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Algae Extracts and Zeolite Modulate Plant Growth and Enhance the Yield of Tomato *Solanum lycopersicum* L. Under Suboptimum and Deficient Soil Water Content

José Antonio Miranda-Rojas [1], Aurelio Pedroza-Sandoval [1], Isaac Gramillo-Ávila [1], Ricardo Trejo-Calzada [1,*], Ignacio Sánchez-Cohen [2] and Luis Gerardo Yáñez-Chávez [1]

[1] Unidad Regional Universitaria de Zonas Aridas, de la Universidad Autonoma Chapingo, Km. 40 Carr. Gómez Palacio–Chihuahua, Bermejillo C.P. 35230, Durango, Mexico; sr.mirandaja@gmail.com (J.A.M.-R.); apedroza@chapingo.uruza.edu.mx (A.P.-S.); igramillo4@gmail.com (I.G.-Á.); yachgl@chapingo.uruza.edu.mx (L.G.Y.-C.)

[2] Centro Nacional de Investigación Disciplinaria en Relaciones Agua Suelo Planta Atmósfera del Instituto Nacional de Investigaciones Forestales Agrícolas y Pecuarias, Km. 6.5 Canal de Sacramento, Gómez Palacio C.P. 35079, Durango, Mexico; sanchez.ignacio@inifap.gob.mx

* Correspondence: rtrejo@chapingo.uruza.edu.mx

Abstract

Drought and water scarcity are some of the most important challenges facing agricultural producers in dry environments. This study aimed to evaluate the effect of algae extract and zeolite in terms of their biostimulant action on water stress tolerance to obtain better growth and production of tomato Lycopersicum esculentum L. grown in an open field under suboptimum and deficient soil moisture content. Large plots had a suboptimum soil moisture content (SSMC) of 25% ± 2 [28% below field capacity (FC)] and deficient soil moisture content (DSMC) of 20% ± 2 [11% above permanent wilting point (PWP)]; both soil moisture ranges were based on field capacity FC (32%) and PWP (18%). Small plots had four treatments: algae extract (AE) 50 L ha^{-1} and zeolite (Z) 20 t ha^{-1}, a combination of both products (AE + Z) 25 L ha^{-1} and 10 t h^{-1}, and a control (without application of either product). By applying AE, Z, and AE + Z, plant height, plant vigor, and chlorophyll index were significantly higher compared to the control by 20.3%, 10.5%, and 22.3%, respectively. The effect on relative water content was moderate—only 2.6% higher than the control applying AE, while the best treatment for the photosynthesis variable was applying Z, with a value of 20.9 µmol CO_2 m^{-2} s^{-1}, which was 18% higher than the control. Consequently, tomato yield was also higher compared to the control by 333% and 425% when applying AE and Z, respectively, with suboptimum soil moisture content. The application of the biostimulants did not show any mitigating effect on water stress under soil water deficit conditions close to permanent wilting. These findings are relevant to water-scarce agricultural areas, where more efficient irrigation water use is imperative. Plant biostimulation through organic and inorganic extracts plays an important role in mitigating environmental stresses such as those caused by water shortages, leading to improved production in vulnerable agricultural areas with extreme climates.

Keywords: water stress; plant growth; organic and inorganic amendments; drylands

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1. Introduction

About 85% of the planet's agricultural surface is negatively impacted by drought, which has increased in intensity and frequency due to climate change [1]. Drought and

the resulting water shortage impact agricultural processes and increase the risk of food insecurity [2]. The negative impact depends on the stage of plant development and the level of stress induced by water deficiency [3], causing leaf senescence, flower abscission, chlorophyll destruction, and wilting [4]. Deficient soil moisture content during the reproductive phase of most plants reduces yield [5].

The use of water stress-tolerant plant species [6] complemented with different crop management practices to mitigate water deficit in plants is a real strategy to mitigate the impact of water deficit in agricultural areas with low water availability. Several agronomic practices have been reported to alleviate plant water stress, such as the use of soil moisture retainers based on mulch, or the use of hydrogel or compost [7,8], as well as the use of organic and inorganic biostimulants that improve plant growth, plant vigor, and yield [9,10]. Also, organic product groups such as symbiotic mycorrhizae [11] and some types of algae extracts, as well as inorganic products like zeolite, are playing an important role as biostimulants to enhance plant growth and productivity under constraint conditions [12].

Algae extracts contain a wide variety of biocompounds, such as polysaccharides, phytohormones, and amino acids, that play an important role in plant physiology and are vital to crop growth and yield [13]. Biostimulant application is a promising innovation for the sustainability of modern agricultural systems. These products may improve plant nutrition processes by increasing nutrient use efficiency, tolerance to abiotic stress, quality of traits, and availability of nutrients [14]. Almaroai et al. [15] highlight that the application of 9% algal extract on onion grown under water stress increased the bulb yield by 67 and 102% in 2018 and 2019, respectively. Hassan et al. [16] found that the application of algae *Pediastrum boryanum* at a rate of 2.0 mL L^{-1} significantly increased plant height, number of branches, number of umbels, and fruit yield in fennel (*Foeniculum vulgare* Mill.) plants. In addition, algae and zeolite applied together have been used for the treatment of wastewater for agriculture, improving soil fertility and the protein and carbohydrate contents in maize crops [17].

Inorganic products like zeolite contain different compounds, such as selenium (Se) [18,19], acetylsalicylic acid [9,20], abscisic acid [21], and aluminum polyciliate. Zeolite is being used as a biostimulant to enhance the growth and production of agriculture under water stress conditions. Zeolite is rich in aluminosilicate minerals and other important microelements with beneficial properties for human, animal, and plant health. Zeolite is proving to be very useful for plants, mainly as a mitigator of environmental stress and as a soil moisture-retaining agent when water availability is limited, as well as for detoxification processes, antioxidant action, and assimilation of different nutrients in plants [22]. In addition, zeolite has been evaluated as a soil moisture retainer [23] and as a soil fertility enhancer [24], as well as for improving the physical and chemical properties of soil water [10]. It is a compound whose structure has an oxygen/metal ratio of 2, tetrahedra of SiO_2 and AlO_2 composition, and a negative charge equal to the number of aluminums in the structural position [25]. This inorganic product has properties that improve soil moisture retaining, and facilitate the gradual and continuous uptake of nutrients by the plant, acting as a fertilizer [26].

Silicon (Si) is the second most abundant element on Earth. This element has been classified by the International Plant Nutrition Institute as a beneficial nutrient in plants [27]. Si has been associated with plant responses to several biotic and abiotic stresses. The role of Si in response to heavy metals, salinity, water stress, and extreme temperatures has been associated with its effects on secondary metabolism and particularly the production of phenolic and polyamine compounds [28,29]. The other important microelement contained in zeolite is aluminum (Al), which is the third most abundant metal in the Earth's crust. Aluminum is not an essential element for plants. However, there are many scientific

articles evidencing beneficial effects on plants [30,31], such as increasing plant growth and mitigating biotic and abiotic stress when applied at a low concentration [32,33]. These microelements (Si and Al) are subjects of important studies in agriculture. Hazrati et al. [34] reported that zeolite application alleviates water stress and improves plant growth and yield of *Aloe vera* by increasing water use efficiency, while Selahvarzi et al. [35] showed that treatment with 20% zeolite resulted in the highest leaf area, total dry weight, and carotenoid contents in *Festuca arundinacea* grass grown under water stress conditions.

For all the above, it is important to develop innovative strategies to aid marginal agriculture in drylands, such as those in northern Mexico. This region has an intensive agricultural production system, with crops such as fodders, fruit trees, and vegetables being the most common farming activity in the valley. All these crops have a high water demand and are irrigated with groundwater, which has caused a gradual depletion of the aquifers, with lower volumes of water pumped that also has a high salt content and heavy metals [36]. Integrated water management in arid-zone agriculture is crucial to improve the use efficiency of this vital natural resource, mostly where water scarcity is the main limiting factor [37,38].

Moreover, tomato is one of the most important vegetables in the agri-food industry worldwide, and it is widely cultivated in northern Mexico. However, tomato plants are highly sensitive to various environmental constraints, especially water stress [39]. In addition, in the survey area, tomato are grown year-round under greenhouse conditions due to the extreme climate and, in very small areas, this vegetable is cultivated under open-field conditions where the high temperatures and water deficit in summer are the cause of a high rate of floral senescence and consequently drastically decrease tomato yield [40]. The assumption of this study was to develop a tomato production strategy under open-field conditions in extreme environments such as arid zones and explore the possibility of making a more efficient use of water by applying low water volumes and using native materials native to the region to mitigate plant water stress. The study aimed to evaluate algae extract and zeolite as biostimulants to mitigate water stress and its impact on the water status of plants, growth, chlorophyl index, photosynthesis, and yield of tomato (*Solanum lycopersum* L. Cv. Saladette) under suboptimum and deficient soil water contents in open fields in northern Mexico.

2. Materials and Methods

2.1. Geographic Location

The study was conducted in the Unidad Regional Universitaria de Zonas Aridas of the Universidad Autónoma Chapingo, Bermejillo, Durango, Mexico, located at 25.8° NL and 103.6° WL at 1130 m. The climate is BWhw(e) semi-warm with summer rainfall and extreme temperatures, with an average temperature of 21 °C, a maximum of 33.7 °C, and a minimum of 7.5 °C. The average annual precipitation is 199.60 mm [41].

2.2. Chemical Features of Organic and Inorganic Products

2.2.1. Algae Extract

Algae extract was obtained according to Drygas et al. [42] from the brown alga *Ascophyllum nodosum* (L). Twenty-five grams of crushed plant and algal material were weighed using an analytic balance (SHIMADZUM, AW320, Kyoto, Japan) and subsequently extracted with a 1:1 (*v*/*v*) mixture of H_2O (0.05 µS deionized water, and EtOH (analytical grade PA-01-0300-W, PAE001, 110 Pol-Aura) in an ultrasonic bath for two 30 min intervals at 40 °C. The resulting extract was filtered through a 1 mm mesh and combined, and the final volume was adjusted to 500 mL in a volumetric flask.

Algae extract analysis shows a relatively high content of organic compounds, including nitrogen derivates, hormones, and vitamins. Also, this extract contained macronutrients, micronutrients, and trace elements. It is noteworthy that there was a high content of silicon, a beneficial element (Table 1).

Table 1. Physical–chemical–biological characteristics of the algae extract.

Physical Characteristics	Chemical and Biological Characteristics		
	Macronutrients (ppm)	**Micronutrients (ppm)**	**Phytohormones and Vitamins (ppm)**
Humidity: 97.02 Proteins: (Nx6.25) 2.27 Total solids: 2.98 Biochar: 0.406 Organic matter: 0.700 Carbohydrates > 40.00	N: 5500 P: 67,300 K < 43,700 Ca: 1660 Mg: 882.5 S: 1200	Zn: 2005 Mg: 1204.5 Fe: 932.6 Si: 3800 Bo 1:00	Cytokinin: 2900 Ascorbic acid: 129 Carotenes: 60 Niacin: 30 Riboflavin: 10 Thiamin: 5

2.2.2. Zeolite

Zeolite is a granulate inorganic compound and contained four macronutrients and two micronutrients. It also contained high concentrations of aluminum and silicon, both recognized as beneficial elements [43] (Table 2).

Table 2. Physical and chemical characteristics of zeolite.

Physical Characteristics	Chemical Characteristics
Color: Greenish pink Odor: Odorless–earthy pH of 5% aqueous solution: 7.9 Element adsorption: Rapid Selectivity: N > P > K > Ca Element release: Slow	Al_2O_3 (11.99%) SiO_2 (53.45%) CaO (8.06%) Na_2O (1.16%) Fe_2O (33.96%) K_2O (6.11%) MgO (4.76%) MnO (0.09%) P_2O (50.23%)

2.3. Experimental Design

A randomized block experimental design in a split-plot arrangement with three replicates was used. The large plots were the soil moisture contents: suboptimum soil moisture content (SSMC) of 25% ± 2 (28% below of FC) and deficient soil moisture content (DSMC) of 20% ± 2 (11% above WP). The soil moisture content at FC and PWP were 32% and 18%, respectively. A soil water potential curve was determined using a Soil Moisture Equipment® model 1500F1 membrane pot (St. Barbara, CA, USA) according to the methodology described by Richards [44] (Figure 1). The small plots had four treatments: algae extract (AE) 50 L ha^{-1}, zeolite (Z) 20 t ha^{-1}, a combination of both products (AE + Z) at doses of 25 L ha^{-1} and 10 t ha^{-1}, respectively, and the control (without application of either product). This experimental design was selected to facilitate the application of irrigation levels, establishing the two-soil moisture contents into each large plot to turn on/off irrigation control valves according to the irrigation timing for each soil moisture content evaluated in this study (Figure 2).

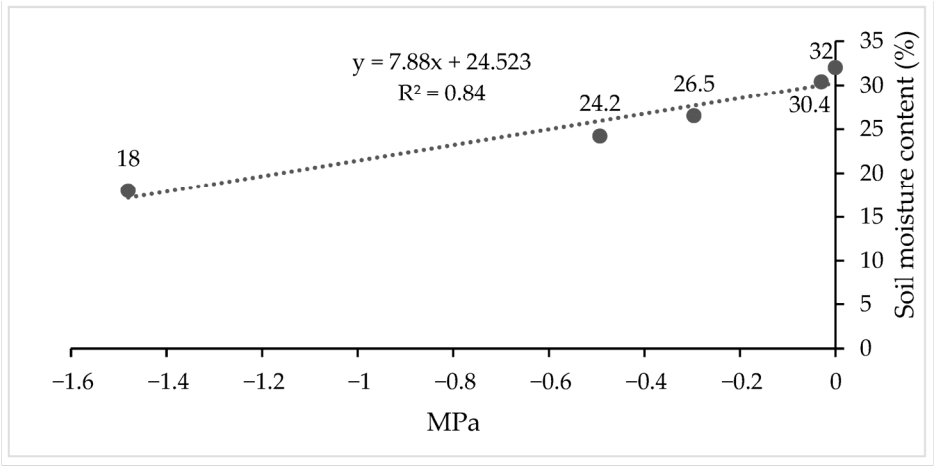


Figure 1. Soil moisture depletion from field capacity (FC) to permanent wilting point (PWP) in terms of MPa vs. moisture percentage in a clay–loam soil.

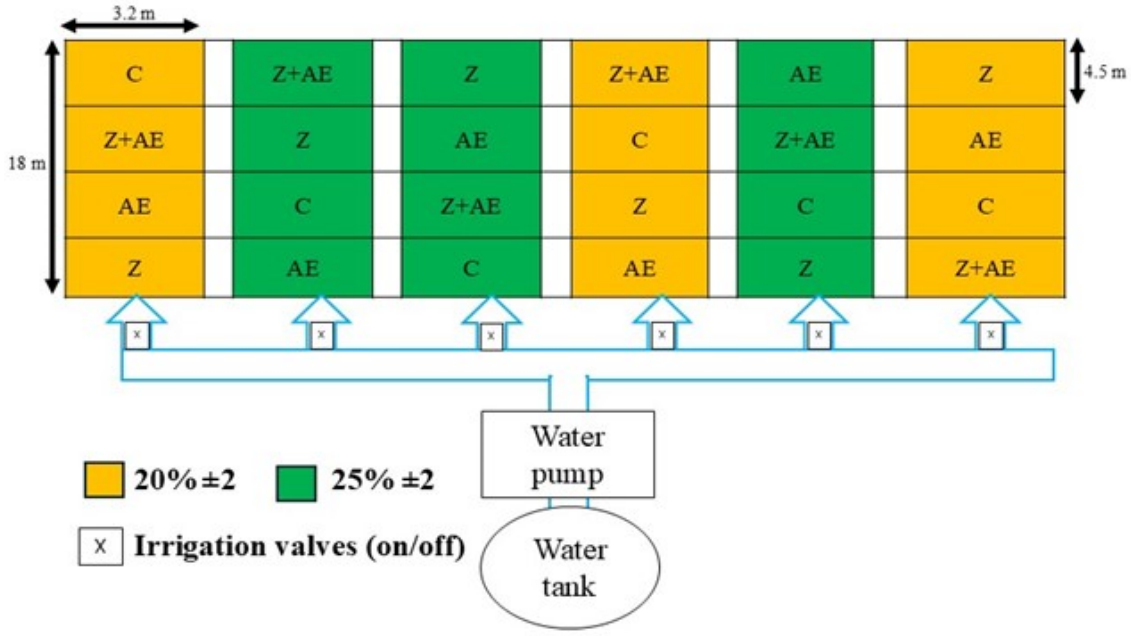


Figure 2. Randomized block experimental design in a split-plot arrangement for the evaluation of algae extract and zeolite applied separately and combined, plus the control, on each soil moisture content (20% ±2 and 25% ±2). AE is algae extract (50 L ha^{-1}); Z is zeolite (20 t ha^{-1}); AE + Z is both products combined (25 L ha^{-1} of AE + 10 t ha^{-1} of Z, respectively); C is the control (no application of either product).

2.4. Application of Algae Extract and Zeolite

Two field applications of AE and Z were made at the indicated rates for each treatment. The aqueous algae extract was applied using a foliar sprayer (Lola Safe 289020, SWISSMEX, Mexico City, Mexico) at rates 0.4 mL L^{-1} and 0.8 mL L^{-1} according to doses of 25 L ha^{-1} and 50 L ha^{-1}. Two applications were made: the first at 14 days after transplanting (DAT) and the second at 56 DAT.

As for zeolite, which is a granulated powder, it was applied once to the soil during soil preparation, 20 days before tomato transplanting in the field. Soil preparation included harrowing and leveling with agricultural machinery. The zeolite was applied manually using a 1 kg-capacity multi-perforated cap test tube, spreading the granulated powder evenly in each treatment, according to doses of 10 and 20 t ha^{-1}, and adjusting the product volume to a surface area of 14.4 m^2 per treatment (4.5 × 3.2 m). After applying zeolite,

furrows were formed with a plow so that the product was covered by the soil. The furrows were 20 cm high.

2.5. Irrigation System

Irrigation treatments were applied through a polyvinyl chloride (PVC) main irrigation line (2″), which was connected to PVC perpendicular irrigation lines (1/2″) for each large plot (soil moisture content). The irrigation water supply was controlled by on/off valves, which irrigated four rows through one line tape per row (see Figure 2). Self-compensating drippers (Chapin® drip tape, Jain Irrigation Systems Ltd., Watertown, NY, USA) were used 20 cm apart, with an emission of 2 L h^{-1} for each one. Each large plot corresponded to the moisture content in each replicate; the water flow was controlled according to the irrigation program using a stopcock. Pre-transplant irrigation was standardized to FC with an irrigation time of 15.4 h, with a flow rate per dripper of 30.8 L h^{-1} at a pressure of 2.7 kg cm^{-2}, corresponding to an irrigation depth of 30 cm. For 7 days, the watering was uniform to FC in the whole experimental area, and after this date, the two soil moisture regimes were programmed and maintained in their corresponding ranges: SSMC to 25% ±2 and DSMC to 20% ±2. To maintain the soil moisture regimes, after reaching an SSMC of 27%, the soil moisture content was allowed to drop to 22% and then it was increased to 27%; for DSMC, after reaching the upper soil moisture limit (22%), irrigation was stopped until it dropped to 18%, after which irrigation was reinitiated until it rose to the upper limit of 22%. The above means that once the moisture contents were differentiated, the subsequent irrigation time was 4 h every third day to recover the moisture content to the maximum limits from the lower levels of each soil moisture range. Soil moisture content was measured periodically using a digital moisture meter reading in real time (Lutron model PMS-714, Lutron Electronic Enterprise Co., Taipei, Taiwan) to a depth of 30 cm.

2.6. Variables

2.6.1. Climate

The environmental temperature and pluvial precipitation were recorded from February to June 2024, which is the tomato cycle time. A Davis Instruments model 6162 microclimatic station (Hayward, CA, USA) located 600 m from the experimental area was used.

2.6.2. Plant Growth (Plant Height, Stem Thickness, and Plant Vigor)

Plant height was measured using a tape graduated in cm, and stem thickness was measured using a vernier caliper in mm; plant vigor, rated on a scale of 0 to 10, where 0 is no vigor (wilted plant) and 10 is a completely vigorous plant, was determined according to the scale proposed by Horsfall & Barrat [45]. Plant growth variables were measured at 42 DAT, corresponding to the vegetative stage.

2.6.3. Physiological Indicators

Three physiological indicators were measured. The first was the chlorophyll content index (CCI), obtained using a CM 1000 chlorophyll meter (model 29950, Brand Spectrum Technologies Inc., Aurora, IL 60504, USA) according to the methodology reported by De Lima et al. [46]. The second physiological indicator was the relative water content (RWC), measured using the formula proposed by Browne et al. [47]. Saturated weight was stirred after immersing the tissue in distilled water for 24 h. Dry mass was obtained by drying the plant in an oven with air circulation at 65 °C until constant weight was reached. The results were expressed as a percentage (%) using the following formula:

$$\mathrm{RWC} = \frac{(fm - dm)}{(sm - dm)} \times 100$$

where *fm* = fresh mass, *dm* = dry mass, and *sm* = saturated mass.

In addition, the photosynthetic activity (μmol CO_2 m^{-2} s^{-1}) was measured using the Infrared Gas Analyzer Brand LI-6400XT (LI-COR®, Inc., Lincoln, NE, USA).

2.6.4. Yield Components and Tomato Yield

The components of yield such as number of fruits per plant and fruit weight per plant (kg) were recorded, as was tomato yield (kg m^{-2}). These variables were measured in two harvest stages from 56 to 70 DAT, corresponding to early and late maturity stages.

2.7. Data Analysis

An ANOVA–Tukey statistical analysis was performed to contrast treatments, along with a simple Pearson correlation analysis using the Minitab 16 and SAS version 9.0 statistical programs. Excel program v. 6.0 was used for figure design.

3. Results

3.1. Climatic Behavior in the Study

From January to June 2024, the highest rainfall was in February, with 23.6 mm; after this time, the pluvial precipitation was low, with values of 0, 0.4, 2, and 0.6 mm in March, April, May, and June, respectively. Maximum and minimum temperatures showed an upward trend during this period, reaching up to about 35 °C and 20 °C in June, respectively (Figure 3). These high temperatures are harmful to tomato plants, especially in conditions of water deficit, resulting in floral abscission during the fruiting step [9].

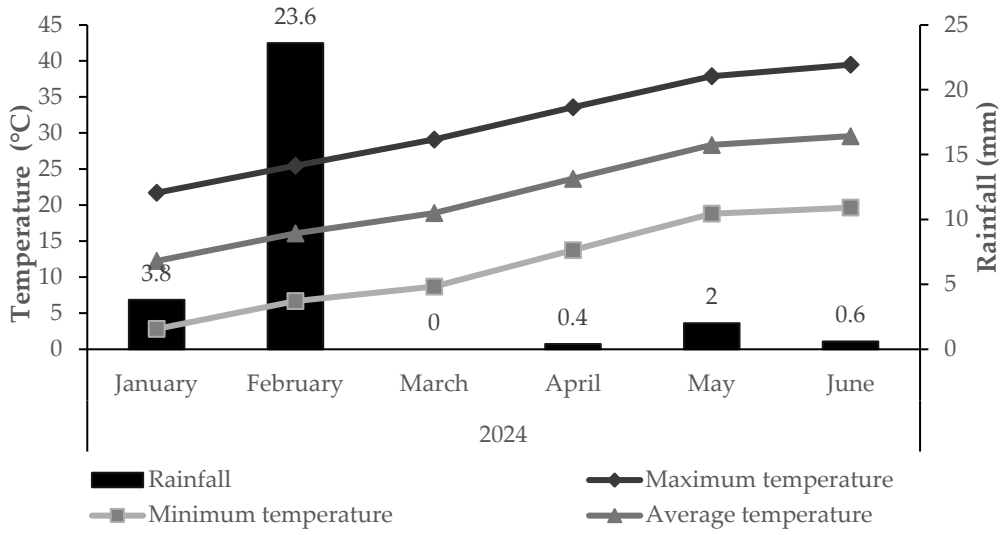


Figure 3. Temporal dynamic of maximum and minimum temperatures and rainfall in the experimental area during the crop cycle from February to June 2024.

3.2. Analyis of Variance

According to the analysis of variance, the significance for the source of variation in "blocks" was significant ($p < 0.05$) and highly significant ($p < 0.01$) for all the variables measured, which means that the randomized block design used was correct, based on the assumption that there was variation in uncontrolled factors in the experimental area and that they were part of the experimental error. Meanwhile, in the variation factor "treatments," a highly significant response was recorded ($p < 0.01$), so it was correct to perform the statistical analysis with all possible interactions of soil moisture content and biostimulation treatments plus the control (Table 3).

Table 3. Analysis of variance of different morphometric variables, chlorophyll index, tomato yield, and productivity indicators.

VS	DF	Variable	Prob. > F	Significance
Blocks	2	Height plant	<0.0173	*
Treatments	7		<0.0001	**
Blocks	2	Stem thickness	<0.0142	*
Treatments	7		<0.0001	**
Blocks	2	Plant vigor	<0.0195	*
Treatments	7		<0.0001	**
Blocks	2	Relative water content	<0.0001	**
Treatments	7		<0.0001	**
Blocks	2	Chlorophyll index	<0.0001	**
Treatments	7		<0.0001	**
Blocks	2	Photosynthesis	<0.0001	**
Treatments	7		<0.0001	**
Blocks	2	Number of fruits harvested per plant^{-1}	<0.2907	*
Treatments	7		<0.0001	**
Blocks	2	Fruit weight per plant^{-1}	<0.0001	**
Treatments	7		<0.0001	**
Blocks	2	Yield m^{-2}	<0.0001	**
Treatments	7		<0.0001	**

VS is variation source; DF is degrees of freedom; * means significant probability ($p < 0.05$), and ** means highly significant probability ($p < 0.001$).

3.3. Plant Growth (Plant Height, Stem Thickness, and Plant Vigor)

At 42 DAT, the height and vigor of the tomato plants had values of 51.5 cm and 9.4, respectively, when algae extract was applied (Figure 4A), and 47.3 cm and 9.0 when zeolite was applied (Figure 4C), respectively. These values were statistically higher than those of the control under suboptimum soil moisture content (25% ± 2). Also, they were equivalent to increases of 20.3% and 10.5% in plant growth, and of 14.6% and 9.7% in plant vigor when applying AE and Z, respectively. Stem thickness did not vary among treatments involving the application of the biostimulant products, which were statistically equal to the control under suboptimum soil moisture content, but slightly higher than the treatments under deficient soil moisture content, mainly when Z was applied, with 7.5 mm, compared to the control, which was 8.4 mm. There was no effect on plant height or chlorophyll index content, since differences were not significant under suboptimum soil moisture conditions (25% ± 2) (Figure 4A). Stem thickness and plant vigor did not vary significantly under suboptimal soil moisture conditions (25% ± 2) and only slight variations under deficient soil moisture content (20% ± 2) according to Figures 4B and 4C, respectively.

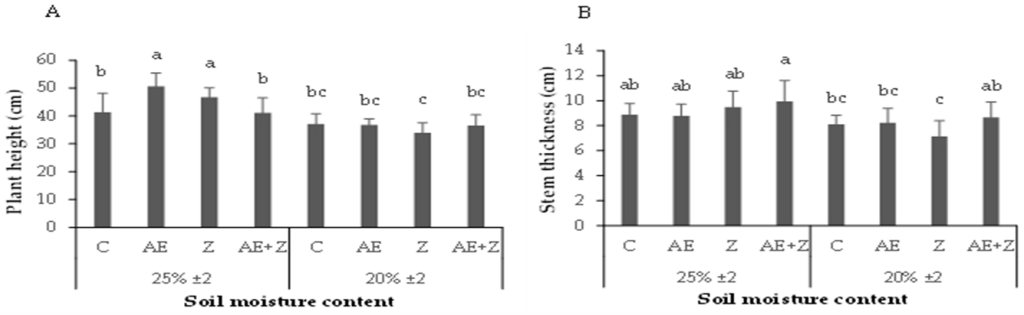


Figure 4. *Cont.*



Figure 4. Effect of algae extract and zeolite on plant height (**A**), stem thickness (**B**), and plant vigor (0–10) (**C**) on tomato plant *Solanum lycopersicum* L. var. Saladette under suboptimum (25% ± 2) and deficient (20% ± 2) soil moisture contents. Tukey test ($p < 0.05$). In treatments C is control, AE is algae extract; Z is zeolite; and AE + Z is algae extract plus zeolite. Figures with the same letters on the bars are statistically equal. The vertical line on each bar is the standard deviation.

3.4. Physiological Indicators

Overall, relative water content (CRA) had low treatment effect, with a slightly better biostimulant response from AE, Z, and AE + Z under suboptimum soil moisture conditions compared to deficient soil water in the soil. Algae extract (AE) showed the greatest effect, with 4% higher CRA when applied at 50 L ha^{-1} under suboptimal soil moisture conditions (25% ± 2) compared to deficient soil water conditions (20% ± 2), and 2.6% more compared to the control (Figure 5A).

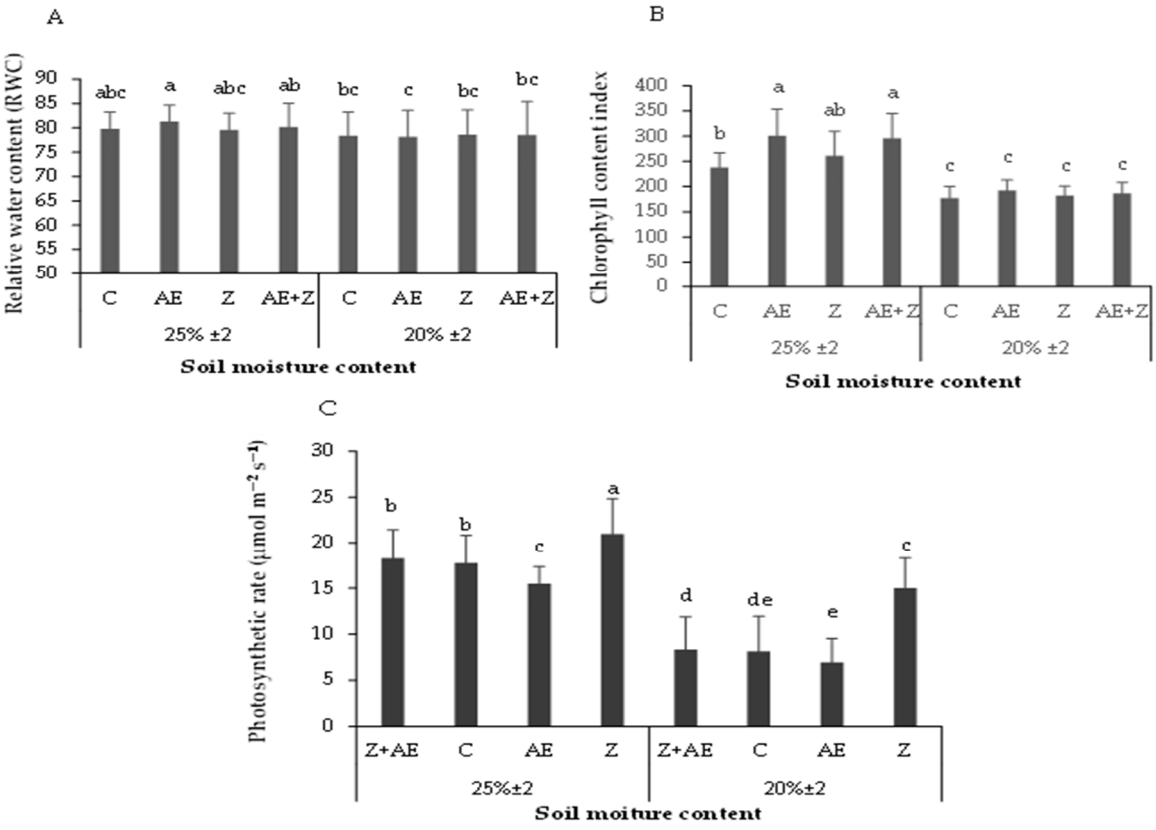


Figure 5. Effect of algae extract and zeolite on relative water content (**A**), chlorophyll index (**B**), and photosynthetic rate (µmol m^{-2} s^{-1}) (**C**) on tomato plant *Solanum lycopersicum* L. var. Saladette under suboptimum (25% ± 2) and deficient (20% ± 2) soil moisture contents at 42 DAT. In the treatments C is control, AE is algae extract, Z is zeolite, and AE + Z is algae extract plus Zeolite. Tukey test ($p < 0.05$). Figures with the same letters on the bars are statistically equal. The vertical line on each bar is the standard deviation.

Chlorophyll index content registered a similar behavior, with results statistically higher than those of the control, with a value of 295.2 for the AE + Z treatment, representing an increase of 22.34% compared to the control under suboptimum moisture content. Second in importance were the treatments AE and Z, with values of 281.4 and 270.7, respectively, without a statistical difference between them. These results are equivalent to increases of 16.6% and 12.1% compared to the control. The lowest treatment values were obtained under deficient soil moisture content, which were not statistically different compared to the control (Figure 5B).

Photosynthesis showed a similar pattern to the behavior of the other plant growth and physiological variables, with a biostimulating effect at suboptimum soil moisture content (25% ± 2), where the best treatment was applying Z, which had an 18% higher photosynthesis rate compared to the control, and the lowest effect was applying AE, which was even lower than the control, with values of 20.9, 15.5, and 17.8 µmol CO_2 m^{-2} s^{-1}. The AE + Z treatment was statistically equal to the control. No effect was found for these products when applied under deficient soil moisture contents (20% ± 2) (Figure 5C).

3.5. Productivity Indicators and Tomato Yield

The number of tomato fruits per plant was significantly higher when AE, Z, and AE + Z were applied compared to the control, with values of 6.62, 5.62, and 6.41, respectively. The differences were not significant, which means an average increase of 248.4% compared to the control. In terms of fruit weight per plant and yield m^{-2}, application of Z and AE recorded 0.17 kg $plant^{-1}$ and 0.9 kg m^{-2}. These results mean increases of 425% and 333.3%, respectively, with both results under suboptimum soil moisture conditions. On the other hand, under deficient soil moisture conditions there was no biostimulant effect of these products applied as AE, Z, or AE + Z, with values statistically equal to those of the control, with only a slight variation in the case of the number of fruits per plant, with better action when AE + Z was applied and a statistically lower value than the control when applying Z (Table 4).

Table 4. Tomato yield of Solanum lycopersicum L. var. Saladette as a result of the application of algae extract and zeolite under soil water deficit. The values are an accumulation of two harvest dates, 56 and 70 DAT.

Soil Moisture Content (%)	Organic and Inorganic Products	NFHPP	Fruit Weight (kg $Plant^{-1}$)	Yield (kg m^{-2})
25% ± 2	Control	2.5 bc ± 0.35	0.04 ab ± 0.009	0.27 ab ± 0.01
	Algae extract (AE)	6.62 a ± 0.17	0.16 ab ± 0.02	0.90 a ± 0.04
	Zeolite (Z)	5.62 a ± 1.23	0.17 a ± 0.1	0.3 ab ± 0.2
	AE + Z	6.41 a ± 0.38	0.15 ab ± 0.09	0.63 ab ± 0.31
20% ± 2	Control	1.85 bc ± 0.17	0.03 b ± 0.01	0.18 b ± 0.09
	Algae extract (AE)	2.00 bc ± 0.35	0.03 b ± 0.01	0.16 b ± 0.1
	Zeolite (Z)	1.75 c ± 1.41	0.03 b ± 0.02	0.1 b ± 0.06
	AE + Z	4.5 ab ± 0.7	0.04 ab ± 0.02	0.20 b ± 0.12

Tukey test ($p \leq 0.05$). Figures with the same letters within the same column are statistically equal. NFHPP = number of fruits harvested per plant. ± The value of standard deviation.

Finally, a simple Pearson correlation analysis showed a highly significant correlation ($p < 0.01$) among all variables, which means that plant height, stem thickness, plant vigor, and chlorophyll content index contributed to a greater number of fruits harvested per plant (NFHPP), weight of fruits harvested per plant (WFHPP), and the consequent yield of tomato per unit of surface area (kg m^{-2}) (Table 5).

Table 5. Correlation between growth, development, and physiological variables with yield and the components of tomato *Solanum lycopersicum* L. var. Saladette.

	CCI	PH	ST	VIG	NFHPP	WFHPP	YIELD
CCI	1.00000	0.54398 < 0.0001	0.36819 0.0002	0.52466 < 0.0001	0.50271 < 0.0001	0.53735 < 0.0001	0.53735 < 0.0001
PH		1.00000	0.42651 < 0.0001	0.53038 < 0.0001	0.3890 < 0.0001	0.50671 < 0.0001	0.50671 < 0.0001
ST			1.00000	0.42944 < 0.0001	0.31766 0.0016	0.29390 0.0037	0.29390 0.0037
VIG				1.00000	0.57788 < 0.0001	0.71558 < 0.0001	0.71558 < 0.0001
NFHPP					1.00000	0.73931 < 0.0001	0.73931 < 0.0001
WFHPP						1.00000	1.00000 < 0.0001
YIELD							1.00000

Simple Pearson correlation ($p < 0.01$) is highly significant. CCI = chlorophyll content index; PH = plant height; ST = stem thickness; VIG = vigor; NFHPP = number of fruits harvested per plant; WFHPP = weight of fruits harvested per plant.

4. Discussion

The accumulated rainfall in the study region from January to June 2024 was 30.4 mm, with maximum rainfall in February of 23.6 mm, which shows the non-interference of this environmental phenomenon in the moisture content of the soil in the open field since, at this time, the plants were growing in trays under controlled shade mesh conditions.

4.1. Plant Growth

The potential benefit of the organic and inorganic products on the plant was evident under suboptimum soil moisture content (25% ± 2), possibly by a biostimulant action influenced by better plant nutrition, as reported by Murnane et al. [24], and by improving the quantity of irrigation water [10]. Arminjon & Lefort [48] reported that applying plant growth-promoting microorganisms (PGPMs) at the seedling stage increased tomato productivity under salinity stress conditions, since the irrigation water in our experiment is based on using saline water pumped from a deep well [49].

Algae extract contains a great diversity of biomolecules such as phytohormones, amino acids, vitamins, and macro- and microelements to promote better plant vigor and growth [50]. Additionally, it contains active compounds such as polysaccharides, phenols, sterols, and betaines, which are biostimulants in the growth of plants [51], particularly in the early stages of tomato development, since the tomato seedling stage is sensitive to adverse environmental factors linked to the stomatal regulatory function [52]. Moreover, Ntanasi et al. [53] reported that tomato plants can respond and be resilient to adverse factors such as salinity through biostimulant activity induced by applying nutrient solutions based on algae extracts.

In addition, Sfechis et al. [54] conducted a review to highlight the potential of zeolite-based amendments in agriculture, reporting several benefits to plants. Chávez et al. [55] found that applying zeolite at the pre-harvest phase improves the growth of the tomato plant (*Solanum lycopersicum* L.). Zhang et al. [56] reported an improvement in growth parameters such as plant height, stem thickness, root length, and photosynthesis rate in tomatoes by applying zeolite. Additionally, applying macronutrients and zeolite together improves the physical–chemical properties of the soil and makes efficient use of water and nutrients for better plant growth [57,58]. According to Méndez et al. [59], tomato

seedlings in a substrate mixture with 30% zeolite had improved leaf area, root length, and stem diameter, but there was no significant effect on the chlorophyll index. Deshmuck et al. [60] reported that Si, which is contained in zeolite, could improve stomatal function and root hydraulic conductance by regulating aquaporins, while aluminum, also contained in zeolite, can stimulate plant growth, modulate the color of flowers, and increase the vase life of some plant species [61].

Thus, positive plant growth response shown by indicators such as plant height, stem thickness, and vigor, with treatment average values of 47.2 cm, 9.84 mm, and 9.1 when AE, Z, or AE + Z were applied, respectively, under suboptimum soil water content 28% below that of FC may be due to an increase in plant nutrient availability [16,17,24,35]. In particular, the application of Z showed, additional availability of nutrients due to better soil moisture retention [34]. However, in deficient soil moisture content (11% upper of PWP), the tomato plants were unable to respond to the biostimulant benefits applied either as AE, Z, or AE + Z, where the growth and yield indicators were negatively affected.

4.2. Physiological Indicators

Relative water content (RWC) is directly related to the plant's water potential [62], which is an indicator of tissue water content and is essential for continued metabolic activity and plant growth [63]. This variable was only biostimulated under suboptimal soil moisture content (25% 2), not under deficient conditions (20% 2), where biostimulants apparently no longer achieved their beneficial action and the response was equal to that of the control. The beneficial action at medium soil moisture content was achieved by applying AE, Z, or AE + Z at doses of 50 L h^{-1}, 10 f ha^{-1}, or 25 L ha^{-1} + 5 t ha^{-1}, respectively, mainly when AE was applied, suggesting that this organic product may be a viable alternative for mitigating water stress by maintaining better cell turgor and plant vigor [64,65] (Figure 5A).

Chlorophyl index is an indicator of photosynthesis, and this variable showed the lowest values of plant growth and chlorophyll index in the deficient soil moisture content (20% $\pm$ 2), with no statistical difference among treatments under deficient soil moisture content in comparison to the control (Figure 5B). These results suggest that the tomato plant is highly sensitive to water deficit, in accordance with the findings reported by Florido et al. [66]. AE and AE + Z were the best biostimulating treatments for the chlorophyll index under moderate soil moisture conditions (25% $\pm$ 2), compared to the control and Z. These results may be indicative that AE and AE + Z have an effect on chlorophyll stability in addition to the effect on maintaining the turgor of the cells through a better RWC, which allows better growth and development [64]. The effects of the applied biostimulants may be achieved through different routes, such as the availability of macronutrients and vitamins, and growth promotion [67].

Photosynthesis is directly linked to the water and chlorophyll content of the plant, due to the relationship between the stability of the cellular organelles responsible for the metabolic activity for the growth and development of the plant [56,68]. In this case, the best treatment was the application of zeolite, which suggests that it is related to the dual function of this inorganic compound, as a water retainer in the soil, and through the contribution of some microelements such as Si [28,29] and Al [30,31], among other minerals that act as nutrients. Also, Z could influence a greater availability of macro- and micronutrients for the plant by maintaining better moisture content in the soil [23,24]. Algal extract did not seem to have a biostimulating effect on photosynthetic activity under suboptimal soil moisture conditions (25% $\pm$ 2) and even less under water deficient conditions for the plant (20% $\pm$ 2).

4.3. Productivity Indicators and Tomato Yield

The application of either of the two products evaluated in this study failed to mitigate water stress in tomato plants under deficient soil moisture content. This suggests that the plant was unable to respond to the biostimulant action of algae extract and zeolite under extreme water stress conditions due to a general weakening of vigor and a high rate of flower absorption, with a significantly lower fruit production per plant and consequently a lower yield [69]. The worst and best response of chlorophyll content under deficient and suboptimum conditions of water availability in the soil is a result of the genotype–environment interaction effect, as reported by Majid et al. [70] in their study on chlorophyll content and yield of different maize cultivars under water stress conditions.

This means that if the objective is to make efficient use of water in drylands, medium–high-level irrigation can be sufficient for growing tomatoes and obtaining a moderate yield under open-field conditions in drylands. However, when the necessary water is available, irrigation can be applied to FC, where the response can be improved in terms of growth and tomato yield using either algae extract or zeolite or both together.

4.4. Tomato Yield

In terms of tomato yield, a very similar dynamic was recorded in the treatments under deficient soil moisture content (20% $\pm$ 2) but with less difference between them over time, where the control practically behaved the same as or slightly better than the treatments where the algae extracts and zeolite products were applied, mainly at the end of the growth stage, confirming the null compensatory or mitigation effect of these products under deficient soil moisture content. Contrary to these results, but under optimum irrigation conditions, Soca & Lorente [71], in a study with a mixture of zeolite and compost, found a positive effect on tomato yield. This suggests that the benefit of some biostimulants, such as algae extracts or zeolite, occurs under suboptimum (28% low FC) or deficient soil water (11% upper PWP) conditions, but the effect of mitigating environmental stress not occurs when the water stress is induced by soil moisture content close to the wilting point. Therefore, in agricultural areas with sufficient and high-quality water availability, biostimulant products can be useful for productivity purposes, and in agricultural areas with scarce and poor-quality water, these products can be useful for mitigating water stress and improving crop growth and yield.

The above confirms the beneficial action of the two organic and inorganic products, applied either together or separately, but only when there is a suboptimum soil moisture content close to FC. The productivity increases shown in tomato yield and its components, such as the number of fruits per plant and the weight of fruits per plant, are sufficiently encouraging to justify promoting tomato productivity in areas where water is not a limiting resource. The average tomato yield under suboptimum soil moisture (25% $\pm$ 2) in the open field is 9 t ha^{-1} when applying algae extract, for instance, which can be considered relatively low. However, the very unfavorable environmental conditions of the region must be considered, particularly the extremely high temperatures of greater than 35 °C in summer and water with a high salt content with an electrical conductivity of approximately 2.5 dS m^{-1}, very close to the maximum value of 3 dS m^{-1} allowed for irrigation water based on the Official Mexican Standard NOM-127-SSA1-2021 [72], although its effect is cumulative, and the value can reach and exceed this limit over time. Mesa et al. [73] reported that tomato is widely affected by temperatures above 32 °C, resulting in decreased fruit production even when the plant produces antioxidant activity to mitigate heat stress, while Biglia et al. [74] showed that tomato plants are sensitive to water and salt stress, similar to the conditions under which the tomato plants were studied in the open field in this study.

Zeolite and algae extracts contain beneficial elements such as silicon and aluminum. There is evidence that silicon modulates the secondary metabolism of plants, thereby increasing antioxidant responses to biotic and abiotic stresses [29]. Silicon may alleviate the effects of several environmental stress factors, such as drought, salinity, pests, and diseases [61]. In tomato grown under suboptimum soil moisture conditions and high temperatures, it is likely that the silicon contained in the zeolite and algae extract contributed to a better response by reducing deleterious effects and promoting a greater number of fruits, with a higher weight and final yield than control plants.

Also, extreme temperatures recorded from March onwards could have influenced the response of the tomato yield. This is because the plant is very susceptible to high temperatures, causing flower abortion, which reduces the number of fruits per plant and, therefore, decreases the tomato yield per hectare [74]. This extreme environment is the main reason why tomato cultivation in the region is carried out under greenhouses, which increases production costs and reduces the harvested area [75], hence the interest in evaluating some innovative management practices that can mitigate plant stress under open-field conditions.

Overall, the lack of response to algae extracts and zeolite under deficient soil moisture content close to PWP suggests that the plant is entering a severe stress condition that inhibits the response to the biostimulating effects of these organic and inorganic products. Thus, a medium–high and possibly optimum water content to trigger the physiological processes for good plant growth and yield is required [76].

Finally, according to the Pearson Simple Correlation, the results suggest that with a higher chlorophyll content, there is greater photosynthetic activity that produces a greater quantity of photo-assimilates, which results in greater plant growth, better vigor, and, therefore, a higher tomato yield per unit of surface area. Murshed et al. [77] reported antioxidant activity as a mitigation mechanism for water stress during the fruiting phase of tomato (*Solanum lycopersicum* L.). Xiao et al. [78] reported that the intensity and quality of light influence plant growth and leaf size in tomatoes. Studies in tomato found that chlorophyll content, photochemical efficiency of PSII, and the activities of superoxide dismutase (SOD) and catalase (CAT) increased due to silicon application, reducing the negative effects of salt stress. One of the possible effects of algae extracts and zeolite may be related to their silicon content [79]. It is recognized that a series of adaptation strategies are involved in the tomato plant, mainly the redox activities of antioxidants that activate cellular processes to mitigate oxidative stress and induce acclimatization to drought [80]. In this way, plants have developed complex physiological and biochemical adaptations to adjust and adapt to a variety of environments that produce stress [81].

5. Conclusions

These results provide some highlights into the use of algae extract applied at a rate of 0.8 mL L^{-1}, or algae extract and zeolite (AE + Z) at a rate 0.4 mL L^{-1} and 10 t ha^{-1}, respectively, since they were the best treatments, with tomato yield up to 333%, and 442% higher than the control, respectively, under suboptimum soil moisture content (25% $\pm$ 2). This increase in the tomato yield was obtained due to a favorable response of biostimulation in growth and physiological indicators such as plant height and plant vigor, as well as chlorophyl index, relative water content, and photosynthesis. Tomato plants were unable to respond to the biostimulant action of these products to mitigate plant stress induced by deficient soil moisture content (20% $\pm$ 2). This is relevant to water-scarce agricultural areas, where more efficient water use is imperative. The findings of this study show that tomato cultivation with moderate irrigation is possible by supplementing the application

of biostimulants such as algae extract and zeolite, which mitigate water stress without the need for field capacity irrigation (30%), thereby saving water in dry areas.

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