Arch Biol Sci. 2024;76(1):71-82 https://doi.org/10.2298/ABS240101003R

Impact of different zinc concentrations on growth, yield, fruit quality, and nutrient acquisition traits of tomato (*Lycopersicon esculentum* L.) grown under salinity stress

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Received: January 1, 2024; **Revised**: January 23, 2024; **Accepted**: January 24, 2024; **Published online**: January 30, 2024

Abstract: Salinity stress affects plant growth, development, nutrient uptake, and yield. Applications of micronutrients, specifically zinc (Zn), can mitigate the harmful consequences of salt stress. During the winter season of 2022, an experiment was conducted in the net house of BINA substation Satkhira, Bangladesh, to examine the impact of different Zn concentrations (5 and 10 kg ha^{-1}) on tomato (*Lycopersicon esculentum* L.) growth, yield, fruit quality, and nutrient acquisition abilities under different salt stress (SS) conditions (SS0.5%, SS1.0%, and SS1.5% NaCl). The result of the study showed that different stress conditions lowered the plant height, the number of branches per plant, flower clusters, and fruits per plant, plant yield, vitamin C, protein and lycopene contents, and the acquisition of different nutrients, i.e., nitrogen (N), phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg), zinc (Zn) and iron (Fe). The application of 10 kg Zn ha^{-1} (Zn10) increased all previously mentioned parameters in both saline and usual conditions. On the other hand, a decrease in the amount of Na in fruit was observed when Zn application was increased from 5 to 10 kg ha^{-1}. Plant Na/K ratios were consequently lowest at the highest Zn concentration. Therefore, the findings indicate that Zn application improves tomato growth, yield, fruit quality, and nutrient acquisition traits by mitigating the negative impacts of saline environments.

Keywords: fruit quality; nutrient acquisition; salinity; tomato; zinc

INTRODUCTION

Understanding how crops react to environmental stressors is essential to pursue sustainable agriculture. An ongoing issue in agriculture, salinity stress, has significant effects on crop productivity and stands in the way of establishing an irrigated area's ability to produce food in a sustainable manner [1-2]. Salinity is a major crop productivity barrier in many parts of the world and is frequently observed [3-5]. Salinity affects around 1,125 million ha worldwide and is expected to increase in the future [6]. Soil salinity is a global issue, with estimates predicting that salinity will affect 50% of all arable land by 2050. As a result, understanding crop sensitivity to salinity is crucial for reducing economic loss and enhancing food security [7]. Salinity is a significant problem in Bangladesh, as about 53% of the country's coastal areas are affected by various levels of salinity [8]. Plants respond to salinity stress in multiple ways at different levels of plant structural organization. Depending on plant salinity tolerance and salt content in the environment, this can harm plants or hinder plant growth [9-10]. Salt causes three main limitations for plants: oxidative damage, ionic imbalance, and osmotic stress. An excessive intake of harmful salt ions, primarily Na^+ and Cl^-, which interfere with the plant's regular metabolic processes, causes ionic stress. Significantly lower cytosolic K^+ levels coincide with toxic Na^+ and Cl^- buildup, which impacts a cell's ability to metabolize and survive [11-13]. Salinity,

How to cite this article: Rabbi RH Md, Aktar N, Mahamud A Md, Paul NC, Halder D, Imran S. Impact of different zinc concentrations on growth, yield, fruit quality, and nutrient acquisition traits of tomato (*Lycopersicon esculentum* L.) grown under salinity stress. Arch Biol Sci. 2024;76(1):71-82.

therefore, inhibits plant growth, resulting in losses in qualitative and quantitative yields [14-17].

Plants require Zn, an important micronutrient, for several physiological functions, including nucleic acid metabolism and enzyme activation. Zinc is involved in processes such as root formation, antioxidant defense mechanisms, and the synthesis of chlorophyll [18-19]. Zinc also lessens the uptake of too much Na in saline conditions by altering the permeability and structural integrity of the stem cell membrane [20]. When plants are exposed to salinity, zinc supplementation effectively reduces Na accumulation and improves the K/Na ratio [2]. In addition, to mitigate the adverse effects of salt stress, Zn supplementation stimulates the expression of stress-sensitive genes and the creation of secondary metabolites [21]. Tomato (*Solanum lycopersicum* L.) is widely cultivated worldwide and in practically every region of Bangladesh, and it contains many antioxidants and nutritious nutrients [22-23]. Tomatoes are high in lycopene, vitamin C, protein, phenolic, and flavonoids, which act as chemoprotective agents against several chronic diseases [24]. According to the Bangladesh Bureau of Statistics [25], tomato production in Bangladesh reached about 4.5 million metric tons, covering 73 thousand acres of land in 2022, making it the third most produced vegetable in the country after potato and brinjal, with the production of tomatoes increasing over the years. Salt stress inhibits tomato development and yield, much like it does for other crops. The most frequent adverse effects of salinity on tomatoes include a reduction in plant height, a decline in yield-related characteristics, and an impairment in product quality [26]. Research on the impact of ZN concentrations on tomato growth, yield, and fruit quality under salinity stress has yielded mixed results. Salama et al. [27] found that a low concentration of zinc-EDTA (0.35 g/pot) led to the highest growth and yield, while Alharby et al. [28] reported that zinc oxide nanoparticles mitigated the effects of salinity, with a lower concentration being more effective. Similarly, Alpaslan et al. [29] observed that increasing zinc levels alleviated the harmful effects of salinity on plant weight and sodium and chloride concentrations. However, Zhang et al. [30] noted that salinity stress negatively affected tomato growth and yield, although it did improve fruit quality. These studies collectively suggest that zinc can positively impact tomato growth and yield under salinity stress, but the specific concentration and form of zinc may vary.

To our knowledge, few studies show how supplementation with different nutrients affects tomato growth and development when exposed to salinity stress. However, it has been reported that N fertilization reduces the adverse effects of saline environment and enhances the growth and yield of tomato [31]. Khursheda et al. [32] demonstrated that foliar application of Ca^{2+} substantially mitigated the negative effects of salinity on plant biomass production or morphology and the physiology and fruit production in tomatoes. Similarly, Shabani et al. [33] reported that the addition of Ca^{2+} and K^{+} can also alleviate the harmful effects of high salinity on tomatoes. Forghani et al. [34] stated that $Ca(NO_3)_2$ also improved the chlorophyll content and the dry weight, modulated ion hemostasis, and decreased the negative salt stress in tomato plants. However, Khan et al. [35] indicated that under salt stress conditions, foliar application of K_2SO_4 maximized the growth and yield of tomatoes. Elsadek et al. [36] observed that increased tomato fruit production was obtained from plants primed with potassium humate and exogenous application of potassium humate and potassium silicate mixture under salt stress conditions. As a result, this work draws upon an extensive repository of information to add to the extending discourse about sustainable agriculture by offering a comprehensive viewpoint on optimizing Zn management for resilient tomato growing in salinity-affected environments.

MATERIALS AND METHODS

Study location and pot preparation

A pot experiment was conducted in the net house of BINA substation Satkhira, Bangladesh, in the winter of 2022. The experimental site was 5 m above sea level at geographic coordinates 22.7167°N 89.0750°E. The location is part of the Non-Calcareous Dark Grey Floodplain soil under the Ganges Tidal Floodplain's Agro-ecological Zone (AEZ-13) [37]. The experimental location featured a tropical monsoon environment characterized by high average temperatures ranging from around 25-35°C and high humidity of 70-80% throughout the year. Significant rainfall was reported, notably during the monsoon season, but limited rainfall, low humidity, low temperature, and a short day were also observed during the winter season (October to March). The soil used in the experiments was collected from the farm area of BINA substation Satkhira. Surface soils were collected at depths that ranged from 0 to 15 cm. Initially, the physical and chemical properties of the soil were investigated [38-41]. Supplementary Table S1 provides the physical and chemical parameters of the initial soil samples. Ten kg of prepared soil was placed in each plastic pot, allowing roughly 5 cm of space at the top, and each pot was properly tagged.

Test crop and treatment conditions

The BARI Tomato-15, a winter variety with high production and disease-resistant properties, was selected as a test crop for the experiment and collected from the On-Farm Research Division, Gopalgonj, Bangladesh Agriculture Research Institution (BARI). Three salinity levels (i.e., 0.5% (SS0.5%), 1.0%, and 1.5% NaCl) were used in the experiment. The salinity levels were chosen following a previous study by Singh et al. [42]. Similarly, two Zn concentrations, i.e., Zn5=5 mg kg^{-1} and Zn10=10 mg kg^{-1} Zn (in the form of $ZnSO_4.7H_2O$), were chosen based on previous literature [43]. The interaction of both salinity stress and different levels of Zn (Zn5+SS0.5%, Zn5+SS1.0%, Zn5+SS1.5%, Zn10+SS0.5%, Zn10+SS1.0%, and Zn10+SS1.5%) were also examined. A pot without salt stress and Zn was maintained as the control (C) treatment. The treatment conditions are given in Supplementary Table S2. All treatments had three replications. Every pot received an equal amount of other nutrients at the rate of 125 mg kg^{-1} urea, 80 mg kg^{-1} triple superphosphate (TSP), 60 mg kg^{-1} muriate of potash (MoP), and 15 mg kg^{-1} gypsum, respectively [23,43]. Vermicompost was applied at a rate of 500 kg ha^{-1} and incorporated into the soil seven days before seedling transplanting to break down the supplied nutrients into their simpler forms, thereby boosting their absorption by the plant [44]. Throughout the crop's growing stage, intercultural operations were performed as needed. Bamboo stakes were used to support the plants to prevent lodging. Weeding and irrigation were performed as required. After 45 days, salinity was introduced (SS0.5%, SS1.0%, SS1.5%, Zn5+SS0.5%, Zn5+SS1.0%, Zn5+SS1.5%, Zn10+SS0.5%, Zn10+SS1.0%, and Zn10+SS1.5%) at four different times using irrigation water at three-day intervals [45]. Distilled water was used for irrigation to keep the salinity-free treatment (control, Zn5 and Zn10) pots at field capacity. Growth, yield, biochemical, and chemical contents were measured in each pot.

Determination of biochemical and mineral nutrients of BARI tomato-15 fruit

According to the described procedure [46-47], garden-fresh fruit samples from each pot were subjected to chemical analysis to determine the biological components, such as the protein, lycopene, and vitamin C. The wet oxidation method was used to generate plant and fruit extracts, following the instructions of [48]. The extract was utilized to analyze the amounts of Na, P, K, Ca, Mg, S, Zn, and Fe using conventional procedures [41,49-53].

Statistical analysis

IBM SPSS Statistics V.25 was used for statistical analysis. Significant differences were ascertained using one-way ANOVA, followed by Tukey's HSD test ($P<0.05$). To construct a heatmap and conduct hierarchical clustering analysis using Euclidean distances in R 4.3.2, the "pheatmap" package was used. Principal component analysis (PCA) was done using the "GGally" and "factoextra" packages.

RESULTS

Impact of different Zn concentrations on the growth and yield of tomato under salinity stress

All investigated metrics showed the lowest results when salinity stress was introduced in tomato plants, whereas the application of varying Zn concentrations provided the maximum value of all growth parameters and yield (Figs. 1 and 2). The highest plant height, numbers of branches per plant, flower cluster per plant, fruit per plant, fruit yield per plant, and yield ha^{-1} were obtained after the application of Zn10. The lowest levels of all the parameters mentioned above were obtained from the SS1.5% stress condition. Interestingly, the results also indicated that Zn application in different salt-stress conditions contributed to better growth and yield when compared to the SS0.5%, SS1.0%, and SS1.5% salinity stress conditions (Fig. 1, 2). Plant height increased

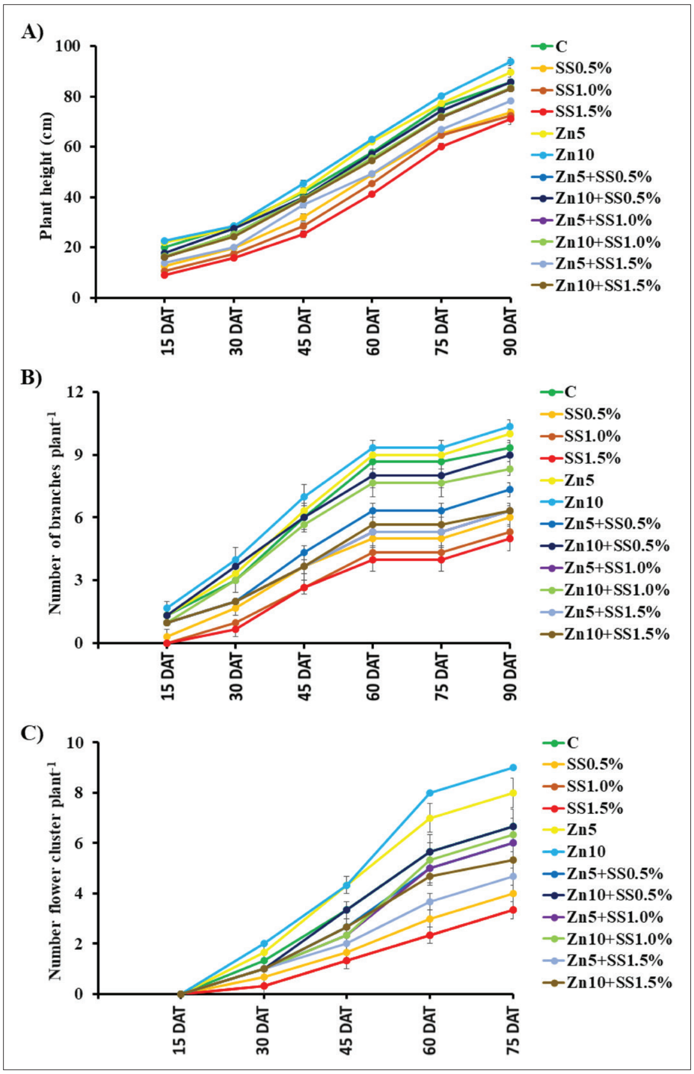

Fig. 1. The influence of different Zn concentrations on **A** – plant height, **B** – number of branches per plant, and **C** – number of flower clusters per plant of tomato grown under different salinity stress conditions. The data are presented as means of 3 replicates±SE, with a sample size n=3. C – control, SS0.5% – 0.5% NaCl, SS01.0% – 1.0% NaCl, SS1.5% – 1.5% NaCl, Zn5 – 5 mg kg^{-1} Zn, Zn10 – 10 mg kg^{-1} Zn, Zn5+SS0.5% – 5 mg kg^{-1} Zn+0.5% NaCl, Zn10+SS0.5% – 10 mg kg^{-1} Zn+0.5% NaCl, Zn5+SS1.0% – 5 mg kg^{-1} Zn+1.0% NaCl, Zn10+SS1.0% – 10 mg kg^{-1} Zn+1.0% NaCl, Zn5+SS1.5% – 5 mg kg^{-1} Zn+1.5% NaCl, Zn10+SS1.5% – 10 mg kg^{-1} Zn+1.5% NaCl.

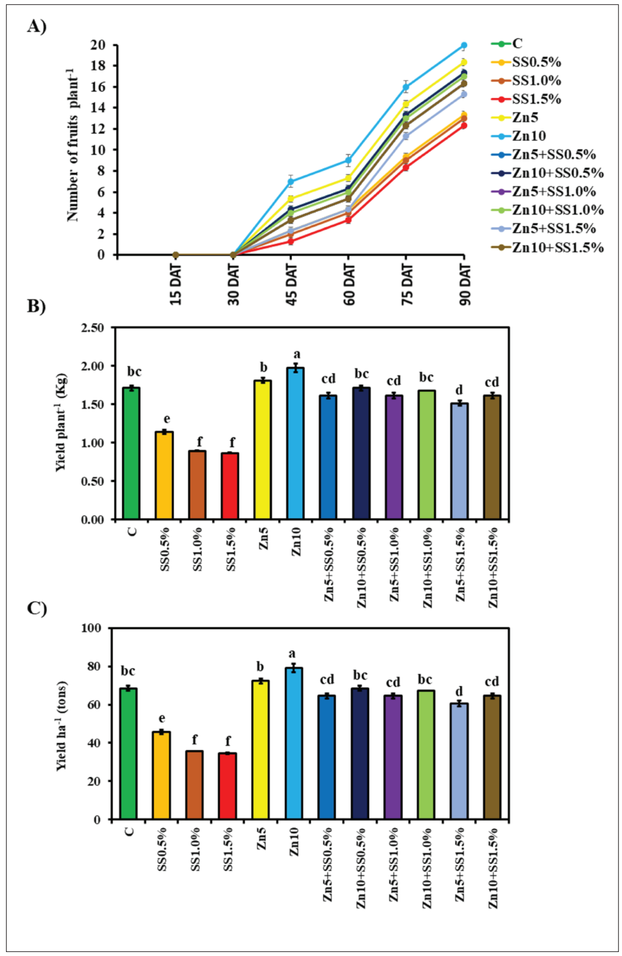

Fig. 2. The influence of different Zn concentrations on **A** – number of fruits plant^{-1}, **B** – yield plant^{-1}, and **C** – yield ha^{-1} of tomato grown under different salinity stress. The data are presented as means of 3 replicates ± SE, with a sample size n=3. Statistical analysis was performed using one-way ANOVA with Tukey post hoc test; different lowercase letters indicate statistically significant differences ($P<0.05$).. C – control, SS0.5% – 0.5% NaCl, SS01.0% – 1.0% NaCl, SS1.5% – 1.5% NaCl, Zn5 – 5 mg kg^{-1} Zn, Zn10 – 10 mg kg^{-1} Zn, Zn5+SS0.5% – 5 mg kg^{-1} Zn+0.5% NaCl, Zn10+SS0.5% – 10 mg kg^{-1} Zn+0.5% NaCl, Zn5+SS1.0% – 5 mg kg^{-1} Zn+1.0% NaCl, Zn10+SS1.0% – 10 mg kg^{-1} Zn+1.0% NaCl, Zn5+SS1.5% – 5 mg kg^{-1} Zn+1.5% NaCl, Zn10+SS1.5% – 10 mg kg^{-1} Zn+1.5% NaCl.

slowly up to 45 days after transplanting (DAT) and then increased rapidly till the final harvest, when all the treatments followed a similar trend of growth (Fig. 1A). The number of branches per plant increased gradually up to 60 DAT and showed no change at 75 DAT and slightly increased at 90 DAT (Fig. 1B). It was also noticed that flowering started from 30 DAT and continued to increase up to 75 DAT (Fig. 1C).

Fruit appeared after 45 DAT, and showed a slower increasing trend up to 60 DAT, followed by a rapid increase in the number of fruits per plant till the final harvest (Fig. 2A). In Fig. 2B and C, salinity stress and different Zn applications and their interaction had a significant influence on fruit yield per plant and yield per hectare. Salt-treated plants significantly lowered the fruit yield per plant and yield per hectare compared to control plants (Fig. 2B, 2C). Results demonstrated that

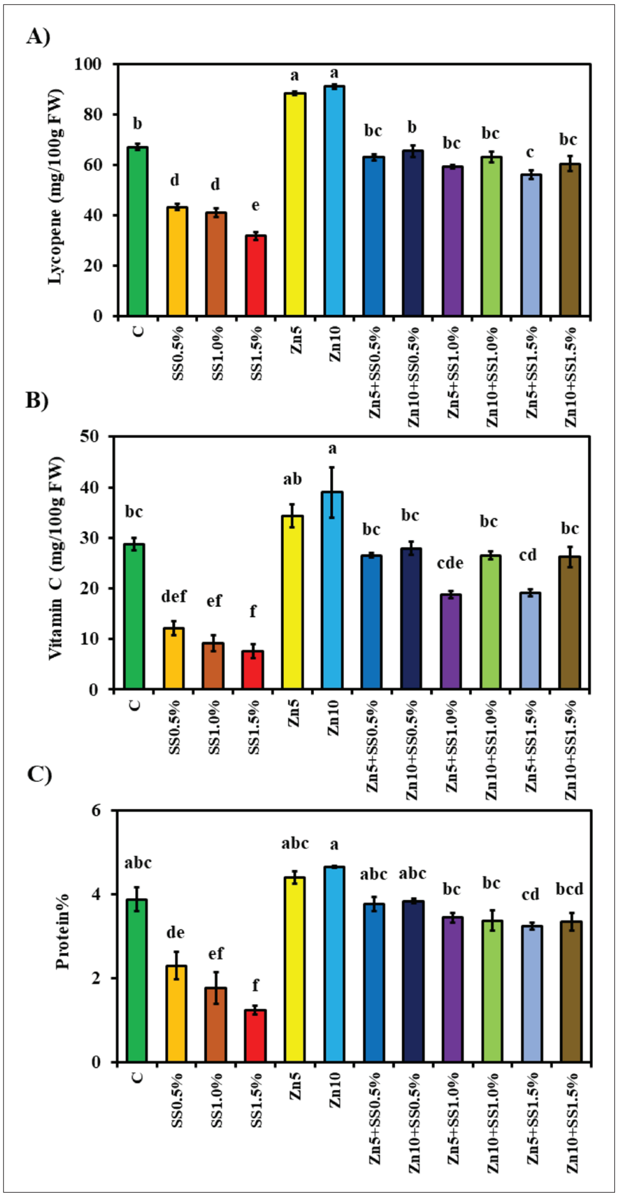

Fig. 3. The influence of different Zn concentrations on fruit quality of tomato grown under different salinity stress levels. **A** – lycopene content; **B** – vitamin C content; **C** – protein content. The data are presented as means of 3 replicates±SE, with a sample size n=3. Statistical analysis was performed using one-way ANOVA with Tukey post hoc test; different lowercase letters indicate statistically significant differences ($P<0.05$). C – control, SS0.5% – 0.5% NaCl, SS01.0% – 1.0% NaCl, SS1.5% – 1.5% NaCl, Zn5 – 5 mg kg^{-1} Zn, Zn10 – 10 mg kg^{-1} Zn, Zn5+SS0.5% – 5 mg kg^{-1} Zn+0.5% NaCl, Zn10+SS0.5% – 10 mg kg^{-1} Zn+0.5% NaCl, Zn5+SS1.0% – 5 mg kg^{-1} Zn+1.0% NaCl, Zn10+SS1.0% – 10 mg kg^{-1} Zn+1.0% NaCl, Zn5+SS1.5% – 5 mg kg^{-1} Zn+1.5% NaCl, Zn10+SS1.5% – 10 mg kg^{-1} Zn+1.5% NaCl.

Zn5 and Zn10 application significantly increased fruit yield per plant and yield per hectare under SS0.5%, SS1.0%, and SS1.5% saline conditions compared to SS0.5%, SS1.0%, and SS1.5% respectively (Fig. 2B, 2C). Together, these results indicated that Zn10 produced better results for the growth and yield of tomatoes than Zn5 under salt stress conditions.

Impact of different Zn concentrations on fruit quality of tomato under salinity stress

The salt-stressed plants showed significantly lower levels of lycopene (Fig. 3A), vitamin C (Fig. 3B), and protein (Fig. 3C) compared to control plants. Plants treated with Zn10+SS0.5% followed by Zn5+SS0.5% exhibited significantly increased lycopene (Fig. 3A), vitamin-C (Fig. 3B), and protein (Fig. 3C) contents in comparison to SS0.5%-treated plants. When compared with SS1.0%-treated plants, the lycopene (Fig. 3A) and vitamin C (Fig. 3B) contents were significantly increased with Zn10+SS1.0%-treated plants, followed by Zn5+SS1.0%-treated plants, while plants treated with Zn5+SS1.0%, followed by Zn10+SS1.0% displayed significantly increased protein content (Fig. 3C). Similarly, Zn10+SS1.5%-treated plants, followed by Zn5+SS1.5%, had significantly increased lycopene (Fig. 3A), vitamin C (Fig. 3B) and protein (Fig. 3C) contents than SS1.5% plants. These findings suggested that Zn10 rather than Zn5 provided superior fruit quality in tomato fruit stressed by salt.

Impact of different Zn concentrations on nutrient acquisition traits and Na/K ratio of tomatoes under salinity stress

As shown in Table 1, the salt-stressed plants displayed significantly decreased N, P, K, Ca, Mg, Zn, and Fe content and increased Na content and Na/K ratio compared to control plants. When compared with SS0.5%-treated plants, Zn10+SS0.5% treated plants followed by Zn5+SS0.5%-treated plants significantly increased N, P, K, Ca, Mg, Zn, and Fe content, while the Na content and Na/K ratio were significantly decreased in case of Zn10+SS0.5%-treated plants followed by Zn5+SS0.5%-treated plants (Table 1). Again, the P, K, Ca, Mg, Zn, and Fe contents of the plants treated with Zn10+SS1.0% followed by Zn5+SS1.0% showed a significant increase, whereas the Na content and

Table 1. The influence of different Zn concentrations on nutrient acquisition and Na/K ratio of tomatoes grown under different salinity stress levels. The data are presented as means of 3 replicates±SE, with a sample size n=3. Statistical analysis was performed using one-way ANOVA with Tukey post hoc test and different lowercase letters indicating statistically significant differences (P<0.05).

Treatments	Fruit nutrient content								
	N%±SE	P%±SE	K%±SE	Na%±SE	Na/K±SE	Ca%±SE	Mg%±SE	Zn (mg/Kg)±SE	Fe (mg/Kg)±SE
C	0.62±0.046 abc	0.53±0.047 ab	0.61±0.003 b	0.18±0.036 cd	0.30±0.060 c	0.42±0.012 ab	0.44±0.023 ab	50.08±1.305 b	52.42±1.887 ab
SS0.5%	0.37±0.053 de	0.22±0.011 d	0.19±0.043 de	0.89±0.008 a	5.32±1.565 b	0.26±0.012 de	0.22±0.011 cde	23.70±1.274 d	29.00±1.044 d
SS1.0%	0.28±0.059 ef	0.16±0.008 d	0.14±0.020 de	0.89±0.121 a	6.19±0.105 b	0.20±0.035 ef	0.19±0.025 de	19.15±2.621 de	25.67±2.028 d
SS1.5%	0.20±0.017 f	0.12±0.023 d	0.10±0.007 e	0.95±0.075 a	9.60±1.238 a	0.14±0.026 f	0.16±0.010 e	14.19±1.958 e	13.23±1.680 e
Zn5	0.70±0.024 ab	0.53±0.019 ab	0.65±0.007 ab	0.14±0.026 d	0.22±0.041 c	0.46±0.009 a	0.48±0.014 ab	82.66±1.020 a	50.17±3.002 abc
Zn10	0.74±0.004 a	0.62±0.015 a	0.79±0.083 a	0.12±0.024 d	0.16±0.018 c	0.46±0.011 a	0.48±0.026 a	89.03±0.303 a	56.63±4.420 a
Zn5+SS0.5%	0.60±0.026 abc	0.43±0.010 bc	0.41±0.001 c	0.45±0.053 bc	1.09±0.131 c	0.39±0.017 abc	0.43±0.014 ab	44.51±1.194 b	41.49±2.197 bc
Zn10+SS0.5%	0.61±0.008 abc	0.43±0.019 bc	0.41±0.014 c	0.40±0.065 bcd	0.97±0.173 c	0.40±0.009 ab	0.43±0.007 ab	44.93±1.466 b	41.60±1.704 bc
Zn5+SS1.0%	0.55±0.020 bc	0.37±0.013 c	0.40±0.011 c	0.49±0.048 b	1.21±0.095 c	0.36±0.009 bc	0.39±0.009 b	44.36±0.878 b	41.05±0.986 c
Zn10+SS1.0%	0.54±0.038 bc	0.38±0.018 c	0.43±0.018 c	0.41±0.018 bcd	0.94±0.018 c	0.36±0.018 bc	0.42±0.017 ab	44.51±0.789 b	41.34±1.601 bc
Zn5+SS1.5%	0.52±0.014 cd	0.36±0.018 c	0.29±0.047 cd	0.55±0.045 b	1.96±0.323 c	0.32±0.008 cd	0.28±0.028 cd	35.16±2.265 c	40.62±0.980 c
Zn10+SS1.5%	0.54±0.034 bcd	0.42±0.027 bc	0.41±0.002 c	0.51±0.075 b	1.25±0.181 c	0.34±0.014 bcd	0.30±0.015 c	43.67±1.302 b	40.89±2.112 c

C – control, SS0.5% – 0.5% NaCl, SS01.0% – 1.0% NaCl, SS1.5% – 1.5% NaCl, Zn5 – 5 mg kg^{-1} Zn, Zn10 – 10 mg kg^{-1} Zn, Zn5+SS0.5% – 5 mg kg^{-1} Zn+0.5% NaCl, Zn10+SS0.5% – 10 mg kg^{-1} Zn+0.5% NaCl, Zn5+SS1.0% – 5 mg kg^{-1} Zn+1.0% NaCl, Zn10+SS1.0% – 10 mg kg^{-1} Zn+1.0% NaCl, Zn5+SS1.5% – 5 mg kg^{-1} Zn+1.5% NaCl, Zn10+SS1.5% – 10 mg kg^{-1} Zn+1.5% NaCl

Na/K ratio of the Zn10+SS1.0%-treated plants followed by Zn5+SS1.0%-plants exhibited significant decreases compared to those of the SS1.0%-treated plants (Table 1). The N content was significantly increased in Zn5+SS1.0%-treated plants, followed by Zn10+SS1.0%-treated plants compared to SS1.0%-treated plants (Table 1). Likewise, in comparison to SS1.5%-treated plants, Zn10+SS1.5%-treated plants followed by Zn5+SS1.5%-treated plants showed a significant rise in N, P, K, Ca, Mg, Zn, and Fe content, as well as a decrease in Na content and Na/K ratio (Table 1). These findings suggested that the tomatoes' nutritional content was better preserved by Zn10 than by Zn5 under salt stress.

Assessment of treatment-variable interaction in a heatmap and PCA

All of the morphological, biochemical, and yield mean values were used to create a heatmap with hierarchy-based clustering and PCA (Fig. 4). Based on hierarchical clustering, three clusters (I, II, and III) were identified in the variable axis (Fig. 4A). Na and Na/K are present in cluster-I. Cluster I values indicated a tendency towards a decrease in Zn5, Zn5+SS0.5%, Zn5+SS1.0%, Zn5+SS1.5%, Zn10, Zn10+SS0.5%, Zn10+SS1.0%, and Zn10+SS1.5% plants, and a rising trend in SS0.5%, SS1.0%, and SS1.5% plants. The variables P, Fe, Ca, protein (Pro), N, branches per plant at 15 DAT (BR15D), plant height at 45 DAT (PH45D), yield per plant (YP), yield ha^{-1} (YH), plant height at 30 DAT (PH30D), Mg, vitamin-C (VitC), plant height at 15 DAT (PH15D), 60 DAT (PH60D), and 75 DAT (PH75D), flower clusters per plant at 60 DAT (FC60D), and 75 DAT (FC75D), plant height at 90 DAT (PH90D), fruit per plant at 75 DAT (FP75D), and fruit per plant at 90 DAT (FP90D) were included in cluster II. Cluster II parameters indicated a tendency towards decrease for the SS0.5%-, SS1.0%-, and SS1.5%-treated plants, and towards an increase in C in Zn5, Zn5+SS0.5%, Zn5+SS1.0%, Zn5+SS1.5%, Zn10, Zn10+SS0.5%, Zn10+SS1.0%, and Zn10+SS1.5% plants. Cluster III included branches per plant at 30 DAT (BR30D), 45 DAT (BR45D), 90 DAT (BR90D), 60 DAT (BR60D), 75 DAT (BR75D), lycopene (Lyc), Zn, flower clusters per plant at 30 DAT (FC30D), K, flower clusters per plant at 45 DAT (FC45D), fruit per plant at 45 DAT (FP45D), and 60 DAT (FP60D). Cluster III parameters

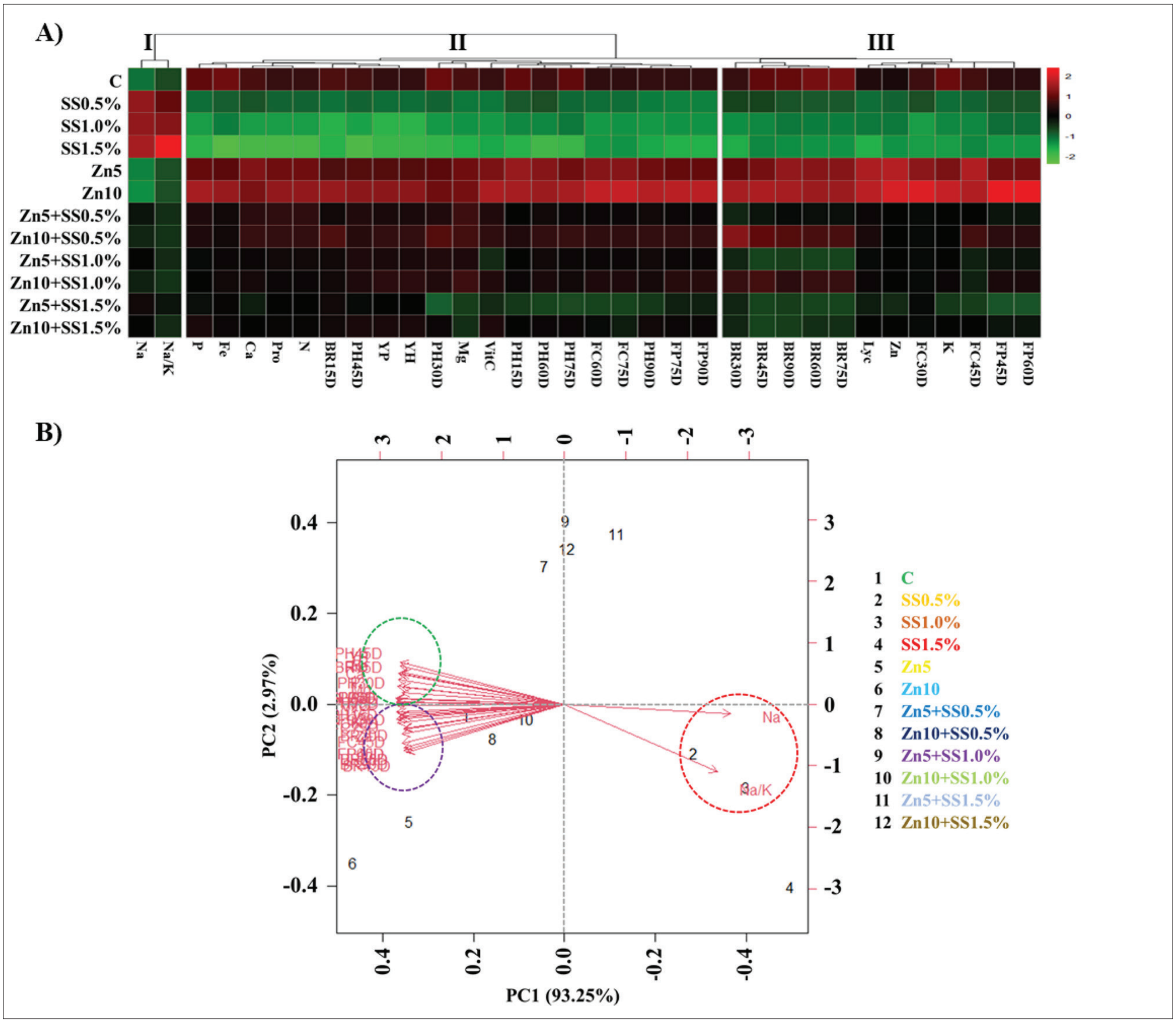

Fig. 4. Principal component analysis (PCA) and a hierarchically clustered heatmap were used to visualize the interactions between the treatments and the studied factors. The scaled average values of every parameter that was examined for the tomato is shown in the **A** – heatmap with a clustering approach. **B –** PCA performed on all data. The studied parameters were plant height at 15 DAT (PH15D), plant height at 30 DAT (PH30D), plant height at 45 DAT (PH45D), plant height at 60 DAT (PH60D), plant height at 75 DAT (PH75D), plant height at 90 DAT (PH90D), branches per plant at 15 DAT (BR15D), 30 DAT (BR30D), 45 DAT (BR45D), 60 DAT (BR60D), 75 DAT (BR75D), 90 DAT (BR90D), flower clusters per plant at 30 DAT (FC30D), 45 DAT (FC45D), 60 DAT (FC60D), 75 DAT (FC75D), fruit per plant at 45 DAT (FP45D), 60 DAT (FP60D), 75 DAT (FP75D), 90 DAT (FP90D), yield per plant[1] (YP), yield ha^{-1} (YH), protein (Pro), vitamin-C (VitC), lycopene (Lyc), N, P, K, Na, Na/K, Ca, Mg, Zn, Fe.

likewise revealed a tendency towards a decrease in plants treated with SS0.5%, SS1.0%, and SS1.5%, and towards an increase in the C in Zn5, Zn5+SS0.5%, Zn5+SS1.0%, Zn5+SS1.5%, Zn10, Zn10+SS0.5%, Zn10+SS1.0%, and Zn10+SS1.5% lines.

In addition, we ran a PCA to explain how treatments SS0.5%, SS1.0%, SS1.5%, Zn5, Zn5+SS0.5%, Zn5+SS1.0%, Zn5+SS1.5%, Zn10, Zn10+SS0.5%, Zn10+SS1.0%, and Zn10+SS1.5% related to clusters I, II, and III (Fig. 4B). In all, PC1 and PC2 showed 96.22% of data variability across the treatments and the examined components of tomatoes (Fig. 4B). PC1 demonstrated 93.25% data variability, and in this case separated the control (C), Zn5, Zn5+SS0.5%, Zn10, Zn10+SS0.5%, and Zn10+SS1.0% from SS0.5%, SS1.0%,

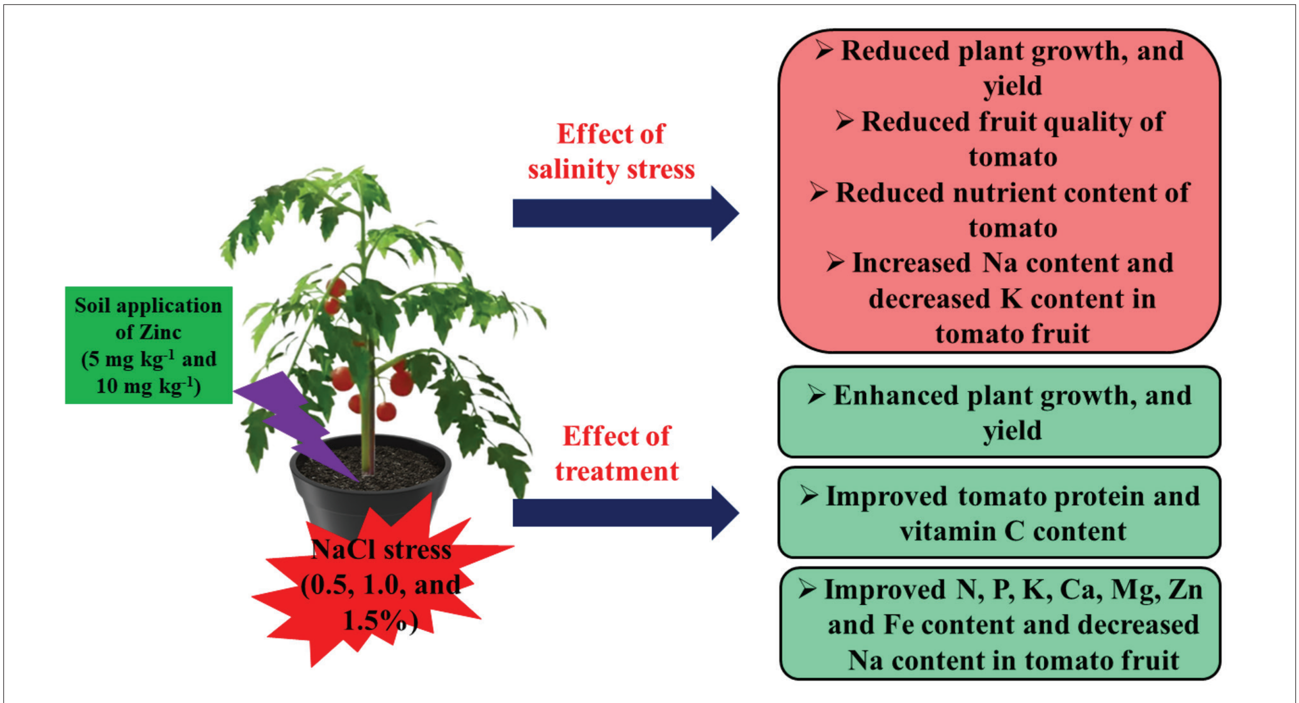

Fig. 5. Simplified chart illustrating the effect of Zn applications on the growth, yield, fruit quality, and nutrient acquisition of tomatoes grown under salinity stress.

SS1.5%, Zn5+SS1.0%, Zn5+SS1.5%, and Zn10+SS1.5% plant treatments for their positive and negative PC scores, respectively (Fig. 4B). PC2 displayed just 2.97% data variability (Fig. 4B).

DISCUSSION

Excess salt in soil or water significantly impacts tomato growth, adversely affecting yield and fruit quality by disturbing nutrient absorption and water balance in plants. Our research revealed that when tomato plants were exposed to salinity stress, all measured factors, including plant growth factors, yield, biochemical constituents, and nutrient acquisition, exhibited their lowest values (Fig. 5). Similarly, Habibi et al. [54] observed that salinity caused a significant reduction in plant height, root length, flower count, photosynthesis, transpiration, and stomatal conductance, and increased leaf temperature; it also caused decreased sugar levels alongside heightened organic acids, MDA, and proline, typical responses to salt stress, ultimately leading to a lower fruit yield compared to the control. Moreover, Salama et al. [27] observed similar outcomes in tomatoes, Tolay [45] reported comparable effects in basil, Aktas et al. [20] in peppers, and Ahmad et al. [55] in mustard, indicating that salinity adversely affected growth, yield, and nutrient composition across these diverse plant species. On the other hand, plant nutrients play a crucial role in crop growth by serving as essential cofactors in enzymatic reactions, influencing processes such as photosynthesis, respiration, nutrient uptake, and stress tolerance [56]. Forghani et al. [34] observed that macronutrients such as K and Ca reduced the ionic imbalance caused by salinity and increased the growth and yield of tomatoes. Potassium humate and silicate were also found to be effective in alleviating the salt stress in tomatoes [36]. Gul et al. [57] observed that the application of exogenous micronutrients, e.g., boron, manganese, and iron, effectively promotes growth parameters, making them beneficial for enhancing cowpea growth in the presence of salt stress. The application of Zn influenced tomato growth, yield, quality, and nutrient composition and proved essential in our study, resulting in the highest values across all measured factors when applied to tomato plants. Zn is an essential plant nutrient, vital for enzyme activation, protein synthesis, photosynthesis, hormone regulation, and nutrient uptake, crucially impacting the growth and development of plants [58].

Research findings have consistently demonstrated that applying Zn enhances the growth and development of various crops [59-60]. According to Prasad et al. [61], the application of zinc resulted in elevated total soluble solids (TSS), titratable acidity, vitamin C, and lycopene content and extended the shelf life of tomatoes. In our study, we observed that the application of zinc had a beneficial effect in counteracting the negative impact of salinity. This included mitigating the reduction in growth, nutrient uptake, and biochemical parameters and potentially improving overall plant health and performance in saline conditions. Several studies also showed that zinc enhanced nutrient and water uptake and chlorophyll synthesis and maintained leaf water balance, mitigating the uptake of toxic ions (Na^+ and Cl^-) and ultimately boosting plant growth and yield in saline conditions [27,62-63]. Aktas et al. [20] found that adequate Zn nutrition potentially limits excessive sodium uptake by roots in saline conditions through its impact on root cell membrane integrity and permeability. Moreover, Zn triggers several biological processes that reduce oxidative stress, such as cell signaling, the promotion of gene expression, and the production of stress-responsive proteins, antioxidants, hormones, and osmolytes [21,54]. Our findings indicate that applying Zn is a promising approach to alleviate salt-induced stress in plants, fostering improved growth and development by optimizing nutrient uptake while minimizing sodium absorption.

CONCLUSIONS

Crops grown under various abiotic stress conditions exhibit better growth, yield, and fruit quality after receiving soil-applied micronutrients like Zn. The treatment with Zn improved growth-related parameters, tomato yield, and nutritional qualities under salt stress. According to this study's findings, 10 mg kg^{-1} Zn performed better for growth promotion, yield, and nutritional qualities of tomatoes under salt stress. In summary, the results indicated that zinc supplementation could lessen the adverse effects of salt stress and is very effective for tomato production, even in saline areas.

Funding: This research was funded by the Ministry of Science and Technology, Bangladesh (No.: 39.00.0000.012.20.011.22.56 Reg. No.: 171).

Author contributions: Conceptualization, Rakibul Hasan Md. Rabbi and Shahin Imran; methodology, Rakibul Hasan Md. Rabbi, Nayema Aktar and Shahin Imran; experiment conduct, Rakibul Hasan Md. Rabbi and Nayema Aktar; formal analysis, Shahin Imran; writing-original draft preparation, Rakibul Hasan Md. Rabbi, Nayema Aktar, Md. Asif Mahamud, Newton Chandra Paul, and Dipok Halder; writing-review and editing, Rakibul Hasan Md. Rabbi and Shahin Imran; visualization, Shahin Imran. All authors have read and agreed to the published version of the manuscript.

Conflict of interest disclosure: The authors declare no conflict of interest.

Data availability: Data underlying the reported findings have been provided as a raw dataset, which is available here: https://www.serbiosoc.org.rs/NewUploads/Uploads/Rabbi%20et%20al_Raw%20dataset.pdf

REFERENCES

1. El Sabagh A, Hossain A, Barutçular C, Iqbal MA, Islam MS, Fahad S, Sytar O, Çiğ F, Meena RS, Erman M. Consequences of salinity stress on the quality of crops and its mitigation strategies for sustainable crop production: an outlook of arid and semi-arid regions. In: Fahad S, Hasanuzzaman M, Alam M, Ullah H, Saeed M, Khan IA, Adnan M, editors.. Environment, Climate, Plant and Vegetation Growth. Cham: Springer; 2020:503-33. https://doi.org/10.1007/978-3-030-49732-3_20
2. Nadeem F, Azhar M, Anwar-ul-Haq M, Sabir M, Samreen T, Tufail A, Awan HU, Juan W. Comparative response of two rice (*Oryza sativa* L.) cultivars to applied zinc and manganese for mitigation of salt stress. J Soil Sci Plant Nutr. 2020;20:2059-72. https://doi.org/10.1007/s42729-020-00275-1
3. Shrivastava P, Kumar R. Soil salinity: A serious environmental issue and plant growth promoting bacteria as one of the tools for its alleviation. Saudi J Biol Sci. 2015;22(2):123-31. https://doi.or/10.1016/j.sjbs.2014.12.001
4. Imran S, Sarker P, Hoque MN, Paul NC, Mahamud MA, Chakrobortty J, Tahjib-Ul-Arif M, Latef AA, Hasanuzzaman M, Rhaman MS. Biochar actions for the mitigation of plant abiotic stress. Crop Pasture Sci. 2022;74(2):6-20. https://doi.org/10.1071/CP21486
5. Rhaman MS, Tania SS, Imran S, Rauf F, Kibria MG, Ye W, Hasanuzzaman M, Murata Y. Seed priming with nanoparticles: An emerging technique for improving plant growth, development, and abiotic stress tolerance. J Soil Sci Plant Nutr. 2022;22(4):4047-62. https://doi.org/10.1007/s42729-022-01007-3
6. Shaaban M, Wu Y, Núñez-Delgado A, Kuzyakov Y, Peng QA, Lin S, Hu R. Enzyme activities and organic matter mineralization in response to application of gypsum, manure and rice straw in saline and sodic soils. Environ Res. 2023;224:115393. https://doi.org/10.1016/j.envres.2023.115393
7. Butcher K, Wick AF, DeSutter T, Chatterjee A, Harmon J. Soil salinity: A threat to global food security. Agron J. 2016;108(6):2189-200. http://dx.doi.org/10.2134/agronj2016.06.0368

8. Islam R, Ahmed R, Dey B, Haque MS, Aktar S, Bhuiyan MS, Arif MS, Ador MA, Haque MM, Saha N. Salinity hazard drives the alteration of occupation, land use and ecosystem service in the coastal areas: Evidence from the south-western coastal region of Bangladesh. Heliyon. 2023;9(8):e18512. https://doi.org/10.1016/j.heliyon.2023.e18512
9. Abbas G, Amjad M, Saqib M, Murtaza B, Asif Naeem M, Shabbir A, Murtaza G. Soil sodicity is more detrimental than salinity for quinoa (*Chenopodium quinoa* Willd.): A multivariate comparison of physiological, biochemical and nutritional quality attributes. J Agron Crop Sci. 2021;207(1):59-73. https://doi.org/10.1111/jac.12363
10. Zhao C, Zhang H, Song C, Zhu JK, Shabala S. Mechanisms of plant responses and adaptation to soil salinity. Innovation. 2020;1(1):100017. https://doi.org/10.1016/j.xinn.2020.100017
11. Shabala L, Zhang J, Pottosin I, Bose J, Zhu M, Fuglsang AT, Velarde-Buendia A, Massart A, Hill CB, Roessner U, Bacic A. Cell-type-specific H^+-ATPase activity in root tissues enables K^+ retention and mediates acclimation of barley (*Hordeum vulgare*) to salinity stress. Plant Physiol. 2016;172(4):2445-58. https://doi.org/10.1104/pp.16.01347
12. Wu H, Zhang X, Giraldo JP, Shabala S. It is not all about sodium: revealing tissue specificity and signaling roles of potassium in plant responses to salt stress. Plant Soil. 2018;431:1-7. https://doi.org/10.1007/s11104-018-3770-y
13. Rubio F, Nieves-Cordones M, Horie T, Shabala S. Doing 'business as usual'comes with a cost: evaluating energy cost of maintaining plant intracellular K^+ homeostasis under saline conditions. New Phytol. 2020;225(3):1097-104. https://doi.org/10.1111/nph.15852
14. Marschner H, editor. Marschner's mineral nutrition of higher plants. Academic press; 2011. https://doi.org/10.1016/C2009-0-63043-9
15. Shabala L, Mackay A, Tian Y, Jacobsen SE, Zhou D, Shabala S. Oxidative stress protection and stomatal patterning as components of salinity tolerance mechanism in quinoa (*Chenopodium quinoa*). Physiol Plant. 2012;146(1):26-38. https://doi.org/10.1111/j.1399-3054.2012.01599
16. Imran S, Mahamud MA, Paul NC, Chakrobortty J, Sarker P, Paul S, Tahjib-Ul-Arif M, Rhaman MS. Seed priming and exogenous application of citric acid enhance seedling growth and photosynthetic pigments and mitigate oxidative damage of soybean (*Glycine max*) under salt stress. Arch Biol Sci. 2023;75(4):407-18. https://doi.org/10.2298/ABS230804033I
17. Hossain MM, Ferdush J, Akter K, Talukder FU, Asaduzzaman M, Imran S. Citric Acid and Hydro-Priming and Exogenous Application Alleviate Salt-Inhibited Seed Germination and Seedling Growth of Chilli (*Capsicum annuum* L.). J. Agric Crops. 2023;9:495-502. https://doi.org/10.32861/jac.94.495.502
18. Umair Hassan M, Aamer M, Umer Chattha M, Haiying T, Shahzad B, Barbanti L, Nawaz M, Rasheed A, Afzal A, Liu Y, Guoqin H. The critical role of zinc in plants facing the drought stress. Agriculture. 2020;10(9):396. https://doi.org/10.3390/agriculture10090396
19. Hamzah SM, Usman K, Rizwan M, Al Jabri H, Alsafran M. Functions and strategies for enhancing zinc availability in plants for sustainable agriculture. Front Plant Sci. 2022;13:1033092. https://doi.org/10.3389%2Ffpls.2022.1033092
20. Aktaş H, ABAK K, Öztürk L, Çakmak İ. The effect of zinc on growth and shoot concentrations of sodium and potassium in pepper plants under salinity stress. Turk J Agric For. 2006;30(6):407-12. https://doi.org/10.3906/tar-0609-2
21. Shao J, Tang W, Huang K, Ding C, Wang H, Zhang W, Li R, Aamer M, Hassan MU, Elnour RO, Hashem M. How does zinc improve salinity tolerance? Mechanisms and future prospects. Plants. 2023;12(18):3207. https://doi.org/10.3390/plants12183207
22. Biondi A, Guedes RN, Wan FH, Desneux N. Ecology, worldwide spread, and management of the invasive South American tomato pinworm, Tuta absoluta: past, present, and future. Annu Rev Entomol. 2018;63:239-58.
23. Rabbi RH, Chowdhury MA, Saha BK. Agronomic approaches to biofortify iron in tomato. J Bangladesh Agril Univ. 2022;20(4):362-72. https://doi.org/10.5455/JBAU.120912
24. Collins EJ, Bowyer C, Tsouza A, Chopra M. Tomatoes: An extensive review of the associated health impacts of tomatoes and factors that can affect their cultivation. Biology. 2022;11(2):239. https://doi.org/10.3390/biology11020239
25. Bangladesh Bureau of Statistics (BBS). Yearbook of Agricultural Statistics. Statistics Division, Ministry of Planning, Govt. of Peoples Republic of Bangladesh. 2023:346-347.
26. Sharma KK, Sachan HK. Effect of varieties and salinity on the growth and yield performance of tomato under greenhouse conditions in central Fiji. Res Crop. 2023;24(3):559-66. http://dx.doi.org/10.31830/2348-7542.2023.ROC-982
27. Salama YA, Nagwa MK, Saleh SA, Zaki MF. Zinc amelioration effects on tomato growth and production under saline water irrigation conditions. Res J Appl Sci. 2012;8(12):5877-85.
28. Alharby HF, Metwali EM, Fuller MP, Aldhebiani AY. Impact of application of zinc oxide nanoparticles on callus induction, plant regeneration, element content and antioxidant enzyme activity in tomato (*Solanum lycopersicum* Mill) under salt stress. Arch Biol Sci. 2016;68(4):723-735. https://doi.org/10.2298/ABS151105017A
29. Alpaslan M, İnal A, Güneş A, Çikili Y, Özcan H. Effect of zinc treatment on the alleviation of sodium and chloride injury in tomato (*Lycopersicum esculentum* (L.) Mill. cv. Lale) grown under salinity. Turkish J Bot.1999;23(1):1-6.
30. Zhang P, Senge M, Dai Y. Effects of salinity stress on growth, yield, fruit quality and water use efficiency of tomato under hydroponics system. Rev Agric Sci. 2016;4:46-55. https://doi.org/10.7831/ras.4.46
31. Farooq H, Bashir MA, Khalofah A, Khan KA, Ramzan M, Hussain A, Wu L, Simunek L, Aziz I, Samdani MS, Alghanem SM. Interactive effects of saline water irrigation and nitrogen fertilization on tomato growth and yield. Fresenius Environ Bull. 2021;30(04):3557-64.
32. Khursheda P, Ahamed KU, Islam MM, Haque MN. Response of tomato plant under salt stress: role of exogenous calcium. J Plant Sci. 2015;10(6):222-33. https://doi.org/10.3923/jps.2015.222.233
33. Shabani E, Tabatabaei SJ, Bolandnazar S, Ghasemi K. Vegetative growth and nutrient uptake of salinity stressed cherry tomato in different calcium and potassium level. Int Res J Appl Basic Sci. 2012;3:1845-53.
34. Forghani A, Forghani A H, Altafi M, Hashemi Majd K, Sofalian O. The effects of different sources of potassium and calcium

on yield and ionic balance of tomatoes under salinity stress in hydroponic cultivation. NBR 2021;8(3):206-219. http://dx.doi.org/10.52547/nbr.8.3.206
35. Khan F, Aman F, Zaman R, Sana MZ, Amir M, Ahmad M. Effect of foliar application of potassium on the growth and yield of tomato (*Solanum lycopersicum* L.) under salinity stress. J Xi'an Shiyou Univ Nat Sci Ed. 2023;19(2):936-62.
36. Elsadek MA, El-Shaieny AH, Hosseny MH, Eldamarany AM. Impact of potassium humate and silicate on alleviation of salt stress in tomato plants. JSAS. 2019;4(1):1-6. https://doi.org/10.21608/jsasj.2019.229222
37. FAO-UNDP. Land Resources Appraisal of Bangladesh for Agricultural Development. Report 2. Agroecological Regions of Bangladesh. 1988. BGD/81/035.
38. Olsen RV, Dean LA, Black CA. Methods of Soil Analysis, Part-2. Wis. 1954;9:966-7.
39. Black AC, Evans DD, White JL, Ensminyer EL, Clark EF. Methods of soil analysis. Madison Wisconsin, USA: American Society of Agronomy; 1965.
40. Jackson ML. Soil Chemical Analysis. New Delhi, India: Prentice Hall of India Pvt. Ltd; 1973. P. 151-4.
41. Page AL, Miller RH, Keeney DR. Methods of Soil Analysis. Part 2. Chemical and Microbiological Properties. Madison Wisconsin, USA: American Society of Agronomy; 1982. 1159 p.
42. Singh J, Sastry ED, Singh V. Effect of salinity on tomato (*Lycopersicon esculentum* Mill.) during seed germination stage. Physiol Mol Biol Plants. 2012;18:45-50. https://doi.org/10.1007/s12298-011-0097-z
43. Gurmani AR, Khan SU, Andaleep R, Waseem K, Khan A. Soil application of zinc improves growth and yield of tomato. Int J Agric Biol. 2012;14(1):91-96.
44. Chanda GK, Bhunia G, Chakraborty SK. The effect of vermicompost and other fertilizers on cultivation of tomato plants. J Hortic For. 2011;3(2):42-5.
45. Tolay I. The impact of different Zinc (Zn) levels on growth and nutrient uptake of Basil (*Ocimum basilicum* L.) grown under salinity stress. PLoS One. 2021;16(2):e0246493. https://doi.org/10.1371/journal.pone.0246493
46. Ranganna S. Handbook of Analysis of quality control for fruit and vegetable products. New Delhi: Tata Me GrawHill pub. Co. Ltd.; 2004.
47. Sharma SK, Le Maguer. Lycopene in tomatoes and tomato pulp fractions. Ital J Food Sci. 1996;2:107-13.
48. Handa SS. An overview of extraction techniques for medicinal and aromatic plants. In: Handa SS, Khanuja SPS, Longo G, Rakesh DD, editors. Extraction technologies for medicinal and aromatic plants. Trieste, Italy: United Nations Industrial Development Organization and the International Centre for Science and High Technology; 2008. p. 21-52.
49. Cramer GR, Alberico GJ, Schmidt C. Salt tolerance is not associated with the sodium accumulation of two maize hybrids. Funct Plant Biol. 1994;21(5):675-92. https://doi.org/10.1071/PP9940675
50. Tandon HLS. Methods of analysis of soils, plants, water and fertilizers. New Delhi: Fertilizer Development and Consultation Organization; 1995.
51. Nielsen SS. Complexometric determination of calcium. In: Nielsen SS, editor. Food analysis laboratory manual. Food science texts series. Boston, MA: Springer; 2010. p. 61-7. https://doi.org/10.1007/978-1-4419-1463-7_8
52. Paul V, Pandey R, Ramesh KV, Meena RC. Atomic absorption spectroscopy (AAS) for elemental analysis of plant samples. In: Paul V, Pandey R, Pal M, editors. Manual of ICAR sponsored training programme for technical staff of ICAR institutes on physiological techniques to analyze the impact of climate change on crop plants. 2017. p. 84-6.
53. Stammer AJ, Mallarino AP. Plant tissue analysis to assess phosphorus and potassium nutritional status of corn and soybean. Soil Sci Soc Am J. 2018;82(1):260-70.
54. Habibi N, Sediqui N, Naoki T, Atsushi S, Koshio K. Effects of salinity on growth, physiological and biochemical responses of tomato. J Int Soc Southeast Asian Agric Sci. 2021;27:14-28.
55. Ahmad P, Ahanger MA, Alyemeni MN, Wijaya L, Egamberdieva D, Bhardwaj R, Ashraf M. Zinc application mitigates the adverse effects of NaCl stress on mustard [*Brassica juncea* (L.) Czern & Coss] through modulating compatible organic solutes, antioxidant enzymes, and flavonoid content. J Plant Interact. 2017;12(1):429-37. https://doi.org/10.1080/17429145.2017.1385867
56. Banerjee A, Roychoudhury A. Role of beneficial trace elements in salt stress tolerance of plants. In: Hasanuzzaman M, Fujita M, Oku H, Nahar K, Hawrylak-Nowak B, editors. Plant nutrients and abiotic stress tolerance. Singapore: Springer; 2018. p 377-90. https://doi.org/10.1007/978-981-10-9044-8_16
57. Gul H, Arif M, Husna YK, Sayyed A. Effect of boron, manganese and iron on growth, biochemical constituents and ionic composition of cowpea grown under salinity. J Appl Environ Biol Sci. 2019;9(3):1-12.
58. Hacisalihoglu G. Zinc (Zn): The last nutrient in the alphabet and shedding light on Zn efficiency for the future of crop production under suboptimal Zn. Plants. 2020;9(11):1471.
59. Hasan MR, Sabil AS, Haque MM, Ahamed KU, Imran S, Mahamud MA. Growth and yield performance of hybrid rice varieties under varying Zn concentrations. Arch Agric Environ Sci. 2023;8(3):281-9. https://dx.doi.org/10.26832/24566632.2023.080302
60. Afrin S, Akhtar N, Hossain F. Application of Zinc Mitigates the Salt-Induced Effects on Growth of Soybean (*Glycine max* L.). Int J Ecotoxicol Ecobiol. 2021;6(3):59-64. https://dx.doi.org/10.11648/j.ijee.20210603.13
61. Prasad PN, Subbarayappa CT, Sathish A, Ramamurthy V. Impact of zinc fertilization on tomato (*Solanum lycopersicum* L.) yield, zinc use efficiency, growth and quality parameters in eastern dry zone (EDZ) soils of Karnataka, India. Int J Plant Soil Sci. 2021;33(7):20-38. https://doi.org/10.9734/ijpss/2021/v33i730447
62. Ahanger MA, Mir RA, Alyemeni MN, Ahmad P. Combined effects of brassinosteroid and kinetin mitigates salinity stress in tomato through the modulation of antioxidant and osmolyte metabolism. Plant Physiol Biochem. 2020;147:31-42. https://doi.org/10.1016/j.plaphy.2019.12.007
63. El-Badri AM, Batool M, Mohamed IA, Khatab A, Sherif A, Wang Z, Salah A, Nishawy E, Ayaad M, Kuai J, Wang B. Modulation of salinity impact on early seedling stage via nano-priming application of zinc oxide on rapeseed (*Brassica napus* L.). Plant Physiol Biochem. 2021;166:376-92. https://doi.org/10.1016/j.plaphy.2021.05.040

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SUPPLEMENTARY MATERIAL

Supplementary Table S1. Initial soil physical and chemical properties

Physical characteristics	**0-15 cm depth**
Textural class	Silty Clay
Sand (%)	11.59
Silt (%)	59.11
Clay (%)	29.30
Chemical characteristics	**0-15 cm depth**
pH	5.38
Total N (%)	0.07
Organic matter (%)	2.16
Extractable P (mg kg^{-1} soil)	3.50
Extractable K (cmol kg^{-1} soil)	0.17
Extractable S (mg kg^{-1})	20.00
Available Zn (mg kg^{-1})	0.36
Available Fe (mg kg-^{1})	25.9
Available Cu (mg kg^{-1})	4.58
Available Mn (mg kg^{-1})	6.35

Supplementary Table S2. Treatment conditions

Treatments	**Acronym**
Control	C
0.5% NaCl	SS0.5%
1.0% NaCl	SS1.0%
1.5% NaCl	SS1.5%
5 mg kg^{-1} Zn	Zn5
10 mg kg^{-1} Zn	Zn10
5 mg kg^{-1} Zn+0.5% NaCl	Zn5+SS0.5%
10 mg kg^{-1} Zn+0.5% NaCl	Zn10+SS0.5%
5 mg kg^{-1} Zn+1.0% NaCl	Zn5+SS1.0%
10 mg kg^{-1} Zn+1.0% NaCl	Zn10+SS1.0%
5 mg kg^{-1} Zn+1.5% NaCl	Zn5+SS1.5%
10 mg kg^{-1} Zn+1.5% NaCl	Zn10+SS1.5%