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Original Article

Enhancing Growth and Productivity of Broccoli through Natural Biostimulants: A Comparative Study of Seaweed and Moringa Leaf Extracts

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Abstract

Background: Broccoli is a nutrient-dense crop that is increasingly in demand because of its health-promoting phytochemicals. However, the heavy reliance on chemical fertilizers has raised environmental issues, leading to the need for sustainable alternatives. This study investigated the impact of natural biostimulants, specifically seaweed extract (SWE) and moringa leaf extract (MLE), on broccoli growth and yield under field conditions. **Methods:** The experiment was conducted at Lovely Professional University's research farm in Phagwara, Punjab, using a Randomized Block Design with nine treatments, including different concentrations (25, 50, 75, and 100%) of SWE and MLE, along with a control. Foliar applications were done every 10 days from transplantation until curd initiation. Growth metrics, including plant height, leaf number, and leaf area, as well as yield indicators such as curd weight, diameter, dry matter, and plot yield, were measured. **Results:** Biostimulant application significantly improved growth and yield compared to the control. The highest performance was observed with 100% SWE, which produced the greatest plant height (49.347 cm), number of leaves (17.333), leaf area (474.390 cm²), curd weight without leaves (571.183 g), diameter (19.073 cm), dry weight (70.977 g), and yield (17.137 kg per plot), closely followed by 100% MLE (47.133 cm, 16.267, 465.207 cm², 544.130 g, 18.033 cm, 69.123 g, and 16.323 kg, respectively). **Conclusion:** Overall, these findings suggest that natural biostimulants, especially seaweed extracts, can enhance broccoli productivity and support environmentally friendly farming practices.

Keywords: *Biostimulants; Broccoli; Moringa Leaf Extract; Seaweed Extract; Sustainable Agriculture*

Introduction

Broccoli (*Brassica oleracea* var. *italica*) is an important cole crop cultivated worldwide for its high nutritional value (Iqbal *et al.*, 2023). It is well known for its phytochemicals, and regular consumption has been linked to various health benefits, including cancer prevention and support for heart, bone, and digestive health. It is a rich source of sulfur-containing glucosinolate compounds, isothiocyanates, and sulforaphane. Sulforaphane gives broccoli a slightly bitter taste and may reduce cancer risk in humans by supporting detoxification processes and protecting cells from DNA damage. Broccoli also contains measurable amounts of antioxidants that may prevent oxidative stress and cellular damage (Sujata *et al.*, 2023). The fiber, potassium, and antioxidants in broccoli support cardiovascular health by helping regulate blood pressure and reduce cholesterol levels**.** The high levels of vitamin K and calcium in broccoli support bone density and strength, potentially lowering the risk of osteoporosis.

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The health benefits of broccoli consumption have driven its growing demand. To fulfill this demand, chemical fertilizers are being used indiscriminately. Though chemical fertilizers are crucial for boosting crop yields and improving soil fertility, they also degrade the soil's physical, chemical, and biological properties. Continuous use, however, reduces soil organic matter (SOM), lowers soil quality, and decreases the availability of micronutrients such as exchangeable Ca and Mg (Dikir, 2023). Overusing chemical fertilizers is a cause for concern because it decreases fertility and contributes to soil and water pollution and toxicity (Ahmad, 2025). It also diminishes essential soil nutrients and minerals, posing environmental risks. Relying solely on chemical fertilizers weakens microbial activity, disrupts soil pH, promotes pest outbreaks, causes soil acidification, and forms soil crusts (Pahalvi *et al*., 2021). Long-term use of chemical fertilizers reduces organic matter, humus, and beneficial organisms and can hinder plant growth while increasing greenhouse gas emissions.

Natural biostimulants are an alternative nutrient source that is biodegradable, non-toxic, non-polluting, and environmentally safe. Natural biostimulants contain a wide range of bioactive compounds that can enhance several processes, stimulating plant growth and development by increasing nutrient use efficiency, increasing resistance to biotic and abiotic stresses, and reducing fertilizer use without affecting nutritional quality or yield. Thus, biostimulants may bridge the gap between crops and agrochemicals, balancing agricultural input markets and economic benefits (Mannino, 2025; Buss *et al*., 2026). Over the past few years, significant efforts worldwide have explored the potential of biostimulants in crop management because of their growth-promoting and stress-resistance effects, without adverse environmental impacts.

Seaweed extracts, particularly those derived from brown algae such as *Ascophyllum nodosum*, are rich in phytohormones, vitamins, amino acids, and minerals (Thirumalesh *et al*., 2025). Applying these substances to horticultural crops has been associated with improved plant vigor, stress tolerance, and enhanced nutrient uptake (Singh *et al*., 2025). These extracts act as biostimulants, enhancing plant growth, yield, and stress resilience. Their efficacy is attributed to a complex mix of bioactive compounds that act as phytoelicitors, triggering plant defense mechanisms and promoting plant growth. The synergistic effects of the whole extract were more effective than those of the isolated components, underscoring the importance of their complex composition. Given their organic nature and compatibility with other agricultural inputs, seaweed extracts are well-suited to integrated, environmentally conscious farming practices (Ali *et al*., 2021). Specifically, in broccoli, studies have shown that foliar application of seaweed extracts can significantly increase marketable yield and quality parameters. Seaweed extracts are organic fertilizers that contain osmolytes (betaine), hormones (auxins, cytokinin, abscisic acid, ethylene, and gibberellins), polysaccharides (fucoidan, alginic acid, carrageenan, and agar), minerals, and antioxidants (Pawaiya *et al*., 2025). Some studies have demonstrated that foliar application of seaweed extracts to broccoli can enhance growth parameters, including plant height by 11%, dry weight by 4%, leaf area by 7%, and yield per plant by 5% (Iqbal *et al*., 2023).

Moringa leaf extract contains growth-promoting hormones, such as cytokinins, along with essential nutrients and antioxidants. MLE is rich in antioxidants, amino acids, vitamins, and minerals, which contribute to its beneficial effects (Hoque *et al*., 2020; Yaseen *et al*., 2023). Foliar spraying of MLE has been reported to improve growth parameters, yield, and biochemical constituents of crops (Yuniati *et al*., 2022). MLE has been shown to stimulate growth in various plants by enhancing chlorophyll content, thereby improving photosynthesis and biomass accumulation. The MLE application mitigated salt-induced adverse effects on plant growth, suggesting enhanced stress tolerance (Abdelhameed *et al*., 2025). MLE improved the tolerance index of shoots and roots and increased thiol compounds in leaves, suggesting a potential role in mitigating stress (Radi *et al*., 2023). Although many studies have examined the use of SWE and MLE across various crops, it is essential to explore the feasibility of applying these biostimulants in broccoli to achieve better growth and yield. Given the significance of SWE and MLE as growth-promoting biostimulants, the current study evaluated their effects on broccoli productivity.

Materials and Methods

Experimental Site and Location

The investigation was conducted at the main agricultural research field of Lovely Professional University, Phagwara, Punjab, during 2024-25. The field is situated at a latitude of 31º 15' N, a longitude of 75º 41' E, and an altitude of 245 m above the mean sea level. Jalandhar is located in a region characterized by well-irrigated, high-yielding farmland, specifically between the Beas and Sutlej Rivers. It covers a large area of 2624 square kilometers, or 5.3% of the state's total area.

Climatic Conditions

The experimental field was located in the state's Central Zone (PB3). Both the northeast and southwest monsoons provide precipitation to this region, which is characterized by a lower coefficient of variation and a uniform distribution from June to September (Lallawmkima *et al*., 2018). The region has a subtropical climate, and the climatic conditions during the experiment are shown in Table 1.

Table 1: *Weather Parameters During the Cropping Season*

Month	Temperature (^{0}C)		Relative humidity %		Rainfall (mm)
	Maximum	Minimum	Maximum	Minimum	
October	34.10	18.10	93.30	52.30	0.30
November	27.20	12.30	94.60	56.40	0.00
December	18.40	6.30	92.40	55.40	0.10
January	37.49	24.14	81.79	53.82	0.36
February	32.47	23.52	88.23	63.12	19.2

Experimental Details

Green Magic Broccoli is a hybrid broccoli variety developed by the Japanese seed company Sakata Seed Corporation. The 30-day-old seedlings with 3-4 true leaves were transplanted at a spacing of 60 cm x 45 cm. After transplantation, the seedlings were thoroughly watered to ensure proper moisture retention. The experiment followed a Randomized Block Design (RBD) with nine treatments: a control (T_0) and biostimulant concentrations of 25%, 50%, 75%, and 100% (seaweed (T_1 to T_4) and moringa leaf extracts (T_5 to T_8)). The liquid seaweed extract (SWE) used in this study was a commercially available product, 'Sagarika,' with a manufacturer-recommended dosage of 5 mL per liter of water, which was considered 100% concentration. The moringa leaf liquid extract (MLE) used in the study was a commercial product from Veda Oils, and according to the manufacturer's recommendation, a 100% working extract was prepared by mixing 40 mL of the liquid moringa extract with 960 mL of water. The remaining concentrations (25%, 50%, and 75%) were prepared by dilution in water. These biostimulants were sprayed at 10-day intervals after transplanting (DAT) until curd initiation. The crop was harvested at full maturity, when the curds had a deep green to dark bluish-green head, with no yellowing or discoloration (Kumar *et al*., 2023).

Collection of Experimental Data

Observations on various growth parameters, *viz*., average plant height (cm) and average number of leaves per plant, were recorded for five randomly selected and labelled plants from each treatment and each replication at 15, 30, 45, and 60 DAT. Leaf area (cm²) was measured at 60 DAT, while curd weight (g) with or without leaves and curd diameter were measured at harvest for five randomly selected plants. The dry weight of the curd from five plants was measured in a hot-air oven at 75 °C for 72 h, then weighed on an electronic balance, and the mean value was calculated (Singh *et al*., 2018). The fresh weight of broccoli curds from five plants was weighed on a digital weighing balance; the average value was calculated, multiplied by the total plant population per plot (3 m x 2.7 m), and expressed in kilograms per plot.

Statistical Analysis

The replicated data were analyzed using one-way analysis of variance (ANOVA) at the 5%

significance level. Data from all observations were analyzed using ANOVA, and treatments were compared using the least significant difference test, as suggested by Panse and Sukhatme (1989).

Results

Plant Growth Attributes

The growth attributes of broccoli are determined by the development of foliage, as reflected in the number of leaves and plant height. The average plant height (Table 2) and leaf number per plant (Table 3) of broccoli, measured 15, 30, 45, and 60 days after transplanting (DAT), were significantly affected by the different concentrations of seaweed extract (SWE) and moringa leaf extract (MLE). The effects of SWE and MLE were more pronounced at 45 and 60 DAT. At 15 DAT, all treatments were comparable and significantly better than the control (T0), whereas at 30 DAT, T2 (50% SWE) and T8 (100% MLE) were equivalent (26.85 cm and 25.79 cm, respectively). At 45 and 60 DAT, the highest plant heights (37.033 cm and 49.347 cm, respectively) were recorded with T4 (100% SWE), which was at par with T8 (34.533 cm and 47.133 cm, respectively). However, the lowest plant height at 45 DAT was in T0 (29.067 cm and 35.633 cm, respectively). Although the pattern of increase in broccoli plant height at 30 DAT was not well defined, at 45 and 60 DAT, it was higher in T4 (107.66% and 176.71%), followed by T3 and T8 (Figure 1). The variation in the average number of leaves per plant was significant; however, no substantial effect of SWE and MLE application was observed at 15, 30, and 45 DAT, and many treatments showed similar (at par) results to the control. However, at 60 DAT, treatments consisting of SWE and MLE were significantly better than the control. The highest number of leaves was recorded in T4 (17.333), which was at par with T8 (16.267), while the lowest number of leaves was in T0 (12.467). The pattern of increase in the number of leaves per plant of broccoli was similar at 30 and 45 DAT, while a well-defined increment pattern was observed at 60 DAT, with the highest increment observed in T4 (188.89%), followed by T8 (174.16%) and T2 (169.66%) (Figure 2).

Table 2: *Effect of Biostimulants and Their Concentration on Average Plant Height of Broccoli on Different Days After Transplanting (DAT)*

Treatment	At 15 DAT	At 30 DAT	At 45 DAT	At 60 DAT
T_0	$15.967^{b} \pm 0.396$	$19.647^{f} \pm 0.267$	$29.067^{d} \pm 0.921$	$35.633^{h} \pm 1.250$
T_1	$18.340^{a} \pm 0.636$	$23.833^{bc} \pm 0.212$	$30.713^{cd} \pm 0.581$	$38.553^{fg} \pm 0.550$
T_2	$18.213^{a} \pm 1.038$	$26.847^{a} \pm 0.531$	$31.153^{bcd} \pm 0.937$	$45.033^{bc} \pm 0.304$
T_3	$17.073^{ab} \pm 0.247$	$21.700^{de} \pm 0534$	$32.553^{bc} \pm 0.223$	$43.353^{cd} \pm 0.581$
T_4	$17.833^{a} \pm 0.341$	$22.927^{cd} \pm 0.168$	$37.033^{a} \pm 0.998$	$49.347^{a} \pm 0.568$
T_5	$17.740^{a} \pm 0.491$	$20.947^{ef} \pm 0.789$	$31.053^{cd} \pm 2.056$	$38.047^{g} \pm 0.822$
T_6	$17.360^{ab} \pm 0.129$	$24.447^{b} \pm 0.213$	$32.433^{bcd} \pm 0.523$	$41.500^{de} \pm 0.647$
T_7	$17.153^{ab} \pm 0638$	$22.353^{d} \pm 0.231$	$30.793^{cd} \pm 1.772$	$40.507^{ef} \pm 1.206$
T_8	$18.400^{a} \pm 0.162$	$25.793^{a} \pm 0.468$	$34.533^{ab} \pm 0.690$	$47.133^{ab} \pm 0.425$
C.D.	1.448	1.326	3.435	2.397
SE(m)±	0.479	0.439	1.136	0.793
C.V.	4.723	3.279	6.120	3.260

[T_0: Control, T_1: 25% SWE, T_2: 50% SWE, T_3: 75% SWE, T_4: 100% SWE, T_5: 25% MLE, T_6: 50% MLE, T_7: 75% MLE, and T_8: 100% MLE; the treatments where data value has similar superscript do not vary significantly while that of different superscript show significant difference at 5% level of significance]

Table 3: *Effect of Biostimulants and Their Concentration on The Average Number of Leaves Per Plant of Broccoli on Different Days After Transplanting (DAT)*

Treatment	At 15 DAT	At 30 DAT	At 45 DAT	At 60 DAT
T_0	$5.400^{c} \pm 0.231$	$7.333^{f} \pm 0.133$	$9.067^{e} \pm 0.291$	$12.467^{f} \pm 0.176$
T_1	$6.667^{a} \pm 0.067$	$8.200^{bc} \pm 0.115$	$9.533^{de} \pm 0176$	$15.200^{bcd} \pm 0.577$
T_2	$5.933^{bc} \pm 0.371$	$8.667^{a} \pm 0.176$	$11.200^{a} \pm 0.200$	$16.000^{bc} \pm 0.503$
T_3	$5.733^{c} \pm 0.176$	$7.867^{de} \pm 0.133$	$10.600^{b} \pm 0.155$	$14.467^{de} \pm 0.406$
T_4	$6.000^{bc} \pm 0.115$	$7.933^{cd} \pm 0.067$	$9.733^{cd} \pm 0.176$	$17.333^{a} \pm 0.769$
T_5	$6.400^{ab} \pm 0.416$	$7.600^{ef} \pm 0.115$	$9.533^{de} \pm 0.176$	$13.800^{e} \pm 0.305$
T_6	$6.000^{bc} \pm 0.115$	$8.200^{bc} \pm 0.133$	$10.067^{c} \pm 0.133$	$14.000^{e} \pm 0.305$
T_7	$6.533^{ab} \pm 0.133$	$7.867^{de} \pm 0.067$	$9.533^{de} \pm 0.176$	$14.933^{cde} \pm 0.696$
T_8	$5.933^{bc} \pm 0.371$	$8.467^{ab} \pm 0.067$	$10.933^{ab} \pm 0.133$	$16.267^{ab} \pm 0.405$
C.D.	0.624	0.331	0.483	1.150
SE(m)±	0.206	0.109	0.160	0.380
C.V.	5.892	2.365	2.763	4.410

[T_0: Control, T_1: 25% SWE, T_2: 50% SWE, T_3: 75% SWE, T_4: 100% SWE, T_5: 25% MLE, T_6: 50% MLE, T_7: 75% MLE, and T_8: 100% MLE; the treatments where data value has similar superscript do not vary significantly while that of different superscript show significant difference at 5% level of significance]

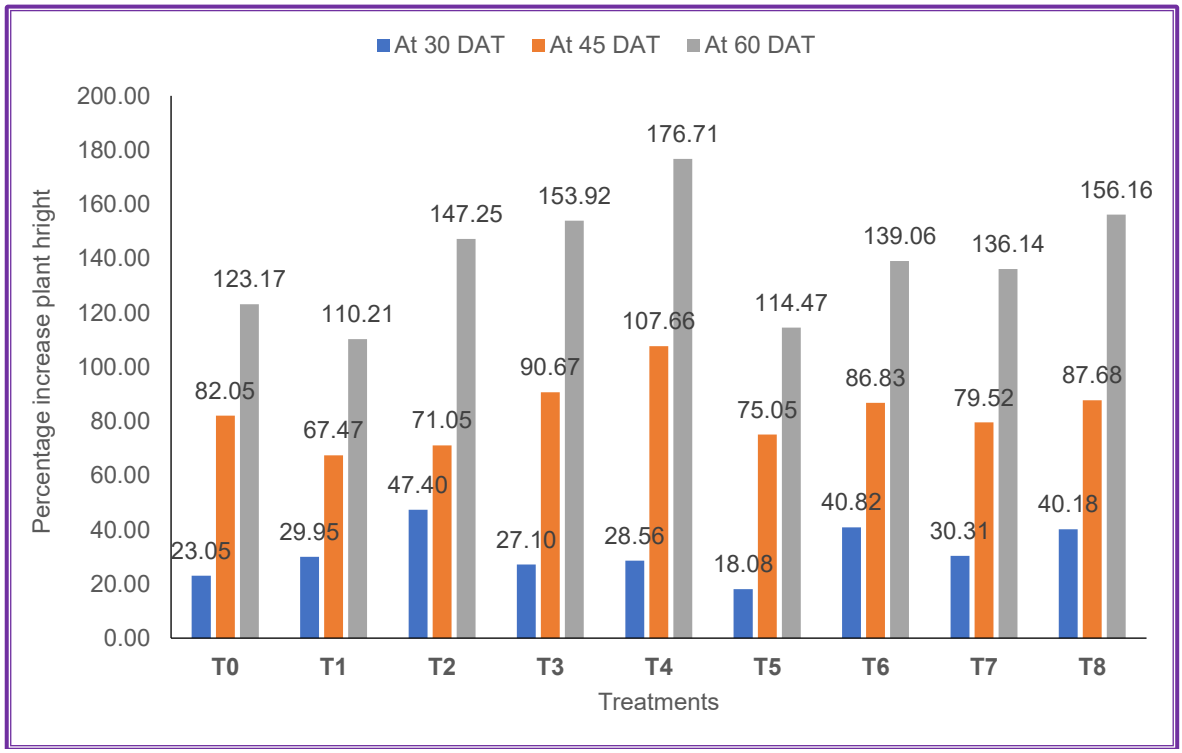


Figure 1: *Percentage Increment in Plant Height of Broccoli After Application of Various Concentrations of Biostimulants [T_0: Control, T_1: 25% SWE, T_2: 50% SWE, T_3: 75% SWE, T_4: 100% SWE, T_5: 25% MLE, T_6: 50% MLE, T_7: 75% MLE, and T_8: 100% MLE]*

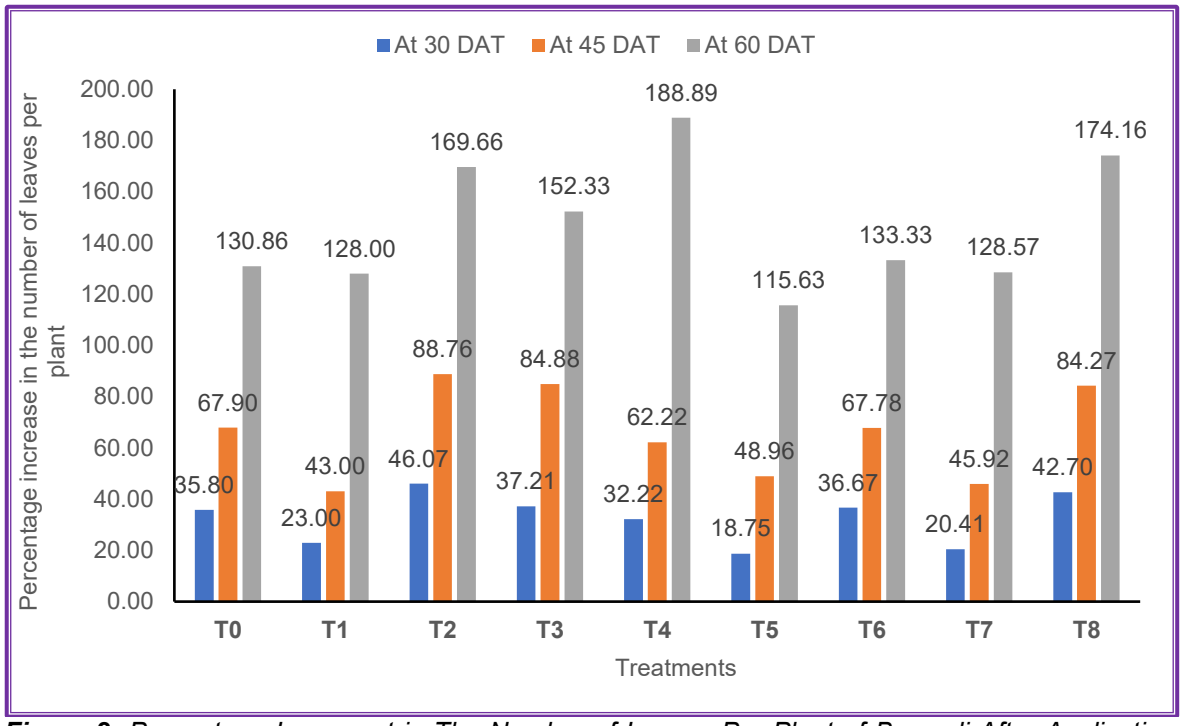


Figure 2: *Percentage Increment in The Number of Leaves Per Plant of Broccoli After Application of Various Concentrations of Biostimulants[T_0: Control, T_1: 25% SWE, T_2: 50% SWE, T_3: 75% SWE, T_4: 100% SWE, T_5: 25% MLE, T_6: 50% MLE, T_7: 75% MLE, and T_8: 100% MLE]*

Yield-Related Attributes

Leaf area defines the photosynthetically active part of plants and contributes to broccoli productivity. Observations of leaf area at 60 DAT showed significant variation among treatments (Table 4). The highest leaf area (474.390 cm²) was recorded for T4 (100% SWE), which was at par with T8 (465.207 cm²), followed by T3 (423.337 cm²) and T2 (407.153 cm²), which were significantly higher than the other treatments. However, the minimum leaf area was observed in T0 (245.310 cm²). Broccoli yield depends on curd weight and size. The average curd weight with leaves (g) and without leaves (g) at harvest was significantly affected by the various concentrations of SWE and MLE (Table 4). The highest (687.457) curd weight with leaves (g) was recorded in T4 (100% SWE), followed by T8 (659.347), T3 (645.753), and T2 (628.047), which were significantly better than other treatments. However, the lowest curd weight with leaves (g) was in T0 (516.840). The highest (571.183) curd weight without leaves (g) was recorded in T4 (100% SWE), followed by T8 (544.130), T3 (528.967), and T2 (516.097), which were significantly better than other treatments. However, the lowest curd weight without leaves (g) was in T0 (397.390). The average curd diameter (cm), dry weight of curd (g), and yield per plot showed significant variation among different concentrations of SWE and MLE (Table 5). The highest curd diameter was recorded (19.073 cm) with T4 (100% SWE), which was at par with T8 (18.033 cm), followed by T3 (15.430 cm) and T2 (14.567 cm). The highest dry weight of curd (g) was recorded with T4 (70.977 g), followed by T8 (69.123 g), T3 (67.727 g), and T6 (65.087 g). However, the lowest dry curd weight (g) was observed in T0 (57.287 g). The highest yield was recorded with T4 (17.137 kg per plot), followed by T8 (16.323 kg), T3 (15.870 kg), and T2 (15.483 kg).

Table 4: *Effect of Biostimulants and Their Concentration on Leaf Area and Curd Weight of Broccoli*

Treatments	Leaf Area (cm^2)	Curd Weight with Leaf (g)	Curd Weight Without Leaf (g)
T_0	$245.310^{h} \pm 1.709$	$516.840^{h} \pm 2.446$	$397.390^{h} \pm 1.724$
T_1	$372.217^{d} \pm 2.481$	$601.987^{f} \pm 4.955$	$484.523^{f} \pm 4.131$
T_2	$407.153^{c} \pm 9.596$	$628.047d \pm 3.970$	$516.097^{d} \pm 2.556$
T_3	$423.337^{b} \pm 2.760$	$645.753^{c} \pm 4.203$	$528.967^{c} \pm 3.952$
T_4	$474.390^{a} \pm 1.556$	$687.457^{a} \pm 5.100$	$571.183^{a} \pm 6.171$

T_5	$310.937^{g} \pm 3.344$	$578.583^{g} \pm 5.811$	$462.540^{g} \pm 4.169$
T_6	$333.930^{f} \pm 3.030$	$614.377^{e} \pm 3.735$	$503.057^{e} \pm 2.144$
T_7	$353.727^{e} \pm 2.428$	$610.703^{ef} \pm 1.844$	$495.767^{e} \pm 2.423$
T_8	$465.207^{a} \pm 1.668$	$659.347^{b} \pm 2.937$	$544.130^{b} \pm 1.216$
C.D.	10.232	11.415	9.880
SE(m)±	3.384	3.775	3.267
C.V.	1.558	1.062	1.131

[T_0: Control, T_1: 25% SWE, T_2: 50% SWE, T_3: 75% SWE, T_4: 100% SWE, T_5: 25% MLE, T_6: 50% MLE, T_7: 75% MLE, and T_8: 100% MLE; The Treatments Where Data Value Has Similar Superscript Do Not Vary Significantly While That of Different Superscript Show Significant Difference At 5% Level of Significance]

Table 5: *Effect of Biostimulants and Their Concentration on Curd Diameter, Dry Weight, and Yield of Broccoli*

Treatment	Curd Diameter (cm)	Dry Weight (g)	Yield Per Plot (kg)
T_0	$11.137^{f} \pm 0.064$	$57.287^{f} \pm 0.333$	$11.920^{h} \pm 0.053$
T_1	$12.253^{e} \pm 0.044$	$63.563^{cd} \pm 1.230$	$14.533^{f} \pm 0.122$
T_2	$14.567^{bc} \pm 0.328$	$62.420^{de} \pm 0.378$	$15.483^{d} \pm 0.077$
T_3	$15.430^{b} \pm 0.529$	$67.727^{b} \pm 0.279$	$15.870^{c} \pm 0.118$
T_4	$19.073^{a} \pm 0.551$	$70.977^{a} \pm 0.514$	$17.137^{a} \pm 0.185$
T_5	$12.763^{e} \pm 0.358$	$61.817^{e} \pm 0.542$	$13.877^{g} \pm 0.124$
T_6	$13.947^{cd} \pm 0.438$	$65.087^{c} \pm 0.240$	$15.093^{e} \pm 0.065$
T_7	$13.100^{de} \pm 0.300$	$64.370^{c} \pm 0.410$	$14.873^{e} \pm 0.072$
T_8	$18.033^{a} \pm 0.301$	$69.123^{b} \pm 0.422$	$16.323^{b} \pm 0.035$
C.D.	1.090	1.602	0.295
SE(m)±	0.360	0.530	0.097
C.V.	4.312	1.418	1.124

[T_0: Control, T_1: 25% SWE, T_2: 50% SWE, T_3: 75% SWE, T_4: 100% SWE, T_5: 25% MLE, T_6: 50% MLE, T_7: 75% MLE, and T_8: 100% MLE; the treatments where data value has similar superscript do not vary significantly while that of different superscript show significant difference at 5% level of significance]

Discussion

Plant Growth Attributes

The current investigation demonstrated that foliar application of SWE and MLE significantly enhanced broccoli growth attributes compared to the control. The improved growth observed after SWE application may be attributed to natural biostimulatory compounds, including auxins, cytokinins, gibberellins, amino acids, vitamins, and essential macro- and micronutrients, that collectively stimulate physiological and biochemical processes in plants. These bioactive components improved nutrient uptake, chlorophyll synthesis, and stress tolerance, thereby promoting cell division and elongation, which are essential for biomass production and vegetative growth (Rahman *et al.*, 2024).

SWE showed a dose-dependent effect on broccoli growth attributes, and SWE (100%) significantly enhanced plant height, number of leaves per plant, and their percentage increments compared with the other treatments. This effect may be associated with improved root growth and nutrient use efficiency, facilitating greater absorption of essential nutrients such as nitrogen, phosphorus, and calcium and further highlighting its potential to improve biomass in broccoli (Tofiq *et al.*, 2025). The superior performance of SWE in the current study is in agreement with the findings of Ismael*et al.* (2024), who also showed that applying humic acid and seaweed extract at 4 ml L^{-1} each, combined with organic manure, significantly improved vegetative growth parameters, including plant height, number of leaves per plant, and number of heads per plant in the broccoli cultivar 'Agassirz'. Similarly, Baldaniya *et al.* (2023) reported that the foliar application of seaweed extract at 3 ml L^{-1} combined with Jeevamrut at 3% at 30 and 60 days after transplanting (DAT) significantly enhanced growth

parameters such as plant height, number of leaves per plant, leaf dimensions, and leaf area at both 60 DAT and harvest in broccoli cv. Pusa KTS-1. These findings collectively demonstrated that SWE can effectively promote biomass production in broccoli by improving nutrient uptake, assimilation, and physiological efficiency.

Likewise, MLE also reflected dose-dependent effects on the morphological attributes of broccoli. In the current study, foliar application of MLE (100%) significantly enhanced broccoli vegetative growth compared to the control and other treatments, yielding results similar to those of SWE (100%). The positive effects of MLE are attributed to its rich mix of natural plant growth-promoting substances, including cytokinins (especially zeatin), auxins, gibberellins, vitamins, amino acids, antioxidants, and essential macro- and micronutrients (Arif *et al*., 2023). These bioactive elements are essential for systemic action across various physiological processes, such as cell division and elongation, and chlorophyll production, thereby promoting enhanced plant growth (Irshad *et al.,* 2025). The increase in plant height and leaf number under MLE treatment likely results from improved photosynthesis and nutrient use. Moringa leaf extract contains natural zeatin, a cytokinin that encourages cell growth, delays leaf aging, and preserves chlorophyll, extending the crop's photosynthetic period (Andriyani *et al*., 2022). Applying these nutrients directly to leaves can increase the availability and absorption of minerals such as nitrogen, potassium, calcium, magnesium, iron, and zinc, thereby enhancing metabolic activity and improving crop growth. Additionally, antioxidants in MLE, including ascorbic acid, phenolic compounds, and flavonoids, may help shield plants from oxidative stress, enhancing resilience and growth under various environmental challenges (Yuniati *et al*., 2023; El-Sherbiny *et al*., 2024).

Yield-Related Attributes

The improvement in yield and related attributes after application of SWE (100%) and MLE (100%) may directly reflect the vegetative growth observed under these treatments. An increased number of leaves expands the photosynthetic surface area, enhancing light capture and increasing the production and storage of photosynthates (Pawaiya *et al*., 2025). These compounds are then transported to developing curds, improving initiation, growth, and marketable yield. An adequate supply of nutrients such as nitrogen and calcium—delivered or mobilized through SWE-mediated processes—further facilitates rapid cell division and expansion during curd development, thereby increasing curd size and weight (Asif *et al.*, 2023). The beneficial effects of seaweed extract (SWE) on broccoli productivity may also stem from naturally occurring plant growth regulators and bioactive substances in the extract that influence source–sink dynamics. For example, cytokinins in seaweed extracts can delay foliar senescence and sustain photosynthesis for extended periods, while auxins and gibberellins promote growth and direct assimilates toward valuable plant organs. Consequently, plants treated with SWE show enhanced growth, improved nutrient utilization, and higher yields than untreated counterparts.

SWE application improves plant growth, enhances nutritional traits, and lowers oxidative stress indicators (Sogoni *et al.*, 2024). These effects are particularly relevant in plant stress management, as tocopherols and chlorophylls play crucial roles in mitigating oxidative stress and protecting against photodamage under adverse conditions (Zamljen *et al.*, 2024). The study revealed that the biostimulants significantly improved plant tolerance to these abiotic stresses by enhancing antioxidant activity, increasing glucosinolate content, and modulating phytohormones involved in stress regulation (Di Sario *et al*., 2025). These physiological and biochemical improvements are translated into greater biomass production, better physiological performance, and enhanced nutritional quality, particularly with elevated glucosinolate levels, which benefit plant defense (Thirumalesh *et al*., 2025). Treated plants outperformed untreated ones in growth and quality, underscoring the promise of biostimulants to enhance resilience and productivity in challenging environments (Asif *et al.*, 2023; Montesinos *et al.*, 2024). These findings underscore the value of seaweed extracts in advancing sustainable, climate-resilient agriculture and offer practical guidance on their field-level application.

Similarly, the improved vegetative growth from MLE application may directly boost yield attributes and curd productivity. The yield advantages associated with MLE may also be attributed to higher levels of bioactive compounds, macro- and micronutrients, minerals, plant hormones, essential amino acids, and vitamins, thereby enhancing enzymatic activity and hormonal equilibrium within the plant (Marie *et al*., 2025). Naturally occurring growth regulators present in moringa extract stimulate cell division and expansion, while amino acids and vitamins support protein synthesis and metabolic functions. Collectively, these effects promote improved plant growth, more efficient nutrient utilization, and elevated yield potential. Furthermore, MLE has been demonstrated to augment plant tolerance to abiotic stresses by increasing antioxidant enzyme activities and preserving cellular integrity under adverse conditions (Yuniati *et al*., 2022). These physiological benefits may help sustain growth and productivity, particularly under suboptimal environmental conditions. The combined effects of improved nutrient supply, hormonal stimulation, enhanced photosynthesis, and stress resistance likely account for the superior performance of MLE-treated broccoli plants. This study confirms that SWE and MLE are effective biostimulants that boost vegetative growth, physiological function, and broccoli yield. They enhance nutrient uptake, stimulate physiological and biochemical processes, improve vegetative development, and optimize assimilate partitioning, leading to better crop performance. These microbes enhance soil health, boost plant growth, and serve as eco-friendly alternatives to synthetic chemicals by stimulating plant defenses and promoting root development (Singh *et al*., 2025).

Limitations

The current study highlights the potential of different SWE and MLE concentrations on various growth and yield parameters of broccoli. However, this study has certain limitations: it is based on single-season and location data; only one cultivar was used, with a primary focus on growth- and yield-related parameters; and it lacks physiological, biochemical, quality, and economic assessments.

Future Scope

Future research should involve multi-location and multi-season experiments; optimization of SWE and MLE using design of experiments; nutritional parameters; physiological and biochemical aspects; and integrated applications.

Conclusion

This study clearly demonstrates the positive effects of natural biostimulants on broccoli growth and yield. Among the treatments, 100% seaweed extract (SWE) was the most effective, resulting in the greatest plant height (49.347 cm), number of leaves (17.333), leaf area (474.390 cm^2), curd weight without leaves (571.183 g), diameter (19.073 cm), dry weight (70.977 g), and yield (17.137 kg per plot), with 100% moringa leaf extract (MLE) closely following.

Conflict of Interest

The authors declare no conflicts of interest.

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