 a	0.60 ± 0.05 ab	1.41 ± 0.06 c

[1] Values are means ± SE. Different letters indicate significant differences among treatments ($p \leq 0.05$).

These results indicate that certain SWEs, especially NeoAlgae and Fertmar SC, promote carotenoid accumulation and may accelerate fruit ripening. Nevertheless, mechanistic interpretation is limited; therefore, future work should integrate molecular validation to elucidate underlying mechanisms.

4. Conclusions

The macroalgae species *Macrocystis integrifolia* and *Lessonia trabeculata* from the Peruvian coast are promising sources of biostimulants. Extracts from these macroalgae modulate tomato reproductive processes and improve fruit quality in a dose-dependent manner, thereby increasing flowering and fertilization. These biostimulants alter the mineral composition and metabolite profiles associated with fruit quality, leading to higher concentrations of NO_3^-, K+, total soluble solids, photosynthetic pigments, and carotenoids. This pattern indicates a reprogramming of fruit metabolism. Micro-Tom remains an effective model system to study the mechanisms underlying biostimulant responses. The combined use of transcriptomics and metabolomics is essential for establishing links among composition, dose, and biological response, thereby supporting more predictable and reproducible applications. However, additional validation, particularly at the greenhouse level with commercial varieties, is required to confirm broader agronomic relevance.

Supplementary Materials: The following supporting information can be downloaded at the website of this paper posted on Preprints.org.

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