Ulva lactuca Biochar: From Sea to Soil for Enhancing Sustainable Agriculture

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ABSTRACT: The adverse effects of chemical fertilizers on human health and environmental sustainability have driven a shift toward organic farming and sustainable soil amendments. Marine macroalgae, particularly *Ulva lactuca*, have gained attention as promising bioresources due to their rich biochemical composition and nutrient availability. This study explores the potential of *U. lactuca*-derived biochar and raw seaweed as soil amendments to enhance plant growth and physiological performance. Biochar was produced through slow pyrolysis at 450 ± 5°C under oxygen-limited conditions, yielding a material with low carbon (C) and nitrogen (N) content but elevated pH, phosphorus (P), and potassium (K) levels, like poultry manure biochar. A greenhouse experiment conducted in October 2023 evaluated the effects of raw *U. lactuca* at two application rates (SW1, SW2) and its derived biochar (BC1, BC2), both independently and in combination (BC1+SW1, BC1+SW2), on *Pisum sativum* L. seedling development. Growth parameters including root depth, shoot length, fresh and dry biomass—and photosynthetic pigment concentrations (chlorophyll a, chlorophyll b, and carotenoids) were assessed 10 days after sowing. All treatments significantly improved seedling growth and pigment content compared to controls, with the highest biochar rate (BC2) and its combination with SW2 yielding the most pronounced effects. These findings highlight *U. lactuca*-derived biochar as a valuable organic soil amendment, particularly at higher application rates, with potential benefits for sustainable agriculture and crop productivity.

Keywords: *Ulva lactuca,* biochar, soil amendments, Sustainable agriculture, Photosynthetic pigments, biostimulants

INTRODUCTION

The expanded world population is resulting in severe food demand, soil decomposition processes like lack of water holding capacity, erosion, acidification, reduced cation exchange, poor fertility, urbanization, and changing climatic conditions that endanger global food stability (Maitra et al., 2020; Barakat et al. 2021; Duan et al., 2023). Finding a practical solution has become necessary to boost soil health and crop yield; sustainable agriculture is recommended as a safer practice compared with traditional methods (Kumar et al., 2022). Sustainable agriculture involves cooperation among biological, cultural and natural fields to achieve healthy, modern, and eco-friendly renewable cultivation practices (Leng & Huang, 2018; Jena et al., 2022). Seaweeds include thousands of multicellular, macroscopic marine algal species that are classified according to photosynthetic pigments into three primary categories: Chlorophyta, Phaeophyta and Rhodophyta (Dawczynski et al., 2007; Khalid et al., 2018). Marine macroalgae is considered a “millennial promising plant” due to its several benefits compared to terrestrial plants, including no requirements for arable lands, fresh water, manure or insecticides. The produced organic material can be exploited as thickening agent substances, in nutrition, or in renewable fuels as well as their cultivation helps reduce greenhouse gas emissions (Chapman & Chapman, 1980; Dhargalkar & Neelam, 2005; Ismail et al. 2023). Moreover, seaweed grows more rapidly and efficiently, doesn’t occupy more space than land plants, and in ideal conditions can produce higher dry biomass than fast-growing land plants (Gao & McKinley, 1994; Creed et al., 2019). They can also absorb nutrients such as nitrogen and phosphorus and can capture heavy metals either internally or externally in addition to their bioremediation efficiency (Lobban, 1994; Neori et al., 2003; Barrington et al., 2009; Troell, 2009). Concerns about the direct or indirect negative impacts of synthetic fertilizer on human health and the environment have increased, making it necessary to move from traditional chemical farming systems to organic sustainable agriculture (Dubey, 2010). Applying seaweed as it is or its extracts for many plants has achieved notable significance, as they contain essential minerals (Cu, Zn, Fe, Mo, Co, Ni, Mn), hormones that enhance growth, amino acids, cytokinins, vitamins, and antioxidant properties (Sivasankari, 2006; Abdel Khalik et al., 2013; El-Shenody et al. 2023).

Furthermore, marine macroalgal essence increases crop growth and yield and enhances plant's resilience to environmental tension (Eissa et al., 2017; Ashour et al., 2021; Hassan et al. 2021). *Ulva lactuca* is one of the most widely abundant green macroalgae, particularly pioneering for cultivation in wastewater and nutrient reuse for terrestrial crops (Barakat et al. 2022; El-Sayed et al., 2022). It is characterized by high nutritional content, including essential biochemical components (Pengzhan et al., 2003; Mulbry et al., 2005). Sridhar (2011) reported enhancements in seed germination and protein profiles of treated samples with *Sargassum wightii* and *Ulva Lactuca* extract.

Additionally, Ganapathy and Sivakumar (2013) found that using 2% foliar spray of *Ulva reticulata* increased the number of leaf stomata in *Zea mays* and improved the *Vigna mungo* crop. In addition to directly using algal biomass as soil improvements, converting it into biochar is a momentum-gaining technology. This method significantly confines plant biomass carbon into soil carbon, making biochar a more efficient soil additive (Katakula et al., 2020). Biochar is activated carbon made from various feedstocks such as agricultural residues, wood, livestock wastes, sewage sludge, or seaweeds, and it can be obtained through biomass burning in oxygen-deficient conditions, recognized as low-temperature carbonization (Lehmann & Joseph, 2012). It is considered carbon-rich substance that resists degradation and provides stable carbon for a very long period. Moreover, biochar improves soil quality and adjusts its characteristics, like surface elements preservation and water maintenance capacity, significantly improving biofertilizer quality and plant yield (Lehmann & Joseph, 2024). Through pyrolysis, seaweed can be converted into beneficial commodities like biochar, providing eco-friendly solutions to global energy needs (Sekar et al., 2021). Biochar's composition and yield depend on the type of biomass used and thermal decomposition parameters, including applied temperature degree, time on stream, and thermal ramping (Amalina et al., 2022). Bird et al. (2011) mentioned that seaweeds are pioneering raw sources for biochar production, and a temperature of 450 ± 5℃ provides a balanced approach between efficient pyrolysis and mass loss during ignition. Biochar from seaweed has a carbon content (~30-35%) lower than lignocellulosic biochar (>70%); however, it includes more basic nutrients essential for plant growth, significantly benefiting low-fertility soils (Roberts et al., 2015). Organic compost and manures contain higher quantities of carbonaceous and essential elements; incorporating these as biochar feedstocks into soil enhances the existence of essential nutrients like nitrogen, phosphorus, and metal ions such as calcium and magnesium (Gundale & DeLuca, 2006; Xu et al., 2013). Biochar application increases nitrification and induces soil alkalization, changes soil pH that can influence phosphorus availability, and elevates electrical conductivity, increasing surface area for cation exchange and adsorption (Topoliantz & Ponge, 2005; Major et al., 2010).

This study aims to evaluate the potential of *Ulva lactuca*-derived biochar and raw seaweed as sustainable soil amendments for improving plant growth and physiological responses. Specifically, the research investigates the effects of these amendments on the growth performance and photosynthetic pigment content of *Pisum sativum* L. seedlings. The study also assesses the physicochemical characteristics of *U. lactuca* biochar and its impact on soil fertility parameters. While previous studies have explored the benefits of seaweed extracts as biostimulants and biochar as a soil conditioner, limited research has focused on the combined effects of *Ulva lactuca*-derived biochar and raw seaweed on plant growth. This study introduces a recent approach by evaluating different application rates of seaweed and biochar, both independently and in combination, to determine their synergistic effects on *Pisum sativum* L. seedlings. Furthermore, the study provides new insights into the potential of *U. lactuca* biochar as an organic alternative to traditional fertilizers, contributing to the advancement of sustainable agricultural practices.

MATERIALS AND METHODS

Collection and Processing of *Ulva lactuca*

U. lactuca L. specimens were collected from submerged rocks at Boughaz El-Maadya in Abu Qir Bay, Alexandria, Egypt (31°15'N, 30°10'E) during the summer of 2023. Species identification was performed based on morphological characteristics according to previous taxonomic descriptions (Nasr and Aleem, 1948; Shabaka, 2018). Fresh samples were immediately transported to the laboratory in seawater-filled polyethene bags to prevent desiccation. The collected specimens underwent a two-step cleaning protocol: initial rinsing with seawater to remove loose debris, followed by thorough washing with distilled water to eliminate sand, epiphytes, and other contaminants. Cleaned samples were blotted dry using absorbent paper to remove excess moisture. The samples were oven-dried at 50°C until reaching constant weight. The dried material was subsequently pulverized using a mechanical grinder and passed through a 0.5 mm mesh sieve. The resulting powder was stored in sealed polyethene containers at room temperature until further analysis.

Optimization of pyrolysis conditions

The algal biomass was oven-dried at 105°C until it was constant to ensure moisture content uniformity. Samples (100 g) of dried *U. lactuca* were placed in a wire mesh basket and transferred to a sealed stainless-steel reactor. Pyrolysis was conducted under continuous dry nitrogen flow at four different terminal temperatures: 305°C, 414°C, 450°C, and 512°C. Each temperature was maintained for 60 min to ensure complete pyrolysis, followed by cooling to ambient temperature (Bird et al., 2011). The resulting biochar was weighed, homogenized, and gently crushed for subsequent analyses. Based on the optimization results, 450°C was determined to be the optimal pyrolysis temperature, providing an effective balance between pyrolysis efficiency and mass retention. This temperature was selected for subsequent biochar production. Physicochemical characterization of both raw seaweed and biochar samples included total C, N, and H content. pH, and electrical conductivity (EC) were measured using a portable multi-parameter meter (e.g., HI9811-5, Hanna Instruments). These analyses were performed to comprehensively evaluate the physicochemical properties and potential applications of the algal-derived biochar.

Characterization of elemental composition of seaweed and biochar

Physicochemical analyses were performed at the Central Laboratory, Tanta University on both dried seaweed and produced biochar samples. For elemental analysis, 0.20 g of finely ground dried material underwent complete acid digestion in sealed Teflon vessels using a mixture of concentrated HNO_3, $HClO_4$, and HF (3:2:1 ratio, Merck, Germany). The digestion was conducted in triplicate within a sealed stainless-steel block at 50°C under high pressure until completion. The digested samples were diluted to 25 mL with distilled deionized water in PTFE flasks and filtered into acid-washed PVC containers. Metal concentrations were determined using a Perkin Elmer 2830 flame Atomic Absorption Spectrophotometer, with all measurements performed in triplicate. Potassium concentrations were specifically measured using a Corning Clinical flame photometer 410C (El-Said & El-Sikaily, 2013). The analyzed elements included magnesium (Mg), potassium (K), and phosphorus (P). Molecular characterization was performed at the Central Laboratory, Tanta University using Fourier transform infrared (FTIR) spectroscopy to identify key functional groups in both dried seaweed and biochar samples. The specimens were homogenized with potassium bromide (KBr), compressed into pellets, and analyzed across a frequency range of 400–4000 cm^{-1}. This analysis provided detailed information about the molecular structure and functional groups present in the samples (El-Sayed & El-Sikaily, 2013).

Seed Material and Experimental Site

Pisum sativum L. seeds were obtained from the Agricultural Research Center, Giza, Egypt. The experiment was conducted in October 2023 using surface soil collected from the Research Farm, Faculty of Science, Tanta University, Egypt. The soil was air-dried, homogenized, and analyzed for physicochemical properties. The analysis revealed a sandy texture (13.8% sand, 25.5% silt, 56.6% clay) with pH 7.7 and EC 0.6 dS m^{-1}. The soil contained organic matter (3.0 g kg^{-1}), available nitrogen (10.3 mg kg^{-1}), phosphorus (7.3 mg kg^{-1}), and potassium (188 mg kg^{-1}).

Experimental Design and Treatments

The experiment employed a completely randomized block design with seven treatments and three replicates per treatment (Gomez and Gomez, 1984). The treatments consisted of dried *U. lactuca* at 2 g kg^{-1} soil (SW1) and 5 g kg^{-1} soil (SW2); *U. lactuca* biochar at 2 g kg^{-1} soil (BC1) and 5 g kg^{-1} soil (BC2); combinations of SW1+BC1 and SW2+BC2; and an untreated control (C).

Seed Preparation and Cultivation

Seeds were selected for uniformity and surface-sterilized using 2.5% sodium hypochlorite solution for 3 minutes, followed by thorough rinsing with distilled water. Twenty seeds were sown in each 25-cm diameter pot containing homogeneous loamy soil.

Growth and Physiological Measurements

After 10 days, seedlings were carefully extracted and washed to remove soil particles. Growth parameters measured included root depth (cm), shoot length (cm), and fresh and dry weights.

Photosynthetic Pigment Analysis

Chlorophyll a (Chl-*a*), chlorophyll *b* (Chl-b), and total carotenoid content (TCC) were determined spectrophotometrically from acetone extracts. Absorbance was measured at 630 nm and 664 nm for chlorophylls and 450 nm for carotenoids. Pigment concentrations (µg g^{-1} fresh weight) were calculated using the following equations (Jeffrey and Humphrey, 1975; Chan and Matanjun, 2017):

$$Chl-a = 11.47 \times A664 - 0.40 \times A630$$

$$Chl-b = (-0.328 \times OD663 + 1.770 \times OD645)$$

$$Carotenoids = A450 / 25$$

Statistical Analysis

The physical and chemical parameters of seaweed and biochar, growth parameters, and photosynthetic pigment data were recorded as the mean values of three replicates ± standard deviation (SD). To determine significant differences, the data was subjected to a one-way analysis of variance (ANOVA). Duncan's multiple range test was applied at a significant level of $p < 0.005$ to compare the means. All statistical analyses were performed using SPSS Inc. version 15 (2006).

Results and discussion

Collaboration between agricultural scientists and pyrolysis engineers is essential to design "tailored biochars" that meet specific agricultural needs, as the choice of raw materials and pyrolysis parameters can be optimized for desired outcomes (Downie et al., 2012). When used in agriculture, biochar can improve soil structure, porosity, and density, thereby enhancing water retention, nutrient availability, and microbial activity (Amonette & Joseph, 2009). Biochar is characterized by its porous, carbon-rich structure, which includes polycyclic aromatic hydrocarbons and significant amounts of fulvic and humic acids. These components contribute to its chemical stability and microbial balance (Krull et al., 2009). The properties of biochar, such as hydrophobicity, hydrophilicity, acidity, and basicity, vary depending on the feedstock, pyrolysis temperature, and oxygen availability during production (Amonette & Joseph, 2009). Notably, the final pyrolysis temperature has a profound impact on biochar characteristics, including carbon content and physical structure (Downie et al., 2012).

Thermal Analysis and Mass Loss Characteristics

The physical properties of biochar play a critical role in determining its effectiveness for soil enhancement and carbon sequestration. The conditions under which biochar is produced, such as pyrolysis temperature and feedstock type, significantly influence its behaviour when applied to soil (Atkinson et al., 2010). Physical and chemical analyses of raw *Ulva lactuca* and its biochar produced at different pyrolysis temperatures revealed significant trends. As the pyrolysis temperature increased from 305°C to 411°C, the weight loss rose from 24% to 35%. Notably, the minimum mass loss (22%) occurred at 450°C, followed by a substantial increase to 45% at 512°C. The ash content of raw *U. lactuca* was 22%, which increased from 26.5% to 42% as the pyrolysis temperature rose from 305°C to 450°C, before decreasing to 31% at 512°C (Table 1). These findings are consistent with Bird et al. (2011), who reported that biochar derived from seven macroalgal species exhibited a wide range of structural variations, with mass losses during pyrolysis ranging from 20.9% to 54.2% and ash content varying between 16.0% and 73.5%.

Elemental and Chemical Properties

The elemental composition of biochar is significantly influenced by pyrolysis temperature. As the temperature increased from 305°C to 511°C, the carbon, nitrogen, and hydrogen content of the biochar decreased, with carbon dropping from 24.9% to 17%, nitrogen from 4.2% to 2.2%, and hydrogen from 2.4% to 0.8%. This trend aligns with findings from previous studies, which report a general reduction in volatile matter and an increase in fixed

Table 1. Physical and chemical characteristics of raw *Ulva lactuca* and its biochar under different pyrolysis temperatures.

Parameters	**Raw *Ulva lactuca***	***Ulva lactuca* 's biochar**					
Pyrolysis temp. (˚C)	-	305	414	450	512	F value	P value
Ash content %	22±0.81	26.5±2[a]	29.2±1.53[a]	42± 2.14[b]	31±1.53[a]	5.67	0.012
Loss on ignition %	-	24±1.53[a]	35±1[b]	22±1.32[a]	45±2.65[c]	3.45	0.045
pH	-	8±0.58[a]	9.8±0.06[b]	10±0.54[b]	10.1±0.06[b]	7.89	0.001
EC (ms/cm)		40±0.58[a]	53±1.15[a]	51±2.6[a]	50±2[a]	1.23	0.345
Carbon %	22.2±0.82	0.21±24.9[b]	21.7±0.15[b]	18.6±0.21[c]	17±1.53[c]	4.56	0.023
Nitrogen %	3.3±0.14	4.2±0.15[a]	3.1±0.06[b]	2±0.15[c]	2.2±0.15[c]	6.78	0.005
Hydrogen %	3.4±0.12	2.4±0.15[a]	1.5±0.06[b]	0.9±0.03[c]	0.8±0.01[c]	8.90	0.0009
C/N ratio	6.7±0.24	5.9±0.17[a]	7±0.18[a]	9.3±0.77[a]	7.7±0.60[a]	2.34	0.123
Phosphorus mg/kg	3689±2.62	3600±1.73[a]	4810±1.15[b]	6000±3.34[c]	3200±1.58[a]	9.87	0.0005
Magnesium mg/kg	132±1.25	125±1.15[a]	180±0.58[b]	104±1.15[a]	189±1.35[b]	3.21	0.056
Potassium mg/kg	127±1	112±0.58[a]	90±2.08[b]	160±2.15[c]	59±0.85[d]	4.32	0.034

Each result is the mean of three replicates ± standard deviation. Different superscript letters (a, b, c) indicate statistically significant differences ($p < 0.05$). F-values represent the ratio of variance between groups to variance within groups. Values in each parameter with the same letters are insignificant (one way ANOVA).

carbon and ash content at higher pyrolysis temperatures (El-Sheikha & Hegazy, 2020). Additionally, Wei et al. (2017) observed that biochar derived from crop residues showed a decrease in polar acidic functional groups and an increase in aromatic carbon structures with increasing pyrolysis temperature (Wei et al., 2017). Other chemical properties of biochar also varied with temperature. The pH ranged from 8 to 10.1, consistent with studies indicating that biochar pH generally increases at higher pyrolysis temperatures due to the concentration of basic minerals (Lataf et al., 2022). Electrical conductivity fluctuated between 40 and 50 mS cm^{-1}, a behavior also observed in biochars produced from different biomass sources (Altıkat et al., 2024). Phosphorus levels peaked at 6000 mg kg^{-1} at 450°C, like reports showing increased nutrient retention in biochar at mid-range pyrolysis temperatures (Drané et al., 2023). The magnesium concentration at 450°C was 104 mg/kg, lower than that of raw *Ulva lactuca* (132 mg/kg), while potassium levels at 450°C (160 mg/kg) were higher than those of the raw seaweed (127 mg/kg). These trends highlight the complexity of nutrient dynamics in biochar production and their potential implications for agricultural applications.

Analysis of Biochar Properties and Their Effects

Biochar produced from *Ulva lactuca* at 450°C demonstrated relatively low carbon and nitrogen content, like findings from other studies using organic feedstocks. The biochar exhibited high pH levels along with elevated phosphorus (P) and potassium (K) concentrations, suggesting its potential as a soil amendment. These results align with Chan and Xu (2009), who reported biochar from chicken manure at similar temperatures with a high pH of 9.9, 38% carbon, and 2% nitrogen, along with substantial phosphorus content (Chan & Xu, 2009). Similarly, Tagoe et al. (2008) produced chicken manure biochar at 500°C, yielding a high pH of 9.93, 12.3% carbon, and phosphorus levels of 18,170 mg kg^{-1} (Tagoe et al., 2008). In contrast, lignocellulosic biochars generally exhibit higher carbon content, cation exchange capacity, and lower nutrient levels, especially phosphorus, compared to macroalgal biochar (Ozcimen & Ersoy-Mericboyu, 2010). As with other nutrient-rich biochars like chicken manure biochar, macroalgal biochar can improve soil properties, particularly for acidic soils, but it is less effective for carbon sequestration than lignocellulosic biochar (Bird et al., 2011). The rich nutrient profile, however, makes macroalgal biochar a promising option for enhancing soil fertility and mitigating environmental issues such as the disposal of marine waste (Amrullah et al., 2022).

Impact on *Pisum sativum* L. Growth

Table 2 summarizes the effects of applying powdered *Ulva lactuca* seaweed (SW1 or SW2), its biochar produced at 450°C (BC1 or BC2), and combinations of seaweed and biochar (SW1 + BC1 or SW2 + BC2) on *Pisum sativum* L. seeds. The treatments significantly improved growth parameters, including root depth, shoot length, and fresh and dry weights of both root and shoot systems, compared to the control group. The treatments enhanced photosynthetic pigments such as chlorophyll *a*, chlorophyll *b*, and carotenoids. These findings align with previous research indicating that *Ulva lactuca* biochar enhances plant growth by improving soil nutrient availability and promoting root development (Elsharkawy et al., 2019).

The results demonstrated a synergistic effect between seaweed powder and biochar, whether applied individually or in combination. This is consistent with previous studies showing that seaweed extracts and biochar can enhance plant morphology and yield by providing essential nutrients, amino acids, and phytohormones (Özdemir Koçak et al., 2023).

Table 2. Percentage of increase in growth parameters of *Pisum sativum L.* seedling.

Treatments	Root depth	Shoot length	Root system		Shoot system	
			Fresh weight	Dry weight	Fresh weight	Dry weight
(SW1)	7.14	7.89	27.39	26.47	35.60	7.04
(SW2)	7.94	27.63	34.08	32.35	36.93	13.57
(BC1)	25.40	24.30	36.62	67.65	36.55	25.63
(BC2)	39.68	31.58	40.76	52.94	45.88	33.67
(BC1) + (SW1)	46.83	37.72	36.31	100	47.40	39.20
(BC2) + (SW2)	73.81	56.14	65.61	105.88	54.70	38.69

Each result is the mean of three replicates ± standard deviation.

For instance, using SW2 increased root depth and shoot length by 7.94% and 27.36%, respectively, compared to the control. The improvements observed align with findings that seaweed-derived biostimulants enhance antioxidant systems and metabolic processes, thereby boosting plant productivity (Deolu-Ajayi et al., 2022). Salim and Abdel-Rassoul (2016) attributed such improvements to bioactive compounds in seaweed, including essential nutrients, vitamins, fatty acids, amino acids, cytokinins, and auxins, which enhance antioxidant systems, metabolic processes, and overall plant productivity (Chernane et al., 2015; Kumar et al. 2022; Ashour et al., 2023). Seaweed extracts are known to promote root development, nutrient uptake, photosynthetic activity, and stress tolerance in plants due to their rich content of growth regulators and micronutrients (Bhaskar & Miyashita, 2005; Khan et al., 2009; Chernane et al., 2015). They also act as biostimulants, improving plant growth, yield, and quality (Cardozo et al., 2007). Kasim et al. (2015) found that extracts from *Ulva* and *Sargassum* significantly increased root depth, shoot height, and leaf area while mitigating drought-related oxidative stress by supplying micronutrients and hormones and activating antioxidative systems.

Synergistic Effects of Seaweed and Biochar

The application of BC2 alone increased root depth and shoot length by 39.68% and 31.58%, respectively, while the combination of BC2 + SW2 resulted in the highest improvements of 73.81% and 56.1%, respectively (Figure 1). These enhancements are attributed to biochar's ability to improve soil structure, increase nutrient retention, and enhance water-holding capacity (Alburquerque et al., 2013). Studies have shown that biochar enhances phosphorus availability by modifying soil pH, stimulating microbial activity, and releasing soluble phosphorus salts (Atkinson et al., 2010). Studies by Alburquerque et al. (2013), and Olmo et al. (2014) confirmed that biochar enhances soil water retention, increases nutrient availability (N, P, K, Cu, Zn, and Mg), and stimulates root growth, ultimately improving crop yield. Atkinson et al. (2010) highlighted mechanisms by which biochar improves phosphorus availability, such as modifying soil pH, enhancing microbial activity, and releasing soluble phosphorus salts.

Fresh and Dry Weight Improvements

The application of *Ulva lactuca* seaweed and its biochar significantly increased the fresh and dry weights of the root and shoot systems in *Pisum sativum* L. seedlings. For instance, SW2 treatment enhanced root fresh weight by 34.07% and root dry weight by 32.35%, while shoot fresh and dry weights increased by 36.93% and 13.57%, respectively. Biochar treatment alone (BC2) showed even greater improvements, with a 40.76% increase in root fresh weight, 52.9% in root dry weight (Figure 2), 45.88% in shoot fresh weight, and 33.67% in shoot dry weight. The highest growth responses were recorded when biochar and seaweed were applied together (BC2 + SW2), resulting in increases of 65.60%, 105.88%, 54.70%, and 38.69% in root fresh weight, root dry weight, and shoot dry weight, respectively (Figure 3). These results suggest a strong synergistic effect between biochar and seaweed, enhancing overall plant biomass accumulation (Table 2).

The observed improvements align with previous research demonstrating that seaweed extracts and biochar enhance plant growth by improving soil fertility, promoting root elongation, and increasing nutrient uptake (Cuchca Ramos et al., 2025). Seaweed-derived biostimulants are known to contain a wide array of plant-growth-promoting compounds, including amino acids, vitamins, and phytohormones such as auxins and cytokinins, which stimulate cell division and elongation (Shukla et al., 2019 ; Nanda et al., 2021). Additionally, biochar improves soil structure, water retention, and microbial activity, further supporting plant biomass accumulation (Elsharkawy et al., 2019).

In addition to enhancing biomass, the combined application of biochar and seaweed also positively affected the nutrient composition of *Pisum sativum* plants. Higher concentrations of essential macronutrients (nitrogen, phosphorus, potassium) and micronutrients (magnesium, iron, zinc) were found in treated plants compared to the control. This increase in nutrient uptake and retention can be attributed to biochar's porous structure, which improves cation exchange capacity and enhances microbial interactions that facilitate nutrient solubilization and availability (Gupta et al., 2021). The presence of seaweed further amplifies these advantages by providing bioavailable organic compounds that enhance root development and nutrient assimilation.

Additionally, biochar's role in improving soil aeration and reducing nutrient leaching has been documented in multiple studies (Alburquerque et al., 2013). The improved water retention capacity associated with biochar also ensures that plants maintain adequate hydration, reducing drought stress and enhancing overall biomass production (Atkinson et al., 2010).

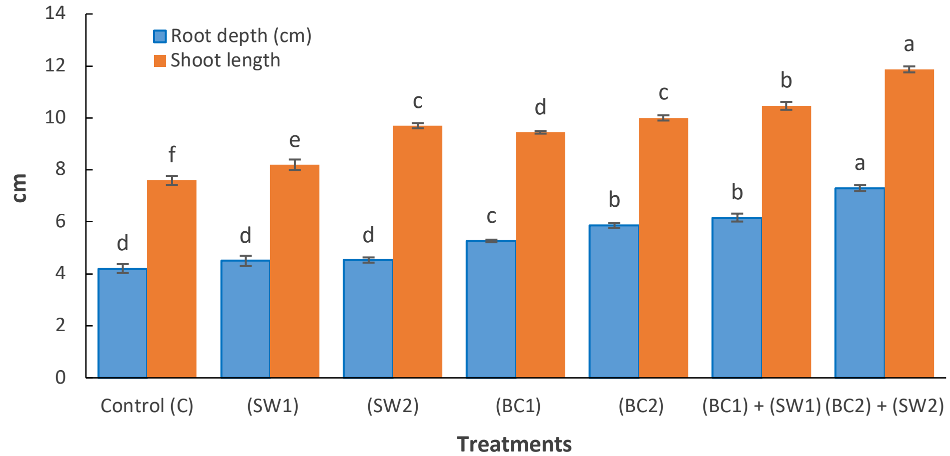

Figure 1. Effects of raw *Ulva lactuca* and its biochar on root depth and shoot length of *Pisum sativum* L. seedling. (Each result is the mean of three replicates ± SD).

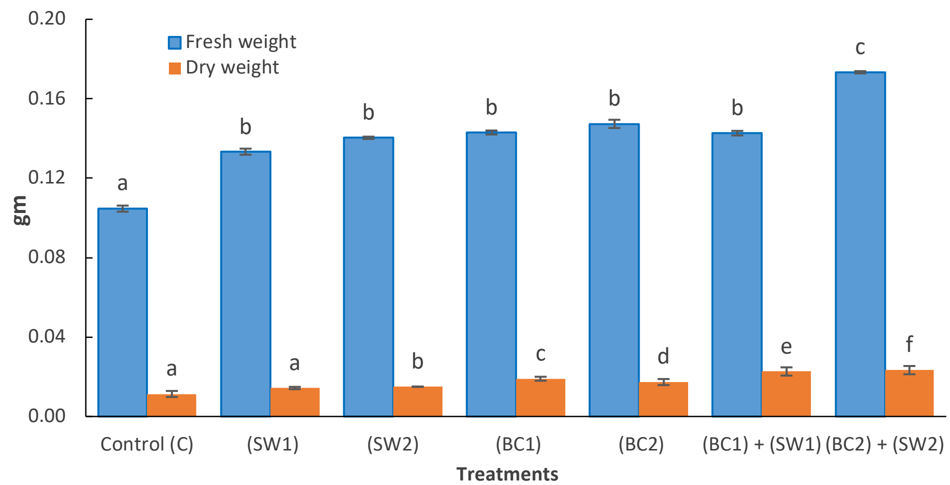

Figure 2. Effects of raw *Ulva lactuca* and its biochar on fresh and dry weight of root system in *Pisum sativum* L. seedling. (Each result is the mean of three replicates ± SD).

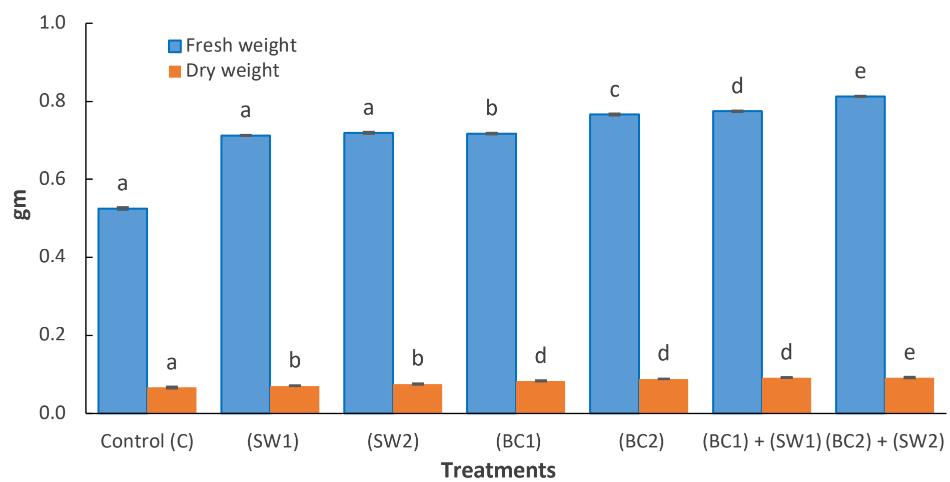

Figure 3. Effects of raw *Ulva lactuca* and its biochar on fresh and dry weight of shoot system in *Pisum sativum* L. seedling. (Each result is the mean of three replicates ± SD).

Overall, these findings highlight the potential of *Ulva lactuca* biochar as a sustainable soil amendment, particularly when combined with seaweed-based biostimulants. The dual application not only enhances plant biomass and nutrient uptake but also contributes to long-term soil health, making it a promising approach for sustainable agriculture and improved crop productivity.

Effect on Photosynthetic Pigments

The application of *Ulva lactuca* seaweed and its biochar significantly enhanced photosynthetic pigment concentrations in *Pisum sativum* L. seedlings, further contributing to improved plant growth and productivity (Figure 4). Specifically, SW2 treatment resulted in increases of 12.33%, 114.65%, and 16.35% in chlorophyll *a*, chlorophyll *b*, and carotenoids, respectively. BC2 treatment led to even greater increases of 34.3%, 148.23%, and 22.99%. The most substantial improvements were observed with the combined application of BC2 + SW2, which elevated chlorophyll *a*, chlorophyll *b*, and carotenoids by 53.38%, 178.28%, and 36.49%, respectively (Table 3).

These results align with previous studies highlighting the role of seaweed-derived biostimulants in enhancing pigment content. Seaweed extracts are rich in growth-promoting compounds such as auxins, gibberellins, cytokinins, and betaines, which regulate chlorophyll biosynthesis and promote leaf expansion (Chrysargyris et al. 2018; Gupta et al., 2021).

Moreover, seaweed contain growth-promoting compounds like auxins, gibberellins, cytokinins, and betaine, which contribute to the enhancement of photosynthetic pigments, supporting leaf development and overall plant growth (Abobaker et al., 2018; Carillo et al., 2019). Additionally, seaweed provides micronutrients like magnesium (Mg), a key component of chlorophyll, and potassium (K), which enhances photosynthesis and stomatal regulation (Weisany & Rari, 2015).

Biochar further amplifies these benefits by improving soil conditions that support chlorophyll biosynthesis. Its high porosity and cation exchange capacity enhance nutrient retention, particularly for nitrogen (N), iron (Fe), and magnesium (Mg), all of which are essential for pigment formation (Alhasan et al., 2021). Studies have shown that biochar application can increase chlorophyll content by modifying soil pH, enhancing microbial activity, and promoting the release of soluble phosphorus and nitrogen—key nutrients for photosynthesis (Zewail, 2014; Salim, 2016; Meng et al., 2022; Asadi, 2022). Furthermore, the improved chlorophyll *b* and carotenoid levels observed with biochar and seaweed application indicate enhanced light absorption efficiency and photoprotective mechanisms. Carotenoids act as antioxidants, protecting chlorophyll from oxidative damage under environmental stress (Cuchca Ramos et al., 2025). The increase in these pigments suggests that plants treated with biochar and seaweed experienced lower oxidative stress and improved photosynthetic capacity.

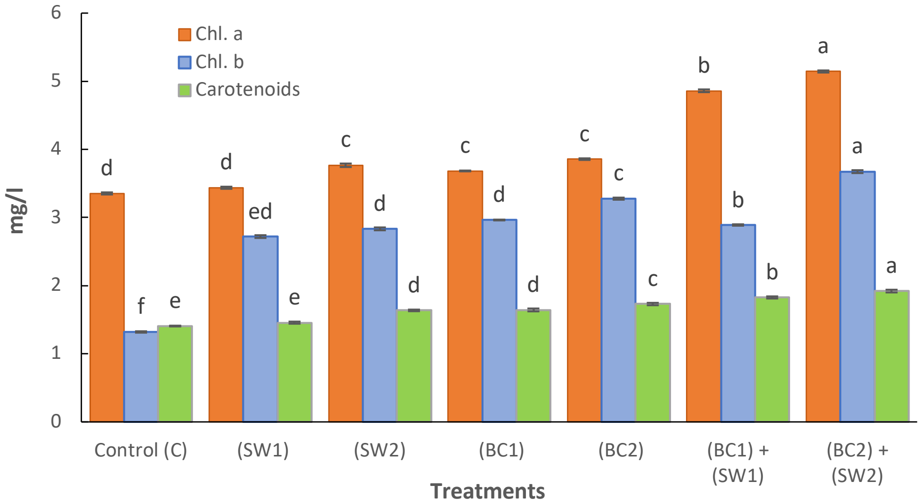

Figure 4. Effects of raw *Ulva lactuca* and its biochar on photosynthetic pigments of *Pisum sativum* L. seedling. (Each result is the mean of three replicates ± SD).

Table 3. Percentage of increase in photosynthetic pigments of *Pisum sativum L.* seedling.

Treatments	Chlorophyll *a*	Chlorophyll *b*	Carotenoids
(SW1)	2.49	106.06	3.55
(SW2)	12.33	114.65	16.35
(BC1)	9.84	124.49	16.82
(BC2)	34.30	148.23	22.99
(BC1) + (SW1)	44.93	118.94	29.86
(BC2) + (SW2)	53.38	178.28	36.49

Each result is the mean of three replicates ± standard deviation.

Overall, the combined application of *Ulva lactuca* biochar and seaweed extract has been shown to significantly enhance photosynthetic pigment levels, leading to improved plant vigor, higher photosynthetic efficiency, and better stress resilience. These findings reinforce the potential of biochar-seaweed amendments as a sustainable agricultural strategy for optimizing crop productivity and plant health.

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