



Sustaining Red Cabbage in Saline Conditions: The Power of Biostimulants in Early Growth Stages

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Abstract. This study investigates the effects of various biostimulants on growth, physiological performance and biochemical traits of red cabbage (*Brassica oleracea* var. *capitata* f. *rubra*) subjected to 50 mM NaCl-induced salt stress. Plants were cultivated in a 1:1 soil-to-peat mixture and treated with different biostimulants—including amino acids, plant growth-promoting rhizobacteria (PGPR), seaweed extract, fulvic acid, chitosan, and vermicompost—applied via foliar spraying and root irrigation. Among the treatments, amino acids led to the most pronounced effect, increasing cabbage head weight by 113.3% compared to the salt-only control, followed by vermicompost with a 34.2% increase. Seaweed extract improved relative water content (RWC) by 43.1%, while vermicompost and amino acids enhanced RWC by 41.8% and 38.3%, respectively. Fulvic acid reduced membrane damage by 85.3%, and vermicompost showed the highest protective effect, decreasing membrane injury by 94.2%. Biochemical analyses revealed a 73.6% increase in total phenolic content with amino acid treatment, while fulvic acid and PGPR notably enhanced antioxidant activity. These findings highlight the potential of biostimulants to mitigate the adverse effects of salinity, improving both stress tolerance and crop performance. Among the tested treatments, amino acids, vermicompost, and fulvic acid emerged as the most effective biostimulants for alleviating the impacts of 50 mM NaCl stress, offering promising strategies for sustainable crop production in salt-affected environments.

Keywords: Stress Mitigation, *Brassica oleracea* L. var. *capitata* f. *rubra*, NaCl damage, salt tolerans

1 INTRODUCTION

Abiotic stress includes various environmental stressors such as salinity, intense light, ultraviolet radiation, extreme temperatures, drought, heavy metals, and hypoxia (Koç et al., 2022). Among these, salinity poses a significant threat to crop productivity and quality, particularly in arid and semi-arid regions. Climate change exacerbates soil salinization, driving land degradation and desertification (Shahid et al., 2020). Human activities, including excessive irrigation and chemical fertilization, further aggravate

the issue (Etesami et al., 2020). Globally, nearly one billion hectares of land are salt-affected, with 1.7% of Türkiye's land and 3.8% of its agricultural land experiencing salinity problems (Anon, 2024). Salinity hinders plant growth through osmotic stress and ion toxicity, impairing enzyme activity, stomatal conductance and photosynthesis (Kumar & Verma, 2018; Kumar et al., 2020). Plants respond to salinity by regulating phytohormones, synthesizing osmolytes, and activating stress-responsive genes (Singh et al., 2022).

Red cabbage (*Brassica oleracea* var. *capitata* f. *rubra*) is valued for its nutrient-rich profile, containing minerals, vitamins, anthocyanins, and glucosinolates, and is known for its long shelf life (Wiczowski et al., 2013), (Ghareaghajlou et al., 2021). However, Brassica species, including red cabbage, are highly sensitive to salinity (Linic et al., 2019).

Biostimulants enhance nutrient uptake, improve stress tolerance, and boost crop quality (Calvo et al., 2014). They are categorized into three main groups: humic substances, hormone-containing products, and amino acid-containing products (Kauffman et al., 2007). Ju Jardin (2015) further classifies them into categories such as humic-fulvic acids, seaweed extracts, protein hydrolysates, and microbial products. Amino acids, essential for protein synthesis, also aid in stress tolerance by accumulating osmolytes like proline and glutamine (Hayat et al., 2012), (Noroozlo et al., 2019). Beneficial bacteria, referred to as PGPR (Plant Growth-Promoting Rhizobacteria), improve plant growth through nutrient mobilization and stress mitigation (Kloepper et al., 1980), (Ram et al., 2013).

Seaweed extracts enhance plant performance by supplying essential nutrients and reducing chemical inputs (Munoz & Diaz, 2020), (Ali et al., 2021). Humic substances, as a primary organic carbon reservoir, support nutrient cycling and plant development (Canellas et al., 2015). Chitosan, derived from chitin, serves as both a growth regulator and a stress tolerance inducer (Ogava et al., 2004), (Türk, 2019). Vermicompost, an organic fertilizer rich in nutrients, improves plant growth, water retention, and stress tolerance (Adhikary, 2012), (Rehman et al., 2023).

This study aims to evaluate the effectiveness of various biostimulants, including amino acids, PGPR, seaweed, humic-fulvic acids, chitosan, and vermicompost, in enhancing the growth, yield, and nutrient content of red cabbage under salt stress conditions. Additionally, it explores the potential to reduce chemical fertilizer use, contributing to sustainable agriculture through improved crop yield, environmental conservation, and fertilizer savings.

2 MATERIALS AND METHODS

This study was conducted in 500 m² glass greenhouses located at the experimental field of the Department of Horticulture, Faculty of Agriculture, Çukurova University. The biostimulants used in the experiment were amino acids (Aminogold brand), seaweed

(Maxicrop brand), fulvic acid (Sacaka brand), vermicompost (Ekosolfarm brand), beneficial bacteria-PGPR (Rizofill brand), and chitosan (Adaga brand). The local red cabbage variety from the Arzuman seed company was used as plant material.

Lettuce plants were cultivated in a cocopeat medium in 2 liter pots with the following eight treatments (Figure 1):

Control: Nutrient solution applied, with only water sprayed on leaves.

Control + Salt: Nutrient solution combined with 50 mM NaCl salt treatment.

Salt + Amino Acids: 50 mM NaCl salt and Aminogold amino acid solution were applied through the nutrient solution, with foliar application of Aminogold.

Salt + Bacteria (PGPR): 50 mM NaCl salt and Rizofill bacterial solution were used along with the nutrient solution, with Rizofill also applied foliar.

Salt + Seaweed: 50 mM NaCl salt and Maxicrop seaweed solution were included with the nutrient solution, with foliar application of Maxicrop.

Salt + Fulvic Acid: 50 mM NaCl salt and Sacaka humic-fulvic acids were mixed with the nutrient solution, with foliar application of Sacaka.

Salt + Chitosan: 50 mM NaCl salt and Adoga chitosan were integrated with the nutrient solution and applied together.

This setup allowed for the investigation of how each biostimulant influences plant growth, nutrient content, and salt stress mitigation.

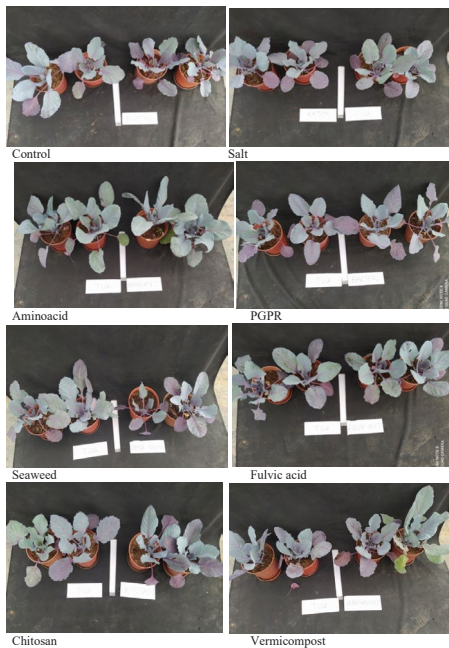


Fig. 1. Mitigating effects of biostimulants on red cabbage plants grown under salt stress.

2.1 Method

Red cabbage seedlings were planted on in pots containing soil:cocopeat mixture in the ratio of 1:1 v/v. Each pot contained one plant, with three replicates, and each replicate included 12 plants. The application of 50 mM salt and biostimulants, expected to mitigate salt stress, began 85 days after seedling transplantation. The biostimulants were applied every 7 days via root irrigation and foliar spraying at the doses shown below. The concentrations of mineral elements in the nutrient solution used in the study are as follows (ppm): N 150, P 40, K 270, Ca 170, Mg 50, Fe 3.00, Zn 0.30, B 0.70, Cu 0.20, Mo 0.10, Mn 0.55. In the control treatment, red cabbage plants were irrigated with a nutrient solution, while in the other treatments, 50 mM NaCl salt and biostimulants were added to the nutrient solution.

Table 1. Doses of biostimulants used in the study for foliar and root irrigation applications per liter

Biostimulants	Foliar Dosages	Irrigation Dosages
Amino acid	0.4 g	1.5 g
PGPR	3.0 ml	1.0 ml
Seaweed	0.4 g	0.7 g
Fulvic acid	1.0 g	1.0 g
Chitosan	3.0 g	1.5 mg
Vermicompost	4 ml	2.0 g

The red cabbage plants were harvested 182 days after planting (97 days of growth under saline conditions with biostimulant) and measurements and analyses were conducted. Plant growth parameters, such as leaf number, leaf weight, and leaf area, were measured. Physiological parameters, such as relative water content, membrane damage index and dry matter ratio were measured. Biochemical parameters, including total phenols, total flavonoids, vitamin C and mineral elements were analyzed, along with measurements of Brix, pH, and EC.

Total Phenol Analysis: The determination of total phenolic content in red cabbage plants was conducted using a modified spectrophotometric method described by Spanos and Wrolstad (1990). The readings were taken at a wavelength of 765 nm using a spectrophotometer (UV-1700 PharmoSpc Shimadzu, Japan). The total phenolic content was calculated based on the absorbance values and a calibration curve prepared with gallic acid (Dasgan et al., 2022), (Ikiz et al., 2024).

Total Flavonoid Analysis: Red cabbage plant samples were analyzed according to the method developed by Quettier et al. (2000) using a spectrophotometer at a wavelength of 415 nm. The total flavonoid content was calculated based on the calibration curve prepared with rutin (Ikiz et al., 2024).

Membrane Damage Index: The membrane damage index (MI) of red cabbage plants under stress conditions was calculated by measuring electrolytes released from the cells using a conductivity meter (EC meter) (İkiz et al, 2024). For this purpose, 1 cm diameter leaf discs were soaked in deionized water for 4 hours, and the EC of the solution was measured. The same discs were then autoclaved at 121°C for 10 minutes, and the EC of the solution was measured again. The membrane damage index was calculated as a percentage compared to the control using the following formula:

$$\text{Membrane Damage Index} = (1 - L_c / L_t - L_c) \times 100$$

Lt: EC of the drought-stressed leaf before autoclaving / EC after autoclaving

Lc: EC of the control leaf before autoclaving / EC after autoclaving

Relative Water Content: The relative water content (RWC) (%) of red cabbage leaves was determined following the methods of Temtek and Dasgan (2022) and Altuntas et al. (2024). After stress treatment, leaf samples were collected to measure their water content. First, the fresh weight (FW) of the leaves was recorded. The leaves were then soaked in distilled water for 4 hours. After soaking, the leaves were dried, and their turgor weight (TW) was measured. Finally, the leaf samples were dried in an oven at 65°C for 48 hours, and their dry weight (DW) was recorded in grams. The relative water content (%) was calculated using the following formula: $RWC = (FW - DW) / (TW - DW) \times 100$,

FW: Fresh Weight, DW: Dry Weight, TW: Turgor Weight

Dry Matter Content: The harvested red cabbage plants were immediately weighed in the greenhouse, and their fresh weight was recorded. The red cabbage leaves were then brought to the laboratory, where they were dried in an oven at 65°C for 48 hours, and their dry weights were measured. The percentage of dry matter content was calculated using the recorded fresh and dry weights with the following formula:

$$\text{Dry Matter Content (\%)} = (\text{Fresh Weight} / \text{Dry Weight}) \times 100$$

pH, EC and Brix Measurements: The juice of red cabbage leaves was extracted, and pH, EC, and Brix measurements were conducted using a pH meter, EC meter, and refractometer, respectively (Keskin et al., 2025).

Vitamin C Determination: The red cabbage plants were processed through a juicer to extract their juice. To 1 ml of the extract, 45 ml of 0.4% oxalic acid was added, and the mixture was filtered through filter paper. From the filtrate, 1 ml was taken, and 9 ml of dye solution was added. The absorbance was measured at a wavelength of 520 nm. As a standard, a solution prepared by adding 9 ml of distilled water to 1 ml of the filtrate was used (Balik et al., 2025).

Nutrient Element Analysis in Leaves: To determine the effects of different treatments on the nutrition of lettuce plants, macro and microelement analyses were performed at harvest. The elements analyzed included potassium (K), magnesium (Mg), calcium (Ca), sodium (Na), iron (Fe), manganese (Mn), copper (Cu), and zinc (Zn). The leaves

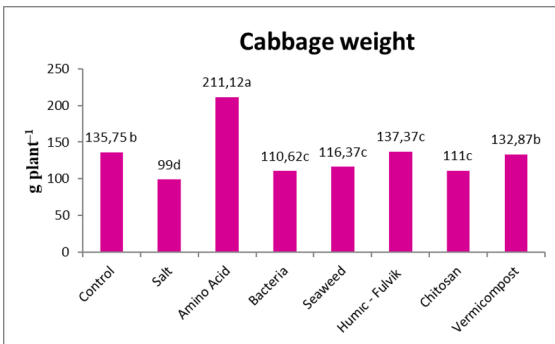
collected from the greenhouse were washed with 0.1% detergent to prevent contamination, rinsed thoroughly, and then washed three times with distilled water. After washing, the samples were dried in an oven at 65°C for 48 hours. The dried samples were ground using a leaf grinding mill. The ground samples were ashed at 550°C for 8 hours, and the resulting ash was dissolved in 3.3% (v/v) HCl. Readings of K, Ca, Mg, and Na were taken in emission mode, while Fe, Mn, Zn, and Cu were measured in absorbance mode using an atomic absorption spectrometer (Daşgan et al., 2023).

Statistical Analysis: The study was conducted in a randomized plot design with three replications. Measurements and analyses were performed with three independent replications. The data were subjected to statistical analysis using the JMP version 13 software package, and the means were compared using the LSD test.

3 RESULTS AND DISCUSSION

Plant Growth Parameter

Amino acid application increased the weight of red cabbage by 113.3% compared to the salt treatment (Figure 2). Fulvic acid resulted in a 38.8% increase, while the control treatment showed a 37.1% improvement. Vermicompost application increased weight by 34.2%, followed by seaweed with a 17.6% increase. Chitosan improved the weight by 12.1%, and bacteria application provided the smallest increase at 11.8%. These results indicate that amino acid application had the most significant positive impact on red cabbage weight under salt stress. Yasin Arslan et al. (2022) investigated the effects of melatonin (MEL) applications on salt stress in cauliflower and broccoli seedlings, using 0, 5, and 10 µM MEL treatments. Their findings demonstrated that MEL effectively mitigated the adverse effects of salt stress, leading to improvements in plant height, stem diameter, biomass, chlorophyll content, carotenoids, anthocyanins, and phenolic compounds. These results highlight the potential of MEL in enhancing plant resilience



under saline conditions.

Fig. 2. Effects of the biostimulants on red cabbage weight under salt stress

Among the treatments, amino acid application produced the most pronounced effect on dry matter content, with a 132% increase compared to salt stress. Vermicompost and fulvic acid applications also enhanced dry matter content by 44.5% and 34.4%, respectively (Table 2). The greatest improvement in leaf area was achieved with fulvic acid application (31.3%), followed by vermicompost (25.5%) and amino acids (15.2%). With respect to leaf number, amino acid application resulted in the highest increase (22.5%), while vermicompost led to a 10.1% increase, and chitosan showed no difference relative to salt stress. Regarding stem diameter, amino acids again induced the highest increase (24.4%), followed by vermicompost (18.9%) and seaweed extract (16.1%).

Amino acid and fulvic acid applications both increased plant height by 26.5% compared to the salt treatment, while vermicompost resulted in a 24.0% increase (Table 2). Vermicompost application led to a significant 73.7% increase in plant diameter. Amino acid application improved diameter by 32.2%, and chitosan resulted in a 19.7% increase. Amino acid application increased plant circumference by 22.1%. Fulvic acid resulted in a 19.3% increase, and vermicompost improved it by 11.7%.

Cabbage Leaf Physiological Parameters

Amino acid application increased the relative water content (RWC) of red cabbage by 38.3% compared to the salt treatment (Figure 3). Fulvic acid resulted in a 34.1% increase, while vermicompost improved RWC by 41.8%. Seaweed application showed a 43.1% increase, and chitosan improved RWC by 19.3%. The control group, not subjected to salt stress, had the highest RWC, with a 48.9% increase compared to the salt treatment. In contrast, bacterial treatment showed the smallest change, with only a 2.0% increase. These results suggest that seaweed, vermicompost, and amino acid applications were the most effective in enhancing water retention under salt stress.

Table 2. Effects of biostimulants on plant growth parameters of red cabbage plants under 50 mm salt stress-1

Treatments	Dry Matter (%)	Leaf Area (cm ² plant ⁻¹)	Number of Leaves per plant
Control	24.5 b	1254 bc	18.20 bc
Salt	16.0 bcd	1054 de	17.80 bc
Amino Acid	37.1 a	1214 bc	21.80 a
Bacteria	10.9 d	969.7 e	16.80 c
Seaweed	12.5 cd	1148 cd	17.40 bc
Fulvic Acid	21.5 bc	1385 a	17.00 c
Chitosan	14.7 b-d	1228 bc	17.80 bc
Vermicompost	23.1 b	1323 ab	19.60 ab
LSD _{0.05}	10.225	112.369	2.354
<i>P</i>	0.0006	0.0001	0.0030

There is no significant difference between means with the same letter in the same column; LSD: the least significant difference.

Table 3. Effects of biostimulants on plant growth parameters of red cabbage plants under 50 mm salt stress -2

Treatments	Plant height (cm)	Plant diameter (mm)	Plant circumference (cm)
Control	25.38 a	20.75 b	42.25 bc
Salt	20.50 c	18.06 d	38.50 de
Amino Acid	25.93 a	23.87 a	47.00 a
Bacteria	24.75 ab	20.31 cd	37.00 e
Seaweed	22.12 c	18.31cd	39.25 d
Fulvic Acid	25.93 a	20.18 bc	45.93 a
Chitason	22.43 bc	21.62 b	40.37cd
Vermicompost	25.43 a	31.37 b	43.00b
LSD _{0.05}	2.373	2.029	2.486
<i>P</i>	0.0002	0.0002	0.0003

There is no significant difference between means with the same letter in the same column; LSD: the least significant difference.

Amino acid application reduced membrane damage by 75.0% compared to the salt treatment. Bacteria and chitosan treatments both achieved a 77.7% reduction. Seaweed reduced membranedamage by 81.5%, while fulvic acid demonstrated an 85.3% reduction. Vermicompost was highly effective, decreasing membrane damage by 94.2%, while the control treatment, which was not exposed to salt stress, showed the greatest reduction at 98.3%. These results indicate that vermicompost, fulvic acid, and seaweed applications were the most effective in mitigating membrane damage under salt stress conditions. Deveci and Tuğrul (2017) reported that salt and drought stress reduce water uptake, leading to decreased leaf water potential and the onset of drought stress. Their study observed that as the amount of available water decreases, the lowest leaf water potential is recorded, while an increase in available water results in higher average leaf water potential. These findings highlight the critical relationship between water availability and leaf water potential under stress conditions. Başdıç and Kabay (2022) observed that the application of vermicompost to spinach plants under salt stress increased leaf relative water content, similar to the findings in our study. This demonstrates the positive impact of vermicompost on maintaining water status in plants exposed to saline conditions.

Cabbage Leaf Biochemical Parameters

Fulvic acid application exerted the greatest effect on Vitamin C levels, increasing them by 155.5% compared to salt stress (Table 3). Bacterial treatment and amino acids followed, with increases of 151.1% and 147.4%, respectively. For total phenolic content, the highest enhancement (73.6%) was observed under amino acid application. Bacterial and fulvic acid treatments also contributed significantly, with increases of 35.8% and 28.1%, respectively. In terms of total flavonoid content, amino acid application produced the best outcome, with a 16.2% increase, followed by vermicompost (14.3%) and

bacterial treatment (13.1%). Şalata and Neumann (2001) reported that the enhancement of plant resistance to salt stress is associated with the antioxidant activity of ascorbic acid (vitamin C) and its partial inhibition of salt-induced lipid peroxidation caused by reactive oxygen species (ROS). This suggests that ascorbic acid plays a critical role in mitigating oxidative damage under saline conditions. Wu et al. (2023) investigated the effects of vermicompost on the yield and quality of tomato fruits grown under salt stress. Their study demonstrated that vermicompost application improved tomato quality under saline conditions, as evidenced by significant increases in the sugar-acid ratio, vitamin C content, and Brix value, along with a substantial reduction in nitrate content. These findings highlight the potential of vermicompost in enhancing fruit quality while mitigating the negative effects of salt stress.

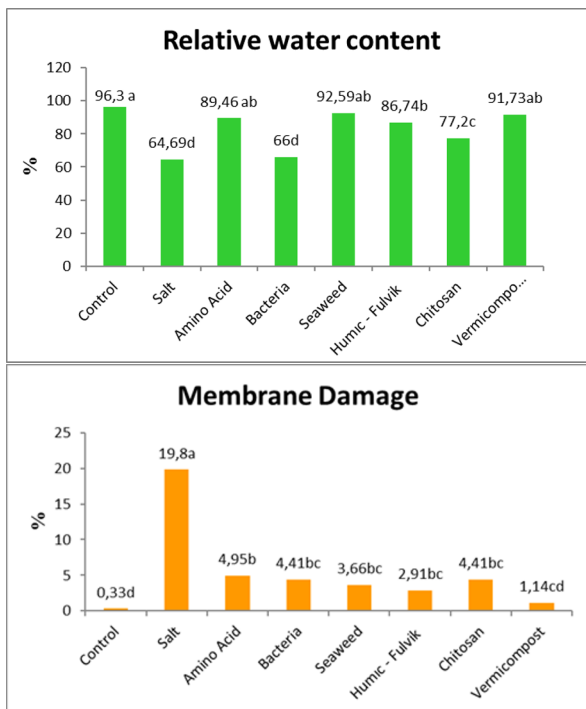


Fig. 3. Effects of biostimulants on RWC and membrane damage in cabbage under salt stress

Linic et al. (2019) reported that abiotic stress alters the cellular redox state, making the involvement of antioxidants essential in plant stress responses. Phenolics, due to their structure, are recognized as potent antioxidants that contribute to the scavenging of reactive oxygen species (ROS). This highlights the importance of phenolic compounds in mitigating oxidative damage under stress conditions. Akkladious and Muhammad (2018) investigated the ameliorative effects of calcium nitrate and humic acid on the growth, yield components, and biochemical properties of pepper plants under salt

stress. Their study demonstrated that these treatments improved fruit antioxidant compounds and fruit quality, including enhancements in capsaicin, lycopene, β -carotene, total phenols, total flavonoids, and antioxidant activity. These findings emphasize the role of calcium nitrate and humic acid in promoting fruit quality and antioxidant capacity under saline conditions.

Fulvic acid showed the highest change in pH with a 0.17% increase. While no change was observed in pH under salt treatment, amino acid application resulted in a slight decrease of 0.17% (Table 4). The highest increase in EC value was achieved with amino acid application at 78.4%. Fulvic acid followed with a 76.2% increase, and bacteria application showed a 48.8% increase. In terms of titratable acidity, no change was observed under salt treatment. Amino acid application resulted in a 2.97% decrease, while seaweed application caused a 16.4% reduction.

Table 4. Effects of Biostimulants on the Biochemical Properties of Red Cabbage under Salt Stress-1

Treatments	Vitamin C (mg 100g FW ⁻¹)	Total phenols (mg GA 100g FW ⁻¹)	Total flavonoids (mg RU 100g FW ⁻¹)
Control	29.5 ab	283 bc	511 ab
Salt	14.0 c	239 c	457 ab
Amino asid	34.7 a	414 a	531 a
Bacteria	35.3 a	324 ab	517 ab
Seaweed	17.8 c	282 bc	515 ab
Fulvic acid	35.9 a	306 b	514 ab
Chitosan	32.9 a	296 bc	490 bc
Vermicomp.	20.8 bc	300 bc	522 ab
LSD _{0.05}	117.973	62.664	40.133
<i>P</i>	0.0020	0.0023	0.0327

There is no significant difference between means with the same letter in the same column; LSD: the least significant difference. FW: Fresh weight, GA: Gallic acid, RU: Rutin

The highest increase in Brix value was observed with vermicompost application at 13.5%. Fulvic acid and chitosan applications each resulted in a 4.3% increase. These results indicate that vermicompost and amino acid applications provided significant improvements in biochemical properties under salt stress. Amino acid was the most effective in increasing the EC value, while vermicompost showed the highest increase in Brix value. Talhouni et al. (2017) examined various plant and fruit characteristics in grafted eggplant plants grown under salt stress. Their study found that salt stress led to an increase in the titratable acidity of eggplant fruits, highlighting the influence of salinity on fruit quality parameters.

Cabbage Leaf Mineral nutrient contents

Potassium (K) content increased under salt stress by 34.50%, 31.58%, and 22.51% with vermicompost, seaweed, and fulvic acid, respectively (Table 5). Sodium (Na) content increased by 52.47%, 8.64%, and 6.17% with fulvic acid, vermicompost, and amino acid, respectively. Calcium (Ca) concentrations increased by 44.41%, 27.94%, and 20.88% with amino acid, vermicompost, and chitosan, respectively. Magnesium levels showed increases of 47.13%, 26.75%, and 24.84% with chitosan, vermicompost, and the control group, respectively. Shalaby (2018), in a study on alleviating salinity stress through urea and sulfur applications in red cabbage plants, reported that soil-applied sulfur significantly affected the N, P, K, Ca, S, and Na contents in cabbage leaves. The contents of N, P, K, and S showed substantial increases, while Ca and Na levels decreased significantly compared to the control treatment. These findings highlight the potential of sulfur application in improving nutrient uptake and mitigating the negative effects of salinity.

Table 5. Effects of Biostimulants on the Biochemical Properties of Red Cabbage under Salt Stress-II

Treatments	pH	EC (dS m ⁻¹)	Acidity (%)	Brix (%)
Control	5.90a	2.23de	1.156b	7.83ab
Salt	5.92a	3.24c	2.293a	7.86ab
Amino acid	5.91a	5.78a	2.225a	7.63ab
Bacteria	5.79b	4.82b	1.685ab	8.15ab
Seaweed	5.89a	2.48cde	1.916a	7.20b
-Fulvic acid	5.93a	5.71ab	1.80ab	8.20ab
Chitosan	5.90a	1.69e	1.84a	8.20ab
Vermicompost	5.89	3.0cd	1.904ab	8.92a
LSD _{0.05}	0.0798	1.0585	0.767	1.318
<i>P</i>	0.0371	0.001	0.1016	0.4266

There is no significant difference between means with the same letter in the same column; LSD: the least significant difference.

Iron (Fe) content under salt stress increased by 237.93%, 106.90%, and 81.72% with chitosan, amino acid, and bacteria treatments, respectively (Table 6). Zinc (Zn) content rose by 116.49%, 85.57%, and 49.48% with amino acid, fulvic acid, and vermicompost, respectively. Manganese (Mn) concentrations increased by 67.77%, 15.13%, and 2.48% with amino acid, seaweed, and bacteria, respectively. Copper (Cu) levels showed increases of 37.93%, 19.52%, and 3.45% with fulvic acid, amino acid, and seaweed, respectively.

Biostimulants have been widely recognized for their potential to mitigate the adverse effects of salt stress by enhancing physiological processes and promoting plant growth. Various studies highlight that biostimulants, such as humic substances, seaweed extracts, and microbial agents, improve stress tolerance by increasing antioxidant activity, nutrient uptake, and water use efficiency. For instance, Lakhdar et al. (2023) emp-

hasized that biostimulants alleviate salinity stress by improving nutrient uptake and stimulating the accumulation of osmolytes, such as proline and sugars, which help maintain osmotic balance.

Table 6. Effects of biostimulants on macro nutrient elements in red cabbage plants under salt stress

Treatments	K	Na	Ca	Mg
Control	3.5 cd	1.8 c	3.9 bc	1.9 b
Salt	3.4 d	3.2 b	3.4 c	1.6 cd
Amino asid	3.8 c	3.4 b	4.9 a	1.9 bc
Bacteria	3.7 cd	3.3 b	4.1 b	1.5 d
Seaweed	4.5 ab	3.4 b	3.4 c	1.7bcd
Fulvic acid	4.2 b	5.0 a	3.5 c	1.6 cd
Chitosan	3.5 d	3.1 b	4.1 b	2.31 a
Vermicompost	4.6 a	3.52	4.4 b	1.9 b
LSD _{0.05}	0.323	0.711	0.494	0.303
<i>P</i>	0.0001	0.0001	0.0001	0.0008

There is no significant difference between means with the same letter in the same column; LSD: the least significant difference.

Table 7. Effects of biostimulants on micro nutrient elements in red cabbage plants under salt stress

Treatments	Fe	Zn	Mn	Cu
Control	72.5b	37.5f	34.0d	13.00c
Salt	29.0e	48.5def	60.5b	14.5bc
Amino as.	59.5bc	105.0a	101.5a	19.0a
Bacteria	60.0bc	42.5ef	63.3 b	12.5c
Seaweed	52.3cd	58.0cd	69.7 b	17.3b
Fulvic acid	54.3bc	90.0b	62.0b	20.0a
Chitosan	98.0a	53.0de	38.0cd	13.5c
Vermicom.	38.0de	70.5c	52.5bc	13.0c
LSD _{0.05}	18.33	12.76	18.00	3.29
<i>P</i>	0.0001	0.0001	0.0001	0.0007

There is no significant difference between means with the same letter in the same column; LSD: the least significant difference.

Seaweed extracts, rich in bioactive compounds, have also been shown to activate anti-oxidant systems, increasing plant resistance to salt-induced oxidative stress and enhancing nutrient absorption (Ali et al., 2021), (Franzoni et al., 2022). These biostimulants not only improve photosynthesis and plant metabolism but also reduce nitrate accumulation, which is a crucial aspect under saline conditions (Frontiers, 2023).

Moreover, microbial biostimulants like plant growth-promoting rhizobacteria (PGPR) and mycorrhizal fungi have demonstrated beneficial effects under salt stress by enhancing root development, nutrient uptake, and soil health (Bulgari et al., 2017). Protein

hydrolysates, another class of biostimulants, promote the synthesis of osmoprotective substances, enabling plants to maintain cellular homeostasis and reduce oxidative damage under stress conditions (Cristiano et al., 2018), (Zulfiqar et al., 2020).

These findings align with the observations in this study, where biostimulant applications improved the physiological performance of red cabbage under salt stress. The improvement in water status, enhanced antioxidant activity, and balanced nutrient uptake observed in previous studies confirm the potential of biostimulants to alleviate the negative impacts of salinity and improve crop quality and productivity.

4 CONCLUSION

The application of biostimulants, particularly amino acids, vermicompost, and fulvic acids, proved effective in mitigating the adverse effects of salt stress on red cabbage plants. Significant improvements were observed in cabbage weight, water status, and antioxidant activity, underscoring the potential of these biostimulants in promoting plant growth and quality under saline conditions. Amino acids were the most effective, increasing total phenolic content by 73.6% and enhancing cabbage weight by 113.3%. Vermicompost demonstrated superior membrane protection, reducing damage by 94.2%. These results highlight the capacity of biostimulants to reduce chemical input dependency while sustaining crop yield and quality under stressful environments. Integrating biostimulants into agricultural practices offers a viable strategy for improving resilience and productivity in salt-affected soils, paving the way for sustainable crop management. As a result of this study, the most effective biostimulants for mitigating the effects of 50 mM salt stress are, in order of efficacy, amino acids, vermicompost, and fulvic acid.

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