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Influence of Brown Seaweed (*Ecklonia maxima*) Extract on the Morpho-Physiological Parameters of Melon, Cucumber, and Tomato Plants

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Abstract: In this study, we evaluated the impact of brown seaweed extract (*Ecklonia maxima*) on the morphology and physiology of three different plant species. We conducted experiments using two types of fertilizers: an artificial fertilizer (0.1 g/L) and a biological extract of brown seaweed (*Ecklonia maxima*) at two concentrations (C1 at 1 mL/L and C2 at 2.5 mL/L). For melon, the application of C1 resulted in significant improvements in photosynthesis parameters, total chlorophyll content, and overall plant growth. When C2 was applied, it further enhanced these parameters, leading to a notable increase in shoot phytomass. In the case of cucumber, C1 led to increased resource allocation towards stems and leaves. Conversely, C2 increased the number of green leaves and contributed to higher shoot phytomass. For tomato plants, the application of C1 resulted in a slight increase in photosynthesis, but it did not significantly impact leaf growth. On the other hand, C2 induced a modest increase in photosynthesis, chlorophyll content, and root growth. In summary, our findings indicate that brown seaweed extract has a discernible influence on the physiology of the studied plants. However, the specific effects on resource allocation largely depend on the plant species and the concentration of the extract applied.

Keywords: brown seaweed extract; *Ecklonia maxima*; plant physiology; photosynthesis; resource allocation; growth enhancement

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1. Introduction

Algae can occur as red, green, or brown algae, with *Ecklonia maxima* being a brown alga [1–3]. Brown algae is the common name for the class Phaophyceae, which belongs to the phylum Ochrophyta [4]. Plant biostimulants are a diverse classification of substances that can be added to the environment around a plant and have positive effects on plant nutrition and growth [1,5,6]. Algae species are often considered underutilized bioresources, due to their use in industrial raw materials and therapeutic and botanical applications [7]. Ali et al. [8] reported that algal extracts are considered biostimulants, not fertilizers, as they promote both plant defense mechanisms and growth responses upon application. Additionally, the composition of algal extracts does not inherently contain a sufficient concentration of fertilizer components to classify them as fertilizers. Recent attention has been directed towards seaweed-based extracts due to research findings demonstrating the presence of diverse biostimulatory compounds within these complex mixtures. These

compounds include various types of carbohydrates, amino acids, limited quantities of phytohormones, osmoprotectants, and proteins. Many categories of specific biostimulants have been the subjects of numerous studies, such as seaweed extracts [7,9], humic and fulvic acids [10], protein hydrolysates [11], and silicon [12].

Biostimulants enhance plant nutrition, with the sole purpose of improving one or more of the characteristics of plants or their rhizosphere. Such characteristics include the efficiency of the use of nutrients present in the environment or supplied via fertilizers and the availability of nutrients confined to the soil or rhizosphere. The growth-stimulating effects of seaweed extracts have been documented in many species [5,6,12,13]. However, the variable and complex nature of these substances makes it difficult to determine exactly which components play key roles in the functioning of a biostimulant [14]. Indeed, characterizing the current composition of the most common commercial seaweed products would be a useful first step to better hypothesize and/or describe, through a cause-and-effect relationship, and their mechanism of action. Mechanical disturbance, spraying, and acid or alkaline extractions are among the most commonly used methods to obtain biostimulants [7].

To survive, plants need water, CO_2, solar energy, and nutrients present in the soil. The best way to feed a plant is to regularly incorporate compost or composted manure or supplement it with fertilizers [15,16]. Using various types of composts and manures over the years ensures that plants will have access to a full range of nutrients [15]. In addition, various raw materials have been used in biostimulating compositions, such as humic acids, hormones, seaweed extracts, and plant growth-promoting bacteria.

Furthermore, Benítez García et al. [17] remain uncertain as to whether enhancements in crop yield and production attributed to the use of algal extracts result from the presence of plant growth regulators (PGRs) in the organic matter of algae or whether other metabolites may also contribute to their biostimulant effects. Consequently, there is a need to investigate the chemical and bioactive composition of newly prepared algal extracts to assess their potential utility as stimulants for plant growth.

Fertilizers are substances intended to provide plant nutrition and to be used in addition to compost. Fertilizers are used in cases of mineral deficiency, in order to increase plant vigor and yield, and also when cultivated plants are very demanding on fertilizer. There are two groups of fertilizers, namely natural fertilizers and artificial fertilizers. However, the disastrous effect of the massive use of artificial fertilizers on the quality of agricultural production and the biological activity in the soil, and even natural resources, suggests a need for other alternatives such as organic fertilizers [18]. One of the basic rules of organic farming is the total ban on synthetic fertilizers [19]. Fertilizers of organic origin (plant or animal residues) or of mineral or biological origin currently represent a promising alternative for sustainable agriculture [20]. Among organic fertilizers, algal extracts and other biofertilizers have recently been used as an alternative to artificial fertilizers [21].

Brown seaweed extracts, rich in plant growth regulators (PGRs) like auxins, cytokinins, gibberellins, and abscisic acid, are prized in horticulture [1–5]. They enhance plant growth, support root development, stimulate cell division, elongate stems, and bolster stress tolerance [6]. Unlike green and red seaweeds, brown seaweeds offer a comprehensive range of PGRs, making them preferred biostimulants [5]. In summary, brown seaweed extracts are essential for robust crop growth and resilience, addressing multiple growth aspects and environmental challenges [1–5].

These extracts improve leaf gas exchange and photosynthetic pigment, protein, and carbohydrate content [22,23]. They also ensure an increase in growth, phytomass production, and yield [2,3,23,24]. Kelpak® seaweed concentrate is made from *Ecklonia maxima* (Osbeck). This solution is used for the correction of soils lacking nutrients (N, P, and K) [1] and showing salt stress [2] and in hydroponics [3,24]. Indeed, it is a genuine source of PGR nutrients, as well as minerals, amino acids, and vitamins [24,25]. The chemical constituents of seaweed extract encompass complex polysaccharides, fatty acids, vitamins, PGRs (plant growth regulators), and mineral nutrients [1,6]. Recent research has shed light on possible

molecular mechanisms activated by seaweed extracts. The chemical constituents of kelp extracts and the physiological effects they induce on plants with particular reference to horticultural crops have previously been reported [3,6].

The benefits of the application of algae in the agricultural field are many and diverse, such as the stimulation of seed germination; the improvement of plant health and growth, namely the elongation of shoots and roots; improved water and nutrient absorption [6]; and enhanced frost and salt tolerance. In addition, biological control and resistance to phytopathogenic organisms, the depollution of contaminated soils, and fertilization are also enhanced by algal extracts [26]. Additionally, seaweed and seaweed-derived products have been widely used as amendments in agricultural production systems due to the presence of a number of plant growth-stimulating compounds. However, the biostimulant potential of many of these products has not been fully exploited due to the lack of scientific data on the growth factors present in algae and their mode of action on plant growth [24]. Algae-based fertilizers have been created to improve germination, deeper root penetration, nutrient uptake, and the yield of the treated crop. Seaweed extracts as biostimulants are emerging as commercial formulations for use as plant growth stimulators and as a method to improve salinity, heat, and drought tolerance [2,5]. Seaweed extracts, containing phytohormonal PGRs, minerals, amino acids, and vitamins [24,25], enhance stress tolerance by targeting multiple pathways. For instance, they can influence the abscisic acid (ABA) signaling pathway, improving drought tolerance in crops [26]. Seaweed extracts target a number of pathways to increase stress tolerance by mitigating its harmful effects; plants employ various natural defense mechanisms. Specifically, reactive oxygen species (ROS) are neutralized through a system of both enzymatic and non-enzymatic antioxidants, including but not limited to superoxide dismutase (SOD), guaiacol peroxidase (GPX), catalase (CAT), and ascorbate peroxidase (APX) [27].

Melon, cucumber, and tomato are among the most cultivated vegetables in the world [27,28] and are of significant economic interest. They are sensitive to unfavorable soil water conditions [29]. Thus, the comparative use of chemical fertilizers and biological biostimulants will make it possible to compare their efficiency in improving crop performance. In this context, knowledge of the physiological effects of these biological extracts, as well as their most suitable concentrations for plant growth promotion, is needed. Thus, this work aims to study the effect of brown seaweed extract (*Ecklonia maxima*) on (i) plant growth, (ii) photosynthetic gas exchange, and (iii) resource allocation and phytomass production in melon (*Cucumis melo* L.), cucumber (*Cucumis sativus* L.) and tomato (*Solanum lycopersicum* L.).

2. Materials and Methods

2.1. Plant Material and Culture Conditions

The tested vegetable crops were melon (*Cucumis melo* L.), cucumber (*Cucumis sativus* L.), and tomato (*Solanum lycopersicum* L.). After one week of germination, the seedlings obtained were transplanted in pots of 1 L capacity (height 20 and diameter 18 cm), which contained well-washed sand to avoid the interference of the nutritive elements of the ground. The experiment was performed in the greenhouse of the Faculty of Sciences of Gafsa at 25 °C, relative humidity of 70%, and a photoperiod of 13 h/11 h (light/darkness). The application of the treatments started on 2 May 2014 and the irrigation was 50 mL per pot. Plants were grown in a mixture of sand and clay soil (2/3:1/3). Five leaves were marked, from newly emerged stage leaves (L1) to aged physiological stage leaves (L5). The fertilizing treatments were carried out for two weeks of growth, after which the measurements began. From stage L5, no difference between the treatments was clear. Three fertilizing treatments were applied for each species. For the control treatment, seedlings were irrigated with a solution of an artificial fertilizer (0.1 g/L), whose composition was as follows.

The product originates from the extract of brown algae (*Ecklonia maxima*), sourced from the marine area of South Africa. The algae grow only in clean, cold waters off the

Atlantic coast of southern Africa. The Benguela current is rich in nutrients and experiences the powerful action of the tides. The algae are sorted, cut into manageable sizes, and washed (Technologie Cellulaire Froide). They were processed by a German company and are commercially available in Tunisia under the name "Kelpak®" algae concentrate. Kelpak Liquid Algae Biostimulant promotes a healthy root system, stronger stems, and leaf growth, ensuring your plants become more tolerant to abiotic stresses. This commercial product contains 79% *Ecklonia maxima* seaweed extract and can be used in organic agriculture in compliance with European regulations. For the plants treated with the chemicals, the Macronutrient (%) ratios are the following—NO_3: 4.4; NH_4: 3.0; Urea Nitrogen 1:2.6; P_2O_5: 20; and K_2O: 20. For the trace elements, the percentages are the following—B: 0.01; Fe: 0.02; Mn: 0.01; Mo: 0.001; and Zn: 0.002.

For the plants treated with the seaweed extract, two concentrations were applied: C1 (0.5 mL litre^{-1} distilled water) and C2 (2.5 mL litre^{-1} distilled water). The composition of the seaweed extract is as follows. The Macronutrients (%) are Nitrogen (N): 0.2; Phosphorus (P): 1; and Potassium (K_2O): 0.2. The trace elements (mg kg^{-1}) are the following—B: 0.25; Cu: 0.17; Fe: 0.61; Mn: 0.01; Zn: 0.56; and MB: 0.11. Other ingredients are as follows—carbohydrates: 4.38%; Cytokinin: 0.03 mg L^{-1}; Auxin: 11 mg kg^{-1}; protein: 4.95%; amino acids: 0.25%; and ash: 1.57%.

2.2. Parameters Measured

2.2.1. Morpho-Physiological Parameters

Leaf midrib length was measured using a graduated ruler for the different leaf stages and treatments (expressed in cm). Leaf specific weight (SLW) was defined as the ratio of leaf dry mass (DL) to corresponding leaf area (LA) and expressed in g cm^{-2}, and it was measured for the different leaf stages and treatments. The number of green leaves and plant height were determined for each species and treatment at the end of the trial. The phytomass values of the shoots and the roots were determined at the end of the experiment after washing the seedlings with water to remove the sand from the fine roots. The shoots were separated from the roots, and then, the shoot phytomass (SP in g plant^{-1}) and the root phytomass (RP in g plant^{-1}) were measured after being dried in an oven at 80 °C for 48 h. The RP/SP ratio was defined as the ratio between the phytomass of the roots (PR) and the phytomass of the shoots (SP). It is given as follows: Rate = (RP/SP) × 100

2.2.2. Photosynthetic Parameters

Leaf gas exchange was measured using a portable photosynthesis system, LCi (ADC BioScientific Ltd., Hoddesdon, UK), in the morning (11 to 12 h). Measurements were taken on different foliar stages for each plant as follows—F1: (youngest leaf); F2; F3; F4; and F5 (oldest leaf), in 4 replicates for each type of leaf and each treatment. Active photosynthetic radiation (PAR) was fixed at 1000 µmole photon m^{-2} s^{-1} and the temperature of each leaf was 25 °C. Several parameters were measured simultaneously to include the rate of net photosynthesis (A, expressed in µmol CO_2 m^{-2} s^{-1}), the rate of transpiration (E, expressed in mole H_2O m^{-2} s^{-1}), and Stomatal conductance (gs, expressed in mole H_2O m^{-2} s^{-1}). The internal CO_2 concentration (Ci, expressed in µmole CO_2 m^{-2} s^{-1}) was calculated. The data recorded in the measuring apparatus were then transferred to a computer and plotted in the software Hyperterminal Private Edition.

2.2.3. Total Chlorophyll Content

The total chlorophyll content was determined using a Chlorophyll Content Meter (CCM 200). The measurement procedure was to place the leaf (the fourth leaf after the emergence leaf) in the leaf chamber. An index called CCI (Chlorophyll Content Index) was displayed on the screen of the device at each measurement (OS1-FL system, Opti-Sciences Hudson, NH, USA). Optical absorbance in two different wave ranges—653 nm (chlorophyll) and 931 nm (near infrared)—was read. Measurements were taken randomly during the experiment.

2.3. Statistical Analyses

All data underwent a two-factor analysis of variance (ANOVA, p), considering the fertilization treatments and leaf age (ranging from L1 to L5), for the species melon, cucumber, and tomato. A comparison of means was made for all treatments, and tests for leaf age were performed based on the Duncan test at 5%. All data were subjected to statistical analysis using SPSS statistical software, version 11.5 (SPSS Institute, Inc., Cary, NC, USA).

3. Results

3.1. Variation in Morpho-Physiological Characteristics

In the three species, the midrib length was not influenced by the algal extract, but this parameter increased significantly from L1 to L5 for melon and cucumber ($p \leq 0.001$) and much less in tomato ($p \leq 0.05$) (Figure 1A, Figure 1B, and Figure 1C, respectively). In the three species, the specific weight of the leaves was not affected by the three treatments with the extract of the algae, but it decreased significantly from L1 to L5 for melon and cucumber ($p \leq 0.05$).

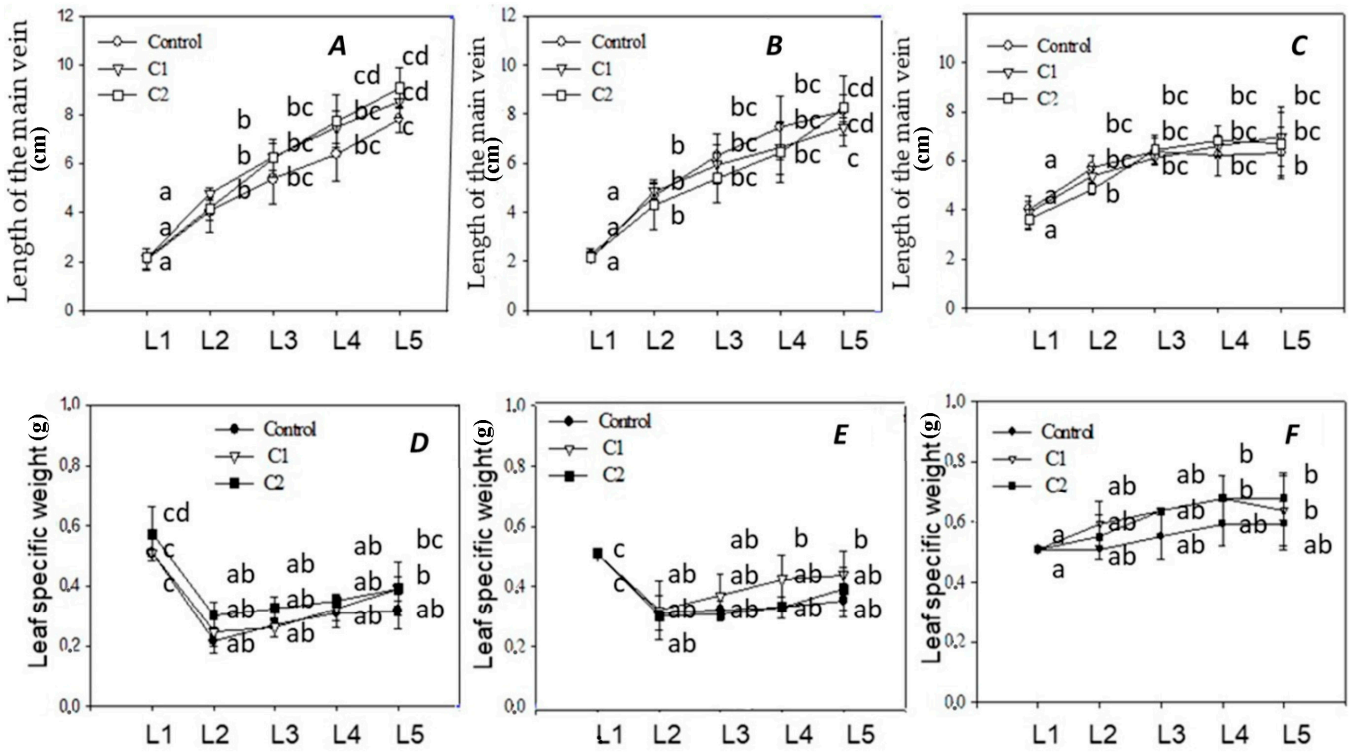

Figure 1. Effect of the algal extract on the length of the main vein of the leaves (cm) and the specific leaf weight (g/cm^2) of melon (**A**,**D**), cucumber (**B**,**E**), and tomato (**C**,**F**). Each value is the average of six replicates. The vertical bar represents the standard deviation of the average. Means followed by the same or common letters are not significantly different across the three species according to the Duncan test at 5%.

C1 and C2 increased the numbers of green leaves in the melon ($p \leq 0.05$) and the cucumber ($p \leq 0.001$) plants, but they did not have a significant effect on tomato (Figure 2A). The height of the plants was improved only for melon and cucumber ($p \leq 0.001$), but not for tomato, except for the treatment with C2, where this parameter increased (Figure 2B). The shoot phytomass increased significantly for the three species, especially for the cucumber ($p \leq 0.01$) and melon ($p \leq 0.01$) (Figure 2C) plants. Root growth was enhanced by the algal extract, especially for the tomato ($p \leq 0.01$) and cucumber ($p \leq 0.001$) plants treated with C1 and C2 (Figure 2C), whereas melon root growth was not affected (Figure 2D).

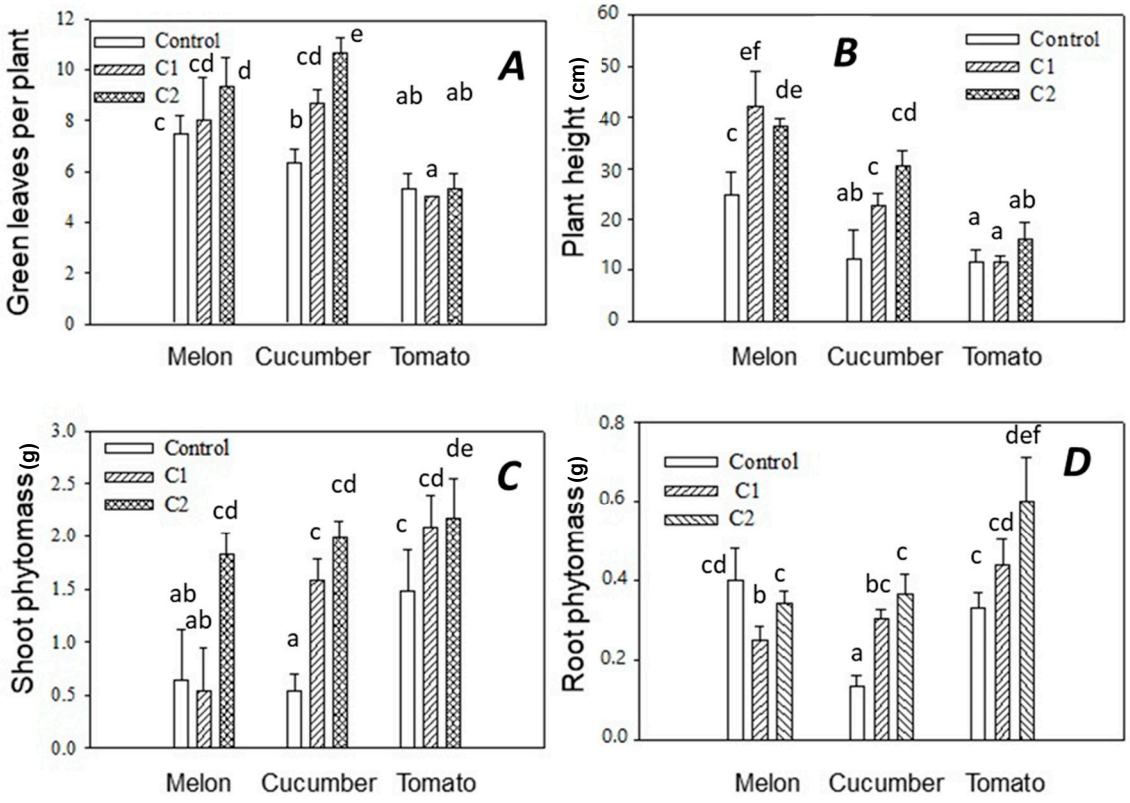

Figure 2. Effect of the algal extract on the number of green leaves (**A**), plant height (**B**), shoot phytomass (**C**), and root growth (**D**) in melon, cucumber, and tomato. Each value is the average of six replicates. The vertical bar represents the standard deviation of the average. Means followed by the same or common letters are not significantly different across the three species according to the Duncan test at 5%.

3.2. Variation in Photosynthetic Characterization

The results showed that the algal extract increased gs only in the oldest leaves in melon (L3–L5) compared to the control ($p \leq 0.001$) (Figure 3A). With regard to cucumber, only the C1 concentration increased gs for L1, L2, and L3. The C2 treatment, on the contrary, reduced gs for all leaves in melon ($p \leq 0.001$). The effect of this extract on tomato revealed that C1 improved gs, starting from L2, but it was only in L2 that C2 caused a significant increase in gs ($p \leq 0.05$).

Under the control treatment, for the melon seedlings, the photosynthesis was maximal exclusively for the leaf type L2, followed by a gradual decrease thereafter (Figure 3D); on the contrary, the algal extract improved A for the leaves L2, L3, L4, and L5 ($p \leq 0.001$). For cucumber, extracts from the algae increased A only for the youngest leaves treated with C1; C2 reduced A, especially for the old leaves in cucumber ($p \leq 0.001$) (Figure 3E). For tomato, the positive effect of the algae extract appeared only for the leaves L2 and L3 when treated with C2 ($p \leq 0.05$) (Figure 3F).

The algal extract increased transpiration in melon, especially for L3, and for L4 and L5, i.e., the oldest leaves. The differences between C1 and C2 were clearer on the youngest leaves ($p \leq 0.01$). For cucumber, E was improved for the leaves L1, L2, and L3 using the concentration C1 whereas C2 improved only the L1 leaves when compared to the control ($p \leq 0.05$). On the contrary, the algal extract increased E in almost all the leaves of tomato ($p \leq 0.001$) (Figure 4C).

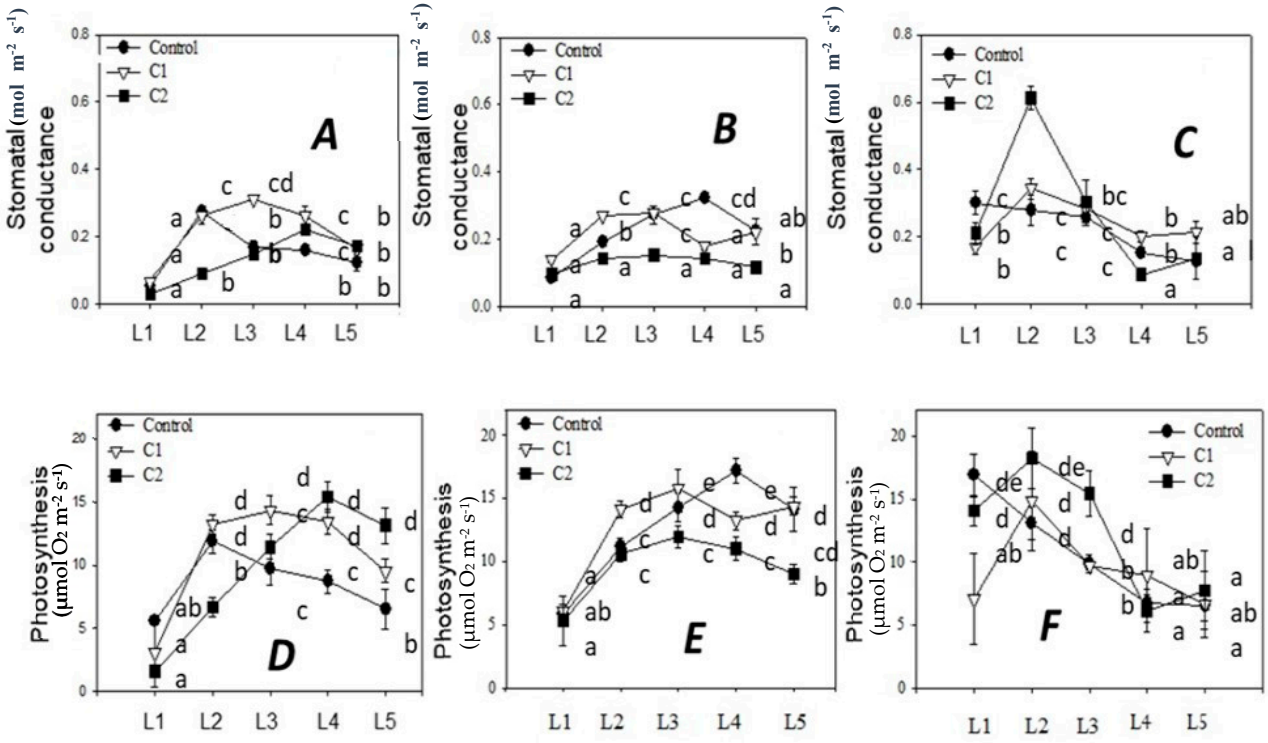

Figure 3. Effect of the algal extract on stomatal conductance and photosynthesis in melon (**A**,**D**), cucumber (**B**,**E**), and tomato (**C**,**F**). Each value is the average of six replicates. The vertical bar represents the standard deviation of the average. Means followed by the same or common letters are not significantly different across the three species according to the Duncan test at 5%.

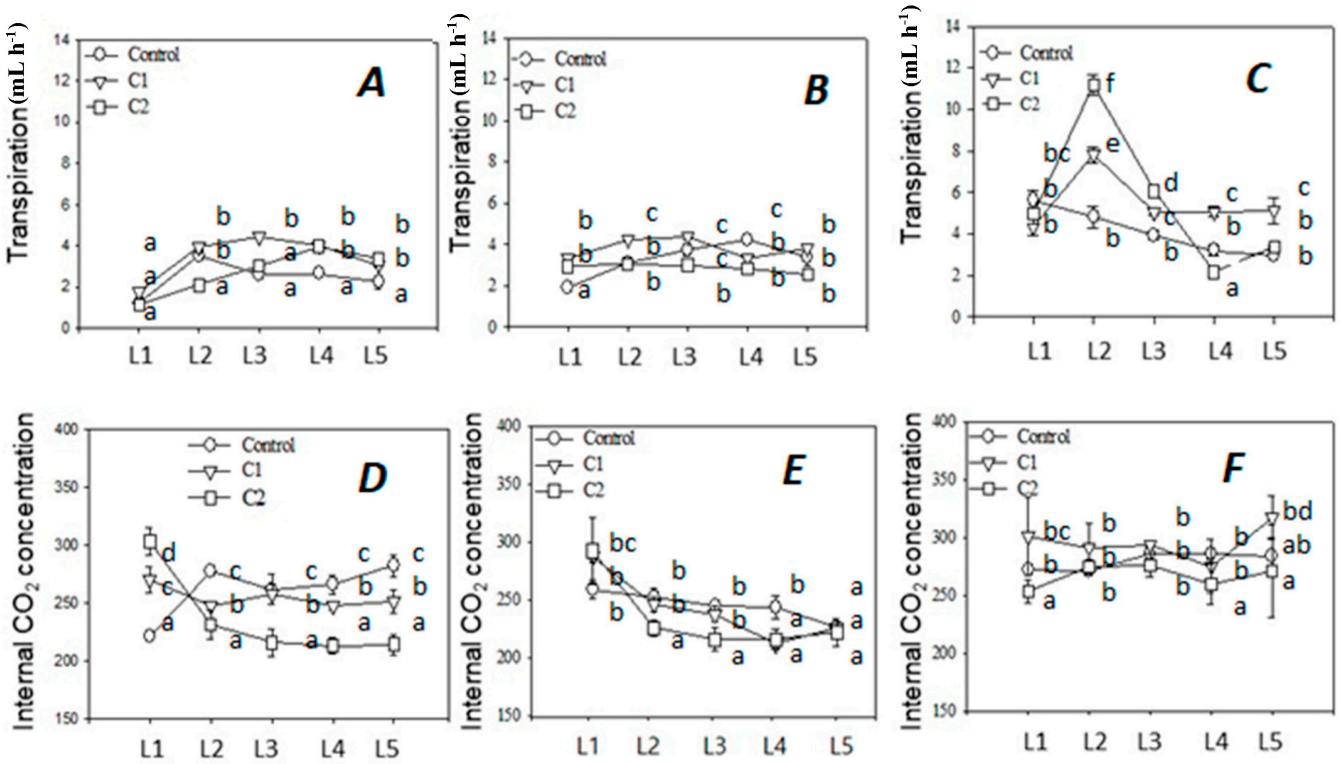

Figure 4. Effect of the algal extract on transpiration and internal CO_2 concentration in melon (**A**,**D**), cucumber (**B**,**E**), and tomato (**C**,**F**). Each value is the average of six replicates. The vertical bars represent the standard deviation of the average. Means followed by the same or common letters are not significantly different across the three species according to the Duncan test at 5%.

The algal extract reduced Ci of the various types of melon leaves. The lowest values were for the leaves treated with C2 ($p \leq 0.001$) (Figure 4D). For cucumber, the effect of the extract of algae on the Ci was low. However, for tomato, C1 slightly increased the Ci for the various types of leaves.

3.3. Variation in the Total Chlorophyll Content

The results obtained showed that the two concentrations (C1 and C2) of the algal extract increased the chlorophyll content in melon (Figure 5A), which was more pronounced for the old leaves treated with C2 ($p \leq 0.001$). For the cucumber plants, the significant effect of the extract of algae was observed only for L3 and L4 treated with C2 ($p \leq 0.01$) (Figure 5B). Concerning tomato, in general, C2 slightly increased the total chlorophyll content while C1 reduced this parameter (Figure 5C).

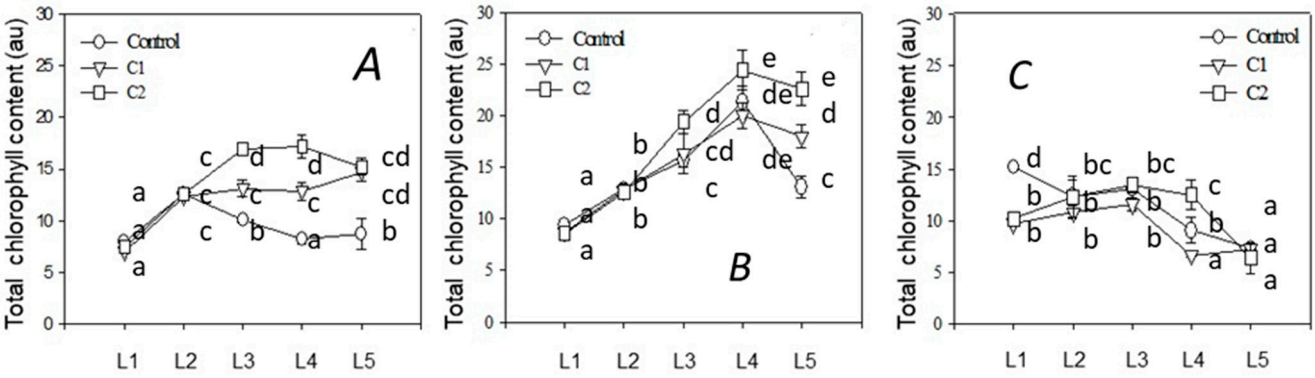

Figure 5. Effect of the algal extract on the total chlorophyll content for melon (**A**), cucumber (**B**), and tomato (**C**). Each value is the average of six replicates. The vertical bars represent the standard deviation of the average. Means followed by the same or common letters are not significantly different across the three species according to the Duncan test at 5%.

4. Discussion

4.1. Effects of Seaweed Extract on Plant Physiology

The photosynthetic improvement of gaseous exchange is explained by the fact that the algal extract increases the content of photosynthetic pigments, which induce an increase in the transformation of light energy into chemical energy, which is useful for the assimilation of CO_2 and carbohydrate synthesis [22,30,31]. This result can be attributed to an increase in electron transport and a more favorable energy metabolism. The seaweed extract from *Ascophyllum nodosum* did not affect leaf gas exchange, yield, or cluster and berry size in grapevine [9,23]. Increased salinity in nutrient solution resulted in decreased marketable yield, shoot biomass, net CO_2 assimilation rate (A), and transpiration rate (E) in *Ecklonia maxima* [2,23].

Indeed, seaweed extract acts as a new biofertilizer that supplies nutrients, growth regulators, polyamines, enzymes, carbohydrates, proteins, and vitamins essential for plant growth. PGRs like auxins and cytokinins stimulate the synthesis of proteins and nucleic acids. Some growth regulators (cytokinins and auxins) and other ingredients (amino acids, proteins, and vitamins) in seaweed extract have positive effects on plant physiology, mediated by improved mineral nutrition [25,26].

Our results agree with other work regarding the observations made for extracts of green algae in grapevine [9]. The better development of the root system likely contributes to a more efficient synthesis of the plant's own cytokinins and explains the results obtained [14,17]. In addition, auxins induce a drop in pH in the cell walls. This increases their plasticity, thus stimulating cell elongation. In addition, this plasticity of the cell wall allows better penetration and, therefore, the better assimilation of nutrients via the foliar route [14,26]. This may explain the observed growth promotion induced by the algal extract [14].

Seaweed extract represents a renewable resource that can be used as a biofertilizer, as a supplement in organic farming, and/or as a supplement to artificial fertilizers for various types of crops [14]. This organic fertilizer contains phytohormones (auxin and cytokinin), nutrients, and trace elements that improve plant growth [17]. In addition, it increases seed germination and phytomass [32]. It also improves soil fertility and the biological activity of microorganisms [33]. Biofertilization is a sustainable agricultural practice that includes the use of biofertilizers to increase nutrient content, resulting in higher productivity [14,25]. The addition of preparations from seaweed species such as *Sargassum* sp. and *Gracilaria verrucosa* induces chemical changes as an indicator soil fertility factor on clay and sandy soils, and adding an algae conditioner to the soil can improve its organic composition [14,25].

Ascophyllum nodosum seaweed extract improved anthocyanin accumulation and increased the content of phenolics in Sangiovese grapes [7]. Therefore, the mid-late application of seaweed extract can be a simple way to promote the chromatic and chemical properties of grapes and wines. Alongside their nutritive effects on plants, algal extracts have protective antifungal [32] and pesticidal [34,35] effects.

4.2. Effects of Seaweed Extract on the Three Studied Plant Species

4.2.1. Melon

The addition of the algal extract at the C1 concentration improves stomatal opening (as revealed by a high stomatal conductance (gs)). This is associated with increased CO_2 assimilation and increased transpiration [2,36]. Increased transpiration increases the absorption of water by the roots. Additionally, the algal extract increased the total chlorophyll content and improved leaf growth and plant height. Similar observations have been made in other crops [2,23,25]. In addition, the C1 concentration further increased shoot phytomass in melon. The application of the algal extract at a higher concentration (C2) increased the rates of net photosynthesis (A) and transpiration (E), as well as the total chlorophyll content, accompanied by improvements in leaf growth. This agrees with previously reported increases in the number of green leaves and plant height (C2). In conclusion, the high concentration promotes shoot phytomass in melon. The C2 concentration is, therefore, optimal for the promotion of growth and development of this species.

4.2.2. Cucumber

The addition of seaweed extract at the low concentration (C1) induces a slight increase in stomatal conductance (gs) and the rate of transpiration (E). On the contrary, it has no effect on the total chlorophyll content. This extract leads to an increase in the number of green leaves and the height of the plant. According to the results, the C1 concentration in cucumber induces an allocation of resources in favor of the root, which agrees with observations previously made for seaweed extracts [37]. The application of the algal extract at a high concentration (C1) induces a reduction in the rates of net photosynthesis (A), stomatal conductance (gs), and the rate of transpiration (E), but results in an increase in the number of green leaves and plant height [23]. Similar work on seaweed extract has been reported [2]. Our results suggest that resource allocation is in favor of leaves and stems, and such results are in line with those reported previously for seaweed extract [27,29]. Comparing the effects of the two concentrations, there are no clear differences between normal and high concentrations.

4.2.3. Tomato

Fertilization with the algal extract (at a low concentration) increases stomatal conductance (gs) and the rate of transpiration [E] [28], but has no net effect on leaf growth. Regarding the production of phytomass, the C1 concentration promotes the development of the aerial part and the roots, and this agrees with previously reported results involving seaweed [2]. The high concentration (C2) of the algal extract increases the rates of net photosynthesis (A), transpiration (E), total chlorophyll content, and root growth [6,37]. The

improvement of the physiological state of the plant after the foliar application of seaweed extract has been reported for different species [22,25,37]. Seaweed extract influences plant physiology by increasing photosynthetic exchanges and, consequently, the growth of shoots and roots [6]. The general response depends largely on the species and the concentration applied [23,29].

4.3. Comparative Effects of Algal Extract on Three Plant Species

When examining the effects of the algal extract on the three species, distinct trends emerge. In the case of melon, a low concentration (C1) promotes increased stomatal opening, resulting in higher stomatal conductance (gs), enhanced CO_2 assimilation, and increased transpiration, all while improving leaf growth, plant height, and total chlorophyll content. The higher concentration, C2, further intensifies net photosynthesis and transpiration, reaffirming enhanced leaf growth [23]. Cucumber responds differently, with C1 inducing slight increases in gs and transpiration along with resource allocation towards the roots, while C2 decreases net photosynthesis and transpiration but favors leaves and plant height. Lastly, tomato responds to C1 by increasing gs and E without a net effect on leaf growth, promoting both aerial and root development, whereas C2 enhances net photosynthesis, transpiration, chlorophyll content, and root growth [6,23]. Thus, responses to algal extracts vary across species and concentrations, highlighting the importance of plant specificity in these interactions.

5. Conclusions

Seaweed extracts represent a renewable resource that can be used as a biofertilizer. An artificial (chemical) fertilizer showed less effectiveness than the organic extract of brown algae *Ecklonia maxima* (C1 and C2).

For melon, C1 increased photosynthesis, total chlorophyll content, and plant growth, while C2 induced an increase in these parameters.

For tomato, C1 caused a slight increase in photosynthesis but did not affect leaf growth. C2 induced a slight increase in photosynthesis, chlorophyll content, and root growth.

As for cucumber, both C1 and C2 favored stem and leaf development.

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