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RESEARCH ARTICLE

Management of salinity stress in tomato (*Solanum lycopersicum* L.) through zinc nutrition

M Sangeetha[1], K Indhumathi[1]*, M Dhandapani[2], R Parimaladevi[3], A Anuratha[4], C Bharathi[5] & M A Vennila[1]

[1]Indian Council of Agricultural Research (ICAR)-Krishi Vigyan Kendra, Tamil Nadu Agricultural University, Dharmapuri 636 809, Tamil Nadu, India
[2]Tamil Nadu Rice Research Institute, Aduthurai 612 101, Tamil Nadu, India
[3]Department of Renewable Energy, Tamil Nadu Agricultural University, Coimbatore 641 003, Tamil Nadu, India
[4]Agricultural College and Research Institute, Keezhvelur 611 105, Tamil Nadu, India
[5]Department of Agronomy, Tamil Nadu Agricultural University, Coimbatore 641 003, Tamil Nadu, India

*Email: indhumathi.k@tnau.ac.in

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Abstract

Soil salinity is an essential threat to the productivity and quality of vegetable crops. Tomatoes are the major vegetable, and their response to salinity and salinity management strategies has been widely studied. However, the studies evaluating alleviation strategies at the field level are meagre. A field experiment was conducted to research zinc nutrition's effect on salinity stress alleviation in two tomato cultivars. The experiment consisted of two cultivars (PKM 1 and Sivam) and four levels of zinc application as $ZnSO_4$ (0, 25, 50 and 75 kg ha^{-1}) with three replications. The growth, yield, physiological and biochemical parameters were recorded during harvest. Results showed that among the cultivars, Sivam recorded the higher plant height (87.9 cm), number of branches (11.2), dry-matter production (139.6 g plant^{-1}), number of fruits (85.1) and fruit yield (83.2 t ha^{-1}). Growth trends and yield attributes were observed under salinity stress with increasing zinc application levels. The highest fruit yield was recorded in Sivam and PKM 1 with $ZnSO_4$ application at the rate of 75 kg ha^{-1}. Applying ZnSO4 at the rate of 75 kg ha^{-1} recorded higher fruit yields of 33.7 and 92.8 t ha^{-1} in cultivars PKM 1 and Sivam, respectively. The percent increase in yield in cultivar PKM 1 and Sivam over control was 27.1 and 27.8, respectively. Nutrient availability and uptake increased with $ZnSO_4$ application and was the highest at 75 kg ha^{-1}. Physiological parameters *viz.* leaf area, specific leaf area, total chlorophyll content, membrane stability index, and chlorophyll stability index were improved with $ZnSO_4$ application. Proline content was not affected by the $ZnSO_4$ application. The activity of catalase and superoxide dismutase was increased by applying $ZnSO_4$. The correlation of $ZnSO_4$ application with the growth, yield, physiological and biochemical parameters shows that zinc sulphate application positively affects all the factors affected by soil salinity. Hence, applying $ZnSO_4$ at the rate of 75 kg ha^{-1} can be compulsorily recommended for tomato growers of the region to overcome zinc deficiency and boost the fruit yield under saline conditions.

Keywords

cultivars; growth; soil salinity; tomato; zinc nutrition

Introduction

Tomato (*Solanum lycopersicum* L.) is an important vegetable crop and is an inevitable part of various culinary traditions. Its global and national demand for fresh and processed forms is always at considerable quantity comparatively. The area affected by salt is increasing due to various reasons. In India, the area under salt-affected soils is 67.4 lakh hectares, of which 29.5 hectares are saline soils and 37.9 lakh are sodic soils (1). In line with the global and national situation, the number of areas in Tamil Nadu affected by salt is increasing. The area under salt-affected soils is about 3.68 lakh hectares in Tamil Nadu, including 0.13 lakh hectares under sodicity (2). In Krishnagiri and Dharmapuri districts, due to inherent soil salinity, the carbonates and bicarbonate accumulation in topsoil owing to capillary movement induced by soil evaporation causes severe zinc deficiency in tomatoes and causes yield reduction. Zinc is essential for normal vegetative growth, synchronous flowering and fruit maturity in tomatoes. Zinc deficiency causes substantial yield reduction in tomatoes, causing reduced income generation for farmers.

Research indicates the deleterious effect of salt stress on tomatoes regarding growth characteristics and productivity (3-8). The physiological effects are crucial as they represent how a crop responds to stress. The photosynthetic rate, transpiration, relative water content, stomatal conductance, chlorophyll content, and nutrient uptake had a negative impact due to salt stress in tomatoes (4, 5). Biochemical characteristics such as proline accumulation, flavonoids, polyphenol oxides, and peroxide content are affected by salt stress in tomatoes (9, 10). Nutrient uptake is also greatly influenced by tomato salinity (11, 12). Understanding the effects of salt stress on tomato growth and quality is essential for optimizing crop production to meet demand (13).

It is essential to work out practical and user-friendly strategies for salinity management. The various strategies followed to manage the increasing salinity from affecting crop productivity are the application of organic amendments, choice of salt-tolerant crops and varieties, fertilizer application, irrigation method, and phytoremediation. Improving the microbial activity in soils through applications of organic manures, raising green manure crops, crop rotations with pulse crops followed by in situ ploughing, and minimum and zero tillage practices could be effectively followed to manage salinity stress. Applying micronutrients and bioinoculants, as well as practices like seed treatments and foliar applications, can quickly minimize the effects of salinity.

Micronutrients, particularly zinc application, are well known to mitigate salt stress. Zinc is necessary for root cell membrane integrity. It positively influences water nutrient uptake and reduces toxic ions (Na^+ and Cl^-), affecting plant growth and yield under saline conditions. The growth, physiological and biochemical characteristics were improved with zinc under salt stress (14, 15, 16). Membrane stability, pigment concentration, and presence of antioxidants show positive responses to zinc application (17, 18, 19). Applying zinc enhances relative water content, chlorophyll content and activities of the stress hormones (3). With this background, a field experiment was undertaken on tomatoes to study the practical utility of zinc fertilization in mitigating salt stress in terms of growth, yield, and quality.

Materials and Methods

Field experiment

A field experiment was conducted in the farmer's holding at Kooduthuraipatty village in the Krishnagiri district of Tamil Nadu. The experimental site is geographically located at 12°23' N latitude 78°35' E longitude at an altitude of 300 m above mean sea level. The region's mean average annual maximum and minimum temperature were 31.5 °C and 20.8 °C, respectively, and received a normal average yearly rainfall of 850 mm. The field was ploughed twice and levelled correctly. The initial soil samples were collected randomly from ten different places and mixed well, and a representative soil sample was taken using the quartering method. It was processed with a 2 mm sieve. The soil of the experimental site was reddish brown and belongs to sandy loam in texture. The processed soil sample was analyzed for pH and electrical conductivity (EC) with 1:2.5 soil water extract (20). The available nutrients such as nitrogen by alkaline permanganate method (21), phosphorus by 0.5 M $NaHCO_3$ extractant (22), potassium and sodium by neutral normal ammonium acetate extractant (23) and zinc by diethylene triamine penta acetic acid extractant (24) were used for estimation. The field experiment consists of eight treatments which include two factors *viz*., M-cultivars (M1-PKM 1, M2- Sivam) and T- zinc levels (T_1-control i.e., 0 kg $ZnSO_4$ ha^{-1}, T_2-25 kg $ZnSO_4$ ha^{-1}, T_3-50 kg $ZnSO_4$ ha^{-1} and T_4-75 kg $ZnSO_4$ ha^{-1}) in factorial randomized block design with three replications. The treatments were imposed randomly in the field. Tomato seedlings were raised in protrays and 35-day-old seedlings were transplanted by adopting the appropriate spacing of 60 × 45 cm. The recommended dose of 200:250:250 kg NPK ha^{-1} and zinc sulphate was applied per the treatment schedule. The crop was maintained by adopting recommended crop production practices.

Observation and sample analysis

At the time of harvest, growth parameters *viz*., plant height, number of branches per plant, dry weight of the plant and yield attributes *viz*., number of fruits $plant^{-1}$, fruit yield (t ha^{-1}) were recorded. The physiological attributes such as leaf area, chlorophyll content, chlorophyll stability index and membrane stability index were analyzed (25-28). The biochemical characteristics such as catalase, superoxide dismutase and proline content were analyzed using the standard procedure (29-31). During analysis, the instruments were calibrated using the parameters' standards. Fruit samples were analyzed for quality parameters *viz*., ascorbic acid using 2,4-dichlorophenol indophenol dye and total soluble solids by handheld refractometer (Abbe) (32). At the time of harvest, plant samples were collected and analyzed for the nutrient content of nitrogen by microkjeldahl method, phosphorus by vanadomolybdo phosphoric acid, potassium and sodium by flame photometry, zinc by atomic absorption spectroscopy (20, 24). The uptake of each nutrient was calculated using the nutrient content data. Post-harvest soil samples were collected, processed, and analyzed using the standard procedure to determine the available nutrient status.

Statistical analysis

The data recorded on various growth and yield attributes were analyzed using the AGRES statistical software package (33). Critical differences were computed at a 5 % significance level, while treatments not showing significant differences were denoted as non-significant. Heat map analysis of various parameters was done by using the clustvis tool.

Results and Discussion

Growth attributes

The effect of treatments on the growth parameters of tomatoes under salinity stress is presented in Table 1. Results showed that the higher plant height (87.9 cm), number of branches per plant (11.2) and number of fruits per plant (85.1) were recorded in Sivam and the shorter plants (67.1 cm) and lower number of branches per plant (8.8) was recorded in PKM 1. Regarding the zinc levels, the plant height and number of branches per plant showed an increasing trend with increasing zinc levels. Significantly higher plant height (82.4 cm) and number of branches per plant (11.7) were recorded in plots supplied with $ZnSO_4$ at the rate of 75 kg ha^{-1} over the control. The interaction effect between the factors *viz.*, cultivars and zinc levels was non-significant. Among the cultivars and zinc levels, Sivam+$ZnSO_4$ at the rate of 75 kg ha^{-1} recorded higher plant height (92.6 cm) and number of branches per plant (13.3) and PKM 1+ $ZnSO_4$ at the rate of 0 kg ha^{-1} recorded lower plant height (60.1 cm) and number of branches per plant (6.9). The incremental increase in zinc application resulted in increased growth parameters in tomatoes under salinity stress maintained under hydroponics (3). Applying zinc improves tryptophan biosynthesis, thereby increasing plant growth under salinity. Various reports have confirmed the positive effects of zinc on plant growth under salinity stress (14, 16, 34-36).

Table 1. Effect of cultivars and zinc levels on growth and yield attributes of tomato under salinity stress

Treatments	Plant height (cm)			Number of branches per plant			Dry matter production (g $plant^{-1}$)			Number of fruits per plant			Fruit yield (t ha^{-1})		
Zinc levels (kg ha^{-1})	PKM 1	Sivam	Mean	PKM 1	Sivam	Mean	PKM 1	Sivam	Mean	PKM 1	Sivam	Mean	PKM 1	Sivam	Mean
T_1: 0	60.1	82.1	71.1	6.9	9.3	8.1	79.0	129.4	104.2	48.5	75.2	61.8	26.5	72.6	49.6
T_2: 25	66.8	87.2	77.0	8.7	10.2	9.5	85.4	135.6	110.5	55.4	79.3	67.4	28.8	79.0	53.9
T_3: 50	69.1	90.0	79.6	9.6	12.1	10.9	93.5	144.9	119.2	60.3	90.8	75.6	31.6	88.4	60.0
T_4: 75	72.3	92.6	82.4	10.1	13.3	11.7	98.1	148.7	123.4	63.2	95.0	79.1	33.7	92.8	63.3
Mean	67.1	87.9	-	8.8	11.2	-	89.0	139.6	-	56.8	85.1	-	30.2	83.2	-
Treatments	M	T	M×T	M	T	M×T	M	T	M×T	M	T	M×T	M	T	M×T
SED	1.7	2.4	3.4	0.22	0.32	0.45	1.33	1.88	2.66	1.10	1.55	2.19	0.62	0.88	1.25
CD (0.05)	3.6	5.1	NS	0.48	0.68	NS	2.86	4.04	NS	2.35	3.33	NS	1.34	1.90	NS

Dry matter production by the plant was significantly increased by factors such as varieties and zinc levels (Table 1). Among the cultivars, Sivam recorded significantly higher dry-matter production per plant (139.6 g $plant^{-1}$) and lower PKM 1(89.0 g $plant^{-1}$). Regarding the zinc levels, applying $ZnSO_4$ at the rate of 75 kg ha^{-1} recorded significantly higher dry-matter production per plant (123.4 g $plant^{-1}$) and was comparable with $ZnSO_4$ at the rate of 50 kg ha^{-1} (119.2 g $plant^{-1}$). The lowest dry-matter production per plant (104.2 g $plant^{-1}$) was recorded in control. The interaction effect between the factors *viz.*, cultivars and zinc levels was non-significant. The significant variation among the tomato genotypes in dry matter accumulation was reported (12). Similar findings of inheritance of salinity tolerance by the genotypes were recorded in tomato, curry leaf, basil, wheat, beetroot, lettuce, etc. (4, 5, 36-39).

Yield attributes

The number of fruits per plant and fruit yield of tomato was significantly increased by both factors (Table 1). Among the cultivars, Sivam recorded the highest number of fruits per plant (85.1) and fruit yield (83.2 t ha^{-1}). The lowest number of fruits per plant (56.8) and yield (30.2 t ha^{-1}) were recorded in PKM 1. Increased zinc levels increased the number of fruits per plant and the fruit yield of tomatoes. Significantly, the highest number of fruits per plant (79.1) and fruit yield (63.3 t ha^{-1}) were recorded in the treatment plot receiving $ZnSO_4$ at the rate of 75 kg ha^{-1} as against control (61.8 and 49.6 t ha^{-1}). The interaction effect between the factors *viz.*, cultivars and zinc levels was non-significant. Among the treatment combinations, a maximum number of fruits per plant (95) and fruit yield (92.8 t ha^{-1}) were recorded in treatment receiving Sivam + $ZnSO_4$ at the rate of 75 kg ha^{-1}. The minimum number of fruits per plant (48.5) and fruit yield (26.5 t ha^{-1}) were observed in treatment receiving PKM 1 + $ZnSO_4$ at the rate of 0 kg ha^{-1}. Similar results were observed in basil, prosomillet and tomato (3, 16, 36). The reduced deleterious effects of salinity stress by applying zinc on growth and performance may have increased yield (3).

Quality attributes

Quality parameters *viz.*, total soluble solids and ascorbic acid content were significantly higher in Sivam than PKM 1 (Fig. 1). application of zinc sulphate did not considerably improve the quality of tomato fruit. Total soluble solids (3.37 %) and ascorbic acid (22.9 mg $100g^{-1}$) content were higher in the treatment receiving $ZnSO_4$ at the rate of 75 kg ha^{-1}. The lowest total soluble solids (3.2 %) and ascorbic acid (21.8 mg $100g^{-1}$) content were observed in the control. Zinc application is reported to enhance sugar accumulation and modulate metabolic processes (40). Applying zinc in foxtail millet under salinity stress increased ascorbate levels (41).

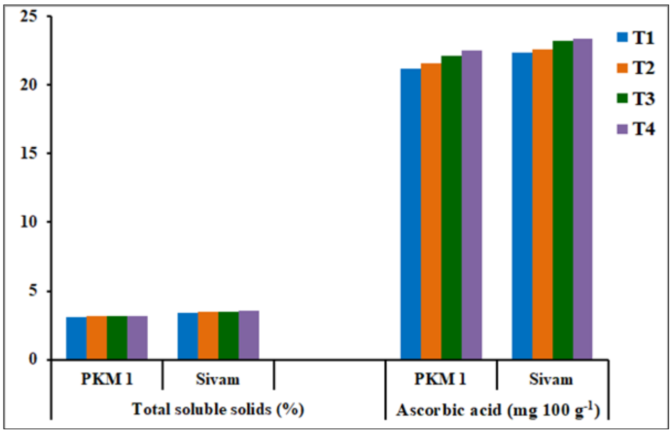


Fig. 1. Effect of cultivars and zinc levels on quality attributes of tomato under salinity stress.

Nutrient uptake

Both the cultivars were significantly different concerning nutrient uptake by crop (Table 2). Uptake of N (2.06 g plant^{-1}), P (0.55 g plant^{-1}), K (2.46 g plant^{-1}) and Zn (6.59 mg plant^{-1}) by crop was maximum in Sivam and minimum in PKM 1. Concerning the zinc levels, application of zinc sulphate at the rate of 75 kg ha^{-1} significantly recorded the higher uptake of N (1.85 g plant^{-1}), P (0.48 g plant^{-1}), K (2.28 g plant^{-1}) and Zn (6.93 mg plant^{-1}) by crop and ZnSO4 followed it at the rate of 50 kg ha^{-1}. The lowest uptake of N (1.45 g plant^{-1}), P (0.31 g plant^{-1}), K (1.66 g plant^{-1}) and Zn (3.0 mg plant^{-1}) by crop was recorded in control. The interaction between cultivars and levels of zinc application was significant for the uptake of Zn, but it was non-significant for the uptake of N, P and K. The maximum uptake of N (2.28 g plant^{-1}), P (0.67 g plant^{-1}), K (2.80 g plant^{-1}) and Zn (9.36 mg plant^{-1}) by crop was recorded in plot receiving Sivam + $ZnSO_4$ at the rate of 75 kg ha^{-1} and minimum was in PKM 1 +$ZnSO_4$ at the rate of 0 kg ha^{-1}.

cation of $ZnSO_4$ at the rate of 75 kg ha^{-1} and higher (0.86 g plant^{-1}) in the control. The reduced uptake of sodium under salinity due to zinc application might be due to a reduction in the activity of plasma membrane-bound nicotinamide adenine dinucleotide phosphate (NADPH) oxidase-producing reactive oxygen species. Zinc application significantly increases the stability of root membranes, alters their ion selectivity and controls sodium uptake under salinity stress (45).

Similar results of increased P, K, and Zn uptake Foliar application of zinc in paddy under salinity in hydroponics showed increased zinc accumulation in shoots (43). In Rosemary, the application of zinc reduced the sodium accumulation and increased potassium sodium ratio and there was also increased uptake of zinc. Zinc application enhanced the salinity tolerance due to flavonoid production and improved osmotic adjustment. Exogenous application of zinc increases the macro and micronutrient content in leaves (44). The decrease in sodium content and concomitant increase in potassium in the plants improve the ionic balance and the performance of maize. Zinc nutrition effectively decreases Na accumulation and improves the K/Na ratio of plants under salinity (45).

Available nutrients

The available nutrient status of the soil was significantly influenced by cultivars and zinc application (Table 3). Among the cultivars, PKM 1 recorded the maximum available N (259 kg ha^{-1}), P (12.5 kg ha^{-1}), K (189 kg ha^{-1}) and Zn (1.05 mg kg^{-1}) content and the minimum was recorded in Sivam. Both the cultivars were significantly different from each other. Regarding the zinc levels, available N, P, K and Zn content showed an increasing trend with increasing zinc levels. Among the different levels of zinc, application of $ZnSO_4$ at the rate of 75 kg ha^{-1} significantly recorded the higher available N (262 kg ha^{-1}), P (13.2 kg ha^{-1}), K (198 kg ha^{-1}) and Zn (1.12 mg kg^{-1}) content of the soil. The available N, P, K and Zn content was minimally controlled. Interaction

Table 2. Effect of cultivars and zinc levels on nutrient uptake of tomato under salinity stress

Treatments	N (g plant^{-1})			P (g plant^{-1})			K (g plant^{-1})			Zn (mg plant^{-1})			Na (g plant^{-1})		
Zinc levels (kg ha^{-1})	PKM 1	Sivam	Mean	PKM 1	Sivam	Mean	PKM 1	Sivam	Mean	PKM 1	Sivam	Mean	PKM 1	Sivam	Mean
T_1:0	1.07	1.82	1.45	0.17	0.45	0.31	1.22	2.10	1.66	1.98	4.02	3.00	0.64	1.09	0.86
T_2: 25	1.18	1.98	1.58	0.21	0.50	0.36	1.42	2.32	1.87	2.82	5.69	4.26	0.63	0.95	0.79
T_3:50	1.34	2.16	1.75	0.27	0.60	0.43	1.60	2.64	2.12	3.55	7.28	5.42	0.61	0.86	0.73
T_4:75	1.42	2.28	1.85	0.29	0.67	0.48	1.76	2.80	2.28	4.50	9.36	6.93	0.51	0.71	0.61
Mean	1.25	2.06	-	0.24	0.55	-	1.50	2.46	-	3.21	6.59	-	0.60	0.90	-
Treatments	M	T	M×T	M	T	M×T	M	T	M×T	M	T	MXT	M	T	MXT
SED	0.029	0.041	0.058	0.015	0.021	0.03	0.024	0.034	0.049	0.10	0.14	0.20	0.019	0.027	0.038
CD (0.05)	0.062	0.088	NS	0.033	0.046	NS	0.052	0.074	NS	0.22	0.31	0.43	0.041	0.058	0.082

Concerning Na, Sivam recorded a significantly higher uptake of Na (0.90 g plant^{-1}) by the crop and lower in PKM 1 (0.60 g plant^{-1}) (Table 2). The plant's uptake of sodium decreased with increasing zinc levels. Among the treatments, the uptake of Na by the plant was significantly lower (0.61 g plant^{-1}) in the treatment plot receiving the appli-

between the cultivars and levels of zinc application was non-significant. Among the treatments, plots receiving PKM 1 + $ZnSO_4$ at the rate of 75 kg ha^{-1} recorded the higher N (267 kg ha^{-1}), P (13.6 kg ha^{-1}), K (205 kg ha^{-1}) and Zn (1.17 mg kg^{-1}) whereas lower N, P, K and Zn content was recorded in Sivam + $ZnSO_4$ at the rate of 0 kg ha^{-1}.

Table 3. Effect of cultivars and zinc levels on post-harvest available nutrient status of soil in tomato under salinity stress

Treat-ments	N (kg ha^{-1})			P (kg ha^{-1})			K (kg ha^{-1})			Zn (mg kg^{-1})			Na (mg kg^{-1})		
Zinc levels (kg ha^{-1})	PKM 1	Sivam	Mean	PKM 1	Sivam	Mean	PKM 1	Sivam	Mean	PKM 1	Sivam	Mean	PKM 1	Sivam	Mean
T_1:0	251	238	245	11.6	10.8	11.2	174	158	166	0.92	0.75	0.84	63.2	57.6	60.4
T_2: 25	254	244	249	12.1	11.5	11.8	185	171	178	0.98	0.82	0.90	58.5	54.3	56.4
T_3:50	262	248	255	12.8	12.3	12.5	193	180	186	1.11	0.93	1.02	52.1	50.7	51.4
T_4:75	267	257	262	13.6	12.8	13.2	205	192	198	1.17	1.07	1.12	50.4	47.1	48.8
Mean	259	247	-	12.5	11.9	-	189	175	-	1.05	0.89	-	56.1	52.5	-
Treatments	M	S	M×S	M	S	M×S	M	S	M×S	M	S	M×S	M	S	M×S
SED	2.17	3.07	4.35	0.24	0.34	0.48	2.41	3.40	4.83	0.02	0.03	0.04	0.88	1.24	1.75
CD (0.05)	4.67	6.59	NS	0.52	0.73	NS	5.18	7.32	NS	0.04	0.06	NS	1.88	2.66	NS

The availability of Na was decreased with the application of zinc. The treatment receiving $ZnSO_4$ at the rate of 75 kg ha^{-1} recorded the minimum available Na (48.8 mg kg^{-1}) and maximum in the treatment without zinc application (60.4 mg kg^{-1}). Similar findings were reported in canola (46).

Physiological parameters

The increasing dose of zinc showed a synergistic effect on the leaf area, specific leaf area and total chlorophyll content (Fig. 2-3). Among the cultivars, Sivam recorded the higher leaf area (48.7 cm^2), specific leaf area (66.0 cm^2 g^{-1}) and total chlorophyll content (1.5mg g^{-1}). Application of $ZnSO_4$ at the rate of 75 kg ha^{-1} significantly recorded the higher leaf area (57.5 cm^2), specific leaf area (72.7 cm^2 g^{-1}) and chlorophyll content (1.65 mg g^{-1}) and lower in control. Among the treatment combinations, plots receiving Sivam + $ZnSO_4$ at the rate of 75 kg ha^{-1} recorded the higher leaf area (67.0 cm^2), specific leaf area (84.4 cm^{2}g^{-1}) and chlorophyll content (1.72 mg g^{-1}). Under salinity stress, the reduction in leaf area and photosynthetic activity are the primary reasons behind the decrease in productivity of crop plants. The application of zinc had a positive effect on the leaf area and chlorophyll content, which, in turn, increased the plant's photosynthetic efficiency. Comparable results were presented by various workers on increased leaf area, leaf area index and leaf chlorophyll contents in various crops by application of zinc to manage salinity stress (47). The increase in chlorophyll content may be due to increased chlorophyll biosynthesis and protection from damage under salt stress (3). Also, zinc is involved in the regulation of magnesium transport, and it may have contributed to the increase in chlorophyll content (42).

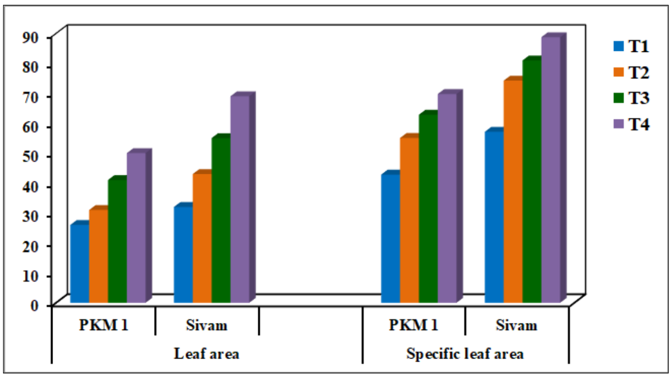


Fig. 2. Effect of cultivars and zinc levels on leaf area (cm^2) and specific leaf area (cm^2 g^{-1}) of tomato under salinity stress.

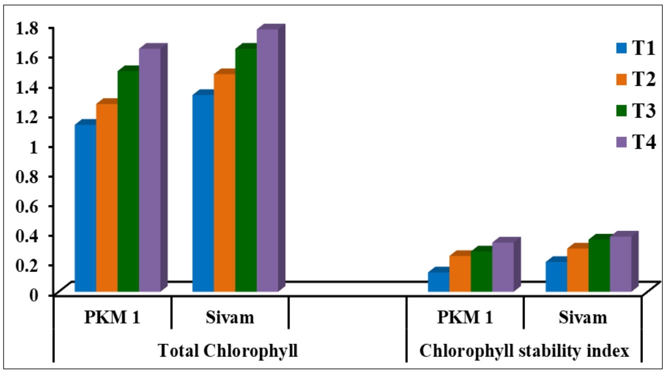


Fig. 3. Effect of cultivars and zinc levels on total chlorophyll content (mg g^{-1}) and chlorophyll stability index of tomato under salinity stress.

The chlorophyll stability index was increased by the application of zinc in the present study (Fig.3). Among the zinc levels, the application of $ZnSO_4$ at the rate of 75 kg ha^{-1} significantly recorded the higher chlorophyll stability index (0.35) and lower (0.16) in control. Zinc application mitigated the negative effect of salt stress by increasing the chlorophyll stability index. The chlorophyll stability index was improved in rice under salinity with the application of zinc, possibly due to its protective role during salinity stress (48). Similar results of an increase in chlorophyll stability index on the application of zinc in prosomillet were reported (16).

Concerning the membrane stability index, the tomato cultivar Sivam recorded higher (63.2 %) and lower in PKM 1 (60.0 %) (Fig. 4). Membrane stability index was

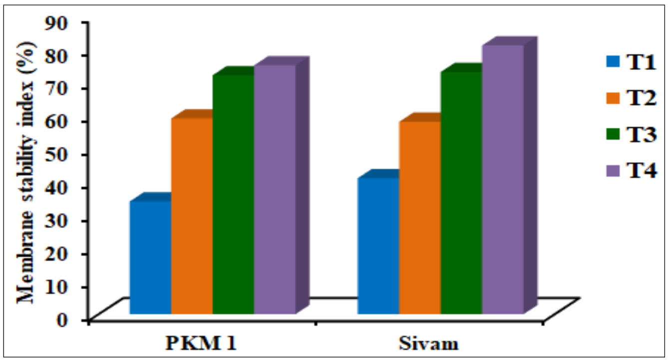


Fig. 4. Effect of cultivars and zinc levels on membrane stability index (%) of tomato under salinity stress.

found to be less in plants without zinc application (37.5 %) compared to the plants applied with zinc sulphate at the rate of 75 kg ha^{-1} (78.0 %). Applying zinc under salinity stress improved the membrane stability index in tomato cultures compared to the control (3). This may be due to the prevention of membranes from oxidative damage. Zinc induces stress tolerance by reducing NADPH oxidase (14). Another possibility of increased stress tolerance by zinc application is reduced sodium uptake, which affects cell membranes' structural integrity and permeability (35).

Biochemical characteristics

The effects of treatments on the biochemical characteristics of tomatoes are presented in Fig. 5. Application of zinc significantly increased the catalase and super oxidase dismutase enzyme activities in both cultivars under salinity stress. Among the zinc levels, applying $ZnSO_4$ at the rate of 75 kg ha^{-1} significantly recorded the higher catalase (74.2µmols of H_2O_2 min^{-1} g^{-1}) and super oxidase dismutase (29.9 U g^{-1}) activities and lower control. Zinc is a co-factor and vital component of antioxidant enzymes such as superoxide dismutase and catalase in detoxifying reactive oxygen species that damage the membrane integrity. The application of zinc did not influence proline content. The maximum proline content was observed in the control (38.5 mg g^{-1}) and the minimum in the treatment receiving $ZnSO_4$ at the rate of 75 kg ha^{-1} (31.4 mg g^{-1}). This is comparable with the results in prosomillet (16). Similar results of reduction in proline content on application of zinc due to the increased activities of peroxidase, superoxidase dismutase and catalase enzymes in tomatoes were reported (3).

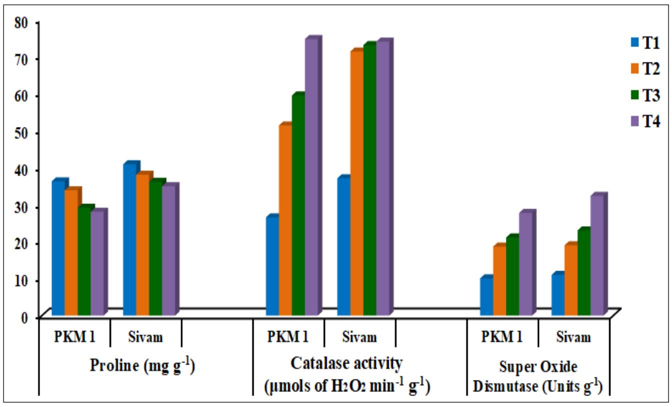
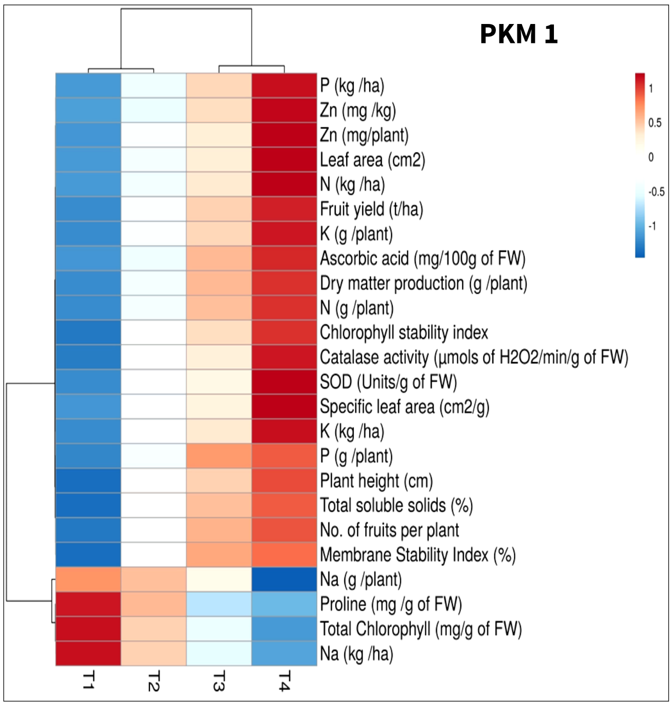


Fig. 5. Effect of cultivars and zinc levels on biochemical characteristics of tomato under salinity stress.

Heat map

The correlation of the application of zinc sulphate with the growth, physiological and biochemical characteristics of both cultivars was presented in Fig. 6. The growth and yield parameters showed positive effects with an increase in the application of zinc sulphate. Though there is an increase in the total chlorophyll content, the correlation was not significant in the heat map. Proline content had no difference with the application of zinc sulphate. Both sodium content in plants and its uptake showed a severe negative correlation with zinc application. This is following the positive effects of zinc in reducing salinity stress.



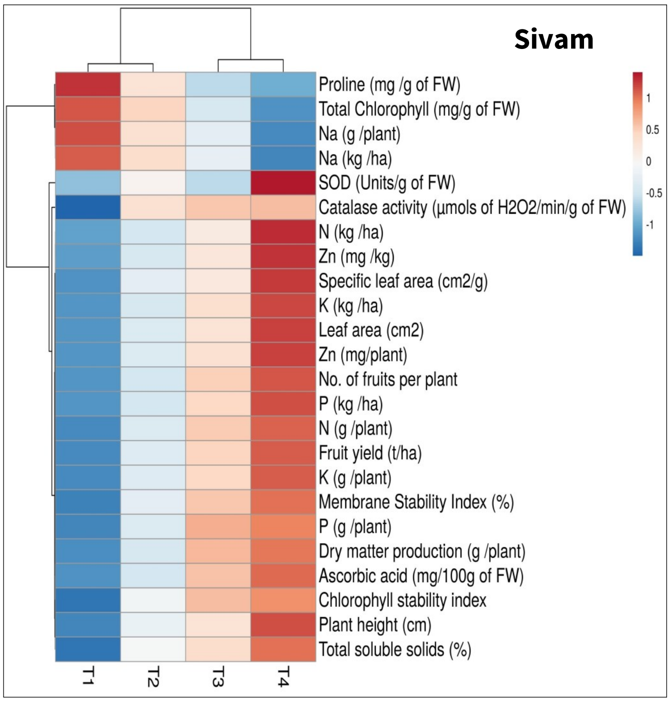


Fig. 6. Heatmap analysis based on the correlation matrix (spearman's) of the variables measured in the salinity-stressed tomato cultivars.

Conclusion

Based on the present study, both Tomato cultivars responded well to zinc application under salinity stress. Zinc application increases plant height, dry matter, yield, membrane integrity, nutrient uptake, and availability, except for sodium. The antioxidant enzyme activities were also enhanced, and physiological and morphological attributes were improved with the application of zinc under salinity stress. Hence, the application of zinc may be recommended as an effective management strategy for alleviating salinity stress in tomatoes. Further studies are needed to optimize the dose and method of zinc application for various crops under various climatic and soil conditions.

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Authors' contributions

MS carried out the field experiment, recorded data, and wrote drafts. KI contributed to sample analysis and manuscript writing. MD helped conduct the field experiment and implement the treatments. RP performed the statistical analysis of data. AA helped analyze soil and plant samples. CB contributed to editing the manuscript. MAV helped edit and revise the manuscript. All authors read and approved the final manuscript.

Compliance with ethical standards

Conflict of interest: Authors do not have any conflict of interests to declare.

Ethical issues: None

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