


## Article

# Desalinated Seaweed-Based Biochar-Amended Vermicompost as a Coco Peat Substitute for Tomato (*Solanum lycopersicum*) Seedling Production and Growth

Elia N. M. Ruben<sup>1,2</sup>, Nils Haneklaus<sup>3,\*</sup> , Simeon S. Hamukoshi<sup>4,5</sup>, Bethold Handura<sup>1</sup> and Hupenyu A. Mupambwa<sup>1</sup> 

<sup>1</sup> Sam Nujoma Marine and Coastal Resources Research Centre, University of Namibia, Sam Nujoma Campus, Private Bag 462, Henties Bay 13005, Namibia; rubenelia6@gmail.com (E.N.M.R.); bhandura@unam.na (B.H.); hmupambwa@unam.na (H.A.M.)

<sup>2</sup> Department of Crop Production and Agricultural Technologies, University of Namibia, Ogongo Campus, Private Bag 5507, Oshakati 15001, Namibia

<sup>3</sup> Faculty of Earth Sciences, Geography and Astronomy, University of Vienna, 1090 Vienna, Austria

<sup>4</sup> Namibia Green Hydrogen Research Institute, University of Namibia, Private Bag 13301, Windhoek 10005, Namibia; shamukoshi@ncrst.na

<sup>5</sup> National Commission on Research, Science and Technology, Private Bag 13253, Olympia, Windhoek 10005, Namibia

\* Correspondence: nils.haneklaus@univie.ac.at

## Abstract

Soilless horticultural media offer a solution to limited arable land but are often nutrient-inert, requiring efficient nutrient management strategies. This study aimed to evaluate the potential of seaweed biochar-amended vermicompost (VC) as a nutrient-supplying growing medium for tomato (*Solanum lycopersicum* L.) seedling establishment and vegetative growth. Coco peat was progressively replaced with VC (0–100%, *w/w*) under fertilized and unfertilized conditions during seedling development, and selected treatments were further evaluated during vegetative growth. Growth parameters, including emergence, plant height, leaf area, stem diameter, biomass, and chlorophyll content, were measured. Treatments significantly affected ( $p < 0.05$ ) all parameters. The highest VC level (100%) reduced seedling emergence by 10.42% compared to the control but significantly improved seedling height (13.69 cm) and leaf area (49.45 cm<sup>2</sup> plant<sup>-1</sup>) under fertilized conditions. During vegetative growth, the control (0% VC) produced the highest biomass (9.55 g) and plant height (67.43 cm), while higher VC rates (75–100%) enhanced chlorophyll content and maintained acceptable plant growth. Overall, VC showed potential as a sustainable growing medium component for tomato production, although plant responses varied according to growth stage and incorporation rate. Reduced emergence at higher VC levels indicates that further research is needed to optimize substrate management strategies for seedling establishment.



Academic Editor: Hao Liu

Received: 8 May 2026

Revised: 1 June 2026

Accepted: 4 June 2026

Published: 6 June 2026

**Copyright:** © 2026 by the authors.

Licensee MDPI, Basel, Switzerland.

This article is an open access article distributed under the terms and conditions of the [Creative Commons Attribution \(CC BY\)](https://creativecommons.org/licenses/by/4.0/) license.

**Keywords:** seedling emergence; chlorophyll content; seedling establishment; soilless media; ammonium sulfate fertilizer

## 1. Introduction

The impacts of climate change in the world are intensifying, thereby complicating the optimization of agriculture due to fluctuations in temperature and rainfall patterns [1]. In addition, land degradation, linked to green revolution technologies such as excessive

chemical fertilizer utilization and conventional farming practices, has been an issue limiting arable land for food production [2]. In contrast, the demand for food is steadily increasing as the population continues to grow, with projections indicating that the global population will reach 9.8 billion by 2050 and 11.2 billion by 2100 [3]. Climate-smart initiatives that can enhance crop productivity need to be promoted in regions with degraded soils, especially in arid countries such as Namibia, which suffer even more under a changing climate than other less arid regions do [2].

A possible solution to climate change might lie in integrated nutrient management strategies and controlled climate horticultural practices, which involve soilless hydroponic farming technologies that make minimal use of water [4]. Hydroponics have emerged as a promising technology owing to their ability to sustain crop productivity. These systems are, however, constrained by the higher nutrient demand of inert media such as coco peat that is used for plant growth [5]. Chemical fertilizers such as urea, ammonium sulfate and potassium nitrate have been widely adopted for use in hydroponic systems, as they have been proven to improve yields, which in turn helps to increase farmers profits [2]. Excessive chemical fertilizer inputs are associated with negative environmental impacts, including eutrophication and biodiversity disturbances, whilst contributing to greenhouse gas emissions [6].

Unlike chemical fertilizers, organic materials have been shown to be ecologically friendly and are currently being promoted as part of sustainable farming practices to optimize yields [7]. In addition, studies have reported that organic fertilizers can supply essential plant nutrients, including nitrogen, phosphorus, and potassium, highlighting that their adoption can minimize chemical fertilizer inputs [8]. On the other hand, most organic materials such as manures and crop residues release nutrients only after microbial decomposition and are associated with nutrient imbalance issues, limiting their suitability for direct horticultural use [9]. Therefore, converting organic materials to vermicompost, an eco-friendly, nutrient-rich, and fast nutrient release amendment, has attracted attention for improving the nutrient profile of horticultural media [10]. While vermicompost improves the physiochemical properties of media, highly water-soluble nutrients, particularly nitrates, can leach quickly from horticultural media owing to its low cation-exchange capacity, limiting nutrient availability [11].

Biochar has been promoted as an amendment that can improve nutrient leaching from horticultural media such as coco peat, peat, and peat moss [10]. Biochar can supplement nutrients, absorb nitrates, and improve the water retention capacity of horticultural media, thereby improving media performance [12]. Therefore, the integration of biochar and vermicompost can be an effective approach for horticultural media nutrient management. Various studies have explored biochar from terrestrial biomass for agricultural applications, with few studies on vermicompost–biochar synergistic effects on horticultural media [11–13]. In contrast, in arid countries such as Namibia, biochar feedstock shortage may be a challenge in the long run due to limited terrestrial biomass, necessitating the exploration of alternative feedstocks for agricultural biochar production [14]. The Namibian coastline is highly productive and enriched with various resources, including seaweeds such as kelp, *Gracilaria*, and *Ulva* species, which are usually discarded on beaches as waste owing to their abundance [15]. Converting this discarded biomass to biochar is a sustainable and climate-smart technology that is currently being promoted, as it contributes to carbon sequestration and has the potential to ameliorate growing media [16,17]. On the contrary, elevated salinity in untreated seaweed biomass-based biochar may limit its usability in vermicomposting technology, as it may negatively impact earthworms and compromise compost quality [18]. Various researchers have indicated that the salinity of seaweed biochar can be reduced through various biomass pre-treatment

methods, ranging from chemical and water washing or soaking to blending it with other organic amendments [19–21]. Among these methods, water pre-treatment and blending with vermicompost appear to be the most viable because they are less costly and their effectiveness have been proven [18,22]. Mupambwa et al. [14] reported that application of seaweed-derived biochar in vermicomposting positively influenced the compost nutrient content; however, at higher application rates caution is advised as it may elevate salinity. This makes the pre-treatment of seaweed biomass for biochar production a crucial step before integration into vermicomposting technology [17]. However, gaps still exist in the literature regarding the use of pre-treated seaweed biochar in vermicomposting and its role in horticultural growing media enhancement, leaving gaps in the optimal rates of seaweed biochar amended with vermicompost to use in growing media. In addition, there is limited information regarding crop performance under seaweed biochar-amended vermicompost (VC) at both the early and late stages of horticultural crops like tomatoes.

Unlike previous studies that mainly focused on terrestrial biomass-derived biochar or conventional vermicompost as growing media amendments [11–13], the present study evaluated desalinated seaweed biomass-derived biochar incorporated during vermicomposting and its subsequent use as a coco peat substitute for tomato production. In addition, the study simultaneously assessed responses during both seedling establishment and vegetative growth stages, thereby providing broader insight into the suitability of seaweed biochar-amended vermicompost for horticultural soilless media applications.

There is therefore a need for studies that evaluate the influence of pre-treated seaweed biomass-derived biochar-enriched vermicompost in soilless horticultural media, such as coco peat, on commercially important horticultural crops. It was hypothesized that the incorporation of desalinated seaweed biochar-amended vermicompost into coco peat would not improve tomato seedling establishment and vegetative growth when supplemented with ammonium sulfate fertilizer, although excessive incorporation rates could negatively influence crop performance due to salinity-related effects. Therefore, the specific objectives of this study were to (1) evaluate the effects of different levels of inclusion of desalinated seaweed-biochar amended vermicompost into coco peat (0%, 25%, 50%, 75% and 100% VC, *w/w*) with and without ammonium sulfate fertilizer, on the early seedling establishment of tomatoes; and (2) to evaluate the effect of different levels of inclusion of desalinated seaweed-biochar amended vermicompost into coco peat (0%, 75%, and 100% VC, *w/w*) with ammonium sulphate fertilizer on the vegetative growth of tomatoes.

## 2. Materials and Methods

### 2.1. Study Site and Source of Materials

This study was conducted in a greenhouse at the University of Namibia (UNAM), Sam Nujoma Campus, in the Erongo region of Namibia (14°30'19" E, 22°55'27" S). The seaweed biomass used for biochar production was collected from the Henties Bay coast, Namibia (22°07'06" S, 14°16'57" E) and identified as *Gracilariopsis funicularis*, a red macroalga commonly found along the Namibian coastline [18]. This species was selected due to its local abundance and availability as a low-cost marine biomass resource, and its use is supported by Ruben et al. [17], who previously pre-soaked this species to remove salts and recommended it for further agricultural research. Seaweed biochar-amended cow manure–paper vermicompost was prepared at the Sam Nujoma Campus. Cow manure and shredded paper were mixed at a C:N ratio of 30:1, followed by the incorporation of 9% (*w/w*) seaweed biochar derived from *G. funicularis*. The mixture was vermicomposted for 12 weeks and then air-dried prior to use in media preparation. The seaweed biochar was produced by soaking biomass in cold water (25 °C) for 6 h, followed by drying and pyrolysis according to the protocol of Ruben et al. [17]. Coco peat was used as an additional

growing medium component. The soaking pre-treatment was conducted to reduce soluble salts and surface impurities from the seaweed biomass prior to pyrolysis [17], thereby minimizing the salinity of the resulting seaweed biochar and improving its suitability for vermicomposting and horticultural media applications. Coco peat, tomato seeds (variety STAR 9009), and Ammonium Sulfate fertilizer were purchased from local hardware shops in Henties Bay and Windhoek, Namibia. Seedling trays (36 cm × 29 cm) used in the seedling experiment and 5 L poly pots (30 cm height and 22 cm top diameter) used in the vegetative growth experiment were obtained from a local hardware shop in Swakopmund, Namibia. The selected physicochemical properties of the seaweed biochar, cow manure, seaweed biochar-amended vermicompost and coco peat used in this study are presented in Table 1.

**Table 1.** Chemical characteristics of seaweed biochar, cow manure, seaweed biochar-amended vermicompost, and coco peat used to prepare the growing media.

Parameter	Seaweed Biochar	Cow Manure	Seaweed Biochar-Amended Vermicompost	Coco Peat
pH	8.75 ± 0.15	7.72 ± 0.06	8.13 ± 0.01	6.22 ± 0.19
EC (mS/cm)	5.40 ± 0.08	4.72 ± 0.03	2.79 ± 0.04	0.593 ± 0.14
Extractable P (mg/kg)	244.74 ± 17.0	850.63 ± 7.59	257.32 ± 10.53	41.75 ± 4.98
NH <sub>4</sub> -N (mg/kg)	14.17 ± 4.58	146.66 ± 19.93	64.01 ± 9.49	13.67 ± 3.38
NO <sub>3</sub> /NO <sub>2</sub> -N (mg/kg)	13.72 ± 0.72	88.63 ± 17.54	40.33 ± 0.82	29.38 ± 0.02
Ca (g/kg)	1.95 ± 0.21	6.04 ± 0.27	5.82 ± 0.14	–
Mg (g/kg)	0.17 ± 0.02	1.26 ± 0.10	1.19 ± 0.07	–
K (g/kg)	21.29 ± 1.61	8.27 ± 0.28	8.90 ± 0.14	–
Na (g/kg)	2.14 ± 0.16	3.80 ± 0.32	3.44 ± 0.14	–
Cr (mg/kg)	<0.01	1.59 ± 0.04	1.51 ± 0.13	–
Zn (mg/kg)	3.49 ± 0.33	1.75 ± 0.11	1.70 ± 0.09	–
Ni (mg/kg)	<0.01	<0.01	<0.01	–
Cd (mg/kg)	<0.01	<0.01	0.208 ± 0.04	–
Cu (mg/kg)	<0.01	1.92 ± 0.10	1.56 ± 0.09	–

Values are presented as mean ± SD (n = 3), “–” denotes parameters not analyzed.

The seaweed biochar-amended vermicompost used in this study originated from a previously established vermicomposting process focused on producing seaweed biochar-amended vermicompost for subsequent horticultural evaluation. Consequently, parameters such as temperature dynamics and moisture regulation during vermicomposting were not monitored in the present study, as the primary objective was to evaluate growing media performance rather than optimize the seaweed biochar-amended vermicompost production conditions.

## 2.2. Seedling Experiment: Treatments and Experimental Design

This experiment had two factors, i.e., two fertilizer application rates (0 kg N/kg without fertilizer and 200 kg N/ha with fertilizer) and five levels of seaweed biochar-amended vermicompost incorporation into the coco peat (0% VC, 25% VC, 50% VC, 75% VC, and 100% VC on a *w/w* basis). The experiment used a 2 × 5 factorial design, which was laid out in a completely randomized design (CRD) with three replicates. Plastic planting trays with 96 holes per tray were used and each replicate consisted of 24 holes on the tray. Each replication covered 24 cavities from a tray, equivalent to 24 seeds, leading to a total of 72 plants in each treatment. Tomato seeds were then sown in seedling trays

in the growing media treatments. The entire seedling experiment took 60 days from sowing to transplanting. Ammonium sulfate fertilizer was applied after emergence at a rate of 200 N kg/ha equivalent to 21.4 g of ammonium sulfate (21% N) fertilizer per tray as recommended by Pandit et al. [23]. Nascimento et al. [24] recommended that splitting fertilizer applications into two or three doses is an effective approach to promoting safe nutrient uptake. For that reason, fertilizer was applied in three split doses at 20%, 40%, and 40% of the total (21.4 g of ammonium sulfate) per tray, on days 8, 16, and 30 after emergence, respectively. The plants were irrigated at 2-day intervals throughout the experiment to maintain consistently moist growing media conditions without visible waterlogging. Irrigation was carried out using municipal tap water, and water quality parameters were not assessed, as water was not considered an experimental factor.

### 2.3. Seedlings Experiment Measured Parameters

To determine emergence, the number of seedlings that emerged in each replication in a treatment was recorded 15 days after sowing. To calculate the emergence percentage in each replication, the recorded number of emerged seedlings was divided by the total number of seeds sown (24 seeds) and multiplied by 100 [25].

Seedling height (cm) and leaf area were collected 60 days after emergence. Seedling height was measured using a ruler by measuring the distance between the stem base and the highest point of the seedling.

The leaf area (cm<sup>2</sup>) was determined using a flatbed scanner (CanoScan LiDE 120, Canon Inc., Ho Chi Minh City, Vietnam) and ImageJ software (version 1.53t). The leaves were removed from three randomly selected seedlings from each replication and scanned with a flatbed scanner. Thereafter, ImageJ software was calibrated with a standard known distance prior to leaf area measurements. The average of leaves sourced from three seedlings was then taken to obtain the leaf area for one seedling from that specific replication within a treatment.

### 2.4. Vegetative Growth Experiment: Treatments, and Experimental Design

This experiment was laid out in a completely randomized design (CRD) with three top-performing treatments from the seedling stage being used. These treatments were 0% VC, 75% VC, and 100% VC, all treated with fertilizer at the recommended rate of 200 kg N per ha. Each treatment was replicated six times in 5 L plastic pots with a top surface area of 380.13 cm<sup>2</sup>. Each poly pot was filled with 5 L of the respective growing medium treatment prior to transplanting. This surface area was used to convert the field fertilizer recommendation (kg ha<sup>-1</sup>) to a per-pot application rate. Treatments were randomly placed in a greenhouse, with the help of a random number generator, to minimize experimental bias. Seedlings established under the same conditions were used to ensure uniformity at the commencement of the post-transplant experiment. Transplanting was done 60 days after emergence, while ammonium sulfate fertilizer was applied at a rate of 3.6 g/pot (equivalent to 200 N kg/ha based on pot surface area conversion), split into three equal doses applied at 2 weeks intervals. During the vegetative growth experiment, each pot received approximately 500 mL of water per day to maintain consistent moisture conditions within the growing media.

### 2.5. Vegetative Growth Measured Parameters

Plant height (cm) was measured with a measuring tape 8 weeks after transplanting, following the same procedure used for seedling height measurements. The stem diameter was measured using Vernier calipers and data was collected from the base of the stem.

The chlorophyll content was measured with a calibrated SPAD Meter (CCM 200 plus, Opti-Sciences, Inc., Hudson, NH, USA). Six fully expanded leaves were randomly selected

from each plant, and one SPAD reading was recorded per leaf, resulting in six readings per plant. The average SPAD value per plant was then used for statistical analysis. Plant leaf area was scanned using a flatbed scanner (CanoScan LiDE 120, Canon Inc., Vietnam) and analyzed using ImageJ software (version 1.53t). All leaves were removed from the plant and scanned. Thereafter, ImageJ, as described for the seedling stage, was used to determine the leaf area. To determine plant dry shoot biomass, the aboveground portion of each plant was cut at the stem base and oven-dried at 65 °C for 48 h. Thereafter, the dried samples were weighed using a calibrated digital scale.

## 2.6. Data Analysis

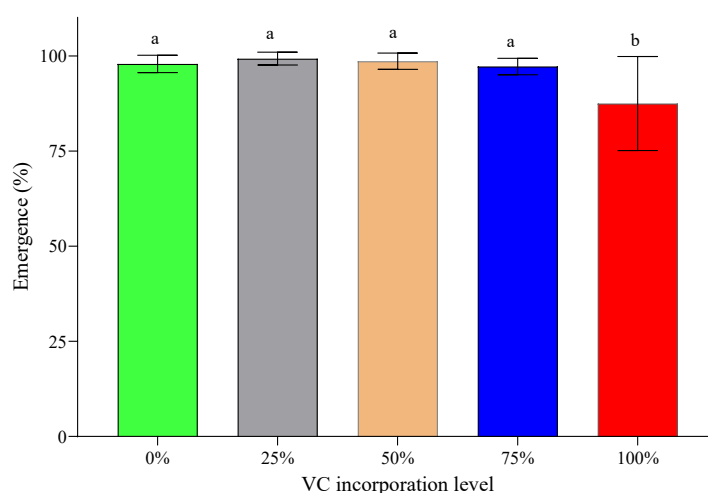
The data obtained from the seedlings trial were analyzed using a two-way Analysis of Variance (ANOVA), using JMP statistical software version (JMP student edition version 18.2.2), except for emergence percentage, which was analyzed using a one-way ANOVA in JMP statistical software. For the vegetative growth experiment, data were analyzed using a one-way ANOVA, using JMP statistical software. Prior to ANOVA, data were assessed for normality using the Shapiro–Wilk test and homogeneity of variances using Levene’s test in JMP statistical software. All variables satisfied ANOVA assumptions; therefore, no data transformations were required. For all significant treatment effects, means were separated at  $p < 0.05$  using Fishers Protected Least Significant Differences. The level of significance used for all statistical tests was 5%. All graphs were plotted using GraphPad Prism version 10.2.2 for Windows (GraphPad Software, Boston, MA, USA).

## 3. Results

### 3.1. Seedling Experiment

#### Tomato Seedling Emergence and Growth

Emergence percentage was significantly affected by treatment (Figure 1). However, no significant differences ( $p < 0.05$ ) were observed among the 0%, 25%, 50%, and 75% VC treatments, which showed similarly high emergence percentages. In contrast, the 100% VC treatment resulted in a significantly lower emergence percentage (87.50%) compared to the other treatments. Relative to the control, the 100% VC treatment showed a 10.42% reduction in emergence.

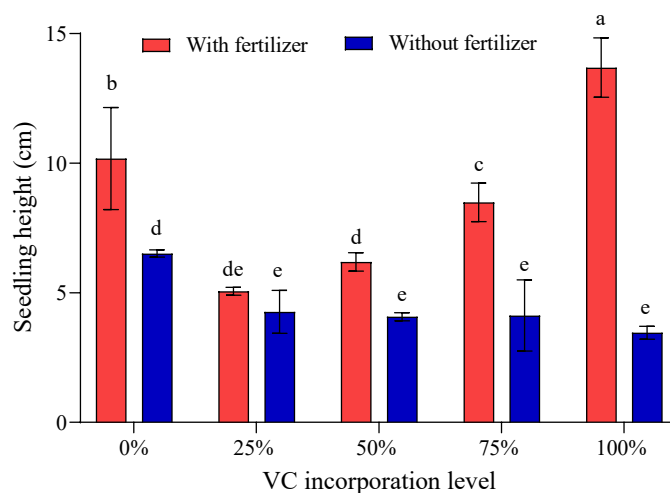


**Figure 1.** Emergence percentage of tomato seedlings under different seaweed biochar-amended vermicompost incorporation levels in coco peat. Error bars indicate standard (SD) deviation, and values are means  $\pm$  SD ( $n = 3$ ). Treatments with different lowercase letters are significantly different ( $p < 0.05$ ).

There was a significant influence ( $p < 0.05$ ) of both seaweed biochar-amended vermicompost incorporation level and fertilizer level on seedling height (Table 2). Furthermore, there was a significant two-way interaction between seaweed biochar-amended vermicompost incorporation level and fertilizer application level on seedling height (Table 2). Generally, fertilizer-treated seedlings showed greater height than unfertilized seedlings across all VC incorporation rates (Figure 2). Under no fertilizer application, the seedling height generally showed a decreasing trend with increasing seaweed biochar-amended vermicompost incorporation (Figure 2). For the treatments under no fertilizer application, the greatest plant height was observed in 0% VC (control) with a value of 6.51 cm and the lowest was observed at 100% VC treatment with a value of 3.46 cm (Figure 2). On the contrary, under fertilizer application, seedling height significantly increased with increasing VC level. However, compared to the 0% VC (control), only the 100% VC treatment showed greater seedling height (Figure 2). In the treatments under fertilizer application, seedling height ranged from 5.06 cm at 25% VC to 13.69 cm under the 100% VC treatment.

**Table 2.**  $p$ -values from two-way Analysis of Variance (ANOVA) for tomato seedling growth parameters under varying seaweed biochar-amended vermicompost incorporation and fertilizer application rates.

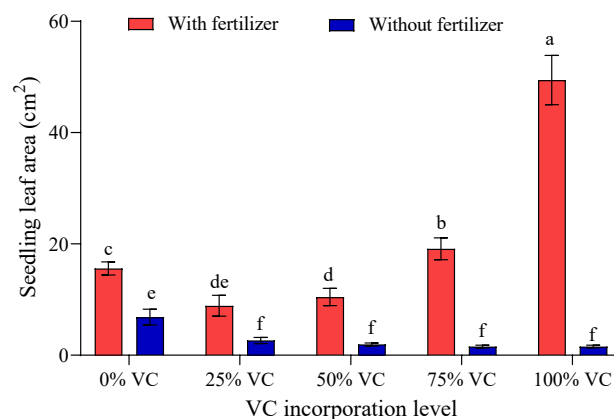
Parameter	Source of Variation		
	Biochar-Amended Vermicompost Level (VC)	Fertilizer Level (FL)	VC × FL
Seedling height (cm)	<0.0001	<0.0001	<0.0001
Seedling leaf area (cm <sup>2</sup> )	<0.0001	<0.0001	<0.0001



**Figure 2.** Effect of seaweed biochar-amended vermicompost incorporation levels in coco peat and ammonium sulfate fertilizer rates on tomato seedling height. Error bars indicate standard deviation, and values are means  $\pm$  SD ( $n = 3$ ). Treatments with different lowercase letters are significantly different ( $p < 0.05$ ).

There was a significant effect ( $p < 0.05$ ) of seaweed biochar-amended vermicompost incorporation level on seedling leaf area, as well as a significant influence of the fertilizer application rate on the seedling leaf area after 8 weeks of growth (Table 2). Furthermore, there was a significant two-way interaction between seaweed biochar-amended vermicompost incorporation level and fertilizer application level on seedling leaf area (Table 2). Across all seaweed biochar-amended vermicompost incorporation rates, the treatments with fertilizer application showed a significantly higher leaf area than treatments without

fertilizer (Figure 3). Without fertilizer application, VC inclusion significantly decreased the leaf area of seedlings in relation to the control (Figure 3). However, with fertilizer application, leaves significantly increased with increasing seaweed biochar-amended vermicompost levels (Figure 3). Without fertilizer application, the highest seedling leaf area was observed in the control treatment with a value of 6.83 cm<sup>2</sup>/plant, while the lowest was observed at 75% VC and 100% VC rate, both with a value of 1.56 cm<sup>2</sup>/plant (Figure 3). Under treatments with fertilizer application, the control had the lowest leaf area with a value of 15.69 cm<sup>2</sup>/plant, and the highest leaf area was observed at 100% VC incorporation rate with a value of 49.45 cm<sup>2</sup>/plant (Figure 3).

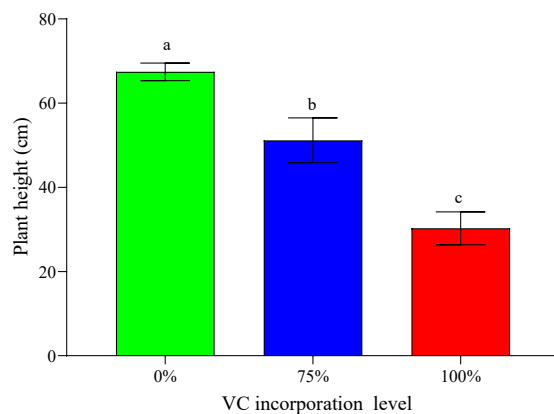


**Figure 3.** Effect of seaweed biochar-amended vermicompost incorporation levels in coco peat and ammonium sulfate fertilizer rates on tomato seedling leaf area. Error bars indicate standard deviation, and values are means  $\pm$  SD ( $n = 3$ ). Treatments with different lowercase letters are significantly different ( $p < 0.05$ ).

### 3.2. Vegetative Growth Experiment

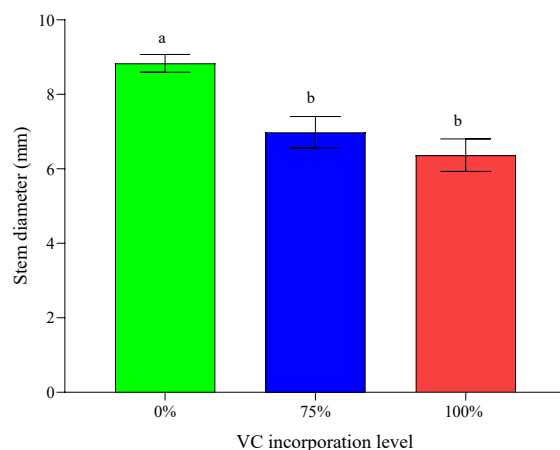
#### Effects on Tomato Vegetative Growth Parameters and Chlorophyll Content

The seaweed biochar-amended vermicompost incorporation level in coco peat had a significant influence ( $p < 0.05$ ) on tomato plant height after eight weeks of growth (Figure 4). Generally, seaweed biochar-amended vermicompost incorporation significantly decreased plant height (Figure 4). The highest plant height was observed in unamended coco peat (control) with 67.43 cm, followed by 75% VC with a value of 51.18 cm and 100% VC with the lowest value of 30.26 cm (Figure 4). Compared to the control, plant height showed a difference of 24.10% and 55.12% in the 75% and 100% VC treatments, respectively.



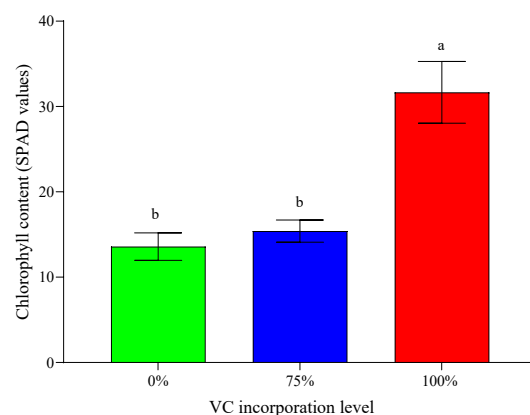
**Figure 4.** Effect of seaweed biochar-amended vermicompost incorporation levels in coco peat on tomato plant height. Error bars indicate standard deviation; values are means  $\pm$  SD ( $n = 6$ ). Treatments with different lowercase letters are significantly different ( $p < 0.05$ ).

In addition, there was a significant influence ( $p < 0.05$ ) of the seaweed biochar-amended vermicompost incorporation level in coco peat on tomato plant stem diameter after eight weeks (Figure 5). The stem diameter decreased with increasing seaweed biochar-amended vermicompost incorporation rate, with insignificant differences between VC-treated treatments and significant differences between the control and VC-treated treatments (Figure 5). The control had the highest stem diameter with a value of 8.83 mm, followed by 75% and 100% VC with a value of 6.96 mm and 6.36 mm, respectively (Figure 5). Relative to the control, this represented a 21.16% and 27.99% difference in stem diameter in the 75% and 100% VC treatments, respectively.



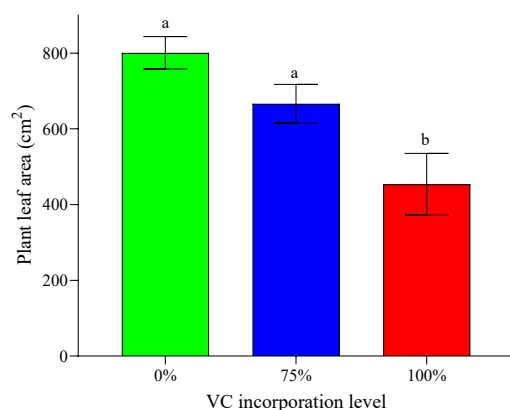
**Figure 5.** Effect of seaweed biochar-amended vermicompost incorporation levels in coco peat on tomato stem diameter. Error bars indicate standard deviation, values are means  $\pm$  SD ( $n = 6$ ). Treatments with different lowercase letters are significantly different ( $p < 0.05$ ).

Unlike the other parameters where the control performed better, for chlorophyll content, the seaweed biochar-amended vermicompost incorporation level in coco peat had a significant influence ( $p < 0.05$ ) on tomato after eight weeks (Figure 6). The 100% VC treatment exhibited the highest chlorophyll content of up to 31.67 SPAD values, followed by 75% VC amended coco peat with 15.40 SPAD values, and the control had the lowest of 13.58 SPAD values, yet not statistically different from 75% VC treatment (Figure 6). The SPAD values for the 100% VC treatment exhibited an increase of 133.2%, while those for the 75% treatment increased by 105.7%, both relative to the control.



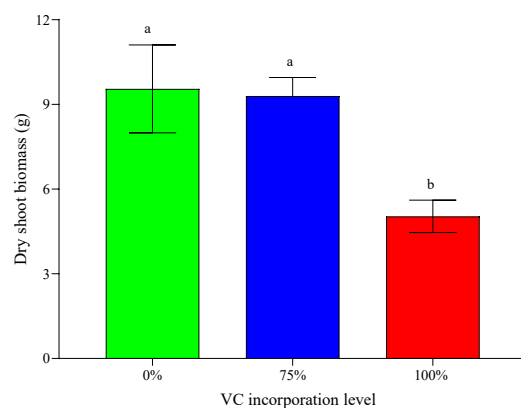
**Figure 6.** Effect of seaweed biochar-amended vermicompost incorporation levels in coco peat on tomato chlorophyll content. Error bars indicate standard deviation; values are means  $\pm$  SD ( $n = 6$ ). Treatments with different lowercase letters are significantly different ( $p < 0.05$ ).

There was a significant effect ( $p < 0.05$ ) of seaweed biochar-amended vermicompost incorporation level in coco peat on tomato leaf area after eight weeks (Figure 7). Generally, in this study, increasing the VC rate decreased the leaf area of tomato plants (Figure 7). Unamended coco peat exhibited the highest leaf area with a value of 800.89 cm<sup>2</sup> per plant (Figure 7). Addition of 75% VC in coco peat reduced the leaf area to 666.53 cm<sup>2</sup>/per plant; however, the reduction was not significant ( $p < 0.05$ ) as shown in Figure 7. The full replacement of coco peat with VC significantly reduced the leaf area of tomatoes up to 453.72 cm<sup>2</sup> per plant (Figure 7). Relative to the control, this finding indicates that 75% VC decreased leaf area by 16.77%, while 100% VC decreased leaf area by 43.34%.



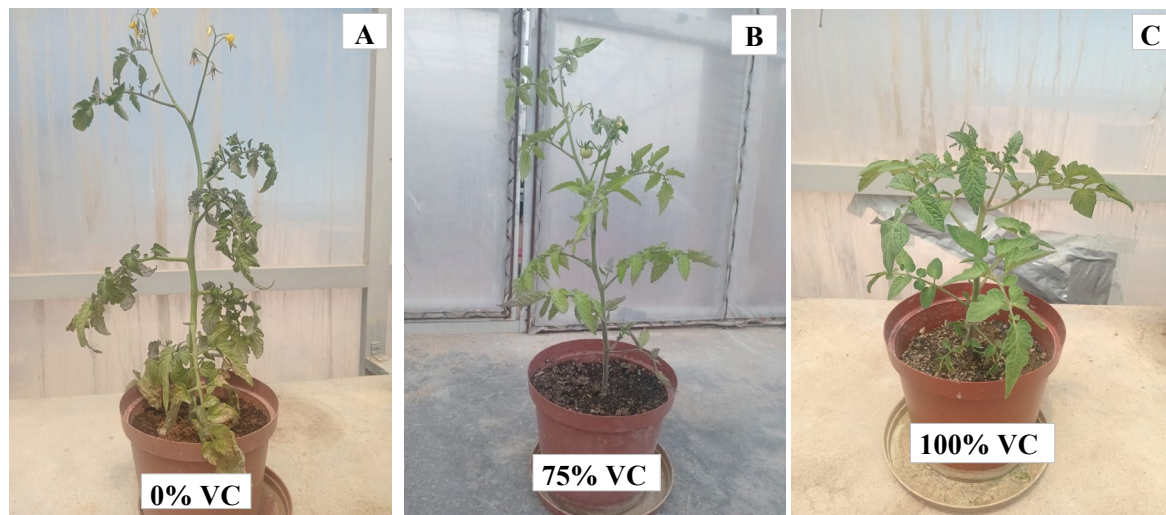
**Figure 7.** Effect of seaweed biochar-amended vermicompost incorporation levels in coco peat on tomato plant leaf area. Error bars indicate standard deviation; values are means  $\pm$  SD ( $n = 6$ ). Treatments with different lowercase letters are significantly different ( $p < 0.05$ ).

The dry biomass of the tomato plants was also significantly influenced ( $p < 0.05$ ) by the seaweed biochar-amended vermicompost incorporation level in coco peat (Figure 8). The inclusion of seaweed biochar-amended vermicompost in coco peat reduced the dry biomass of plants, with a higher rate (100% VC) showing significant reductions (Figure 8). The highest dry biomass was recorded at 0% VC incorporation rate with a biomass of 9.55 g per plant. At the 75% VC inclusion level, the dry biomass was reduced insignificantly to 9.3 g, while at the 100% VC incorporation level, the plant dry biomass was significantly reduced to a value of 5.03 g (Figure 8). Relative to the control, there was a 2.62% and 47.32% reduction in dry biomass in the 75% and 100% VC treatments, respectively.



**Figure 8.** Effect of seaweed biochar-amended vermicompost incorporation levels in coco peat on tomato dry shoot biomass. Error bars indicate standard deviation; values are means  $\pm$  SD ( $n = 6$ ). Treatments with different lowercase letters are significantly different ( $p < 0.05$ ).

Visual observations of tomato plants grown under different rates of seaweed biochar-amended vermicompost (VC) incorporation in coco peat showed differences among treatments. Plants in the 0% VC treatment exhibited visible signs of leaf senescence, particularly in older leaves, leaf yellowing, reduced vigor, and flower loss (Figure 9A). The 75% VC inclusion level demonstrated a generally vigorous appearance, with no signs of leaf senescence, although the leaves were pale green and fruit setting was observed (Figure 9B). The 100% VC treatment appeared vigorous and healthy, characterized by dark green leaves; however, flowering had not yet commenced (Figure 9C).



**Figure 9.** Effects of seaweed biochar-amended vermicompost incorporation levels (0% VC = (A), 75% VC = (B), and 100% VC = (C)) in coco peat on the general visual appearance of tomato plants after 8 weeks of growth.

## 4. Discussion

### 4.1. Effect of Seaweed Biochar-Amended Vermicompost Inclusion Level and Fertilizer Level on Tomato Seedling Establishment

Emergence percentage is a critical parameter in seedling establishment, as it determines the final plant population a farmer can achieve, which in turn influences the overall yield [26]. In this study, the inclusion of seaweed biochar-amended vermicompost at lower rates showed improved emergence of tomato seedlings, indicating a suitable medium in terms of emergence. Previous studies have reported that substrate properties such as aeration, salinity, pH, bulk density, and water infiltration can influence seed germination and seedling emergence [27]. However, these properties were not measured in the present study; therefore, their specific contribution to the observed emergence response cannot be confirmed. Future studies should evaluate the physicochemical properties of the substrate mixtures to better understand the mechanisms underlying seedling emergence in seaweed biochar-amended vermicompost-based growing media. On the other hand, increasing the seaweed biochar-amended vermicompost rate may have altered the physical properties of the growing medium, potentially affecting germination. However, substrate characteristics such as bulk density, compaction, water infiltration, and aeration were not measured in this study, and their influence on the observed response remains speculative [28].

In addition, the pH (8.13) of the original seaweed biochar-amended vermicompost used in our study (Table 1) is outside the optimum pH range (5.5–7.0) reported by Faryal & Muhammad [29]. This could be another reason for the low emergence in the higher VC rate treatment; hence, a higher pH than the optimum can inhibit seed germination by reducing the activities of enzymes responsible for germination, thereby altering emergence [30]. The

seaweed biochar-amended vermicompost EC of (up to 2.79 mS/cm) (Table 1), indicating higher salt concentrations, could also be the cause of reduced emergence, as reported by Irik and Bikmaz [31] that EC up to 2.5 mS/cm reduced germination. Elevated concentrations of salts, such as NaCl, may inhibit germination and emergence due to osmotic stress, ion toxicity, and germination hormonal imbalance [32].

Comparable findings were reported by Sarwar et al. [33], who reported that compost had lower germination than coco peat, peat moss, vermiculite, and sand. However, the present study's seaweed biochar-amended vermicompost findings generally exhibited higher emergence values (87.50%) than Sarwar et al. [33], who reported germination values of 70% in their compost. The differences in germination ranges between the present study and other studies could be attributed to the different test crops used, because tolerance mechanisms to abiotic conditions are species-specific, as reported by [31]. The literature shows no universal standardized acceptable emergence percentage; however, seed germination, a useful metric to estimate emergence, is well standardized, and its values are normally  $\geq$  emergence percentage [34]. Germination above 80% is considered acceptable [35], and in the present study, all treatments achieved emergence values greater than 80%. This implies that seaweed biochar-amended vermicompost can be used as an alternative seedling growing media, thereby helping to minimize coco peat input costs. However, to further improve emergence percentage in the 100% VC treatment, in the future, seeds could be primed before sowing and overwatering should be avoided.

In addition, seedling height was evaluated in this study because fully grown vigorous seedlings are more likely to survive and establish successfully after transplantation [36]. The significant interaction between fertilizer and VC level suggests that seedling height depends on both factors, necessitating the balancing of these two factors to attain the desired seedling height. Fertilizer-treated treatments attained higher height, possibly because ammonium sulfate fertilizer is a fast nutrient-releasing fertilizer which releases N immediately and stimulates fast cell division and stem elongation [37]. On the other hand, although nitrogen is available in the seaweed biochar-amended vermicompost, it may exist in organic forms which require microbial activation before it becomes available to plants, which could explain the lower seedling height in treatments without fertilizer applied [38]. In addition, the seaweed biochar in vermicompost can adsorb mineral nitrogen, which may temporarily immobilize N, when seaweed biochar-amended vermicompost is used alone, making ammonium sulfate supplementation more beneficial [10]. Ghimire et al. [39] reported similar trends that supplementing vermicompost with mineral nitrogen fertilizers (urea) improved vegetative growth traits compared to vermicompost alone. The inclusion of fertilizer improves plant height with increasing seaweed biochar-amended vermicompost rate, suggesting a positive interaction between the fertilizer and vermicompost treatments [40]. However, plant tissue nutrient concentrations were not determined in the present study; therefore, it cannot be confirmed whether the observed response was directly associated with improved nutrient balance or nutrient uptake. Future studies should include plant tissue nutrient analysis to clarify the mechanisms responsible for the enhanced growth response. This finding underscores that the use of VC alone without fertilizer supplementation may not be practically viable for seedling establishment, as seedlings under this condition may find it hard to establish.

In contrast, the higher seedling height recorded in the 100% VC treatment is inconsistent with Büyükarıslan and Demir [41], who reported that the use of 100% VC had the lowest seedling height in pepper and cauliflower compared to lower rates of inclusion. These discrepancies can be attributed to the inclusion of ammonium sulfate fertilizer in the current study, different vermicompost substrates used, and different test crops used. Values in this study in fertilizer untreated seedling height (3.46 to 6.51 cm) are lower than

those reported by Gopaul et al. [42], who reported higher values (7.41 cm to 10.10 cm) under comparable media substrates conditions. These variations could be a reflection of the different performances and varying environmental conditions. Values for fertilizer-treated media (13.06 cm to 13.39 cm) are higher than those reported by Moaaz et al. [43], who indicated that the height of sand-grown, N-fertilizer treated tomato seedlings ranged from 4.5 cm to 7.1 cm. The variation between this study and that of Moaaz et al. [43] could be explained by differences in the growing media used, thus highlighting the role of seaweed biochar-amended vermicompost in seedling height enhancement. Overall, the seedlings established in VC-treated media supplemented with ammonium sulfate fertilizer, especially those grown in 100% VC, can be used to develop seedlings of improved height.

Leaves are crucial sites for most plant biological processes, including photosynthesis and respiration, which influence overall crop performance [44]. Therefore, seedling leaf size was measured because it correlates with physiological processes and can serve as an indicator of overall growth performance [45]. The seedling leaf area depended on the synergistic influence of fertilizer level and seaweed biochar-amended vermicompost level, suggesting the significance of VC rate-fertilizer optimization level consideration. The use of ammonium sulfate fertilizer enhanced leaf area compared to untreated VC treatments, highlighting that fertilizer inclusion is a crucial consideration to attain quality leaves of seedlings. Ammonium sulfate is a source of nitrogen which promotes the vegetative growth of plants by facilitating photosynthesis, which could explain the improved seedling leaf area under this treatment [46]. The findings of the present study therefore suggest that VC inclusion, particularly at 100% VC, is beneficial to tomato seedling leaf development, especially when supplemented with N source fertilizer, such as ammonium sulfate. This highlights the importance of this treatment combination for quality seedling development, which in turn has the potential to enhance post-transplant growth and yield performance. Comparable findings were reported by Aslam et al. [47], who suggested that integrating vermicompost and chemical fertilizers (N and P sources) achieved the highest leaf area compared to vermicompost treatments without fertilizers in wheat crops.

Vermicompost treatments without fertilizers decreased leaf area as the VC rate increased. Previous studies have reported that substrate properties such as pH, salinity, nutrient availability, aeration, and water-holding characteristics can influence leaf development in container-grown plants [40,48]. However, these properties were not measured in the present study; therefore, their specific contribution to the observed response could not be confirmed. These findings are consistent with Ferreira et al. [49], who reported that the use of 100% VC in potting media with no chemical fertilizer supplements inhibited leaf development in *Corymbia citriodora* seedlings due to higher salinity and alkalinity. In addition to substrate physicochemical properties, the composition of the feedstocks used for vermicomposting may also influence plant growth responses. Residual compounds originating from manure, paper waste, or seaweed biochar could potentially affect nutrient availability, microbial activity, or root growth when present at high incorporation rates [50]. However, the chemical composition and potential phytotoxic constituents of the seaweed biochar-amended vermicompost were not characterized in the present study. Therefore, the extent to which such factors contributed to the observed reduction in leaf area remains unclear. Future studies should evaluate the physicochemical characteristics and potential phytotoxicity of seaweed biochar-amended vermicompost to better understand the mechanisms underlying seedling growth responses. Overall, regardless of VC incorporation level, the use of VC alone in coco peat without ammonium sulfate may not be suitable for seedling development.

#### 4.2. Vegetative Growth of Tomatoes Under Varying Levels of Seaweed Biochar-Amended Vermicompost–Coco Peat Mixes

Plant height, stem diameter, leaf size, and dry biomass are among the critical parameters of tomato that quantify plant vigor, growth, bioaccumulation, and are also yield predictors [51–53]. Therefore, these parameters were evaluated for vegetative growth in this study to assess the growth response of tomatoes to changing media conditions. Unlike in the seedling stage, increasing seaweed biochar-amended vermicompost level decreased most plant growth parameters, including height, leaf area, stem diameter, and dry biomass. One possible explanation is the greater contribution of salts from the seaweed biochar-amended vermicompost (Table 1); however, EC of the individual substrate mixtures was not measured during the experiment; therefore, this explanation remains speculative. Higher salt concentrations are associated with osmotic stress and reduced nutrient uptake, which in turn inhibit plant vegetative development [54]. The reduction in growth could also be associated with ammonium supplied by both the fertilizer and seaweed biochar-amended vermicompost [50], although ammonium concentrations within the root zone were not quantified in this study. Elevated ammonium ion concentrations in the root zone plants are reported to disrupt pH and cause nutrient imbalances and phytotoxicity, thereby retarding plant growth [50].

However, this was not the case in the seedling stage because seedlings have a lower nutrient demand, and they are likely not to be influenced by minor nutrient imbalances [55]. In addition, differences between seedling tray and poly pot environments, such as aeration, compaction, and bulk density, may also have contributed to the contrasting responses observed between growth stages [56]. However, substrate properties such as aeration, compaction, and bulk density were not measured; therefore, their influence cannot be confirmed. It is important to note that seaweed biochar-amended vermicompost at higher rates may perform worse than VC treatment at lower rates for shorter durations. However, at extended durations, it is likely to improve as plants adapt to the conditions [57]. This pattern was observed at the seedling stage, whereby plants initially struggled to adapt to higher VC conditions; however, at later stages, 100% VC improved, necessitating the need to conduct similar experiments for extended durations in the future.

Plants in coco peat performed better than those in VC-treated coco peat, likely because the pH (6.22) was within the optimum range (Table 1). In addition, improved aeration in coco peat can favor root penetration, enabling rapid uptake of released N supplied by ammonium sulphate fertilizer [58]. These findings are consistent with those of Gong and Xiulong [59], who reported that the use of vermicompost in potting media (up to 100%) reduced the growth performance of *Allium fistulosum* plants. Comparable results in tomatoes were documented by Erdal and Aktaş [60], who observed a reduction in stem diameter and plant height at elevated vermicompost levels, relative to the control (coco peat only in this study). However, the findings are not consistent with those of Spehia et al. [61], who reported that vermicompost inclusion in coco peat improved height, nutrient uptake, and yield in tomatoes compared to coco peat alone. The variations in plant growth patterns between this study and others can be strongly attributable to crop variety-specific responses, growing media property variations, and experimental duration before data collection [62]. Furthermore, Fikre and Boto [63] reported that a variation in pot sizes may also influence growth parameters, particularly stem diameter; therefore, this could be another source of discrepancies.

This study's findings imply that plants grown in seaweed biochar-amended vermicompost-treated coco peat may not be fully supported by ammonium sulfate fertilizer application alone. Supplementation with other hydroponic fertilizers, such as that used by Mupambwa et al. [64], to supplement their fly ash-amended vermicompost can be considered to ensure

vigorous plants while not completely relying on them. As demonstrated in the seedling stage, 75–100% VC treatment can support plant growth; however, before transplanting seedlings into such a medium, pre-treatments such as leaching out of soluble salts from the seaweed biochar-amended vermicompost may be necessary to dissolve and flush the accumulated salts out of such media [65]. Moreover, the use of seaweed biochar-amended vermicompost at lower rates, such as 25% or less, may be explored in the future, as crops may perform better at lower rates. Finally, this medium may be suitable for use as a potting medium to grow horticultural salt-tolerant crops and halophytes [66].

Chlorophylls are green pigments found on leaves and are responsible for capturing light energy during photosynthesis [67]. Chlorophyll content is not directly a crop growth parameter; however, it is a useful indicator of general plant health [68]. Therefore, it was also measured in this study. Unlike other parameters, chlorophyll content in tomatoes responded positively to increasing seaweed biochar-amended vermicompost rates in coco peat. This response suggests that increasing seaweed biochar-amended vermicompost rates influenced chlorophyll content. Since chlorophyll synthesis is closely associated with nutrient availability, particularly nitrogen and magnesium, the observed increase may reflect improved nutrient supply within the growing medium [68]. However, plant tissue nutrient concentrations and photosynthetic activity were not measured; therefore, the exact mechanisms underlying the increased chlorophyll content cannot be confirmed.

The elevated chlorophyll content observed with increasing seaweed biochar-amended vermicompost rates may be associated with the nutrient composition of the amendment and fertilizer. Table 1 shows that the seaweed biochar-amended vermicompost contained appreciable concentrations of nutrients associated with chlorophyll formation, including Mg and N, while ammonium sulfate supplied additional N and S [46]. However, since nutrient uptake and tissue nutrient concentrations were not measured, this interpretation remains speculative. This may not be the case for other parameters (height, biomass, stem diameter, and leaf area) at the time of data collection, because they required longer time to respond, while chlorophyll responds faster. It is therefore the first notable response to the nutrient status of the media [69]. The seaweed biochar component may also have contributed to nutrient retention through adsorption processes reported in previous studies [70]. However, nutrient dynamics and leaching losses were not quantified in the present study; therefore, this mechanism could not be verified. Furthermore, this response could be due to pH, EC starting to adjust to optimal ranges, and soluble salt reduction after several rounds of irrigation, which ensured sufficient availability of essential nutrients over time [65].

Similar findings were reported by Wang et al. [54], who reported that vermicompost-treated soil used as potting media recorded higher chlorophyll content in tomatoes compared to untreated soil, compost-treated soil, and urea-treated soil media. In contrast, the current study findings are not consistent with those of Erdal and Aktaş [60], who reported that higher vermicompost rates resulted in lower chlorophyll content in tomatoes compared to coco peat alone. In another study, Mupambwa et al. [64] reported that increasing rates of fly ash-amended vermicompost reduced SPAD values in tomatoes. This underscores the potential impact of seaweed biochar in the seaweed biochar-amended vermicompost used in the present study on the enhancement of tomato chlorophyll content. The discrepancies between the present study and others could be caused by the different vermicompost substrates used, particularly the inclusion of seaweed biochar in the present study.

The findings of this work suggest that VC treatment may be a good horticultural potting medium, as demonstrated by the enhanced chlorophyll content in tomatoes. However, special considerations, such as hydroponic fertilizer supplementation and flushing out soluble salts from growing media before transplanting, must be explored in future

studies to further optimize the media. Future studies should also evaluate changes in chlorophyll content and other parameters at different time intervals in this medium to assess the underlying trends.

Despite trends revealed by measured parameters, it was interesting to note that some treatments may show improvement in parameters such as height, stem diameter, and biomass; however, they are generally not healthy-looking as indicated in Figure 9. Therefore, it may be necessary to evaluate media suitability based on the visual morphological characteristics of the investigated plants. For instance, the control exhibited better performance than the other treatments for most measured parameters; however, upon visual examination, it suffered physiological stress. The application of ammonium sulphate fertilizer to coco peat treatment supplied plants with N, allowing rapid uptake of this nutrient and promoting the necessary growth conditions for root and shoot activity [71]. However, at extended durations, the morphological health metrics are likely to reduce due to nutrient imbalance, as reported by Al-Ajlouni et al. [72]. Coco peat has limited concentrations of most essential nutrients for balanced vegetative and health development (Table 1), making the use of ammonium sulfate fertilizer alone in this medium less effective. For instance, senescence of older leaves occurred in the coco peat treatment because the nutrients supplied with fertilizer were possibly depleted from the media, causing nutrient remobilization to support the newly developing flowers and leaves [73]. Comparable findings were reported by Al-Ajlouni et al. [72], who reported that the health of roses grown in unamended coco peat potting media deteriorates at extended durations.

This was not observed in VC treatments, possibly because the seaweed biochar-amended vermicompost provided a broader range of nutrients than coco peat alone (Table 1). However, nutrient release patterns and nutrient concentrations within the root zone were not measured; therefore, this interpretation remains speculative. In addition, chlorosis could occur at lower VC rates due to limited crucial elements, such as Fe, Mn, K, and Mg, which are present in coco peat, while VC at higher rates ensures that these nutrients are adequately available with the help of beneficial microbes [58].

## 5. Conclusions

This study indicated that cattle manure-based vermicompost amended with desalinated *Gracilariaopsis funicularis* seaweed biomass-derived biochar can improve tomato performance in soilless horticultural media. Overall, 100% seaweed biochar-amended vermicompost (VC) combined with fertilizer produced favorable responses for several seedling and plant growth parameters, highlighting its potential as a growing medium amendment. However, the interpretation of these results is limited by the absence of detailed characterization of the growing media properties. Key physicochemical parameters such as bulk density, air porosity, pH, electrical conductivity, and water-holding characteristics were not measured across treatments. In addition, plant nutritional status and tissue nutrient composition were not assessed, limiting a more mechanistic understanding of the observed growth responses. Future research should therefore focus on comprehensive characterization of both substrate properties and plant nutritional uptake to better explain the observed effects. Further studies should also investigate strategies to manage initial substrate salinity, including pre-planting flushing of seaweed biochar-amended vermicompost, as well as evaluate lower incorporation rates and alternative fertilizer regimes. The performance of other crop species, particularly those with varying tolerance to salinity, should also be assessed. In addition, the sustainability of *G. funicularis* harvesting for biochar production should be considered, and alternative seaweed species and cultivation systems should be explored. Finally, future work should also address wastewater generation associated with desalination processes and investigate potential recycling or reuse strategies.

**Author Contributions:** Conceptualization, E.N.M.R. and H.A.M.; methodology, E.N.M.R. and B.H.; software, E.N.M.R.; validation, E.N.M.R., H.A.M. and B.H.; formal analysis, E.N.M.R.; investigation, E.N.M.R. and B.H.; resources, H.A.M.; data curation, E.N.M.R.; writing—original draft preparation, E.N.M.R. and H.A.M.; writing—review and editing, N.H., H.A.M. and S.S.H.; visualization, E.N.M.R.; supervision, H.A.M.; project administration, H.A.M.; funding acquisition, H.A.M., S.S.H. and N.H. All authors have read and agreed to the published version of the manuscript.

**Funding:** This research was funded by the Daures Green Hydrogen Village Project, within the Namibia Green Hydrogen Research Institute under the University of Namibia (R404) with funding from Southern African Science Service Centre for Climate Change and Adaptive Land Management (SASSCAL). This work further received support from the University of Namibia under CA52/2901. This work also received support by the Austrian Federal Ministry of Women, Science and Research (BMFWF) through Austria’s Agency for Education and Internationalization (OeAD) [KoEF 234]. This research was funded in whole or in part by the Austrian Science Fund (FWF) [10.55776/ESP1514224].

**Data Availability Statement:** The original contributions presented in this study are included in the article. Further inquiries can be directed to the corresponding authors.

**Acknowledgments:** The authors acknowledge staff members and students from UNAM, Sam Nujoma Campus, who assisted in experimental setup of this study. Open Access Funding by the University of Vienna.

**Conflicts of Interest:** The authors declare no conflicts of interest.

## Abbreviations

The following abbreviations are used in this manuscript:

ANOVA	Analysis of Variance
C: N	Carbon-to-Nitrogen ratio
CRD	Completely Randomized Design
EC	Electrical Conductivity
NH <sub>4</sub> -N	Ammonium Nitrogen
NO <sub>3</sub> /NO <sub>2</sub> -N	Nitrate/Nitrite Nitrogen
SD	Standard Deviation
SPAD	Soil–Plant Analysis Development (chlorophyll index)
VC	Seaweed Biochar-amended Vermicompost

## References

1. Amiri, N.; Yacoubi, M.; Messouli, M. Population Projections, Food Consumption, and Agricultural Production are Used to Optimize Agriculture Under Climatic Constraints. In *Advances in Environmental Engineering and Green Technologies*; Karmaoui, A., Ed.; IGI Global: Hershey, PA, USA, 2023; pp. 169–192. [[CrossRef](#)]
2. Saleem, H.R.; Levison, J.; Haroon, Z. Environment: Role of precision agriculture technologies. In *Precision Agriculture*; Academic Press: Cambridge, MA, USA, 2023; pp. 211–229. [[CrossRef](#)]
3. United Nations. *World Population Projected to Reach 9.8 Billion in 2050, and 11.2 Billion in 2100*; United Nations, Department of Economic and Social Affairs: New York, NY, USA, 2017; Available online: <https://www.un.org/en/desa/world-population-projected-reach-98-billion-2050-and-112-billion-2100> (accessed on 14 May 2026).
4. Jatav, H.S.; Rajput, V.D. Sustainable nutrient management under climate change. *Front. Agron.* **2025**, *7*, 1625151. [[CrossRef](#)]
5. Rajaseger, G.; Chan, K.; Yee, T.; Ramasamy, S.; Khin, M.; Amaladoss, A.; Kadamb, H. Hydroponics: Current trends in sustainable crop production. *Bioinformation* **2023**, *19*, 925–938. [[CrossRef](#)] [[PubMed](#)]
6. Tripathi, S.; Srivastava, P.; Devi, R.S.; Bhadouria, R. Influence of synthetic fertilizers and pesticides on soil health and soil microbiology. In *Agrochemicals Detection, Treatment and Remediation*; Elsevier: Amsterdam, The Netherlands, 2020; pp. 25–54. [[CrossRef](#)]
7. Tamang, A.; Koushik, G.; Dipta, S.; Mandira, S.; Tarik, M.; Jakir, A.M. Basic Principles of Integrated Nutrient Management. In *Fundamentals of Soil Sciences and Recent Advances*; Cornous Publications LLP: Puducherry, India, 2024; pp. 54–62. [[CrossRef](#)]

8. Pandey, V.C.; Gajic, G.; Lebrun, M.; Mahajan, P. Designer cropping systems in phytoremediation programs. In *Designer Cropping Systems for Polluted Land*; Elsevier: Amsterdam, The Netherlands, 2024; pp. 283–340. Available online: <https://www.cornousbooks.com/cornous-books/chapter/basic-principles-of-integrated-nutrient-management> (accessed on 14 May 2026). [CrossRef]
9. Liu, Y.; Lan, X.; Hou, H.; Ji, J.; Liu, X.; Lv, Z. Multifaceted Ability of Organic Fertilizers to Improve Crop Productivity and Abiotic Stress Tolerance: Review and Perspectives. *Agronomy* **2024**, *14*, 1141. [CrossRef]
10. Alvarez, J.M.; Pasian, C.; Lal, R.; López, R.; Fernández, M. Vermicompost and biochar substrates can reduce nutrients leachates on containerized ornamental plant production. *Hortic. Bras.* **2019**, *37*, 47–53. [CrossRef]
11. Messiga, A.J.; Hao, X.; Dorais, M.; Bineng, C.S.; Ziadi, N. Supplement of biochar and vermicompost amendments in coir and peat growing media improves N management and yields of leafy vegetables. *Can. J. Soil Sci.* **2020**, *102*, 39–52. [CrossRef]
12. Antileo-Mellado, S.; Muñoz, C.; Sanchez-Hernandez, J.C.; Ginebra, M.; Sandoval, M. Effect of Biochar on Vermicompost Production: Chemical, Biochemical, and Biological Properties. *Agronomy* **2024**, *14*, 615. [CrossRef]
13. Kafle, A.; Singh, S.; Singh, M.; Venkataramani, S.; Saini, R.; Deb, S. Effect of biochar-compost amendment on soilless media properties and cucumber seedling establishment. *Technol. Hortic.* **2024**, *4*, e001. [CrossRef]
14. Mupambwa, H.A.; Gawanab, W.; Lilungwe, E.; Howoses, V.A.; Handura, B.; Hausiku-Ikechukwu, M.K. The potential of seaweed biochar and fly ash amendments in enhancing vermi-degradation and the fertilizer value of cow manure, wastepaper-based vermicompost. *Bioresour. Technol. Rep.* **2024**, *28*, 101968. [CrossRef]
15. Harb, T.B.; Chow, F. An overview of beach-cast seaweeds: Potential and opportunities for the valorization of underused waste biomass. *Algal Res.* **2022**, *62*, 102643. [CrossRef]
16. Cárdenas-Aguilar, E.; Gascó, G.; Lado, M.; Méndez, A.; Paz-Ferreiro, J.; Paz-González, A. Characterization of Biochar from Beach-Cast Seaweed and Its Use for Amelioration of Acid Soils. *Land* **2024**, *13*, 881. [CrossRef]
17. Ruben, E.N.M.; Mupambwa, H.A.; Hamukoshi, S.S.; Handura, B. Optimizing the pre-treatment of marine biomass (*Laminaria pallida* and *Gracilariopsis funicularis*) for enhanced production of climate-smart agricultural biochar. *Discov. Agric.* **2025**, *3*, 268. [CrossRef]
18. Katakula, A.A.N.; Gawanab, W.; Handura, B.; Itanna, F.; Mupambwa, H.A. Seaweed (*Gracilariopsis funicularis*) biochar incorporation into a goat manure–food waste vermicompost for optimized vermicompost degradation and nutrient release. *Front. Sustain. Food Syst.* **2022**, *6*, 1005740. [CrossRef]
19. Park, S.; Kim, D.; Kim, S.; Choi, G.; Yoo, H.; Park, S.; Cho, S. Optimization of Desalting Conditions for the Green Seaweed *Codium fragile* for Use as a Functional Food with Hypnotic Effects. *Foods* **2024**, *13*, 3287. [CrossRef] [PubMed]
20. Purnomo; Candra; Suhandi, J.; Asmawati. Types of soak solutions and drying time to *Eucheuma cottonii*'s semi refined carrageenan characteristics. *Russ. J. Agric. Socio-Econ. Sci.* **2021**, *112*, 121–126. [CrossRef]
21. Senanu, S.; Sandquist, J.; Skjermo, J.; Rørvik, S.; Windfeldt, M. Feasibility of Biochar from Seaweed for Ferroalloy Production. *J. Sustain. Metall.* **2024**, *10*, 1380–1392. [CrossRef]
22. Stévant, P.; Marfaing, H.; Duinker, A.; Fleurence, J.; Rustad, T.; Sandbakken, I.; Chapman, A. Biomass soaking treatments to reduce potentially undesirable compounds in the edible seaweeds sugar kelp (*Saccharina latissima*) and winged kelp (*Alaria esculenta*) and health risk estimation for human consumption. *J. Appl. Phycol.* **2018**, *30*, 2047–2060. [CrossRef]
23. Pandit, N.R.; Choudhary, D.; Maharjan, S.; Dhakal, K.; Vista, S.P.; Gaihre, Y.K. Optimum Rate and Deep Placement of Nitrogen Fertilizer Improves Nitrogen Use Efficiency and Tomato Yield in Nepal. *Soil Syst.* **2022**, *6*, 72. [CrossRef]
24. Nascimento, C.S.; Nascimento, C.S.; Cecílio Filho, A.B. Doses and split nitrogen fertilizer applications on the productivity and quality of arugula. *Rev. Caatinga* **2021**, *34*, 824–829. [CrossRef]
25. Guo, J.; Du, M.; Tian, H.; Wang, B. Exposure to High Salinity During Seed Development Markedly Enhances Seedling Emergence and Fitness of the Progeny of the Extreme Halophyte *Suaeda salsa*. *Front. Plant Sci.* **2020**, *11*, 1291. [CrossRef]
26. Finch-Savage, W.E.; Bassel, G.W. Seed vigour and crop establishment: Extending performance beyond adaptation. *J. Exp. Bot.* **2016**, *67*, 567–591. [CrossRef] [PubMed]
27. Wang, P.; Mo, B.; Long, Z.; Fan, S.; Wang, H.; Wang, L. Factors affecting seed germination and emergence of *Sophora davidii*. *Ind. Crops Prod.* **2016**, *87*, 261–265. [CrossRef]
28. Rolletschek, H.; Borisjuk, L.; Gómez-Álvarez, E.M.; Pucciariello, C. Advances in seed hypoxia research. *Plant Physiol.* **2024**, *197*, kiae556. [CrossRef] [PubMed]
29. Faryal, F.; Muhammad, U.J. Seedling and Germination Stages of Tomatoes (*Solanum lycopersicum*) in Pakistan under Home Remedies, Packing and Transported to Other Countries with the Proper Identification of Pest and Diseases. *Acta Sci. Agric.* **2019**, *9*, 57–66. [CrossRef]
30. Mustapha, C.; Nabil, R.; Said, E.; Abdallah, M.; Ghizlane, E.; Kacem, M.; Gabriel, P.; Omar, H.; Mohamed, B. Effects of Temperature, pH, and Salinity on Seed Germination of *Acinos alpinus* subsp. Meridionalis and FTIR Analysis of Molecular Composition Changes. *Sustainability* **2023**, *15*, 4793. [CrossRef]

31. Irik, H.A.; Bikmaz, G. Effect of different salinity on seed germination, growth parameters and biochemical contents of pumpkin (*Cucurbita pepo* L.) seeds cultivars. *Sci. Rep.* **2024**, *14*, 6929. [CrossRef]
32. Karwal, M.; Kaushik, A. Bioconversion of lawn waste amended with kitchen waste and buffalo dung in to value-added vermicompost using *Eisenia foetida* to alleviate landfill burden. *J. Mater. Cycles Waste Manag.* **2021**, *23*, 358–370. [CrossRef]
33. Sarwar, G.; Anwar, T.; Qureshi, H.; Younus, M.; Hassan, M.W.; Sajid-ur-Rehman, M.; Khalid, F.; Faiza; Zaman, W.; Soufan, W. Optimizing germination: Comparative assessment of various growth media on dragon fruit germination and early growth. *BMC Plant Biol.* **2024**, *24*, 533. [CrossRef]
34. Demir, I.; Kenanoglu, B.B.; Özden, E. Seed Vigour Tests to Estimate Seedling Emergence in Cress (*Lepidium sativum* L.) Seed Lots. *Not. Bot. Horti Agrobot. Cluj-Napoca* **2019**, *47*, 881–886. [CrossRef]
35. Chipenete, G.H.N.; Santos, H.O.D.; Chipenete, C.F.; Lino, S.M.D.S.; Andrade Júnior, V.C.D.; Jesus, J.V.M.D. Treatment and preservation of tomato seeds to maintain quality and reduce microbial contamination. *J. Seed Sci.* **2025**, *47*, e202547021. [CrossRef]
36. Bae, Y.H.; Yang, H.C.; Kim, Y.H.; Hyeon, S.J.; Choi, M.S.; Vu, N.T.; Jang, D.C. Seedling Quality and Early Growth After the Transplanting of Tomato Seedlings Grown Using Different Production Methods. *Hortic. Sci. Technol.* **2025**, *43*, 275–285. [CrossRef]
37. Hussain, N.; Yasmeen, A.; Bilal, M. The application of ammonium sulphate and amino acid on cotton: Effects on can improve growth, yield, quality and nitrogen absorption. *Braz. J. Biol.* **2022**, *82*, e240133. [CrossRef]
38. Askari, A.; Khanmirzaei, A.; Shekoofeh, R. Vermicompost enrichment using organic wastes: Nitrogen content and mineralization. *Int. J. Recycl. Org. Waste Agric.* **2020**, *9*, 151–160. [CrossRef]
39. Ghimire, S.; Dhami, D.; Shrestha, A.; Budhathoki, J.; Maharjan, M.; Kandel, S.; Chhetri, B.P. Effectiveness of different combinations of urea and vermicompost on yield of bitter melon (*Momordica charantia*). *Heliyon* **2023**, *9*, e18663. [CrossRef] [PubMed]
40. Sande, T.J.; Tindwa, H.J.; Shitindi, M.J.; Semoka, J.M.; Alovisi, A.M.T. Enhancing sustainable crop production through integrated nutrient management: A focus on vermicompost, bio-enriched rock phosphate, and inorganic fertilizers—A systematic review. *Front. Agron.* **2024**, *6*, 1422876. [CrossRef]
41. Büyükarıslan, D.; Demir, H. Effects of vermicompost as an alternative substrate on yield and quality of cauliflower and pepper seedlings. *Not. Bot. Horti Agrobot. Cluj-Napoca* **2024**, *52*, 13587. [CrossRef]
42. Gopaul, L.; Abraham, B.N.; Homenauth, O. Effects of coco-peat, vermicompost and pro-mix growth media on the growth and development of boudin (*Solanum melongena*) and tomato (*Solanum lycopersicum*) seedlings: A comparative study. *Int. J. Agric. Environ. Res.* **2021**, *7*, 735–754. [CrossRef]
43. Moaaz, M.; Javed, T.; Mauro, R.P.; Shabbir, R.; Afzal, I.; Yousef, A.F. Effect of Seed Priming with Potassium Nitrate on the Performance of Tomato. *Agriculture* **2020**, *10*, 498. [CrossRef]
44. Xu, Y.; Kaste, J.A.M.; Weise, S.E.; Shachar-Hill, Y.; Sharkey, T.D. The effects of photosynthetic rate on respiration in light, starch/sucrose partitioning, and other metabolic fluxes within photosynthesis. *Sci. Rep.* **2025**, *15*, 8389. [CrossRef]
45. Hatfield, J.L.; Dold, C. Photosynthesis in the solar corridor system. In *The Solar Corridor Crop System*; Elsevier: Amsterdam, The Netherlands, 2019; pp. 1–33. [CrossRef]
46. Singh, B.; Singh, S. Essential Plant Nutrients and Their Roles. 2024. Available online: [https://www.researchgate.net/publication/387494898\\_Essential\\_Plant\\_Nutrients\\_and\\_Their\\_Roles](https://www.researchgate.net/publication/387494898_Essential_Plant_Nutrients_and_Their_Roles) (accessed on 14 May 2026).
47. Aslam, Z.; Ahmad, A.; Abbas, R.N.; Sarwar, M.A.; Bashir, S. Morpho-physiological, biochemical and yield responses of wheat (*Triticum aestivum* L.) to vermicompost, simple compost and NP fertilizer applications. *Pak. J. Bot.* **2023**, *55*, 2143–2154. [CrossRef]
48. Patel, K.K.; Priya; Tekam, Y.; Shah, A.K.; Kumar, K.; Kumhare, A.; Dwarka. Effect of Vermicompost on Soil Properties, Plant Growth and Environmental Sustainability: A Review. *Int. J. Plant Soil Sci.* **2024**, *36*, 688–693. [CrossRef]
49. Ferreira, P.H.F.; Cruz, V.H.; Frias, Y.A.; Barretto, V.C.D.M.; Lopes, P.R.M. Vermicompost: A pathway to transform organic waste into substrate for seedling production. *Discov. Agric.* **2025**, *3*, 166. [CrossRef]
50. Shilpha, J.; Song, J.; Jeong, B.R. Ammonium Phytotoxicity and Tolerance: An Insight into Ammonium Nutrition to Improve Crop Productivity. *Agronomy* **2023**, *13*, 1487. [CrossRef]
51. Miao, L.; Wang, X.; Yu, C.; Ye, C.; Yan, Y.; Wang, H. What factors control plant height? *J. Integr. Agric.* **2024**, *23*, 1803–1824. [CrossRef]
52. Qi, Z.; Hua, W.; Zhang, Z.; Deng, X.; Yuan, T.; Zhang, W. A novel method for tomato stem diameter measurement based on improved YOLOv8-seg and RGB-D data. *Comput. Electron. Agric.* **2024**, *226*, 109387. [CrossRef]
53. Wang, X.-X.; Zhao, F.; Zhang, G.; Zhang, Y.; Yang, L. Vermicompost Improves Tomato Yield and Quality and the Biochemical Properties of Soils with Different Tomato Planting History in a Greenhouse Study. *Front. Plant Sci.* **2017**, *8*, 1978. [CrossRef]
54. Kumar, P.; Choudhary, M.; Halder, T.; Prakash, N.R.; Singh, V.V.; Sheoran, V.T.; Longmei, R.K.; Rakshit, N.; Siddique, S. Salinity stress tolerance and omics approaches: Revisiting the progress and achievements in major cereal crops. *Heredity* **2022**, *128*, 497–518. [CrossRef]
55. Nong, H.; Tateishi, R.; Suriyasak, C.; Kobayashi, T.; Oyama, Y.; Chen, W.J.; Matsumoto, R.; Hamaoka, N.; Iwaya-Inoue, M.; Ishibashi, Y. Effect of Seedling Nitrogen Condition on Subsequent Vegetative Growth Stages and Its Relationship to the Expression of Nitrogen Transporter Genes in Rice. *Plants* **2020**, *9*, 861. [CrossRef]

56. Wang, M.; He, D.; Shen, F.; Huang, J.; Zhang, R.; Liu, W.; Zhu, M.; Zhou, L.; Wang, L.; Zhou, Q. Effects of soil compaction on plant growth, nutrient absorption, and root respiration in soybean seedlings. *Environ. Sci. Pollut. Res.* **2019**, *26*, 22835–22845. [[CrossRef](#)] [[PubMed](#)]
57. Raza, A.; Ashraf, F.; Zou, X.; Zhang, X.; Tosif, H. Plant Adaptation and Tolerance to Environmental Stresses: Mechanisms and Perspectives. In *Plant Ecophysiology and Adaptation Under Climate Change: Mechanisms and Perspectives I*; Hasanuzzaman, M., Ed.; Springer: Singapore, 2020; pp. 117–145. [[CrossRef](#)]
58. Kalaivani, K.; Jawaharlal, M. Study on physical characterization of coco peat with different proportions of organic amendments for soilless cultivation. *J. Pharmacogn. Phytochem.* **2019**, *8*, 2283–2286.
59. Gong, S.; Xiulong, O. Optimizing vermicompost-soil ratios for synergistic enhancement of *Allium fistulosum* growth dynamics and phytochemical quality. *Front. Plant Sci.* **2025**, *16*, 1694011. [[CrossRef](#)]
60. Erdal, İ.; Aktaş, H. Comparison of the Perlite, Leonardite, Vermicompost and Peat Moss and Their Combinations with Cocopeat as Tomato Growing Media. *J. Soil Sci. Plant Nutr.* **2025**, *25*, 2726–2741. [[CrossRef](#)]
61. Spehia, R.S.; Singh, S.K.; Devi, M.; Chauhan, N.; Singh, S.; Sharma, D.; Sharma, J.C. Effect of soilless media on nutrient uptake and yield of tomato (*Solanum lycopersicum*). *Indian J. Agric. Sci.* **2020**, *90*, 732–735. [[CrossRef](#)]
62. Melati; Meilawati, N.L.; Arlianti, T. Effect of planting media modification on growth and seed potential of two vanilla varieties. *IOP Conf. Ser. Earth Environ. Sci.* **2023**, *1160*, 012010. [[CrossRef](#)]
63. Fikre, H.; Boto, N. Effects of varieties and pot sizes on the early shoot and root growth of enset (*Ensete ventricosum* (Welw) Cheesman). *Cogent Food Agric.* **2024**, *10*, 2370396. [[CrossRef](#)]
64. Mupambwa, H.A.; Gawanab, W.; Handura, B. Fly ash amended vermicompost as a growing medium for tomato (*Solanum lycopersicum*) and Swiss chard (*Beta vulgaris*): Implications on growth and heavy metal uptake. *Discov. Agric.* **2024**, *2*, 96. [[CrossRef](#)]
65. Shahraini, E.; Ebrahimi, E.; Kamyab, T.; Asilianmahabadi, A.; Hamid, A.A.; Amirinejad, A. Reusing drainage water for leaching of saline and sodic soils in the Khuzestan province, Iran. *Water Supply* **2024**, *24*, 1462–1476. [[CrossRef](#)]
66. Muhammad, M.; Waheed, A.; Wahab, A.; Majeed, M.; Nazim, M.; Liu, Y.-H.; Li, L.; Li, W.-J. Soil salinity and drought tolerance: An evaluation of plant growth, productivity, microbial diversity, and amelioration strategies. *Plant Stress* **2024**, *11*, 100319. [[CrossRef](#)]
67. Simkin, A.J.; Kapoor, L.; Doss, C.G.P.; Hofmann, T.A.; Lawson, T.; Ramamoorthy, S. The role of photosynthesis related pigments in light harvesting, photoprotection and enhancement of photosynthetic yield in planta. *Photosynth. Res.* **2022**, *152*, 23–42. [[CrossRef](#)]
68. Melash, A.A.; Bytyqi, B.; Nyandi, M.S.; Vad, A.M.; Abraham, E.B. Chlorophyll Meter: A Precision Agricultural Decision-Making Tool for Nutrient Supply in Durum Wheat (*Triticum turgidum* L.) Cultivation Under Drought Conditions. *Life* **2023**, *13*, 824. [[CrossRef](#)]
69. Ravier, C.; Quemada, M.; Jeuffroy, M.-H. Use of a chlorophyll meter to assess nitrogen nutrition index during the growth cycle in winter wheat. *Field Crops Res.* **2017**, *214*, 73–82. [[CrossRef](#)]
70. Liao, J.; Hu, A.; Zhao, Z.; Liu, X.; Jiang, C.; Zhang, Z. Biochar with large specific surface area recruits N<sub>2</sub>O-reducing microbes and mitigate N<sub>2</sub>O emission. *Soil Biol. Biochem.* **2021**, *156*, 108212. [[CrossRef](#)]
71. Britz, E.; Cyster, L.; Samuels, I.; Cupido, C.; Masemola, L.; Ngcobo, N.; Manganyi, F.; Müller, F. Nitrogen fertilization increases the growth and nutritional quality of the forage legume, *Calobota sericea*—A preliminary investigation. *Heliyon* **2023**, *9*, e13535. [[CrossRef](#)] [[PubMed](#)]
72. Al-Ajlouni, M.G.; Othman, Y.A.; Abu-Shanab, N.S.; Alzyoud, L.F. Evaluating the Performance of Cocopeat and Volcanic Tuff in Soilless Cultivation of Roses. *Plants* **2024**, *13*, 2293. [[CrossRef](#)]
73. Bhat, M.A.; Lone, H.A.; Mehraj, S.S. Nutrient Remobilization During Senescence. In *Senescence Signalling and Control in Plants*; Elsevier: Amsterdam, The Netherlands, 2019; pp. 227–237. [[CrossRef](#)]

**Disclaimer/Publisher’s Note:** The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.