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An approach toward sustainable use of coastal saline soils *vis-a-vis* the performance of spinach: An *in situ* study

Sajal ROY and Nasrin CHOWDHURY

Department of Soil Science, Faculty of Biological Sciences, University of Chittagong, Chattogram-4331, Bangladesh
<sajal.roy@cu.ac.bd> <nasrin@cu.ac.bd>

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Abstract: Coastal regions characterized by different degrees of soil salinity pose a significant challenge to agricultural productivity. This study investigates an approach for the sustainable use of coastal saline soils, focusing on the cultivation of spinach (*Spinacia oleracea* L.) as a test crop. Through *in situ* experimentation in the south-eastern coastal part of Bangladesh, we analyzed soil amendment techniques and the resilience of spinach in terms of yield and nutritional quality in a moderately saline soil. The present experiment consists of four treatments *viz.* un-amended (T1), only N-P-K dose (T2), vermicompost (VC) at 1% (w/w) with N-P-K (T3), VC plus wood ash (WA) at 1% (w/w) of each (T4). Biomass and dry matter were found in the following sequence T3>T4>T2>T1. The uptake of macronutrients and micronutrients grown in treated soils significantly (p<0.05) increased over control with the highest response in VC amended soils followed by VC plus WA application. The tolerance of spinach to salinity was found to be highest in VC amended soils and minimum in control. Analyses of the soils after harvest of spinach revealed that the availability of all nutrients except Fe and Mn increased in VC plus WA treated condition. The single application of organic amendment (*i.e.*, VC) is recommended for better performance of spinach in soils with neutral (pH 6.75) soil reaction and moderate salinity. The results suggest that proper soil management can enhance productivity, offering a sustainable pathway for coastal agriculture.

Key words: Coastal saline soils, spinach, plant nutrients, vermicompost, wood ash

Introduction

The salinity of soil is one of the most significant abiotic stresses adversely affecting crop production (Singh 2022) and threatening global food security (Wen *et al*. 2020). Salt-affected soils occupy more than 1100 m ha of lands worldwide covering low-lying coastal, irrigated, arid and semi-arid areas (Mishra *et al*. 2023). In Bangladesh, over 1.06 million hectares of land are affected by various intensities of soil salinity (Sultan *et al*. 2023). Most of the agricultural lands in the coastal areas of Bangladesh remain underutilized for crop production due to high soil salinity and the situation is expected to worsen due to factors like salt water intrusion, tidal flooding, and capillary rise of saline ground water (Uddin *et al*. 2011). Moreover, excessive irrigation, and poor soil management lead to the degradation of millions of hectares of farmland. The high salinity in soils limits plant growth through complex mechanisms, such as osmotic stress, nutrient deficiencies [nitrogen (N), phosphorus (P), potassium (K), calcium (Ca) and magnesium (Mg)], and specific ion toxicities [sodium (Na) and chloride (Cl)] (Dhivyapriya *et al*. 2017; Arulmathi and Porkodi 2020). Nutrient deficiencies under salt stress can adversely affect plant metabolism, including uptake and assimilation of essential elements (Singhal *et al*. 2023).

To enhance crop production in saline soils, various reclamation approaches have been explored, including leaching (Shaygan and Baumgartl 2022). However, in water-scarce regions, removing salts through leaching is often impractical. Therefore, the application of soil amendments could be a more effective approach to alleviate salt strass by improving the physical, chemical and biological properties of saline soils (Chaganti *et al*. 2015; Sun *et al*. 2016; Yue *et al*. 2016; Premanandarajah 2017; Ding *et al*. 2020; Yousaf *et al*. 2022; Huang *et al*. 2025; Melebari 2025; Xiao *et al*. 2025). Vermicompost (VC) is an effective, cost-efficient, environmentally friendly, and sustainable organic fertilizer, produced by composting various organic materials, such as animal manure, municipal sewage sludge, and household trash (Pirsaheb *et al*. 2013). In contrast, wood ash (WA), is a solid by-product of wood combustion that can be applied to soils to neutralize acidity and provide essential nutrients (Boh *et al*. 2013).

Spinach (*Spinacia oleracea* L.) is a widely grown and consumed green leafy vegetable with short production cycle, typically ranging from 30 to 48 days (Ribera *et al*. 2021). It is a cool-season crop that is salt-tolerant and thrives in soils with a pH range of slightly acidic to slightly alkaline (6.0-7.5) reactions (Nonnecke 1989; Morelock and Correll 2008; Ors and Suarez 2016;). During the post monsoon period (November-March), much of the agricultural land in salt- affected areas of Bangladesh remains fallow. If spinach can be successfully cultivated in moderately saline soils as a second crop with the appropriate amendments, agricultural saline areas could be utilized for crop production during the post-monsoon season. However, the effects of VC alone or in combination with WA on spinach yield and nutritional quality under field conditions have not been investigated. Therefore, the present field experiment was conducted to examine the effects of various amendments *viz*. VC alone, VC plus WA, and inorganic fertilizer on the yield and nutrient uptake patterns of spinach grown in coastal saline soils of Bangladesh. The study also evaluates the changes in the physico-chemical properties of the soil due to the application of these amendments.

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Bangladesh is one of the most densely populated countries in the world, and ensuring food security is a major challenge. With rising salinity levels, the arability of land is decreasing, threatening food production. Soil degradation due to salinity is a major barrier to sustainable land management worldwide. This study introduces practical, field-tested solutions like organic amendments that can be replicated in other coastal regions worldwide. The study's approach to improving spinach yield in saline soils will provide a framework for sustainable food production in affected regions, thereby contributing to global food security discussions.

Materials and Methods

The growth and nutritional quality of spinach was observed through a field experiment during the post-monsoon period in the south-eastern coastal part of Bangladesh (Fig. 1) consisting of four treatments distributed in twelve plots of 1m×1m size. The soil of the experimental site was moderately saline in nature (ECe 4.46 mS cm^{-1}) and near neutral in reaction (pH 6.75). The initial characteristics of the soil is given in Table 1.

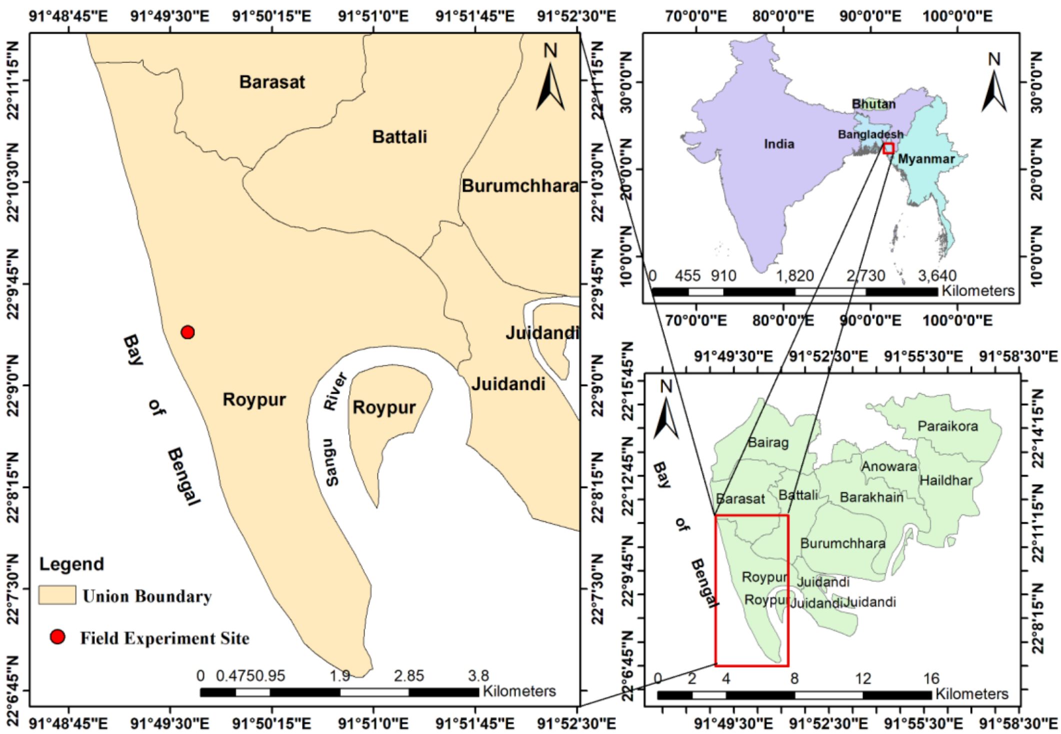

Fig. 1. Location of the experimental site.

Set-up of the field experiment

The treatments for the present field experiment comprised of control (T1), recommended dose of N-P-K (T2), VC at 1% (w/w) (T3) and VC plus WA each at 1% of each (w/w) (T4). The treatments were applied in the plots in a completely randomized way. The hard clods in each plot were uniformly broken with a wooded hammer and homogenized within each plot by mixing-up the soils.

Table 1. Physical and chemical properties of field soil.

Parameters	Properties
pH	6.75
ECe (mS cm^{-1})	4.46
OC (%)	0.61
Sand (%)	38.0
Silt (%)	36.0
Clay (%)	26.0
Available N (mg kg^{-1})	62.50
Available P (mg kg^{-1})	2.81
Available K (mg kg^{-1})	85.22
Available Na (mg kg^{-1})	490.50
Available Ca (mg kg^{-1})	544.00
Available Mg (mg kg^{-1})	756.00
Available Fe (mg kg^{-1})	25.53
Available Mn (mg kg^{-1})	21.94
Available Zn (mg kg^{-1})	0.90

Sowing of seeds and nursing of plots

Seeds were sown on ≈15 cm raised beds with a spacing of ≈30 cm from each other to avoid plot interference. Seeds of spinach were evenly distributed over each plot at the rate of 987×10^3 seeds per hectare two weeks after incorporation of the amendments. The recommended dose of N-P-K was applied in each plot at the rates of 60-18-8 kg ha^{-1} as basal dose in the form of urea, triple super phosphate and muriate of potash (FRG 2012). Seeds in each plot germinated within 7 days of sowing. All plots were irrigated every alternate day by collecting water from nearby pond. The characteristics of irrigation water are shown in Table 2. The water is classified as non-saline based on EC value (Rhoades *et al*. 1992). Weeds were removed from the plots manually by uprooting whenever necessary.

Table 2. Characteristics of water used for irrigation in the field experiment.

Parameters	Properties
pH	7.29
EC (mS cm^{-1})	0.53
Na (mg L^{-1})	22.33
K (mg L^{-1})	9.12
Ca (mg L^{-1})	11.73
Mg (mg L^{-1})	16.80

Harvesting and processing of spinach

Spinach was harvested from each plot manually at the 35th days of growth by uprooting carefully so that roots are not damaged. After harvest, plants were taken in separate polythene bags and transported to the laboratory. After bringing to the laboratory, the plants were separated into root and shoot. The aerial parts of plants were weighed with an electronic balance immediately. The roots were washed several times with tap water and then with distilled water to remove adhering soil particles. Then the roots were dried properly by wrapping between tissue papers and weighed with an electronic balance. The yields in each plot were calculated and reported in t ha^{-1}.

The shoot and root samples were cut separately into small pieces and then the respective parts were well-mixed to make homogeneous. From the bulk shoot and root samples, representative sub-samples for the individual plot were collected. The sub-samples of each plot were first dried at room temperature for few days and then dried in an oven at 65±5^{o}C for 72 hours for complete removal of moisture. During drying at room temperature, care was taken so that samples do not rot. After oven drying the shoots and roots, the samples were ground into fine powder with an electronic grinder and passed through a 0.5 mm stainless sieve (Huq and Alam 2005). The sieved plant samples were later digested with appropriate acid mixture for chemical analyses.

Collection and processing of after harvest soils (AHS)

After the collection of plants from all the plots, the soils were well-mixed within each plot to make the samples homogeneous. Three soil samples from each plot were randomly collected and taken in polythene bags. The polythene bags were labeled properly and transported to the laboratory. After bringing to the laboratory, soil samples were dried at room temperature for several days, crushed with a wooded hammer into small sizes and finally sieved through a 2 mm stainless sieve (Huq and Alam 2005). The sieved soil samples were preserved in plastic jars for further analysis.

Methods of analysis

The pH and EC were measured by pH meter (PHS-25) and EC meter (Adwa AD 330) after preparing the suspension at 1:5 soil to water ratio (w/v) for soil samples and 1:10 ratio (w/v) for VC and WA (Yue *et al*. 2016). The $EC_{1:5}$ of soil samples was converted to ECe by multiplying with a conversion factor as mentioned in Hazelton and Murphy (2007). The particle size of soil was analyzed by the hydrometer method as described in Huq and Alam (2005). The organic carbon content was determined by Walkley and Black wet oxidation method (Huq and Alam, 2005). Available N in soils was extracted with 1N KCl at 1:10 (w/v) ratio by shaking for 60 minutes followed by filtration through Whatman no. 42 filter paper (Keeney and Nelson 1982). The available P in soils was extracted by Bray and Kurtz- 1 solution, while available S was extracted by shaking the samples with KH_2PO_4 at 1:5 ratios (w/v) for 30 minutes followed by filtration with Whatman filter paper 42 (Gupta, 2001). The available Na, K, Ca and Mg were extracted by NH_4OAc (1N, pH 7.0) at 1:5 ratio (w/v) by shaking for 30 minutes followed by filtration (Thomas 1982). The extraction of phytoavailable micronutrients such as iron (Fe), manganese (Mn) and zinc (Zn) in soils was performed using 0.05 M DTPA + 0.01 M $CaCl_2$ + 0.1 M triethanolamine, adjusted to pH 7.30 at 1:2 soil solution ratio (Lindsay and Norvell 1978).

For the analysis of total concentrations of elements except for sulfur (S), a small amount of the samples was first digested by a digestion mixture solution prepared by mixing 350 ml H_2O_2, 0.42 g Se powder, 14 g $LiSO_4$. H_2O and 420 ml concentrated H_2SO_4 as mentioned in Parkinson and Allen (1975). To accomplish the digestion process, the sample and digestion mixture solution was taken in heat resistance Pyrex tubes and heated in a digestion block for several hours with a starting temperature of 50^{o}C that was gradually increased to 350^{o}C until the digest becomes colorless. For total analysis of S, the samples were digested by using HNO_3-$HClO_4$ acid mixture and heated to dryness as described in Hazelton and Murphy (2007).

The available and total N concentrations were determined by collecting NH_3 liberated from the distillation of the extract and digest with strong alkali (40% NaOH) containing boric acid- mixed indicator in an Erlenmeyer flask and the titration of the distillate with 0.01N H_2SO_4 (Bremner and Mulnaney 1982). The available P in the extract and total P in the digest was measured by the ascorbic acid blue color method and vanadomolybdo yellow color method respectively using UV-visible spectrophotometer (SP- 3000 nano Optima, Japan) at a wavelength of 880 nm and 490 nm respectively (Huq and Alam 2005). The concentration of available and total S was determined by a spectrophotometer at a wavelength of 420 nm following turbidimetric method by using Tween-80 (Huq and Alam 2005). The concentrations of Na, K, Fe, Mn and Zn were measured by atomic absorption spectrometer (Agilent Technologies 200 Series AA), whereas Ca and Mg concentrations were determined by the ethylene di-amine tetra acetic acid (EDTA) titrimetric method as described in Huq and Alam (2005).

The uptake of elements was determined by multiplying the concentration of the element with the dry mass of plant parts (Parvin *et al*. 2006; Liu *et al*. 2019) and expressed as the weight of the element per ha of land.

$$\text{Uptake} = \text{Concentration in shoot or root} \times \text{dry weight}$$

The tolerance of spinach to soil salinity in response to the amendments expressed as tolerance index (TI), was calculated considering the plant biomass by using the following equation (Wilkins 1978).

$$\text{TI} = \text{Plant biomass obtained for amendments} \,/\, \text{Plant biomass for control}$$

The shoot-root quotient (C_{shoot}/C_{root}) was calculated to estimate the transfer of the element from the underground part to the aerial part by using the following formula (Marchiol *et al*. 2004).

$$\text{Shoot-root quotient} = C_{shoot} \,/\, C_{root}$$

Where, C_{shoot} = Concentration of the element in shoot
C_{root} = Concentration of that element in root

Statistical analysis of data

Pearson's correlations between the parameters and standard deviation were determined using Microsoft Excel 2016. Duncan's multiple range test (DMRT) was performed by using SPSS (version 16) to measure significant differences between pairs of means of the obtained results. The dendrogram grouping for cluster analysis was performed by IBM SPSS.

Results and Discussion

Fresh and dry weight of spinach

The fresh and dry weight of both shoot and root of spinach significantly ($p<0.01$) varied among the treatments (Fig. 2). Both fresh and dry weight of shoot were found to be highest in VC amended soils, while fresh and dry weight of root were found to be lowest in un-amended soils. The fresh weight of shoot and root increased by 583.42% and 305.69%, while the dry weight of shoot and root increased by 395.10% and 340.41% in T3 compared to corresponding T1. The biomass and dry matter were found in the sequence of T3>T4>T2>T1. The AHC dendrogram indicated that the treatments T3 and T4 are separately clustered from T1 and T2 (Fig. 3). The TI data from Fig. 3 shows that the tolerance of spinach to salinity was maximum in VC treated soils followed by VC plus WA incorporation and N-P-K application.

The application of amendments in saline soils increased the fresh and dry weight of shoot and root of spinach. On the other hand, soil salinity in absence of any amendment adversely affected the growth and yield of spinach. Many researchers have also found the adverse effects of salinity on the growth and yield of different crops (Sahin *et al*. 2018; Al-Taey and Al-Ameer 2023; Javed *et al*. 2024; Li *et al*. 2024; Zhou *et al*. 2024). The effectiveness of VC was found significantly higher in increasing growth and yield of spinach under salt stress. In a pot experiment, Roy and Chowdhury (2022) also found better response of spinach in VC compared to un-amended soils under saline condition. In another experiment, Ding *et al*. (2020) found that the yield and quality of wheat in saline soils improved significantly due to the application of organic amendments.

The tolerance of spinach improved with the application of amendment which was in agreement with the finding of Miranda *et al*. (2016). Wang *et al*. (2014) also found the substantial potential of a combination of green waste compost, sedge peat and furfural residue for ameliorating saline soils in the coastal areas of northern China. The highest biomass in VC treated plots could be due to the improvement in physical properties of soils by increasing porosity, aeration, infiltration and water retention, as well as chemical properties by enhancing organic matter content, cation exchange capacity, availability of essential nutrients which ultimately result in better growth and yield of the crops. The present finding was in consistent with several studies (Sudhakar *et al*. 2002; Manivannan *et al*. 2009; Nada *et al*. 2011; Akhzari *et al*. 2016; Xu and Mou 2016).

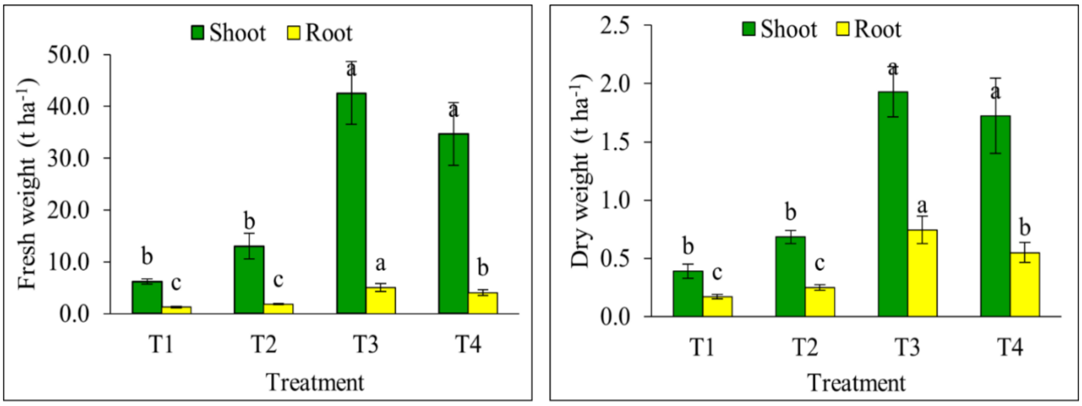

Fig. 2. Fresh and dry weight (t ha^{-1}) of shoot and root of spinach.
Means followed by the same letter (s) among the same colored bars for specific part do not differ from each other at 5% level of significance.

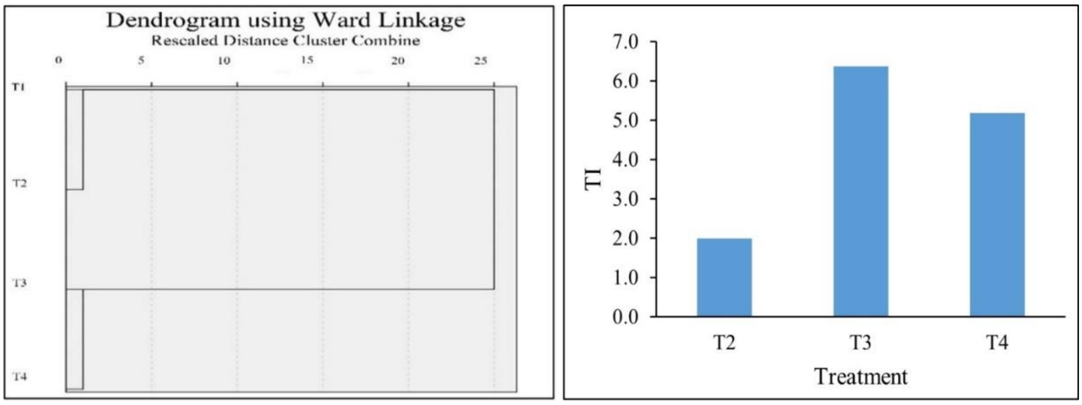

Fig. 3. Dendrogram (left) showing similarities of fresh weight and TI (right) of spinach as affected by different treatments in the field experiment.

Concentration, uptake and distribution of macronutrients in spinach

The concentrations of macronutrients in different parts of spinach are shown in Fig. 4. The concentration of N, P, K and S in the aerial part of spinach grown in amended soils was found significantly higher (p<0.01) over control. On the contrary, treatments had insignificant (p>0.05) effect on the variation of N, K and S concentration in the underground part of spinach. However, the application of either VC or VC plus WA increased N concentration in both shoot and root higher than the inorganic fertilizer application. The concentration of N, P, K and S was found in the range of 1.93–3.60%, 0.41–0.98%, 1.76–3.02% and 0.34–0.43% in shoot, while in the range of 1.55–1.94%, 0.58–1.38%, 1.51–1.72% and 0.17–0.19% in root. The concentration of N, P, S in shoot was observed in the magnitude of T3>T4>T2>T1, while that of the concentration in root was observed in sequence of T3>T4>T2>T1, T4>T3>T2>T1 and T2=T3>T1=T4 as for N, P and S, respectively. On the contrary, the concentration of K in both shoot and root of spinach was found in the order of T3>T2>T4>T1. The concentration of N, P, K and S in T3 increased by 86.82%, 140.77%, 72.28% and 27.39% over T1 for shoot. On the other hand, the concentration of N, K and S in T3 increased by 25.04%, 13.50% and 10.86%, while that of P in T4 increased by 135.90% over T1 as for root part.

The application of amendments resulted in significant difference (p<0.01) in the concentration of Ca and Mg in both shoot and root. The concentration of Ca in both shoot and root was observed in the trend of T4>T3>T2>T1. The Ca concentration ranged from 0.70 to 0.89% in shoot and 0.54 to 0.65% in root. Compared to T1, the concentration of Ca in T4 increased 27.38% and 19.21% respectively for shoot and root. The concentration of Mg was found in the following trend T3>T4>T2>T1 with the range from 0.88 to 1.09% for shoot and T1>T2>T4>T3 with the range from 0.55 to 0.69% for root. The concentration of Mg in shoot increased by 24.36%, while in root decreased by 21.25% in T4 compared to T1.

The uptake of the elements was also found significantly higher (p<0.01) in plants treated with different amendments over control (Fig. 5). The uptake of elements in both shoot and root was observed in the sequence of T3>T4>T2>T1. It was obvious that the shoot uptake of N, P and S in T3 was significantly higher from rest of the treatments, while T3 resulted insignificant variation in the shoot uptake of K, Ca and Mg from rest of the treatments except T4.

The uptake of N, P, K, S, Ca and Mg in aerial part of spinach was found in the range of 7.51–69.38, 1.60–19.06, 6.88–58.75, 1.30–8.25, 2.72–16.64 and 3.42–21.06 kg ha^{-1}, while in the range of 2.64–14.28, 0.99–8.93, 2.53–12.86, 0.29–1.41, 0.91–4.40 and 1.16–4.05 kg ha^{-1} in the underground part of the plant. The shoot uptake of N, P, K, S, Ca, Mg increased by 9.24, 11.90, 8.54, 6.37, 6.11, 6.16 -folds in T3 over T1, whereas the root uptake of N, P, K, S, Ca, Mg increased by 5.42, 9.01, 5.09, 4.89, 4.84, 3.49 -folds in T3 over T1. Irrespective of the treatments, the concentrations of N, K, S, Ca and Mg were found higher in shoot compared to root, while the concentrations of P had the opposite trend.

The application of inorganic fertilizer and organic amendments increased the concentration of macronutrients in spinach which was also reported by several authors. In different experiments incorporation of amendments had been found to increase the

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2025 46(4)

concentration of N, P and K in ryegrass (Rodríguez *et al*. 2019), P and K in spinach (Anwar *et al*. 2017), K and Ca in tomato (Esteban *et al*. 2016) and K content in rice (Zhao *et al*. 2020).

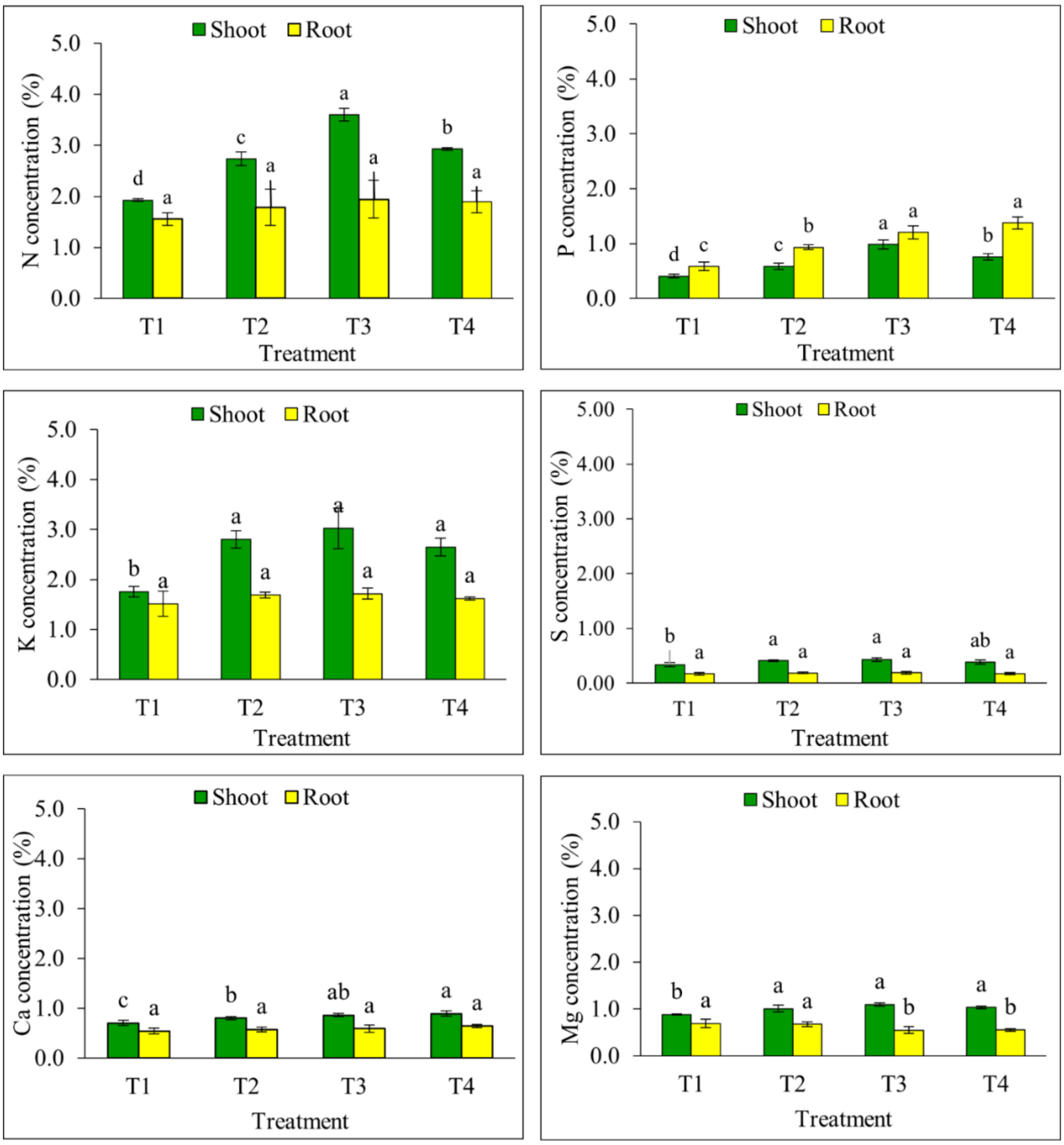

Fig. 4. Concentration (%) of different macronutrients in shoot and root of spinach.
Means followed by the same letter (s) among the same colored bars for specific parameter did not differ from each other at 5% level of significance.

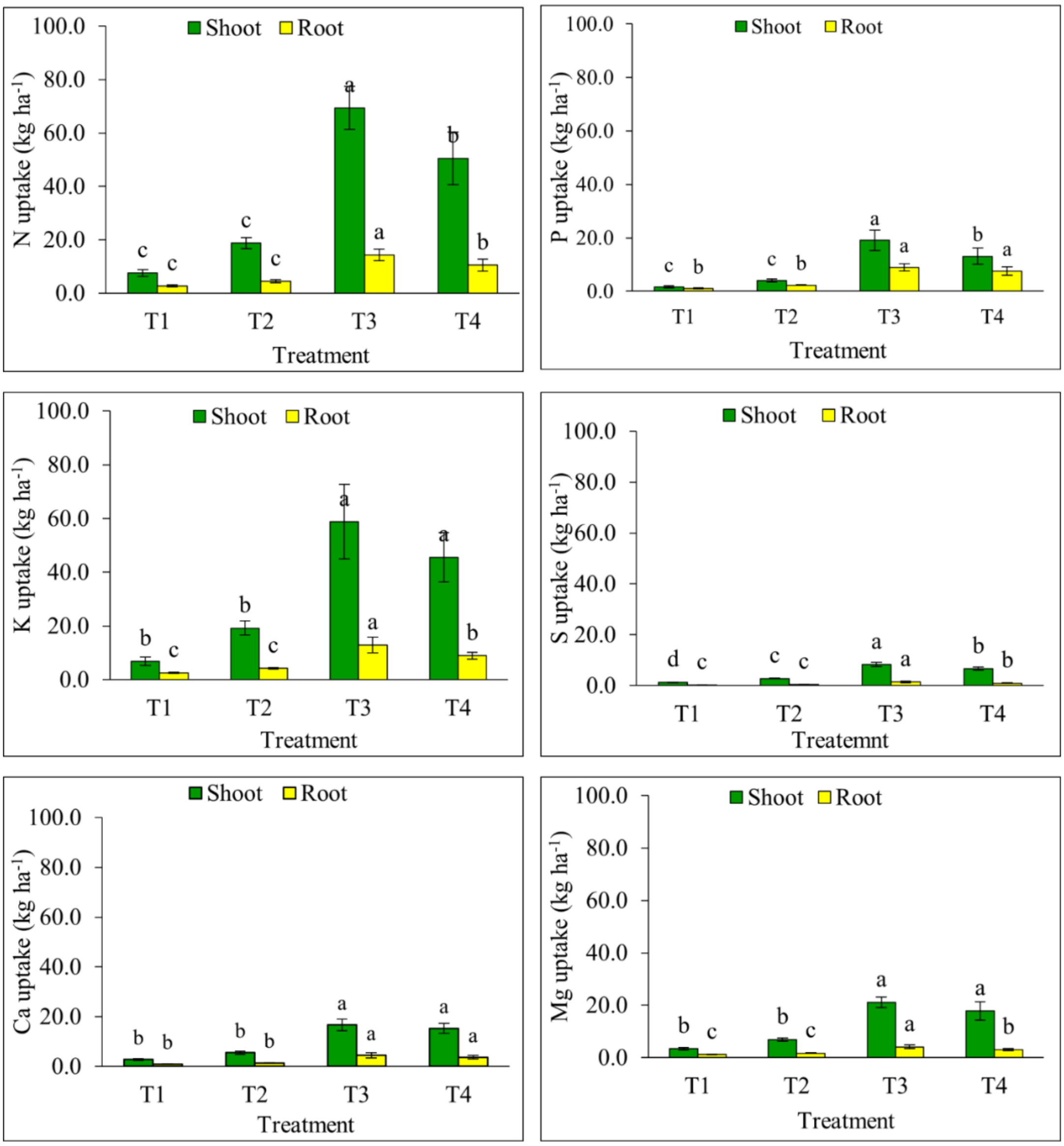

Fig. 5. Uptake (kg ha^{-1}) of different macronutrients in shoot and root of spinach.
Means followed by the same letter (s) among the same colored bars for specific parameter did not differ from each other at 5% level of significance.

The uptake of N, P, K, S, Ca and Mg by spinach also was found higher in treated conditions over control. Rekaby *et al*. (2020) found significant negative relationships between soil salinity with that of the uptake of P, K, Ca and Fe, while a significant positive correlation with that of Na in the vegetative parts of barley. The higher rates of net uptake in VC and VC plus WA amended soils could be ascribed to the result of concentration effect induced by increased shoot and root growth (Al-Karaki 2000).

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2025 46(4)

Concentration, uptake and distribution of micronutrients in spinach

Fig. 6 shows the concentration of Fe, Mn and Zn in shoot and root of spinach. The concentration of Fe in both shoot and root did not vary significantly ($p>0.05$) among the treatments. The concentration of Fe in the shoot and root followed the order of T2>T3>T1>T4 and T3>T1>T2>T4, respectively. The maximum concentration of Fe in T2 and T3 was 1.13 and 1.28-folds higher as for shoot and root respectively compared to their respective lowest concentration found in T4. As for Mn, T1 and T2 resulted in higher concentrations over T3 and T4 with significant variation ($p<0.01$) among the treatments. The concentration of Mn in shoot was observed in the sequence of T1>T2>T3>T4, while in root as T2>T1>T3>T4. The concentration of Mn in T1 was 1.35 and 1.40-folds higher compared to their corresponding lowest values. The concentration of Zn also significantly differed ($p<0.05$) among the treatments following the order of T1>T2>T3>T4 both for shoot and root. Compared to T4, the concentration of Zn in T1 increased by 1.27 and 1.30-times respectively for shoot and root.

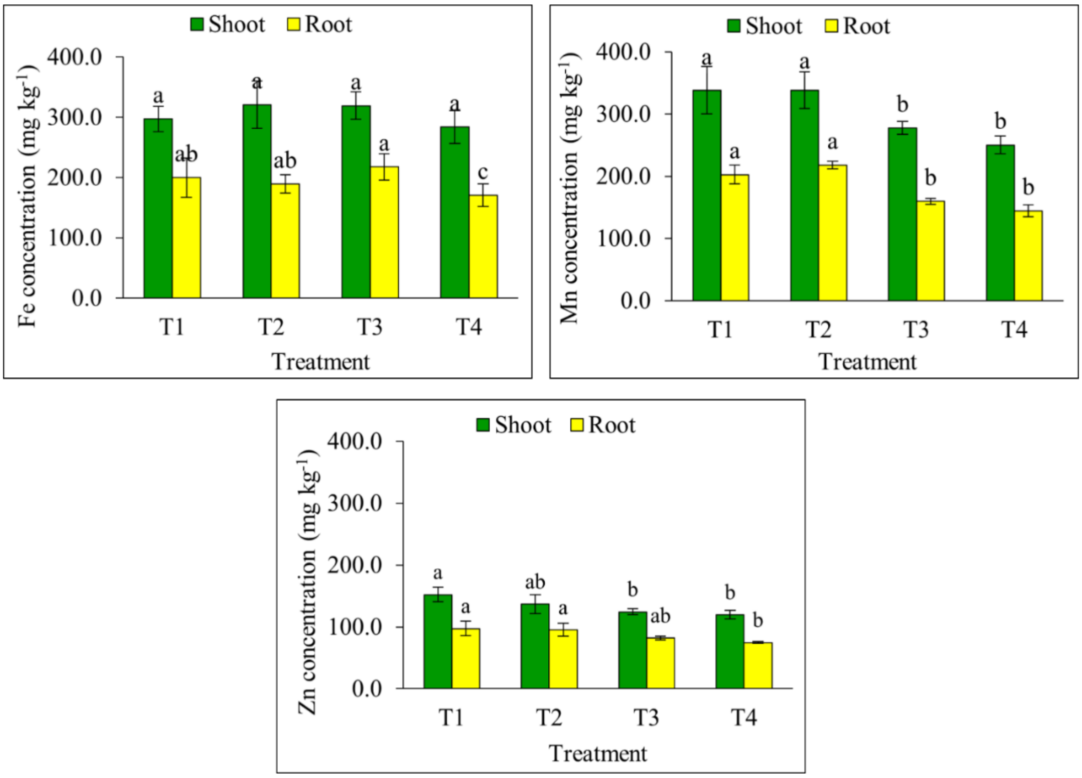

Fig. 6. Concentration (mg kg^{-1}) of micronutrients in shoot and root of spinach.
Means followed by the same letter (s) among the same colored bars for specific parameter did not differ from each other at 5% level of significance.

Fig. 7 shows the uptake of Fe, Mn and Zn in different parts of spinach. The uptake of Fe, Mn and Zn was found to be highest in soils treated with VC and lowest in control. The uptake in both aerial and underground parts of spinach significantly increased (p<0.01) in T3 over T1. As for Fe, Mn and Zn, the magnitude of the uptake in both the aerial and underground parts was observed in the sequence of T3>T4>T2>T1. The uptake of Fe, Mn and Zn in shoot was 5.34, 4.11 and 4.06-folds higher in T3 compared to their corresponding T1, while the uptake in root was 4.86, 3.50 and 3.73-folds higher in T3 compared to their corresponding T1.

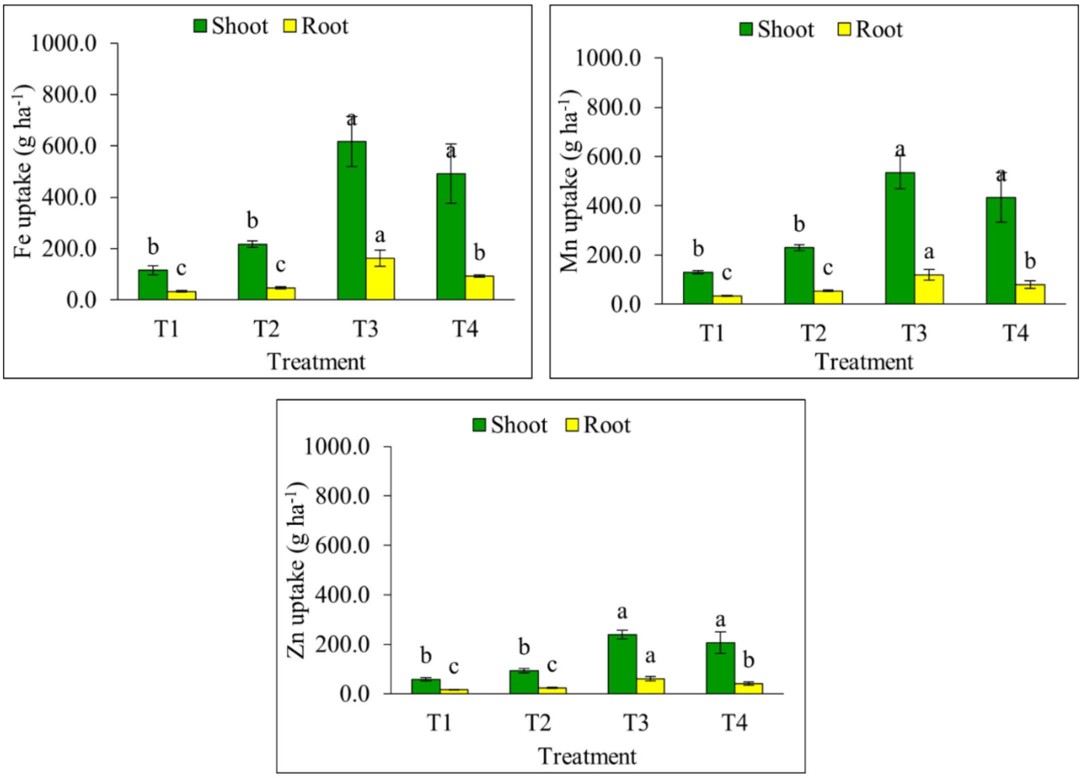

Fig. 7. Uptake (g ha^{-1}) of micronutrients in shoot and root of spinach.
Means followed by the same letter (s) among the same colored bars for specific parameter did not differ from each other at 5% level of significance.

In the present study, the concentration of Mn and Zn in plant parts decreased due to the incorporation of either VC or VC plus WA amendments. A similar observation was found by Anwar *et al*. (2017), where the concentration of Zn in the shoot of spinach decreased due to the application of cow manure after a co-composting with poplar leaf litter. The lower concentration of Zn in shoot and root in amended soils compared to control could be due to the concentration effect, *i.e*., increase in dry matter content in amended condition. The patterns of micronutrients *viz*. Fe, Mn and Zn in plants under saline condition are complex which depend on various factors such as the plant types, parts of the plants, types of soils, degree of soil salinity, the levels and degree of solubility of micronutrients in soils, etc. (Hu and Schmidhalter 2001; Rengel 2015).

C_{shoot}/C_{root} quotient of nutrients

The C_{shoot}/C_{root} quotient of N, P, K, S, Ca, Mg was observed in the range of 1.25–1.90, 0.55–0.82, 1.18–1.76, 2.00–2.30, 1.30–1.47, 1.28–2.02 (Table 3). Irrespective of the treatments, the distribution of Fe, Mn and Zn concentration ranged from 59.48–62.78%, 60.73–63.48% and 58.97–61.51% in the shoot and 37.22–40.52%, 36.52–39.27% and 38.49–41.03% in the root. The C_{shoot}/C_{root} quotient of Fe, Mn and Zn was observed in the range of 1.48–1.71, 1.55–1.74 and 1.45–1.60 with no significant (p>0.05) difference among the treatments (Table 3). Irrespective of the treatments, the C_{shoot}/C_{root} quotient of N, S, Ca, Mg, Fe Mn and Zn greater than 1 indicated their translocation from root to shoot, while of P less than 1 indicated its limited translocation. While, Takarina and Pin (2017) observed the C_{shoot}/C_{root} of Zn greater than 1, Smith *et al*. (2013) observed variable C_{shoot}/C_{root} of Zn ranging from 0.68 to 1.16.

Table 3. C_{shoot}/C_{root} quotient of macro and micro nutrients.

Treatment	N	P	K	S	Ca	Mg	Fe	Mn	Zn
T1	1.25^{b}	0.71^{ab}	1.18^{b}	2.00^{a}	1.30^{a}	1.28^{b}	1.52^{a}	1.68^{a}	1.57^{a}
T2	1.57^{ab}	0.63^{ab}	1.66^{a}	2.24^{a}	1.41^{a}	1.50^{b}	1.71^{a}	1.55^{a}	1.45^{a}
T3	1.90^{a}	0.82^{a}	1.76^{a}	2.30^{a}	1.47^{a}	2.02^{a}	1.48^{a}	1.74^{a}	1.52^{a}
T4	1.56^{ab}	0.55^{b}	1.64^{a}	2.22^{a}	1.39^{a}	1.88^{a}	1.68^{a}	1.74^{a}	1.60^{a}
p value	>0.05	>0.05	<0.01	>0.05	>0.05	<0.01	>0.05	>0.05	>0.05

Means followed by the same letter (s) within the column did not differ from each other at 5% level of significance.

pH and EC of AHS

Table 4 shows the pH and ECe of AHS. The addition of amendments significantly increased (p<0.01) the pH and ECe of AHS with maximum value in T4. The pH and ECe increased by respectively 29.46% and 86.20% in T4 compared to their corresponding lowest values. The application of amendments especially WA in association with VC contributed to higher pH and ECe of AHS which are consistent with the findings of other researchers (Yu *et al*. 2015; Gorgolewski *et al*. 2016; Rodríguez *et al*. 2019; Deighton and Watmough 2020; Ding *et al*. 2020). These increase in pH and ECe after the application of WA could be attributed to the presence of high amounts of such elements as Ca and Mg which occur as oxides and carbonates (Rodríguez *et al*. 2019) as well as high content of K (Ouni *et al*. 2013). Augusto *et al*. (2008) also stated that the dissolution of carbonate pool of Ca and Mg exist in WA contributes to the increase in soil pH.

Table 4. pH and ECe (mS cm^{-1}) values (mean±SD) of AHS.

Treatment	pH	ECe
T1	6.73±0.03[d]	3.37±0.66[b]
T2	6.90±0.13[c]	2.93±0.17[b]
T3	7.28±0.03[b]	3.12±0.18[b]
T4	8.72±0.03[a]	5.46±0.02[a]
p value	<0.01	<0.01

Means followed by the same letter (s) within the column did not differ from each other at 5% level of significance.

Concentration of available and total nutrients in AHS

The concentration of available (Table 5) and total (Table 6) nutrients in AHS varied significantly among the treatments. The concentration of available nutrients was found to be highest in VC plus WA incorporated soils. The concentration of available N, S, K, Na, Ca, and Mg in T4 was 3.65, 1.25, 10.25, 1.28, 6.13 and 1.51-times, while total concentration of N, S, K, Ca and Mg was 2.03, 1.48, 1.01, 3.08 and 1.51-times higher in comparison to their corresponding T1. On the contrary, the joint application of VC and WA resulted in minimum availability of Fe and Mn in AHS, while opposite trend was found in case of Zn with significant difference ($p<0.01$) among the treatments. The concentration of available Fe and Mn decreased by 4.83 and 1.73-times respectively in T4 compared to corresponding highest values, while that of available Zn increased by 3.05-folds. While no significant difference was observed among the treatments for total Fe ($p>0.05$) and Mn ($p>0.05$), significant ($p<0.05$) variation was observed for total Zn concentration. The concentration of total Zn in T4 was found significantly higher ($p<0.05$) from the rest of the treatments. Total concentration of Zn in T4 was found 1.19-fold higher relative to the lowest value found in T2.

In consistent with the present findings, an increase in available macronutrients with the application of amendments was observed by Wang *et al*. (2014) and Ding *et al*. (2020). Similar to our findings, the remarkable influence of WA application was found to increase the concentrations of Ca and Mg (Deighton and Watmough 2020); P, K, Ca and Mg (Augusto *et al*. 2008) in soils. Rodríguez *et al*. (2019) in another experiment with ryegrass observed that the application of WA favored the availability of P, Ca, Mg, and K in soils.

The application of WA along with VC resulted in the lowest amount of available Fe and Mn in soils which could be the consequence of increased pH. A similar observation was found by Barman *et al*. (2014). Khabaz-Saberi and Rengel (2010) also reported that the availability of Fe and Mn decreases with decreasing soil acidity. On the other hand, the availability of Zn increased due to the application of WA plus VC in our present study which is in agreement with the findings of Barman *et al*. (2014) and Rodríguez *et al.* (2019), while in disagreement with Rengel (2015). Among the micronutrients, a small fraction of total Fe was found in available form. Rengel (2015) also reported relatively low solubility of Fe in soils. While the concentrations of available micronutrients among the treatments varied significantly, the total Fe and Mn did not differ. Herencia *et al*. (2008) found similar results where the addition of compost increased available concentrations of Fe, Mn and Zn with no significant effect on the total concentration of these micronutrients.

Table 5. Concentration of available nutrients (mg kg^{-1}) in AHS.

Treatment	N	S	K	Ca	Mg	Fe	Mn	Zn
T1	34.72^{c}	83.64^{ab}	81.15^{b}	476.00^{c}	711.20^{b}	29.79^{a}	31.43^{a}	0.81^{c}
T2	64.23^{b}	81.45^{b}	76.19^{b}	489.33^{c}	730.40^{b}	37.45^{a}	38.23^{a}	0.87^{c}
T3	83.33^{b}	67.35^{b}	97.93^{b}	870.67^{b}	765.60^{b}	31.13^{a}	38.17^{a}	2.07^{b}
T4	126.73^{a}	104.39^{a}	832.50^{a}	2917.33^{a}	1070.40^{a}	7.75^{b}	22.11^{b}	2.48^{a}
p value	<0.01	<0.05	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01

Means followed by the same letter (s) within the column did not differ from each other at 5% level of significance.

Table 6. Concentration of total nutrients in AHS.

Treatment	N (%)	S (mg kg^{-1})	K (%)	Ca (%)	Mg (%)	Fe (%)	Mn (mg kg^{-1})	Zn (mg kg^{-1})
T1	0.16^{b}	209.91^{b}	1.27^{a}	0.18^{b}	0.35^{c}	0.46^{a}	495.00^{a}	85.26^{b}
T2	0.19^{b}	168.66^{d}	1.26^{a}	0.19^{b}	0.39^{bc}	0.47^{a}	466.10^{a}	83.26^{b}
T3	0.36^{a}	180.06^{c}	1.19^{b}	0.23^{b}	0.45^{ab}	0.44^{a}	507.43^{a}	89.63^{b}
T4	0.32^{a}	310.22^{a}	1.27^{a}	0.56^{a}	0.53^{a}	0.54^{a}	475.17^{a}	99.00^{a}
p value	<0.01	<0.01	<0.05	<0.01	<0.01	>0.05	>0.05	<0.05

Means followed by the same letter (s) within the column did not differ from each other at 5% level of significance.

The inhibitory effect of salinity on nutrient uptake and water absorption leads to osmotic stress and physiological dehydration, ultimately compromising plant growth and productivity (Hafez *et al*. 2021). Such stress arises from ionic toxicity, osmotic stress, and oxidative stress stemming from saline water in the plant root zone (Kimera *et al*. 2023). The disruption of ion balance, particularly the competition between Na^+ and essential nutrients like Ca^{2+} and K^+, further exacerbates the negative impacts of salinity on plant physiology, hindering photosynthesis and overall metabolic function (Hafez *et al*. 2021). The observed improvements in spinach growth and tolerance in response to VC application are consistent with findings on other crops, where organic amendments have been shown to enhance plant resilience to salinity stress (Yan *et al*. 2021). The observed variations in fresh and dry weight of spinach shoots and roots across different treatments underscore the complex interplay between soil salinity and plant growth, highlighting the ameliorative potential of organic amendments like VC (Mishra *et al*. 2023). The substantial increase in both fresh and dry biomass in VC-amended soils, in contrast to the diminished growth in un-amended saline soils, emphasizes the detrimental impact of salinity on plant development and the capacity of organic amendments to counteract these effects (Hafez *et al*. 2021). This aligns with the broader understanding of salinity as a significant constraint on agricultural productivity, affecting vast swathes of land globally.

Conclusions

This research addresses the challenge of agricultural productivity in coastal saline soils, particularly in regions vulnerable to climate change, such as Bangladesh. The study evaluates the performance of spinach under different salinity mitigation strategies to determine viable agricultural practices for the region. The yield and nutritional quality of spinach increased in soils grown under the amended conditions. The key points developed from the study are:

1. The fresh and dry weight of spinach shoot and root was significantly influenced by the different treatments applied. This indicates that the treatments had a significant impact on the growth and biomass production of spinach.

2. The dendrogram analysis showed similarities in the fresh weight and TI of spinach under different treatments, suggesting the treatments had varying effects on spinach performance.

3. The concentration and uptake of macronutrients (N, P, K, S, Ca, Mg) and micronutrients (Fe, Mn, Zn) in the shoot and root were affected by the treatments. This highlights how the treatments influenced the nutrient status of the spinach plant.

4. The C_{shoot}/C_{root} quotient indicates the relative distribution of nutrients between shoot and root, was significantly affected by some of the treatments. This suggests the treatments influenced the partitioning of nutrients within the spinach plant.

5. The soil properties like pH and ECe were also altered by the treatments, which in turn likely influenced the nutrient availability and uptake by spinach.

The study confirms that soil amendments, particularly organic matter incorporation along with mineral fertilizers is effective in improving saline soil conditions for spinach cultivation. The present study suggests the superiority of the application of organic amendment *i.e.*, VC at the rate of 1% (w/w), to saline soils with a neutral reaction to combat harmful effects of salt stress, enhancing the yield and nutrient uptake of spinach.

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